

# **Cenozoic sedimentary and volcanic rocks of New Zealand: A reference volume of lithology, age and paleoenvironments with maps (PMAPs) and database**

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**2015**



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# **NEW ZEALAND** PETROLEUM & MINERALS

## PETROLEUM REPORT SERIES

# PR4885

**Title**                    **Cenozoic sedimentary and volcanic rocks of New Zealand: A reference volume of lithology, age and paleoenvironments with maps (PMAPs) and database**

**Operator**

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**Date**                    2015

**Summary**             This volume presents descriptive geological data and text about each Cenozoic sedimentary and volcanic geological unit to formation and member level (in some cases) exposed on land in New Zealand, including their lithology, stratigraphic age and inferred environment of deposition or emplacement. These data are illustrated as two types of PMAPS: a present-day paleoenvironment map of New Zealand; and as restored paleoenvironment maps, one for each million years from 65 Ma to the present. These information and data underpin the development of a new Cenozoic paleogeographic model of New Zealand.

This report has been compiled from material submitted to the New Zealand Government under legislation or voluntarily by exploration companies. An acknowledgement of this work in the following bibliographic format would be appreciated:

Kamp, P.J.J., Vincent, K.A. and Tayler, M.J.S. 2015 Cenozoic sedimentary and volcanic rocks of New Zealand: A reference volume of lithology, age and paleoenvironments with maps (PMAPs) and database . Ministry of Business, Innovation and Employment, New Zealand, unpublished Petroleum Report PR4885, 335 p.

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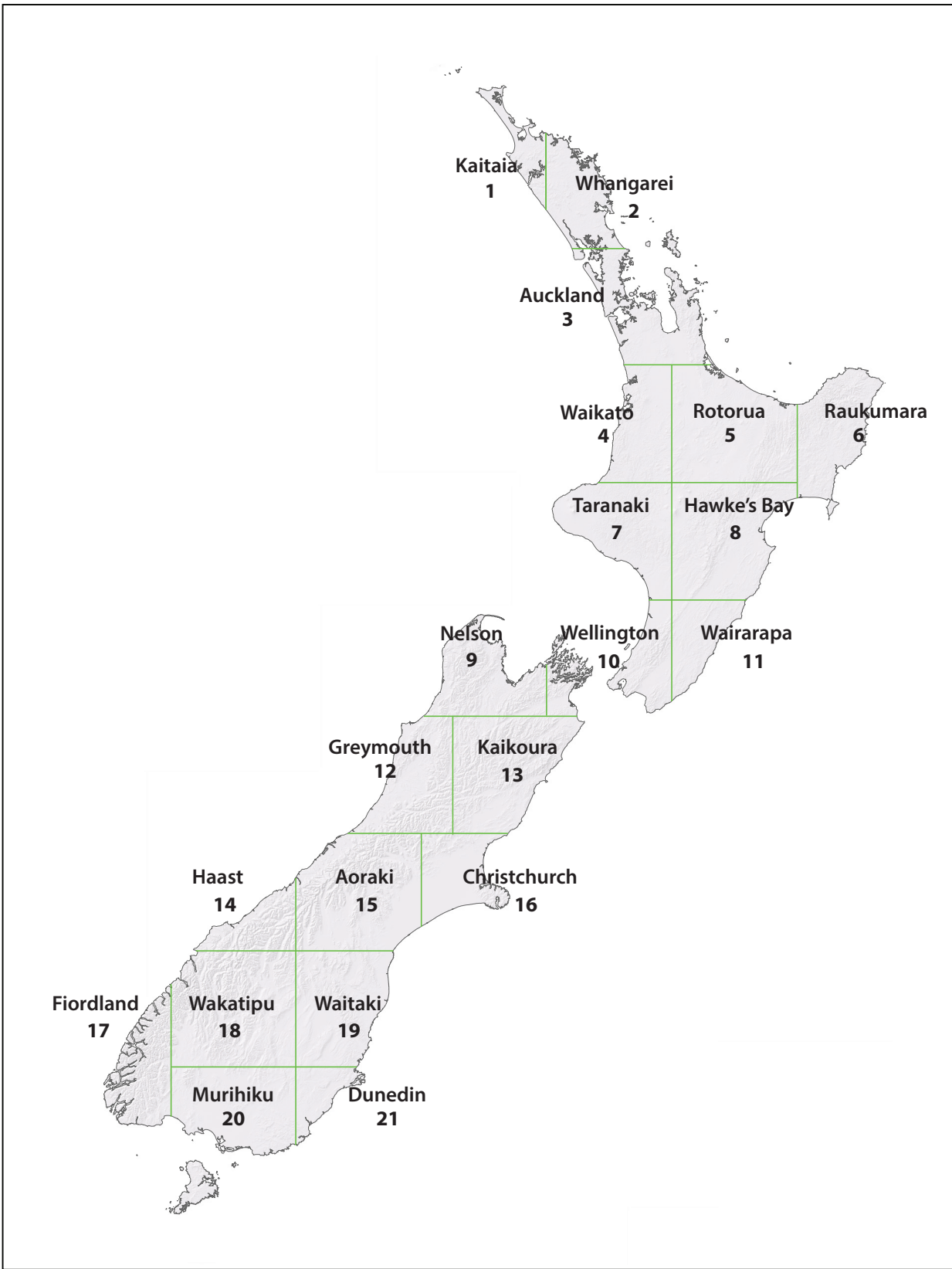
## INTRODUCTION

The Cenozoic geological development of New Zealand essentially involves Paleocene – Middle Eocene subsidence of its continental platform and associated marine inundation, which commenced during the Late Cretaceous, followed by Late Eocene – Recent evolution of the modern Australia-Pacific plate boundary system through the continental platform and associated deformation. To better understand the Cenozoic development of New Zealand we have constructed a numerical model of the deformation resulting from the evolution of the plate boundary system that has driven much of the Cenozoic geological development of New Zealand and its principal expression - changes in paleogeography. Paleogeographic maps have many purposes in scientific endeavours, principal amongst them being the insights they provide for exploration of Earth resources. Well prepared paleogeographic maps can only be constructed at the end of a detailed geological investigation: they embody understanding developed about stratigraphy, age, lithology and paleoenvironments, amongst other characteristics of sedimentary basins. Such maps show the location of sedimentary fairways through time and assist in the development of hydrocarbon plays; that is, concepts about hydrocarbon habitats. How to include the extent of contemporary landforms beyond basin margins (e.g. location of mountain ranges) on paleogeographic maps is a challenge as these features tend to be eroded over time.

Having built a numerical model and successfully tested it against paleomagnetic, structural and thermochronological data sets, we set about using it as the platform to develop a Cenozoic paleogeographic model. The numerical (or tectonic) model incorporates information from basement (Paleozoic – E. Cretaceous) geologic units of New Zealand only; it does not incorporate any elements of Cenozoic stratigraphy or structure because we want to apply the model to gain new insights to the origin of Cenozoic sedimentary and igneous sequences. The importance of having a good tectonic model becomes apparent in the context of there having been about 800 km of dextral displacement through the New Zealand continental platform during the past 27 million years, preceded by substantial extension during 40-27 Ma. Any paleogeographic map series for New Zealand must account for this magnitude of progressive displacement across and along the plate boundary zone. How to do this properly becomes a challenge. The numerical model enables us to restore sedimentary and igneous strata at 1 m.y. intervals to the locations (in a fixed Australia frame of reference) where those strata originally accumulated or were emplaced. This restoration brings into proximity sequences that are now distant from each other as a result of intervening tectonic transport along the plate boundary zone.

The design of our research objectives anticipated completion of the QMAP series, a new set of geological maps of New Zealand at 1:250,000 scale (Rattenbury and Isaac, 2012). This mapping programme resulted in 21 maps covering the on land and near offshore parts of New Zealand (Fig. 1). Importantly, while physical QMAP products and associated bulletins have been published, the mapping programme also resulted in the development of a GIS database containing geological attributes of map units, including their distribution. This has meant that we could “pick up” polygons defining the distribution of geological units and restore them via algorithms built into our numerical model to the localities where those units originally accumulated or were emplaced. To achieve this practically, given that the cells in the numerical model are of 10 x 10 km area and that the QMAP polygons are variable in area and shape, we have represented each of the map polygons as points on our PMAP restored paleoenvironment maps. We restore the locations chiefly of outcrop areas of geological map units, but the method can be applied to the restoration of any geographic or structural feature, including well sites and lineations.

Building a paleogeographic model involves more than the restoration of geological strata, which brings us to the purpose of this volume. It is to document the datasets behind the paleogeographic maps, which necessarily incorporate a level of interpretation. While the interpretations may evolve as new data become available, hopefully the datasets will survive. Thus we have built a GIS data-



**Fig. 1.** Outline of New Zealand showing the name, number and location of published QMAP map sheets (from Rattenbury and Isaac, 2012).

base of the critical features of each of the map units for each 1 m.y. interval from 65 Ma to 1 Ma, including location, lithology and stratigraphic age from which we have assessed paleoenvironments as an intermediate step to the construction of the final paleogeographic maps. The purpose of this volume is to document the data behind the PMAP paleoenvironment maps and to publish these data and maps, whereas the derivative PMAP paleogeographic maps are being published elsewhere. We name the paleoenvironment and paleogeographic map series “PMAP series”. This maintains an obvious link to the QMAP series, while at the same time highlighting differences in the elements represented. The data underpinning the paleoenvironment maps are presented in this volume as text for each geological map unit of Cenozoic age and in the database. Sixty five restored paleoenvironment maps are illustrated here. Each map shows as points the restored positions of QMAP polygons, being sedimentary or igneous units with corresponding age, with the colour denoting the inferred paleoenvironment. The formation/group to which each circle belongs is named on each of these maps. Hence these maps provide the link between the database, the restored geographic positions of formations and the present-day location and distribution of map units.

## **PMAP database and present-day paleoenvironment map of New Zealand**

The paleoenvironment assessments made for each Cenozoic group and formation are illustrated on two types of PMAP paleoenvironment maps. The first is the present-day paleoenvironment map of New Zealand (Fig.2), which shows the extent and paleoenvironment of units in the present-day frame of reference. This map has close parallels with QMAP except that map units are illustrated as paleoenvironments rather than as age units. The second type of PMAP paleoenvironment map we refer to as “PMAP restored paleoenvironment maps” (see below).

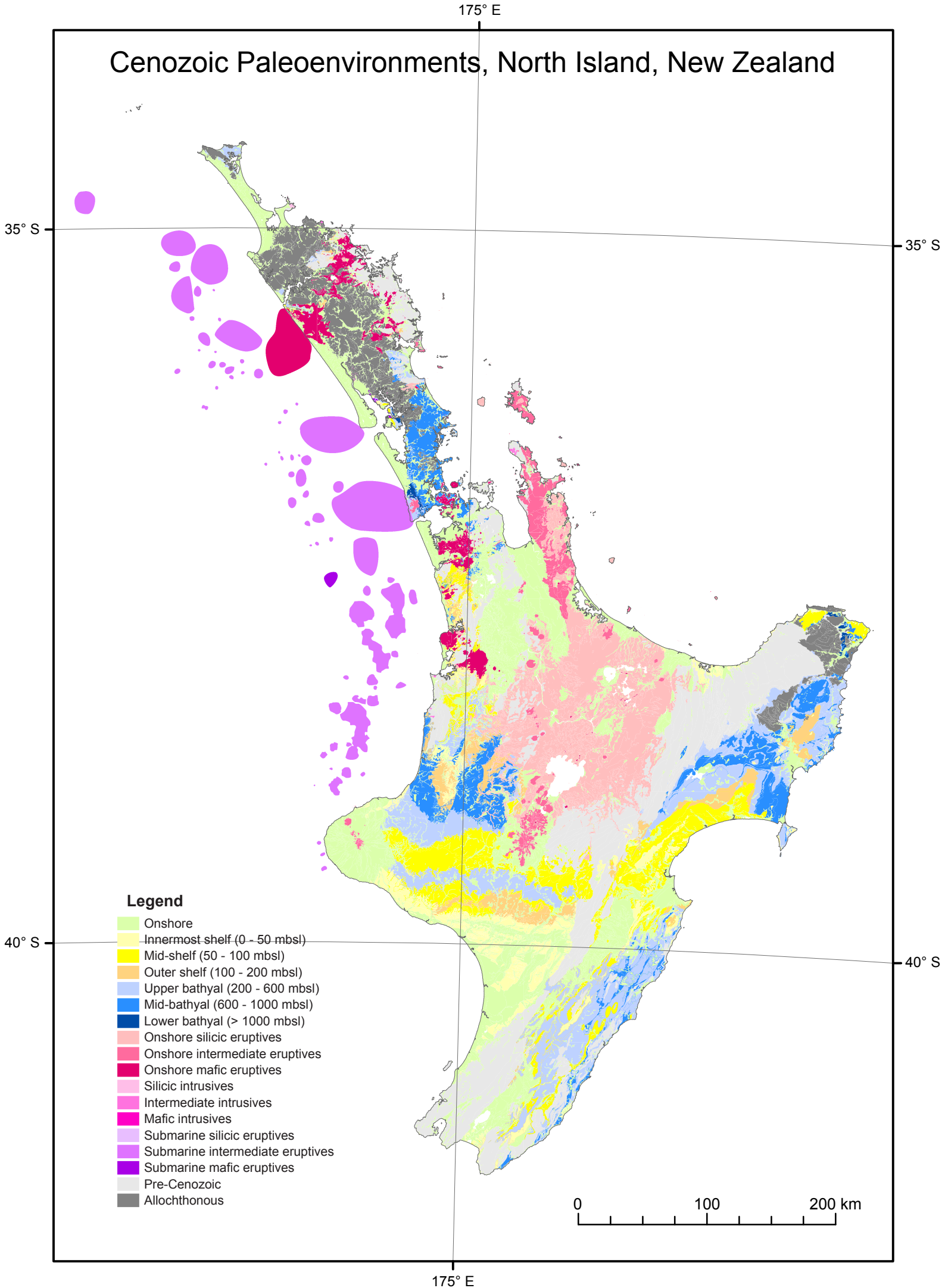
The PMAP GIS database has fields inherited from the QMAP database including: *QMAP* area in which the polygon is located; *Unit code*; *Strat unit* (stratigraphic name of unit); *Main rock* (dominant lithology); *Sub rocks* (other lithologies); and *Map unit* (deposit type). The new fields generated for the PMAP database include: *complex en* (complex environment - the code applied to distinguish units that have multiple paleoenvironments (see “Pre-Quaternary undifferentiated map units and map units with multiple paleoenvironments”)); *duplicate* (relating to complex environments. The youngest formation/member/lithofacies of a unit is duplicate 1; the second youngest is duplicate 2, and so on.); *enviro* (environment of deposition); *min code* (minimum numerical age); and *max code* (maximum numerical age).

The PMAP database is available as an interactive ArcMap document (Enclosure 1) (Other formats available on request). Its value lies in the ability of an operator to identify and select a particular Cenozoic map unit (in the present-day frame of reference) displayed as its inferred paleoenvironment (Fig. 2), assessed by reference to information in the literature and a sedimentological model (Fig. 3). Such a unit can be cross-referenced to the PMAP restored paleoenvironment map of corresponding age (Fig. 4) that shows the location of that unit when it accumulated or was emplaced. The map units/formations are labelled on each paleoenvironment map (Fig. 4), which enables a link to be easily made with their present-day location.

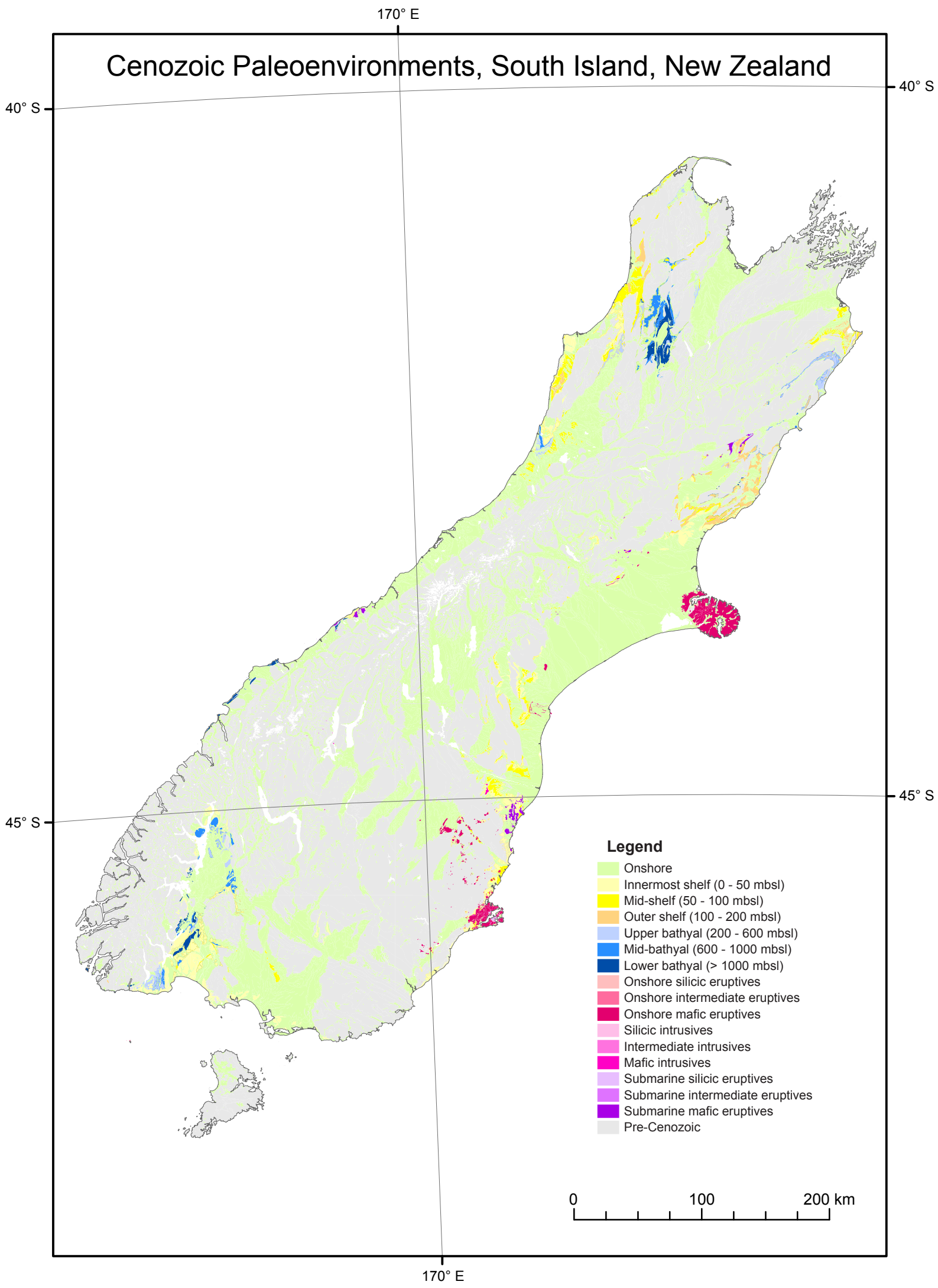
On the paleoenvironment PMAPs, paleoenvironments are classified into the following categories: onshore; innermost, mid- and outer shelf; and upper, mid- and lower bathyal, and include reworked deposits such as lahars and allochthonous units (Fig. 4). Primary igneous rocks are also defined in the database and illustrated (but not labelled) on paleoenvironment maps.

**Fig. 2.** (following pages) PMAP of North Island (A) and South Island (B) in which Cenozoic map units are displayed as inferred paleoenvironments in the present-day frame of reference.

# Cenozoic Paleoenvironments, North Island, New Zealand



# Cenozoic Paleoenvironments, South Island, New Zealand





## Refinement of age of map units

Given the temporal resolution sought for our PMAPs (1 m.y.), it was necessary to refine the stratigraphic age range of map units as defined in the associated database and assign a whole number numerical age. A feature that became evident in this project is that stratigraphic age recorded in the QMAP database varied in precision and duration for units from one sheet to another. Another issue was how to resolve the age of sedimentary units at 1 m.y. intervals when New Zealand Cenozoic Stages to which they are ascribed have durations that may be longer than 1 m.y. (Cooper et al., 2004). There are geological constraints provided by superposition, continuous sedimentation and conformable contacts, therefore we needed to make judgements for particular map units about their age ranges from published data. To assist in this process we appealed to information in Stratlink (Boyes et al., 2011a, b and 12; King et al., 2010), published chronostratigraphic panels (King et al., 1999), FRED (Fossil Record Electronic Database) and data in geological bulletins and journal articles. Radiometric age data are available for many of the igneous Cenozoic rocks of New Zealand and these were accordingly applied. The 1 Ma paleoenvironment map represents 0.5 to 1.5 Ma, the 2 Ma map represents 1.5 to 2.5 Ma and so on back to the first map (65 Ma), which represents 64.5 to 65.5 Ma. Hence, there are 65 maps in the PMAP restored paleoenvironment map series.

To assign a whole number numerical age the stratigraphic age had to be rounded to a whole number such that 0.0 – 0.49 was rounded down and 0.5 – 0.99 was rounded up. As an example, a unit which is defined as, say, Otaian to Waitakian in age, has an absolute age range of 18.7 – 25.2 Ma (after New Zealand Geological Timescale 2010/1, Hollis et al., 2010). This means that it will be present on restored Paleoenvironment Maps 41 – 47 (i.e. 25 – 19 Ma). In the PMAP database this information is contained within fields labelled: “Min\_Code” and “Max\_Code”.

## Method of assigning inferred environments of deposition (EoD)

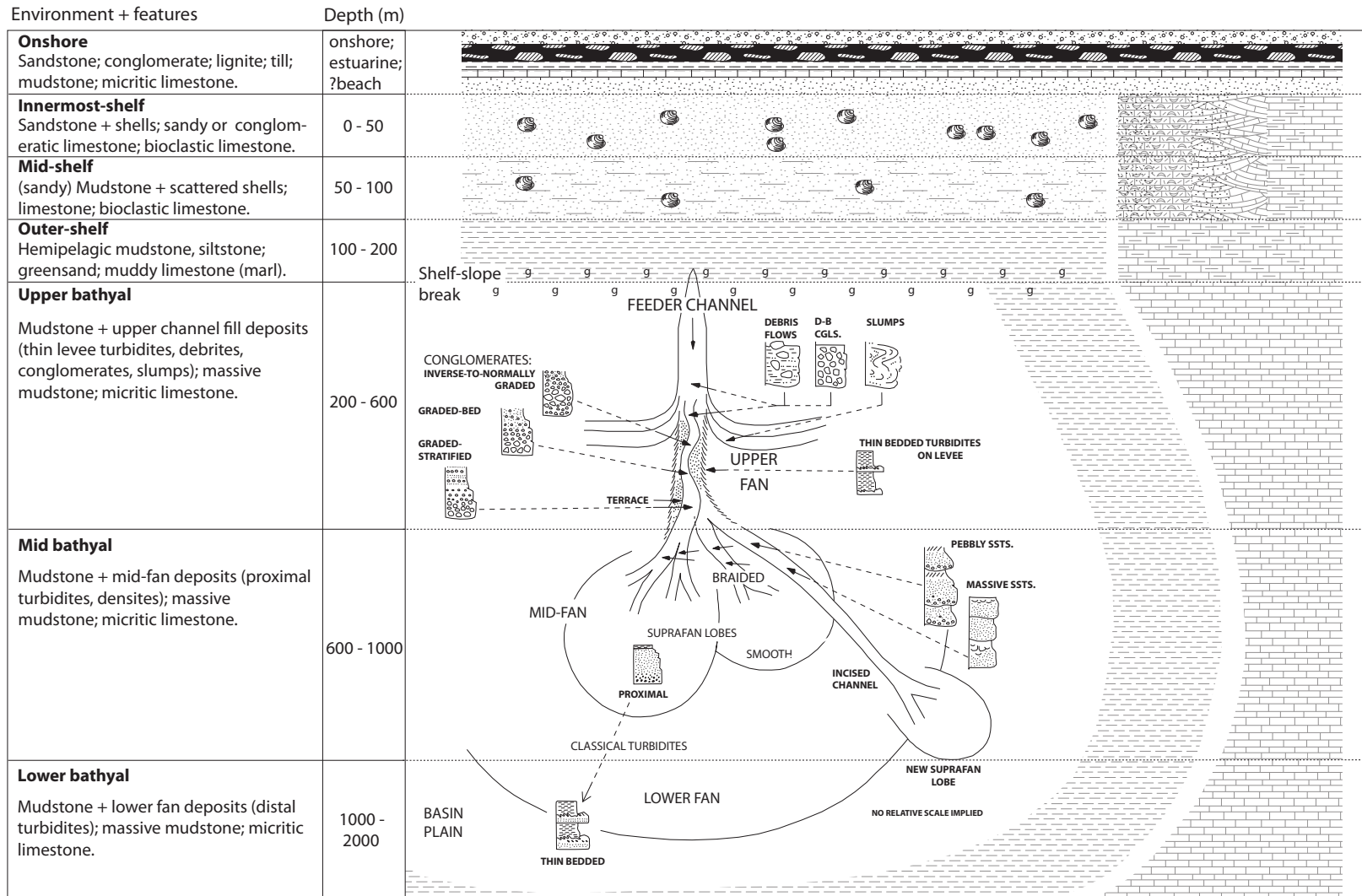
### Pre-Quaternary differentiated map units

The assignment of inferred paleoenvironments to PMAP representations of QMAP polygons are based upon published sources, including QMAP bulletins, New Zealand Geological Survey bulletins, monographs, journal articles, theses, and conference proceedings. These interpretations were tested against our facies model (Fig. 3), which is a general description of the facies characteristics of onshore, shelf and slope deposits. Where no paleoenvironmental interpretation was published for a particular map unit, we referred to the “Main\_Rock” type, “Sub\_Rocks”, and “Description” in the QMAP database and the EoD was inferred from the lithologic description in relation to the facies model (Fig. 3).

If a range of paleoenvironments occur within a single map unit and it is not possible to subdivide the unit stratigraphically or geographically, an average environment of deposition has been assigned to the map unit. An example would be a map unit composed of cyclothems varying in paleoenvironment from innermost shelf to outer shelf. In this case the map unit could be assigned an average mid-shelf depositional paleoenvironment.

### Pre-Quaternary undifferentiated map units and map units with multiple paleoenvironments

Undifferentiated map units can contain several formations, members and/or lithofacies, with each formation/member/lithofacies potentially representing a different paleoenvironment but only one EoD can be assigned to such map units for a particular interval. This issue is partially resolved in this project by giving the undifferentiated map unit multiple paleoenvironments based on the interpreted EoD of its component formations/members/lithofacies. Periods of deposition dominated by a particular component of the undifferentiated unit are assigned that component's EoD. In



**Fig. 3:** Facies and paleoenvironment model used in this report to define the depositional environment of map units. Water depth zones after Hayward et al. (1999, Fig. 40). Onshore facies and environments after Flügel (2010); marginal marine facies and environments after Ekdale et al. (1984); clastic shelf facies after Vonk et al. (2002) and Reading (1996); carbonate shelf facies from Caron et al. (2004) and Reading (1996); micritic limestone facies and environments after Flügel (2010); muddy limestone (marl) facies and environments after Abramovich et al. (2002) and Zachos et al. (1989); and submarine-fan deposition model after Walker (1978). The optimal depth for glaucony (“g”) formation is considered in Odin and Fullagar (1988) to be c. 200 m (outermost shelf – upper slope).

the PMAP database this information is contained in the fields “Complex\_En” and “Duplicate”. The youngest formation/member/lithofacies of a unit is duplicate 1; the second youngest is duplicate 2, and so on. An entry in the “Complex\_En” field may look like this: 13\_Mm\_is\_lb

Where “13” = QMAP number (13 is the Kaikoura Sheet), “Mm” = the unit code (Mangles Formation) and the final set of letters is the total range of EoDs exhibited by this unit. The EoD codes are abbreviated as follows:

ons	onshore	ub	upper bathyal
is	innermost shelf	mb	mid-bathyal
ms	mid-shelf	lb	lower bathyal
os	outer shelf		

This approach does not account for lateral changes in paleoenvironment of undifferentiated map units during an interval. An example of this limitation could be as follows: an undifferentiated unit composed of two formations, Formation A and Formation B, is deposited during 19 Ma to 18 Ma. Formation A consists of upper bathyal deposits and accumulated during 19 Ma to 18 Ma. Formation B consists of mid-shelf deposits and accumulated at 18 Ma. The undifferentiated unit is assigned an upper bathyal EoD for the 19 Ma interval based on the presence of only upper bathyal Formation A. However, at 18 Ma the undifferentiated unit consists of both upper bathyal Formation A and mid-shelf Formation B. This issue is dealt with in this project by basing the undifferentiated unit’s EoD at a particular interval on the paleoenvironment of the dominant formation/member/lithofacies that accumulated during that interval. Additionally, subsidiary areas of an undifferentiated unit (north, south etc.) are noted and referred to when interpreting the derivative paleogeographic map from the parent paleoenvironment map.

A differentiated map unit can also contain a variety of lithofacies, each representing a different depositional environment. These map units are handled in the same way as undifferentiated map units.

### Quaternary map units

The paleoenvironment of most Quaternary deposits are defined in the QMAP database and generally can be assigned either an onshore or shelfal EoD. Dune, estuarine, marine terrace and beach deposits occur near the shoreface-onshore transition and their respective depositional environments are treated as follows: (1) dune and estuarine sediments are defined as onshore deposits, (2) marine terrace sediments are defined as innermost shelf deposits, (3) beach sediments can include both marine and onshore deposits and are defined in this report on a case by case basis, attempting to maintain consistency within geographic areas.

### Primary igneous units

Primary igneous rocks are classified initially by environment into onshore eruptives, intrusives and submarine eruptives. These divisions are further subdivided by silica content into silicic, intermediate and mafic products. The assignment of these environments and compositions was based on the QMAP database, which generally indicates a mechanism of emplacement (e.g. tuff, plug, or pillow lava) and compositional rock type (e.g. rhyolite, diorite, hawaiite). Published information is also used to assign an EoD for some primary igneous units.

Reworked volcanic material (e.g. lahar, fluvial) is assigned a sedimentary EoD (e.g. onshore, innermost shelf) because it is not necessarily by volcanic processes that it accumulated at its present-day location. Its age is therefore the age of the event that resulted in its present location. Volcanic ash that has settled through a water column is treated as a primary volcanic deposit.

## Allochthonous units

Allochthon units are assigned an allochthonous EoD.

## New map units

In some cases we created new polygons/map units in this project. An example are polygons for volcanic edifices, particularly along offshore western North Island.

## Note regarding unit code

Unit codes on several QMAP sheets are different to the unit codes for the related units in the QMAP database. A unit code in the database is given priority in this report.

The QMAP database contains occasional spelling errors and sometimes incomplete entries. Where this occurs, the information is entered in the PMAP database project as in the QMAP database (to allow for ease of use between the two projects). Where this applies to a stratigraphic name (Strat\_Unit) in the QMAP database, it has been corrected and updated in the PMAP database and subsequent products.

## Layout of text information in this volume

This report is divided into chapters by QMAP area. Each chapter then presents the different map units chiefly by age, but sometimes by geographic area and then by age (e.g. Kaikoura Sheet, which divides Cenozoic units into those southeast of the Alpine Fault and then into those northwest of the Alpine Fault). There is some duplication of information from one chapter to another where stratigraphic groups and formations extend across boundaries of neighbouring map sheets, but this is tolerated in the context that this is a reference volume that will be accessed chiefly by users probably working within particular map sheets. We show below examples of the layout of text about environment of deposition (EoD) and stratigraphic age of map units within each map sheet.

## Differentiated units

### MAP AREA (Geological Map name and number)

#### Group Name

*Map unit (unit code as from database)*

***Inferred age:*** X-Y Ma (with reference)

***EoD:*** interpreted environment of deposition

***Basis for interpretation:*** Lithologic descriptions and inferred EoD interpretations are given in normal type based on QMAP database and bulletin text, and other published sources. Environments, water depths or terms relating to EoD of the unit are in bold type – the reasoning behind assignment of the EoD is given in the text in italics. Other possible inferred depositional environments are given in italics and are underlined.

## Undifferentiated units and units with multiple environments

### Group name

#### *Map unit (unit code as from database)*

Additional formations, members, and/or lithofacies included within the map unit (if applicable).

Information relevant to the map unit as a whole, e.g. lithologic description and EoD interpretation are given in normal type based on QMAP database and bulletin text, and other published sources. Environments, water depths or terms relating to EoD of the unit are in bold type.

- Formation/Member/lithofacies name

Information relevant to the specified formation, member and/or lithofacies, e.g. lithologic description and EoD interpretation are given in normal type based on QMAP database and bulletin text, and other published sources. Environments, water depths or terms relating to EoD of the unit are in bold type.

**EoD:** interpreted environment of deposition

***Basis for interpretation:*** the reasoning behind assignment of the EoD is given in the text in italics. Other possible inferred depositional environments are given in italics and are underlined.

***Inferred age:*** X-Y Ma (reference)

***EoD break down:*** A-B Ma: interpreted EoD (stratigraphic units that accumulated during the specific period)

C-D Ma: interpreted EoD (stratigraphic units that accumulated during the specific period)

***Basis for interpretation:*** the reasoning behind assignment of the EoD is given in the text in italics. Other possible inferred depositional environments are given in italics and are underlined.

## ACKNOWLEDGEMENTS

We wish to acknowledge the use we have made of the QMAP database and related bulletins (published by GNS Science Ltd) in the development of our PMAP database and the text of this volume, amongst other published sources and our own information. We thank Kadin Lucas and Betty-Ann Kamp for assistance in producing this volume. We also acknowledge research funding from the New Zealand Ministry of Business, Innovation and Employment (Contract: UOWX0902).

## **CENOZOIC PMAP RESTORED PALEOENVIRONMENT MAP SET FOR ON LAND NEW ZEALAND**

Two types of PMAP paleoenvironment maps are presented in this volume. One is the present-day paleoenvironment map of New Zealand described above and shown in Fig. 2. The second type of paleoenvironment map, which we describe and illustrate below (Fig. 4) is referred to as the Cenozoic PMAP restored paleoenvironment map set for on land New Zealand. This set of restored paleoenvironment maps has been produced to show the positions occupied by geological formations at the time of their accumulation or emplacement and the associated depositional paleoenvironments. The restoration has been accomplished through application of our numerical model that describes for 10 x 10 km cells the deformation through New Zealand in response to the development of the Australia–Pacific plate boundary system. Each QMAP polygon for mapped formations or groups was assigned to the nearest cell in the present day frame of reference and then relocated to its paleo position at the time of its accumulation or emplacement. GIS polygons are represented as points on the maps, effectively being the nodes of the 10 x 10 cells of the numerical model somewhat enlarged. The numerical model, the method underpinning it and its assumptions are described in a paper being published elsewhere. A strength of this model is that it deals with the whole plate boundary system; that is, it addresses the whole of the on land geology of New Zealand, the sum of its deformation and all elements of the plate boundary interactions, and it has been validated against multiple geological and geophysical data sets.

Each of the restored points on the maps has a colour, which represents the inferred sedimentary or igneous environment (see Legend below). All points are labelled with the formation or group name and this may enable users to access the text or database for information about specific units. Alternatively, users may access the maps for the restored positions of formations through time and for the wider context of their paleoenvironmental setting. Points representing the same formations are grouped using either black (default), red or blue polygons, which have no meaning other than to help differentiate points having the same formation or group names and paleoenvironments where there is overlap.

In this volume we do not describe the patterns that emerge from the restored paleoenvironmental information or from the succession of paleoenvironments across New Zealand. As mentioned above, these paleoenvironmental data are input to the PMAP paleogeography map series, which we describe and interpret elsewhere. Those maps also integrate data from the offshore shelf and slope areas of New Zealand and hence have a more extended context, which is appropriate to better understand the depositional systems that formed and evolved during the Early Cenozoic marine inundation of New Zealand and the subsequent marine offlap that accompanied the later stages of the development of the Australia-Pacific plate boundary system.

## Legend - paleoenvironments

### Sedimentary

- O - Onshore
- IS - Innermost shelf (0 - 50 mbsl)
- MS - Mid-shelf (50 - 100 mbsl)
- OS - Outer shelf (100 - 200 mbsl)
- UB - Upper bathyal (200 - 600 mbsl)
- MB - Mid-bathyal (600 - 1000 mbsl)
- LB - Lower bathyal (> 1000 mbsl)
- Allochthonous

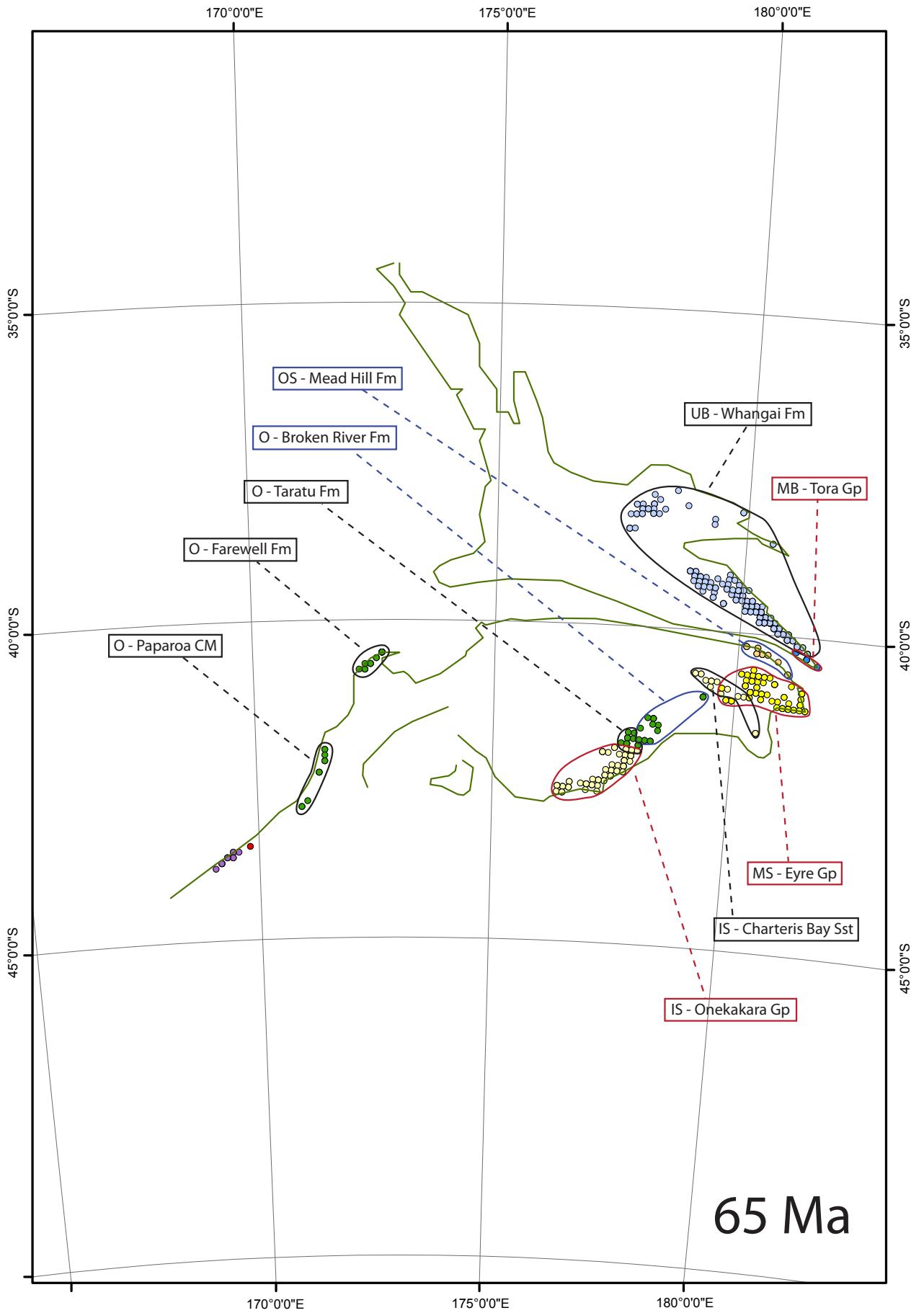
### Igneous

- Onshore eruptives
- Intrusives
- Submarine eruptives

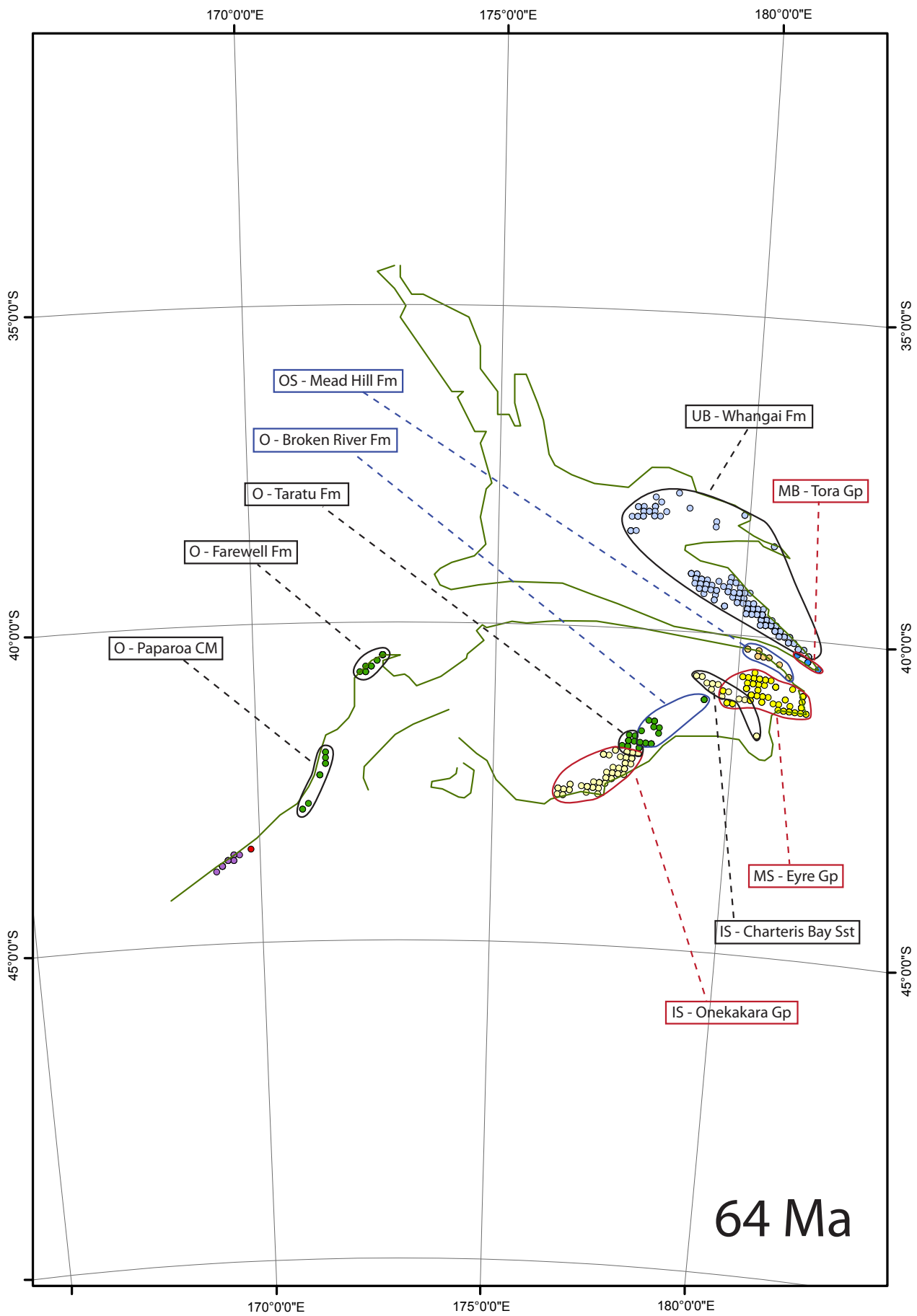


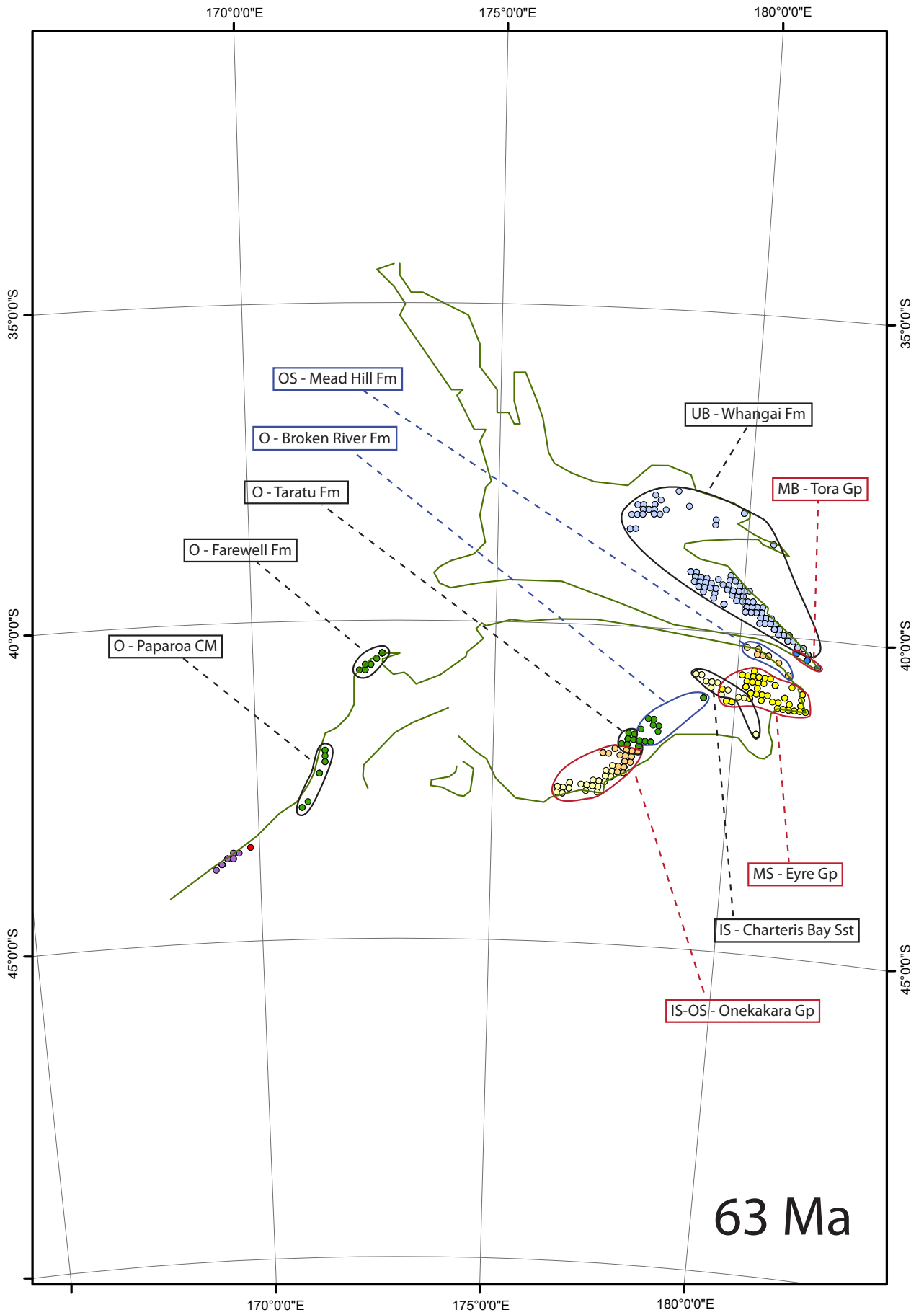
“Shoreline” projected back in time.  
Location of rocks beneath the present day shoreline projected back through time from our numerical model.

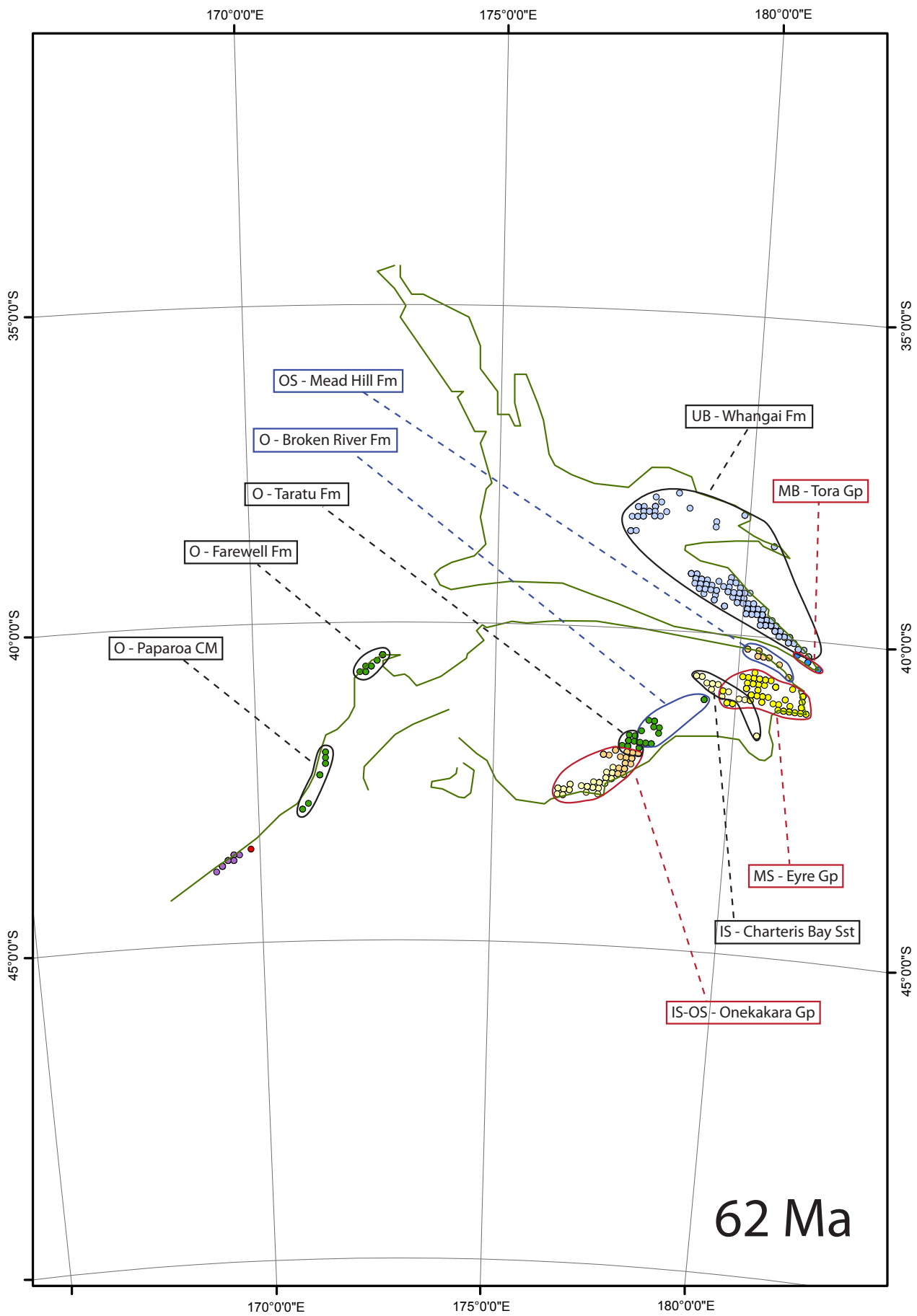
**Fig. 4.** (following pages) Set of restored paleoenvironment maps (part of the PMAP Series) constructed for 1 m.y. intervals through the Cenozoic from 65 Ma (Map 1) to 1 Ma (Map 65). The Legend for the maps is shown above.

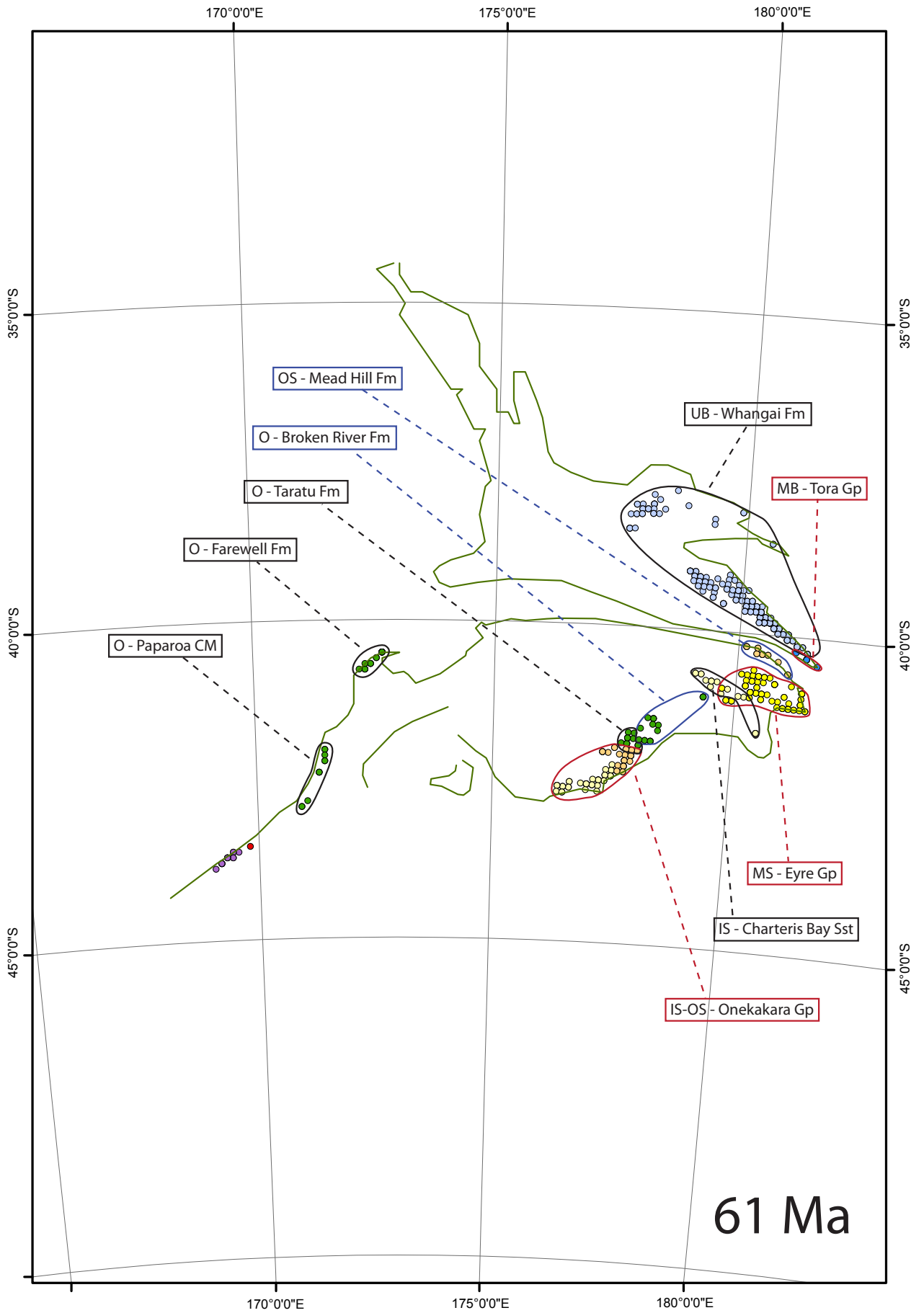


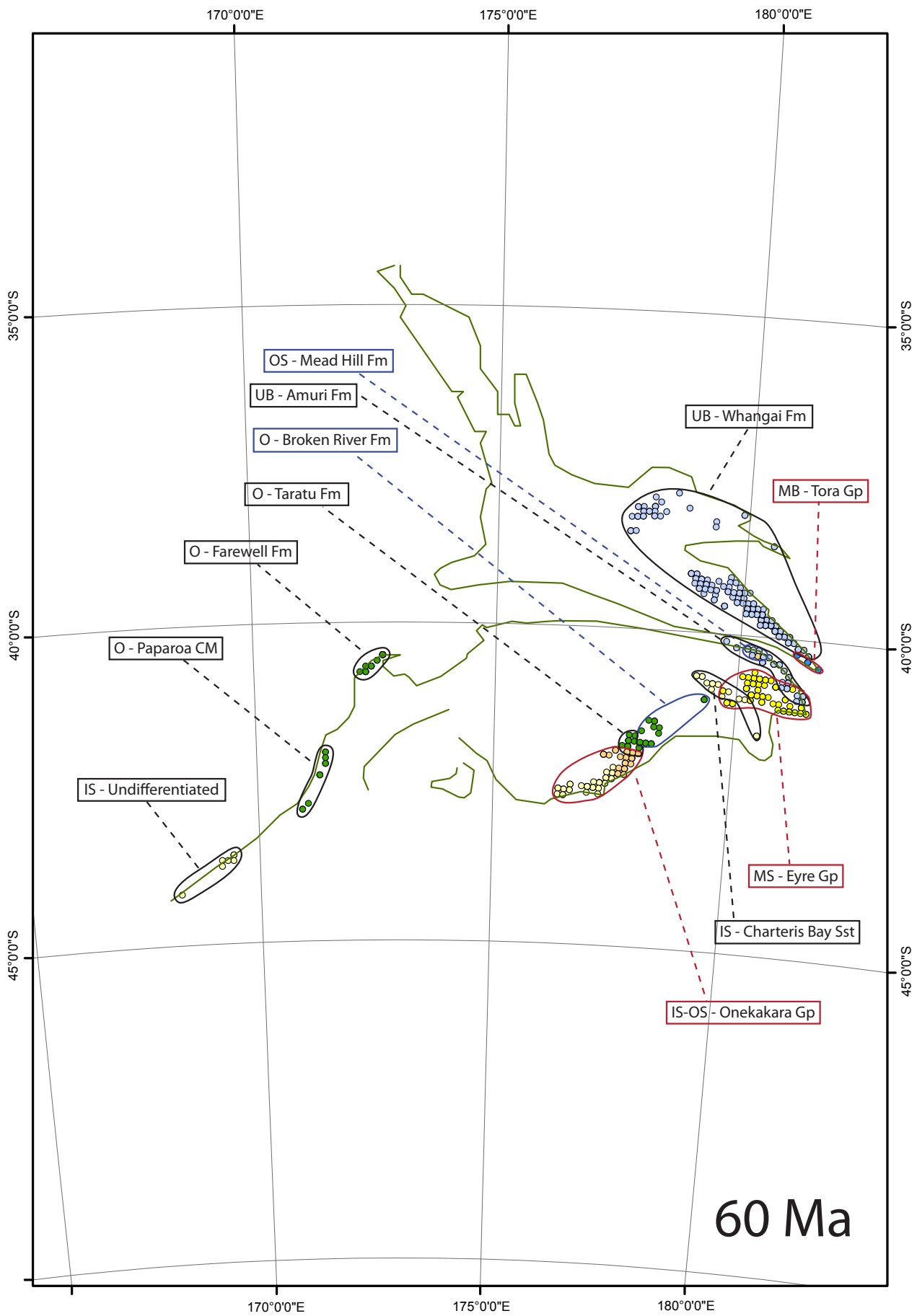


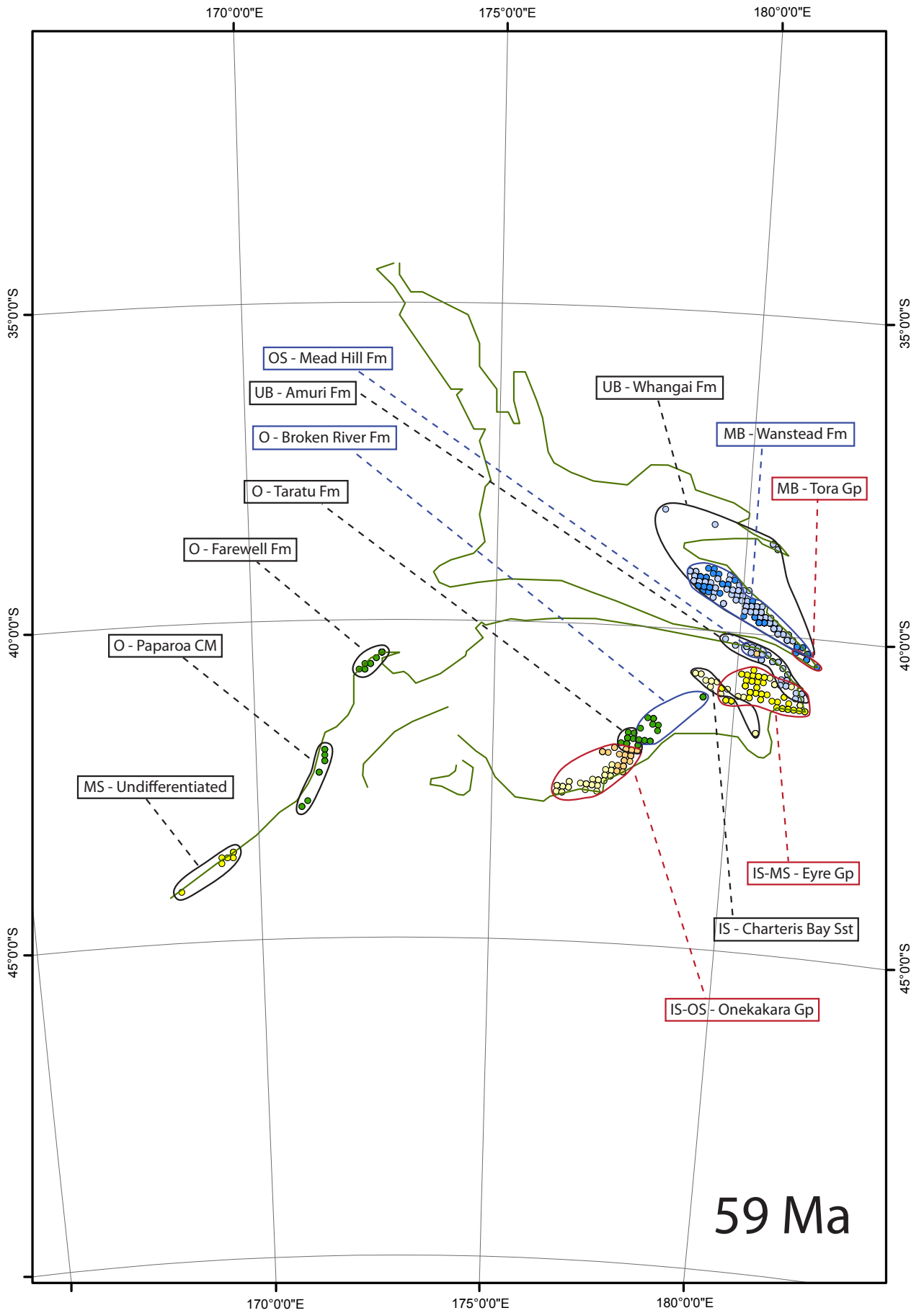


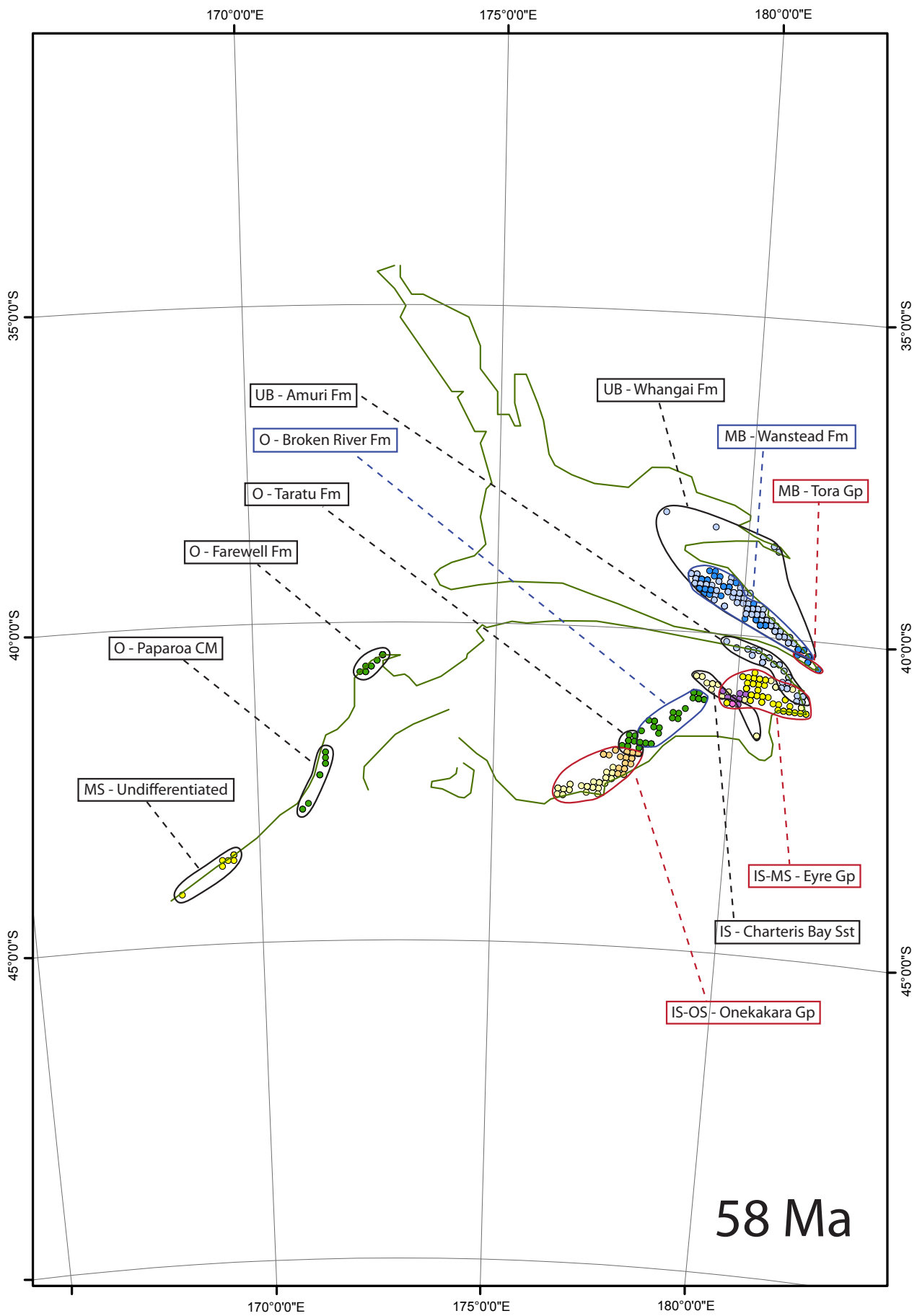


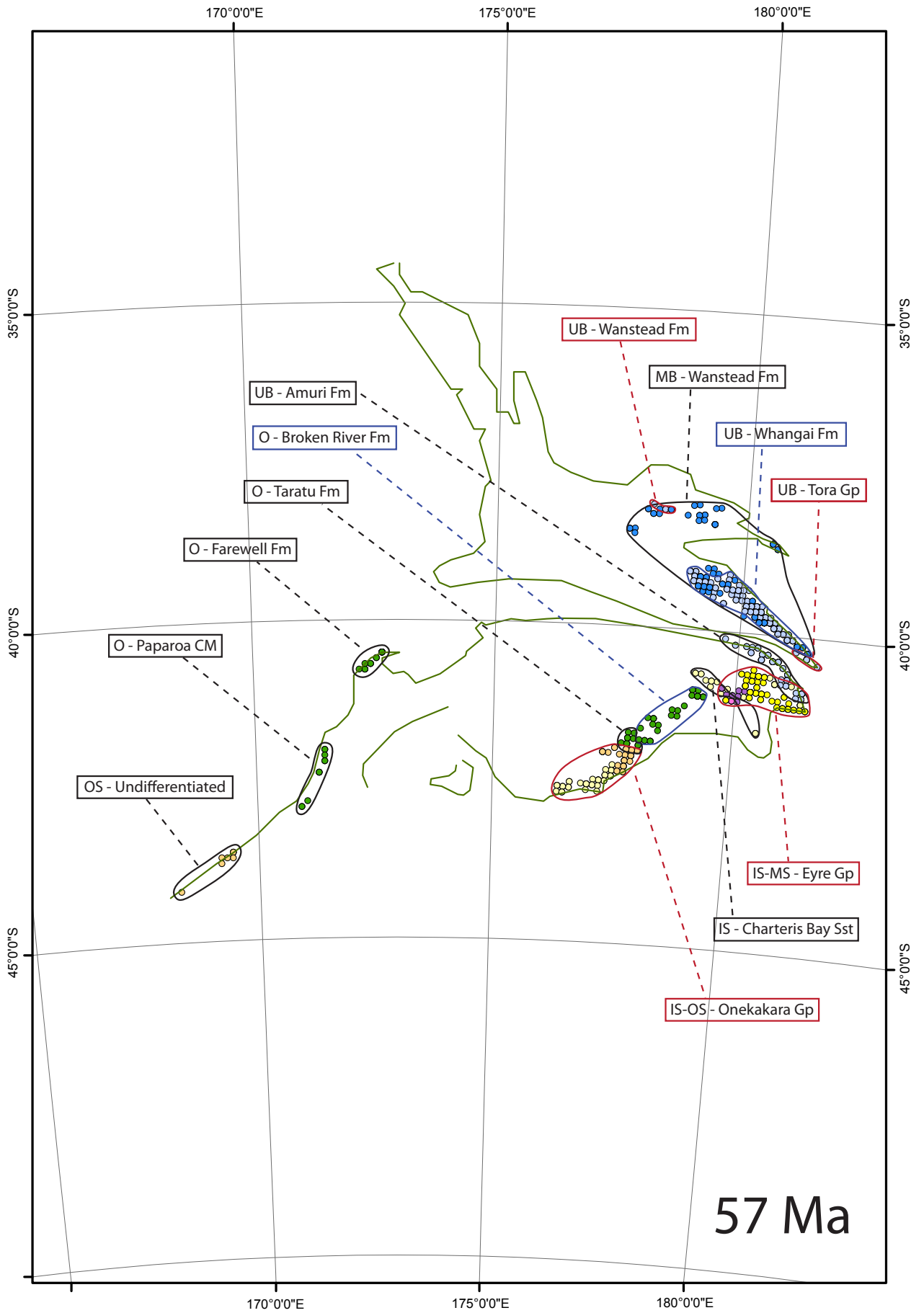




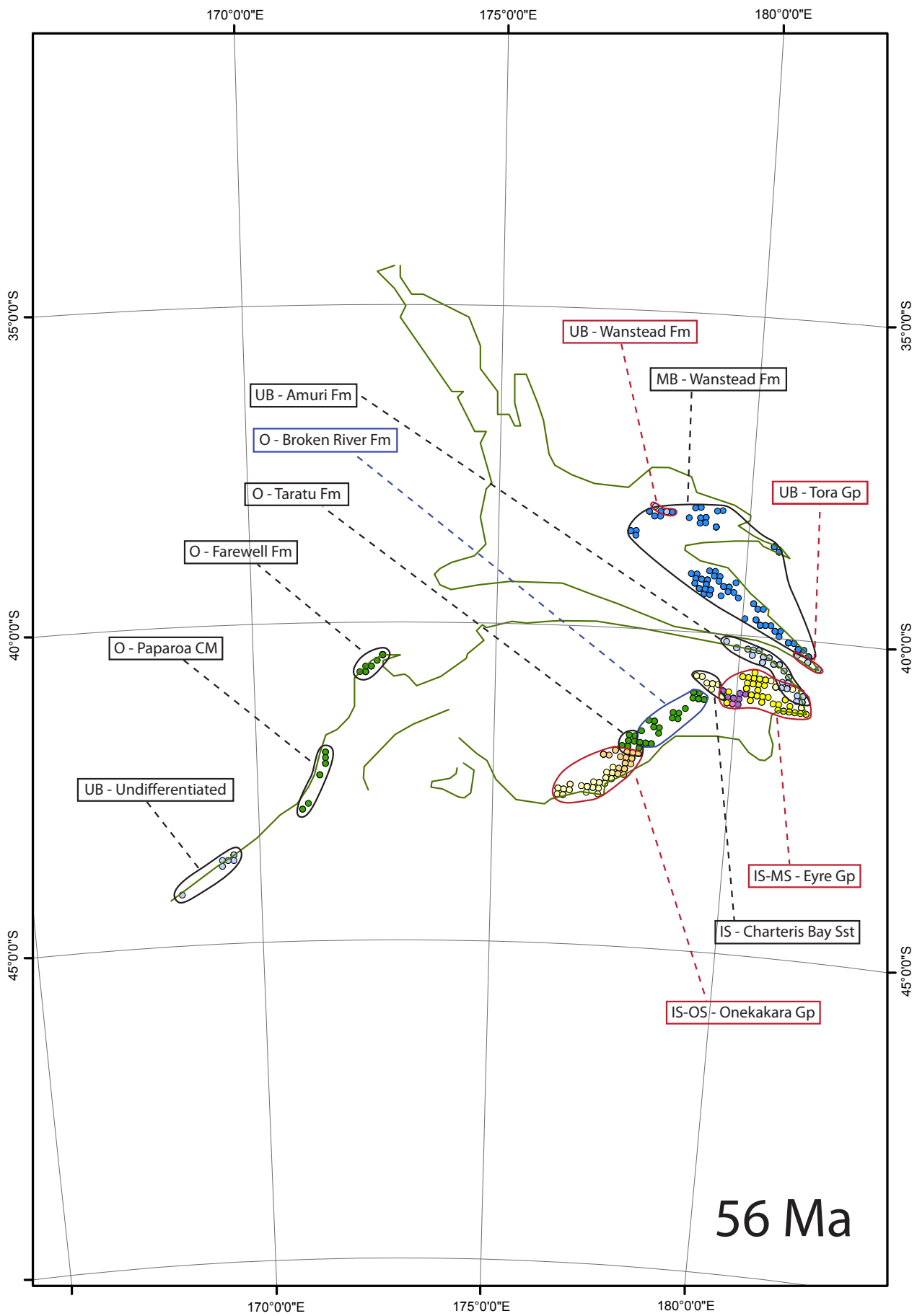


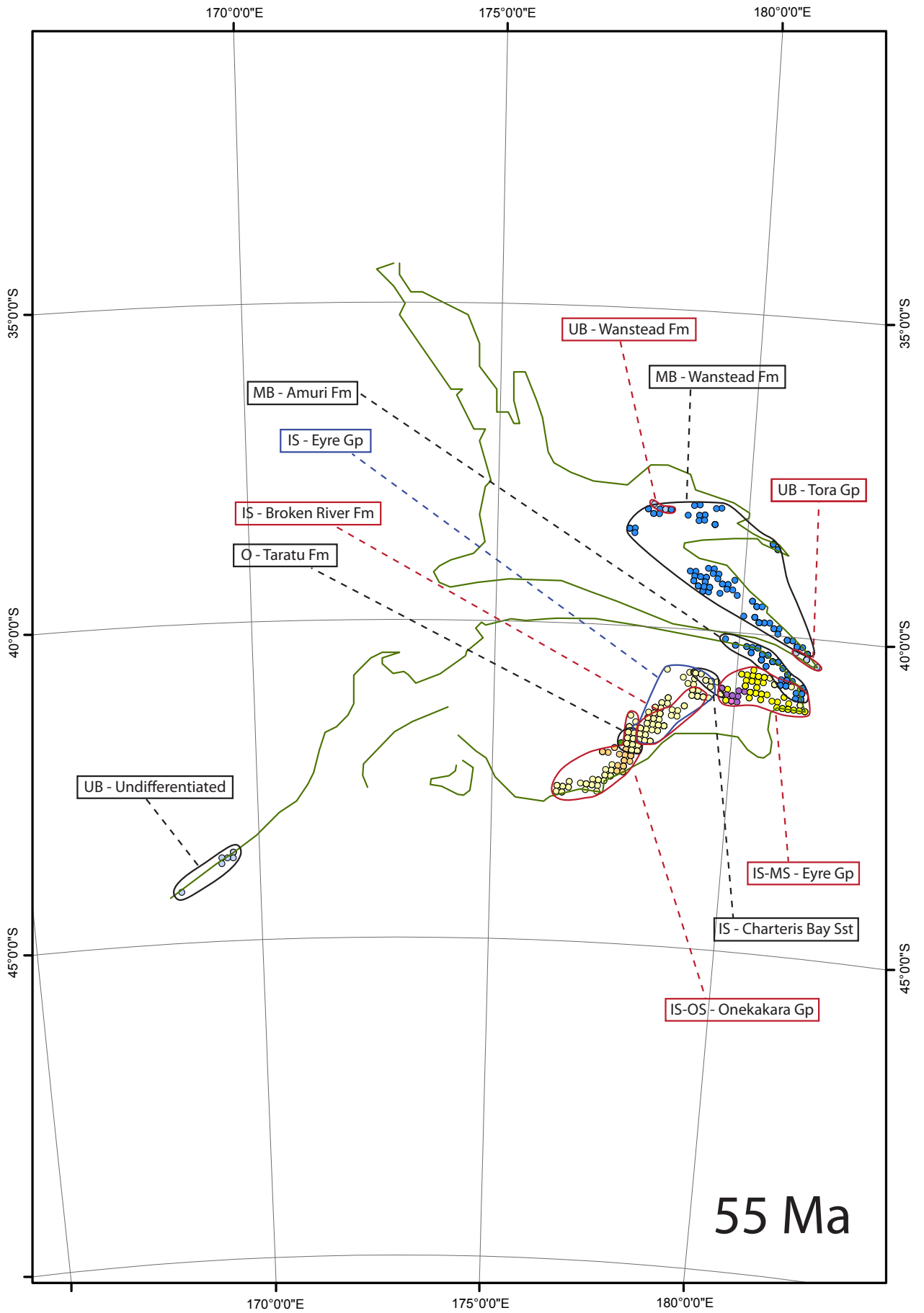


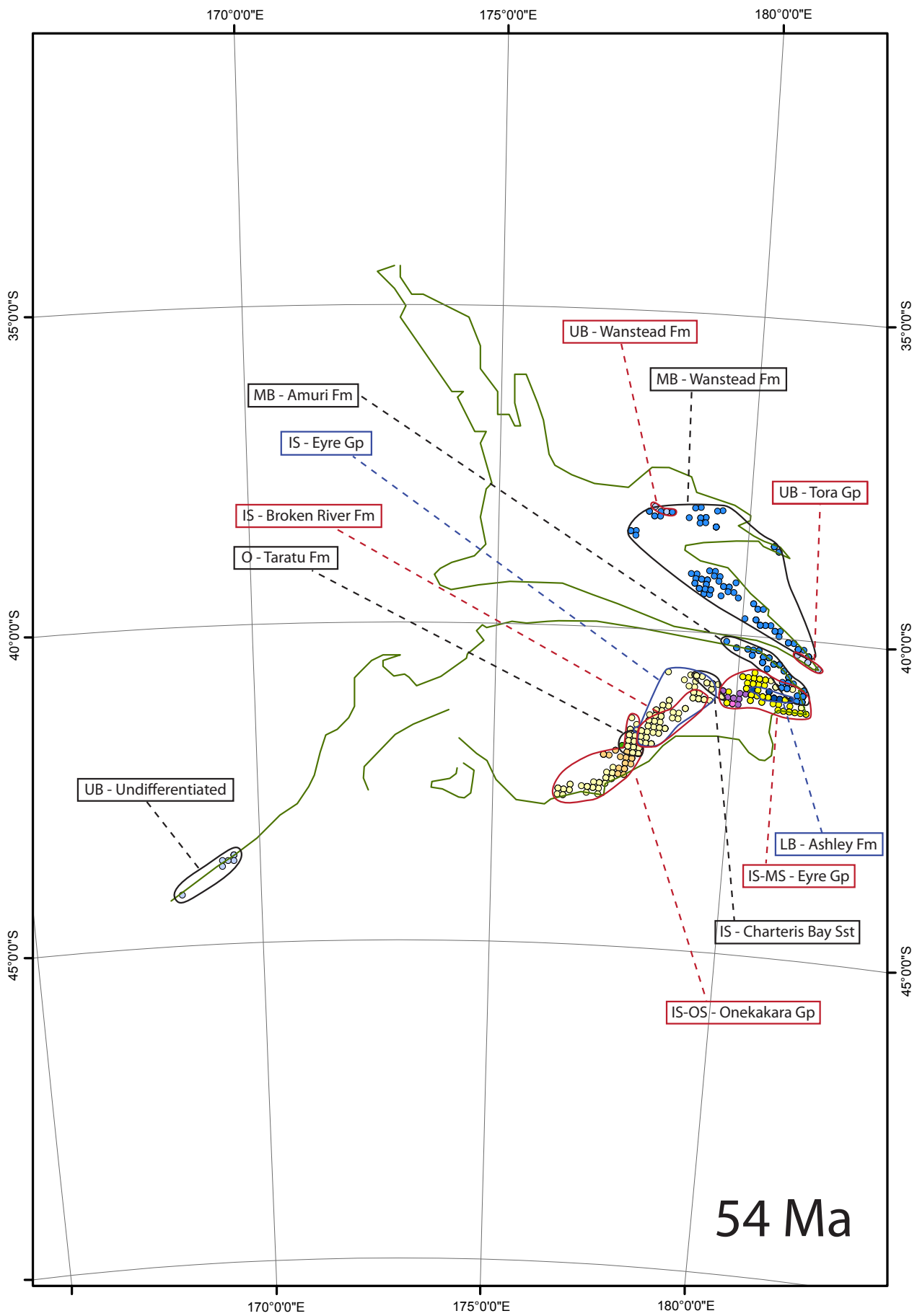


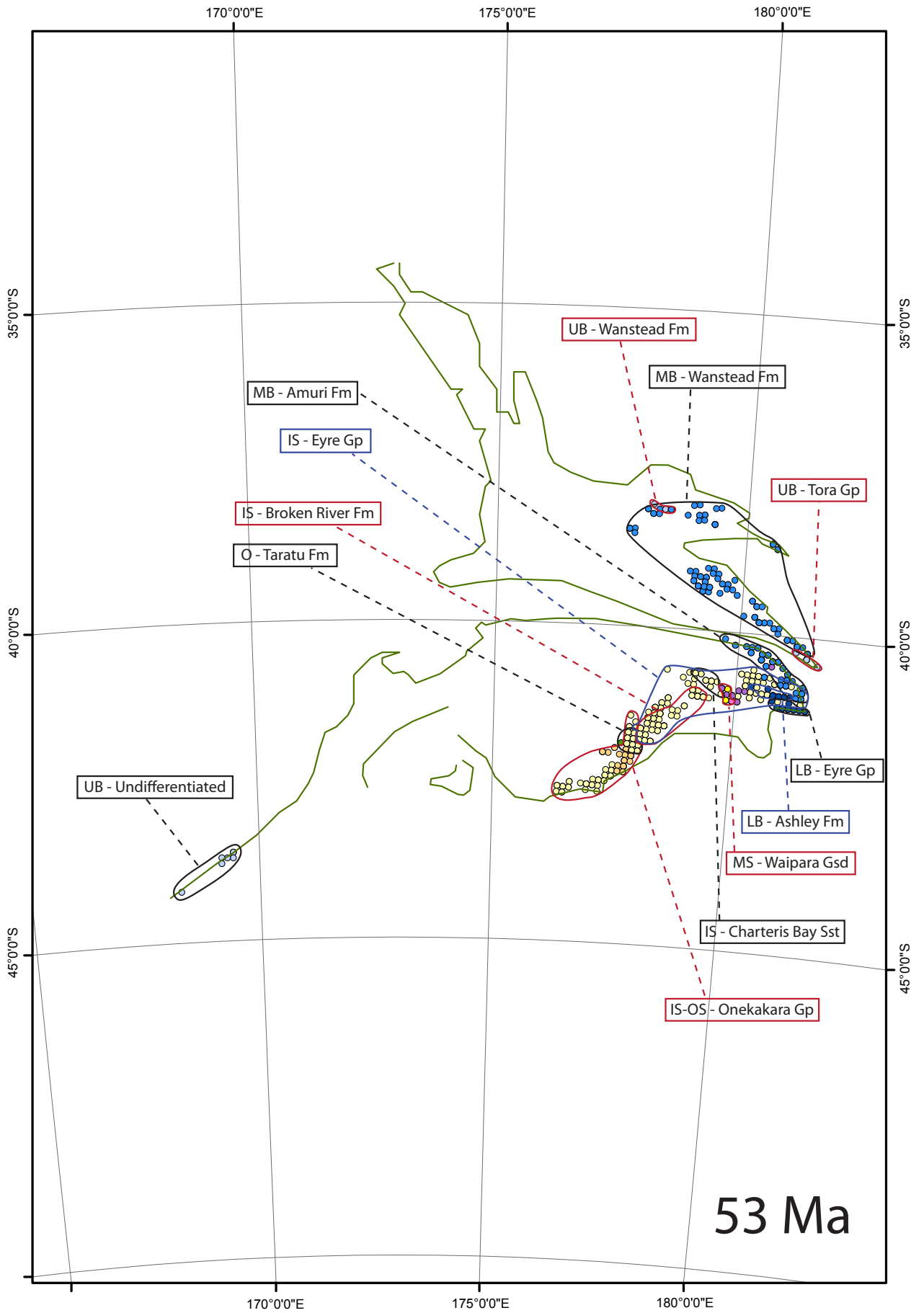


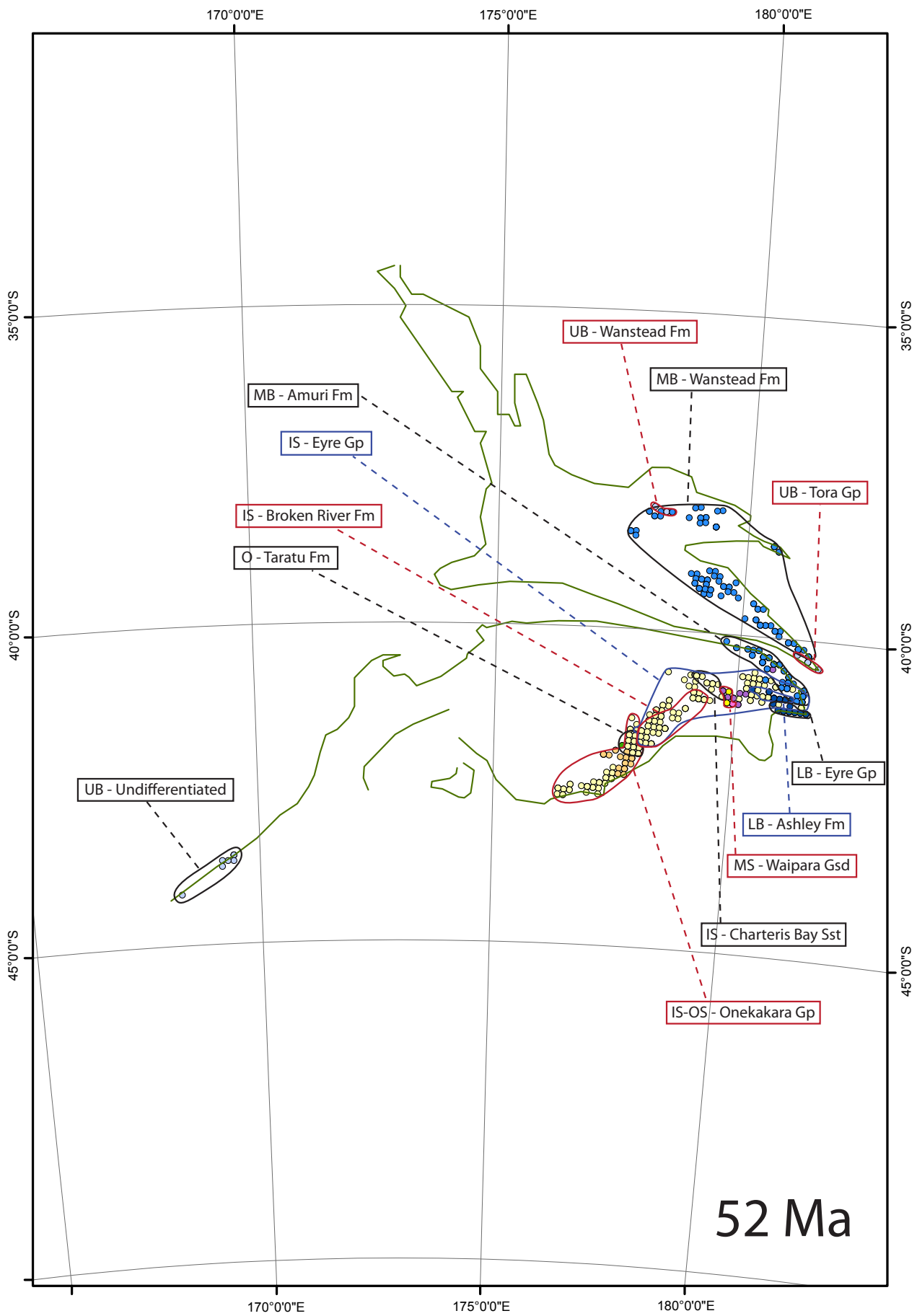


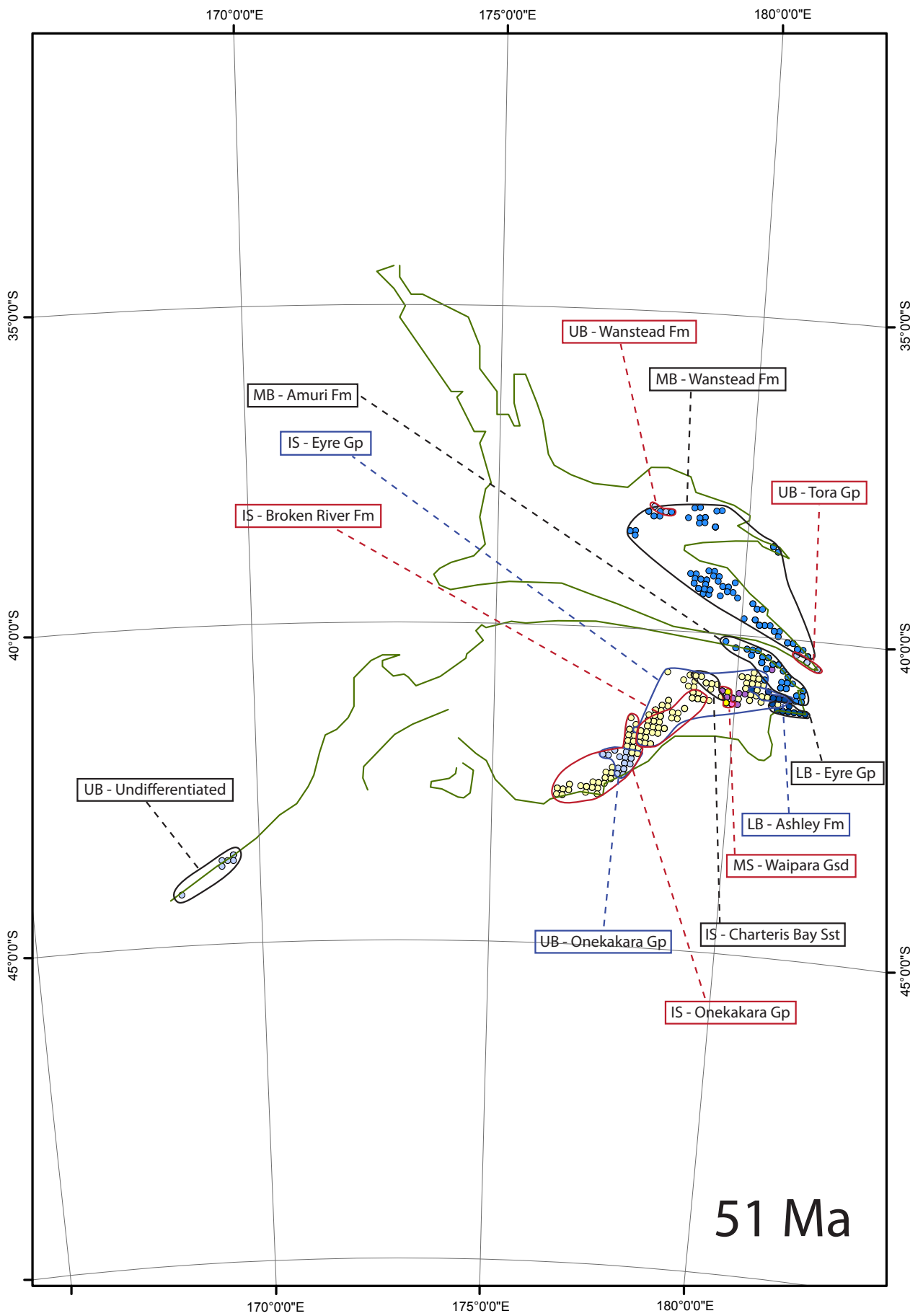


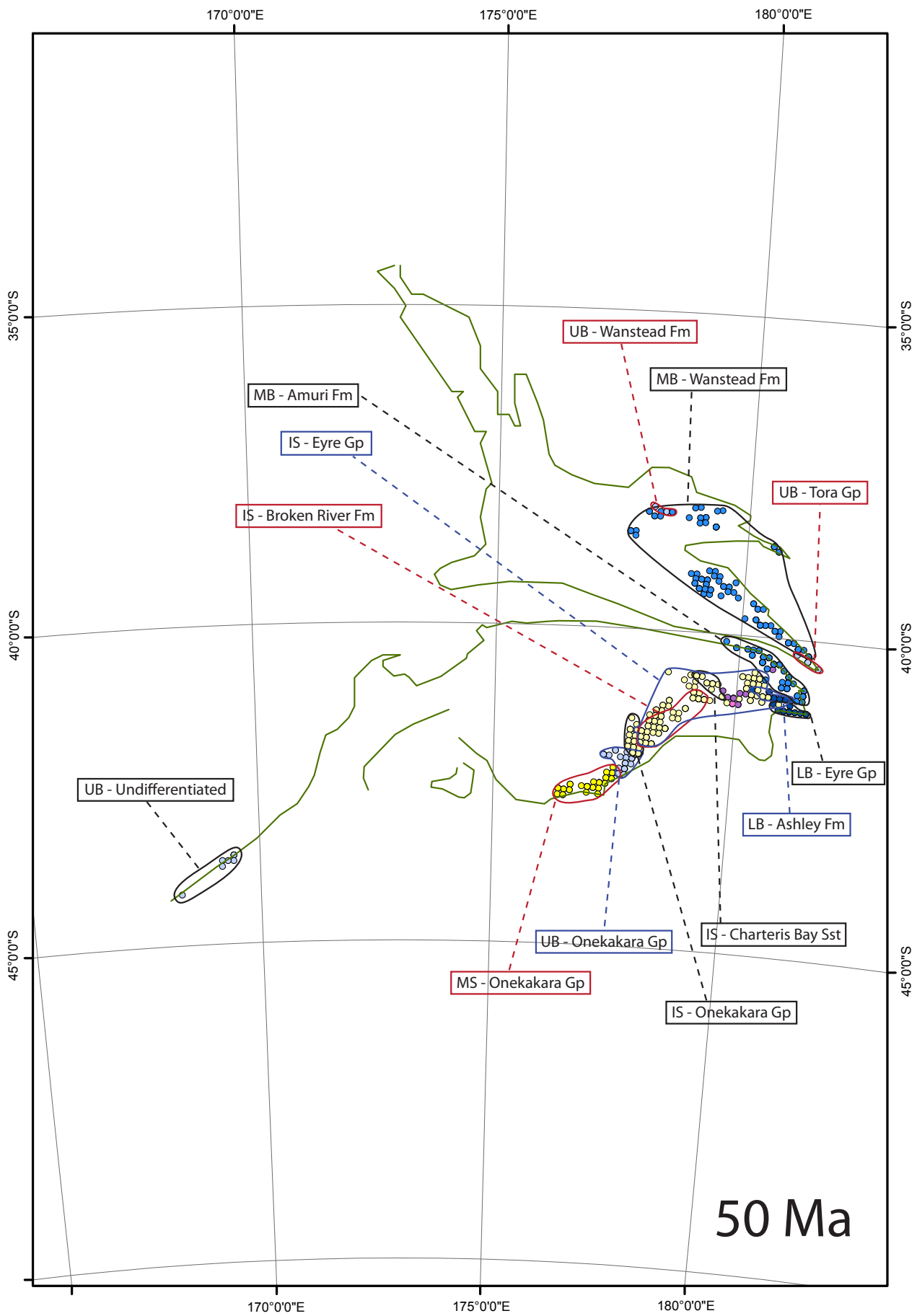


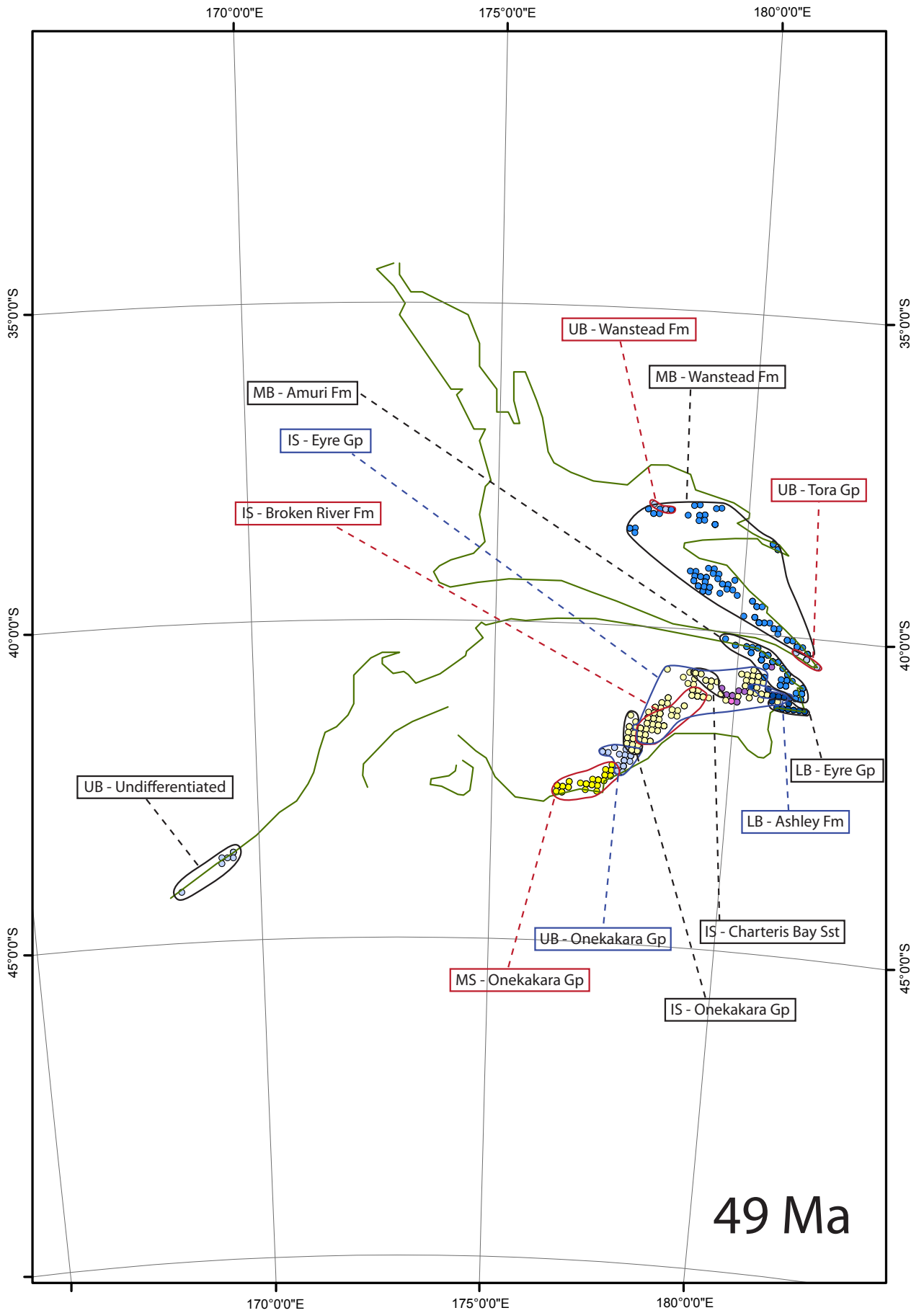




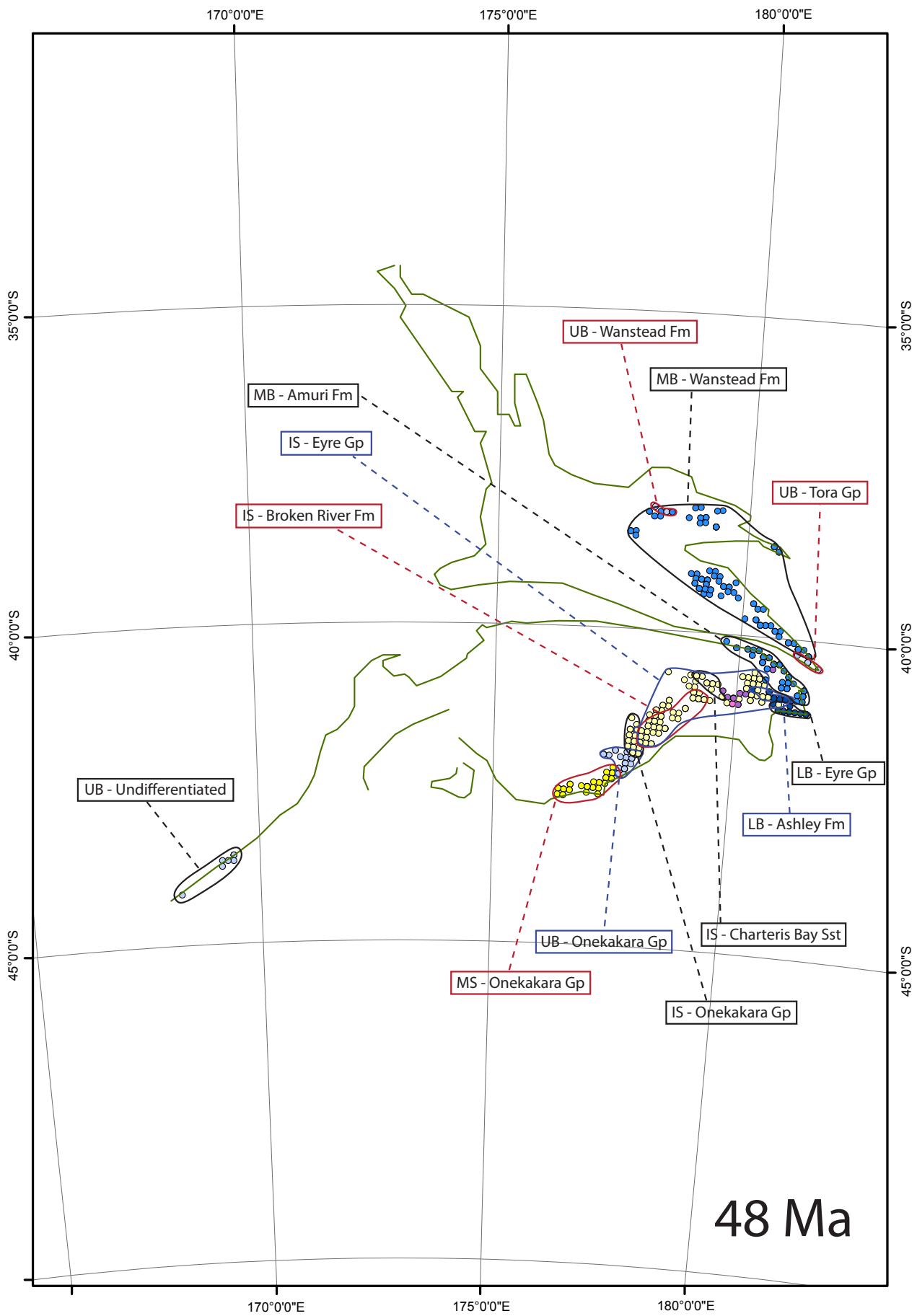


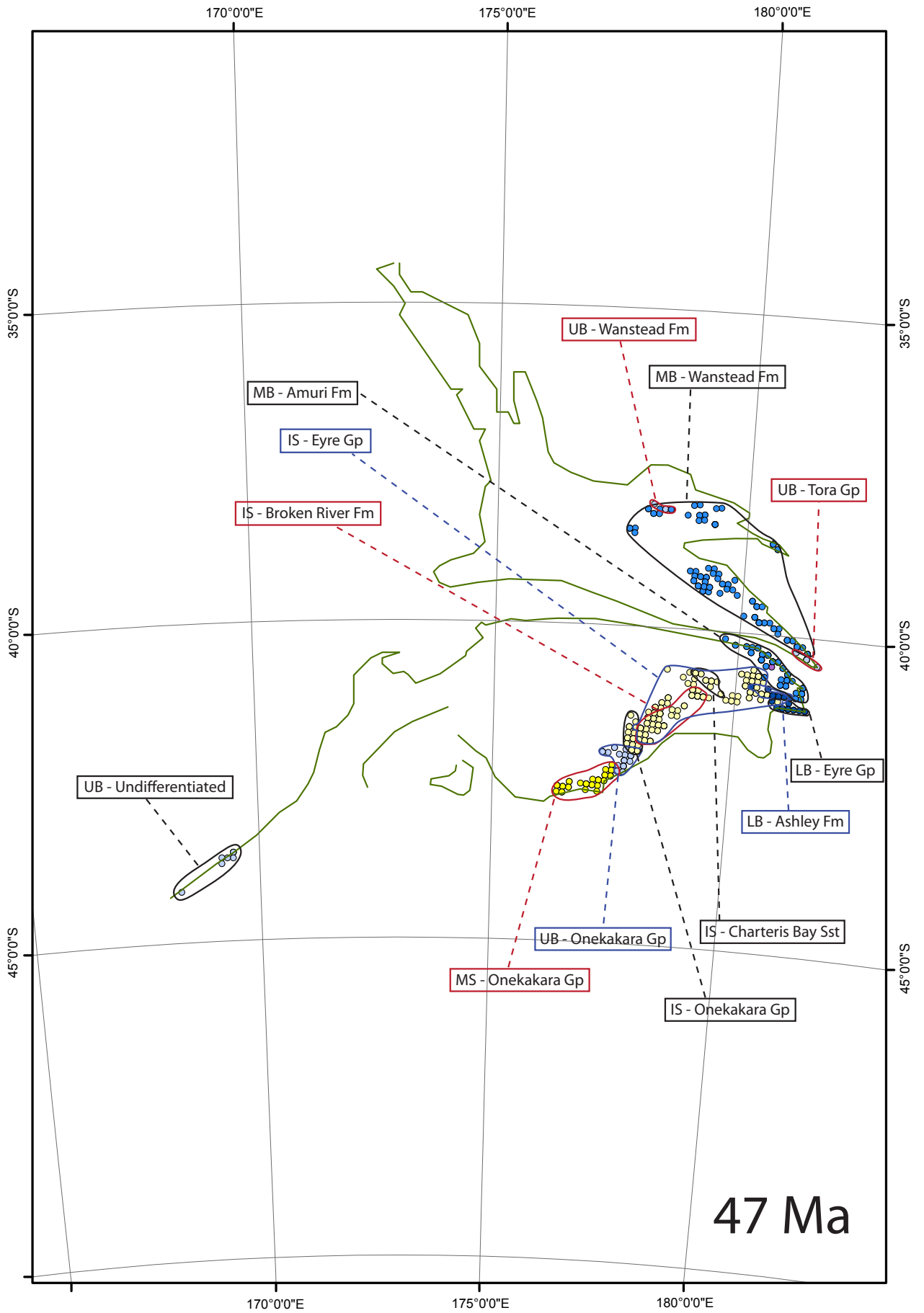


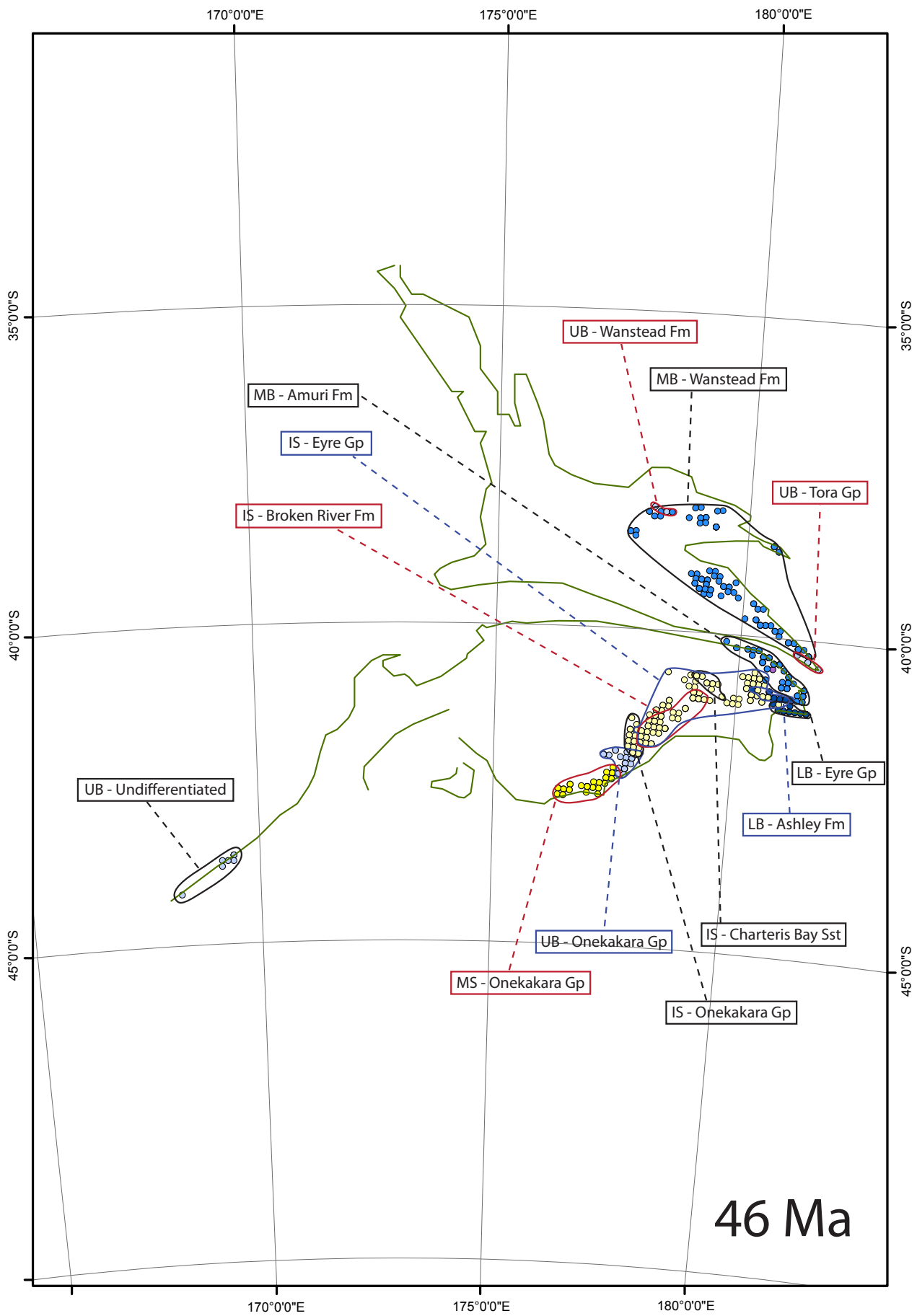


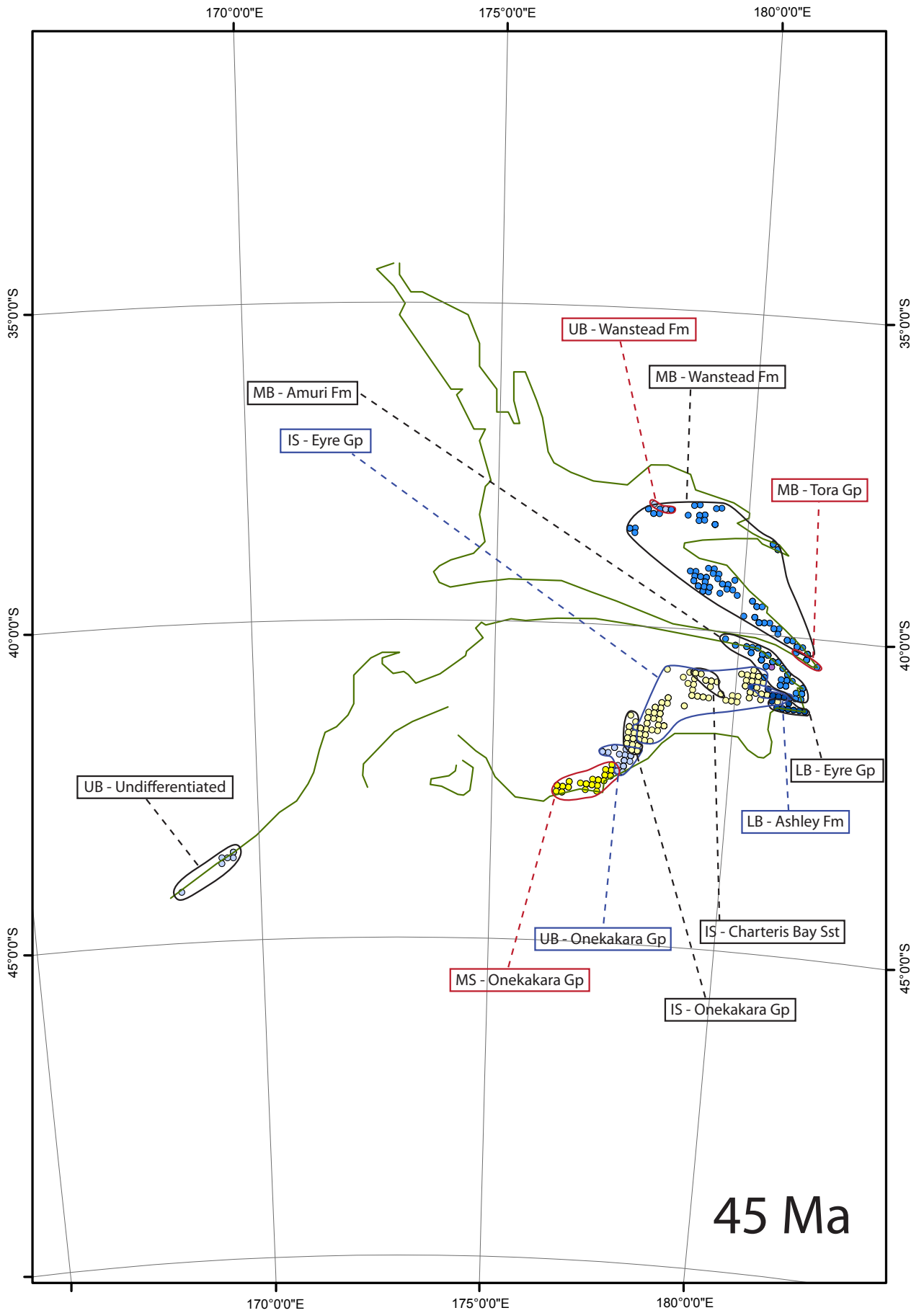


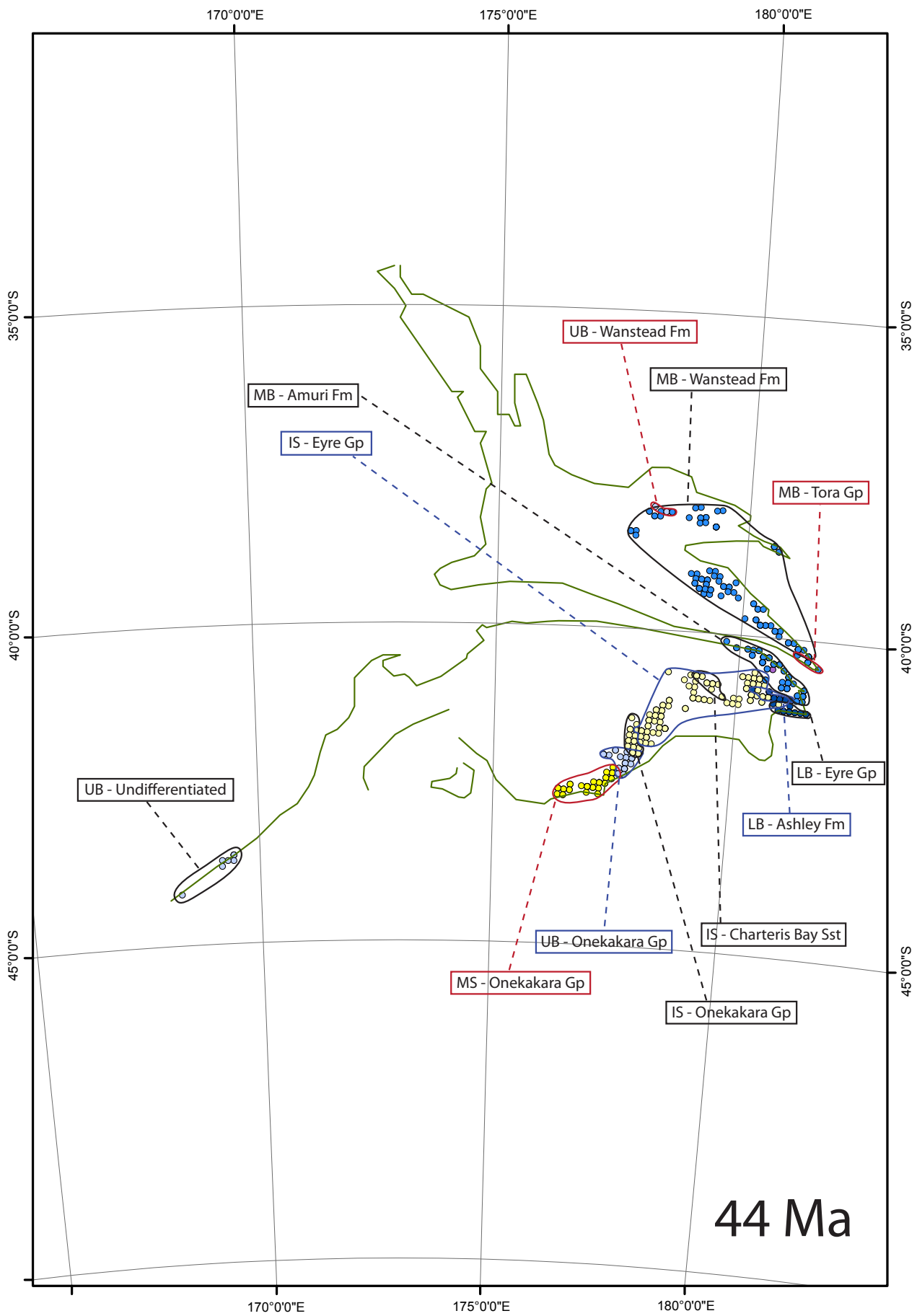


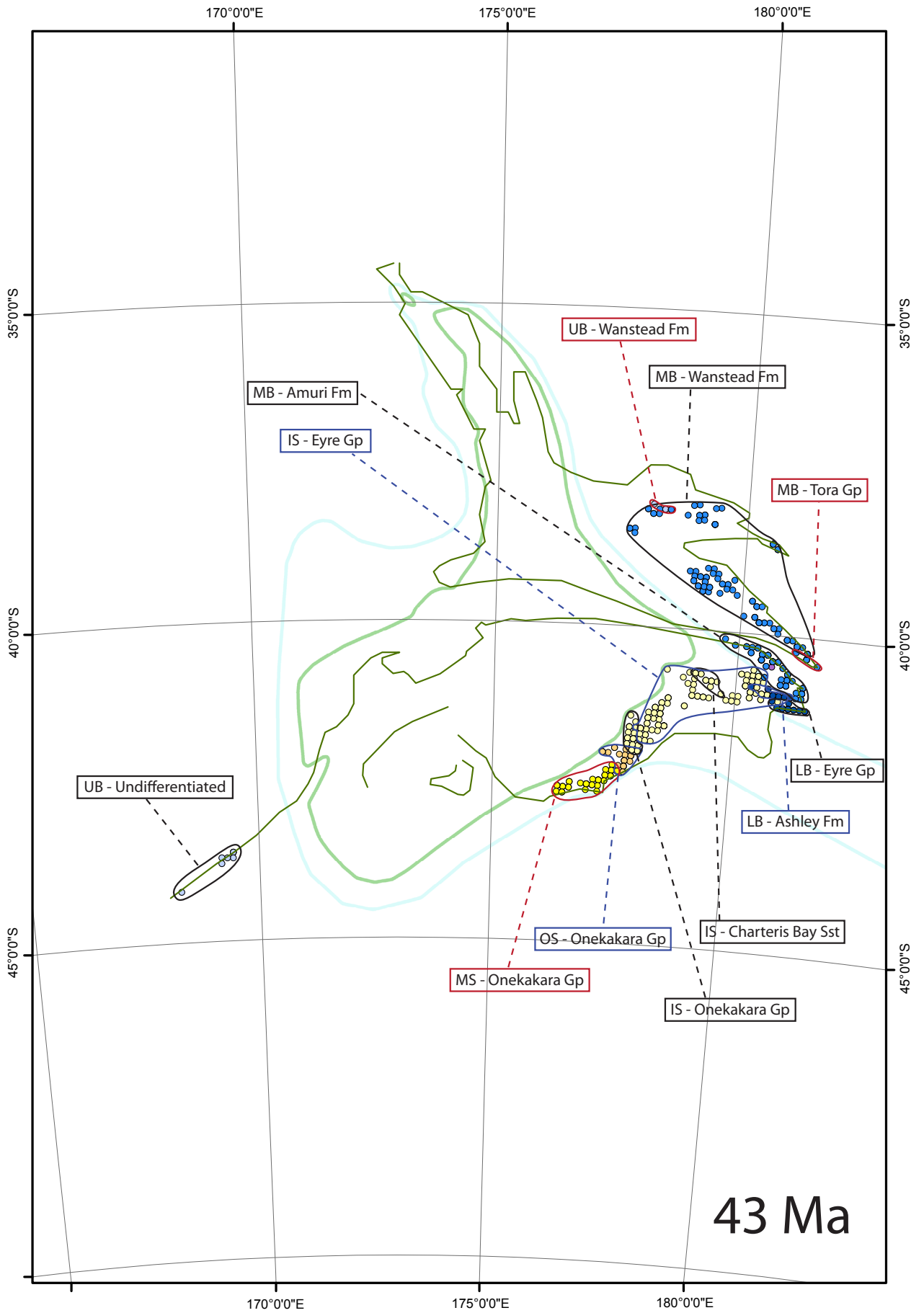


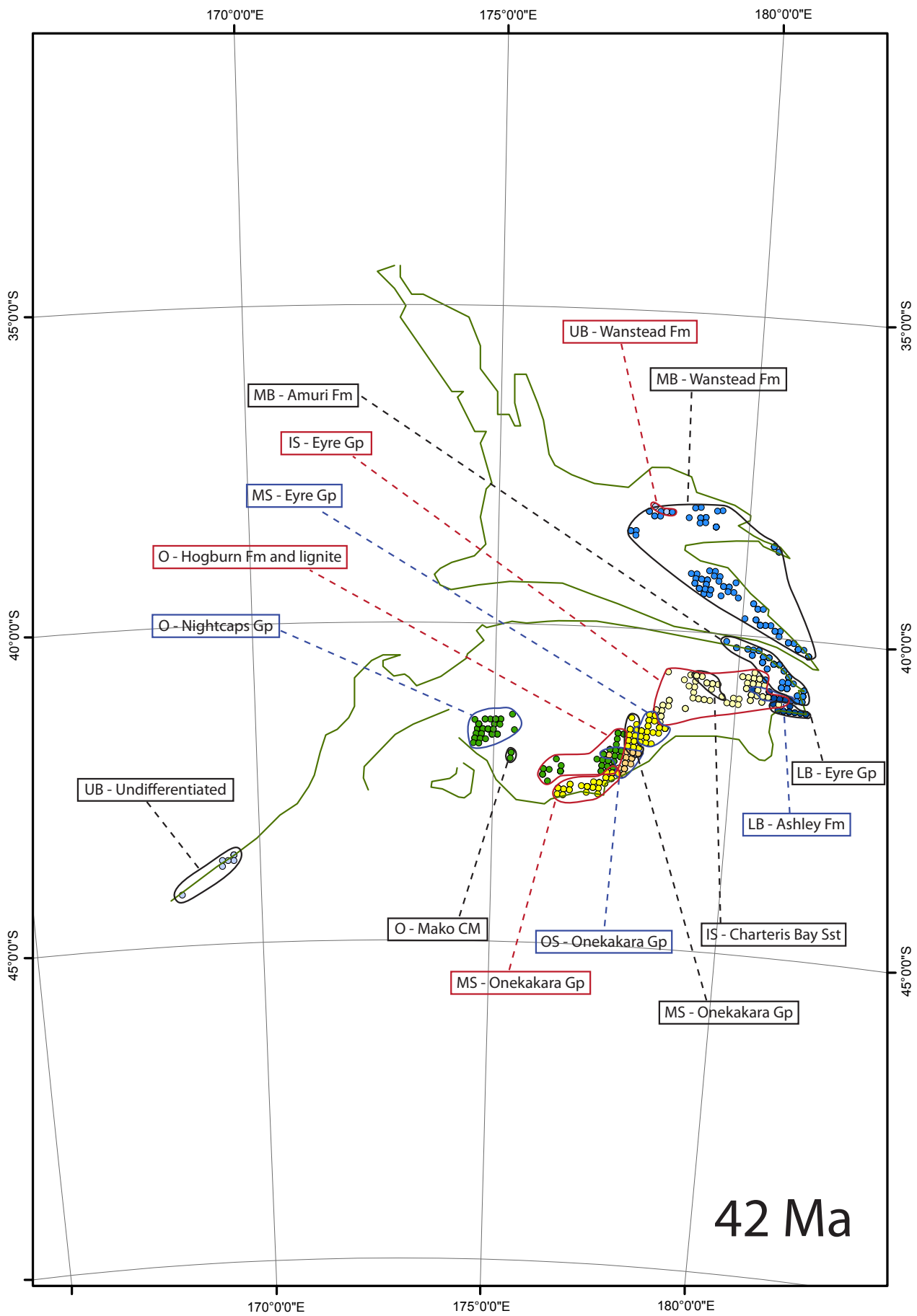


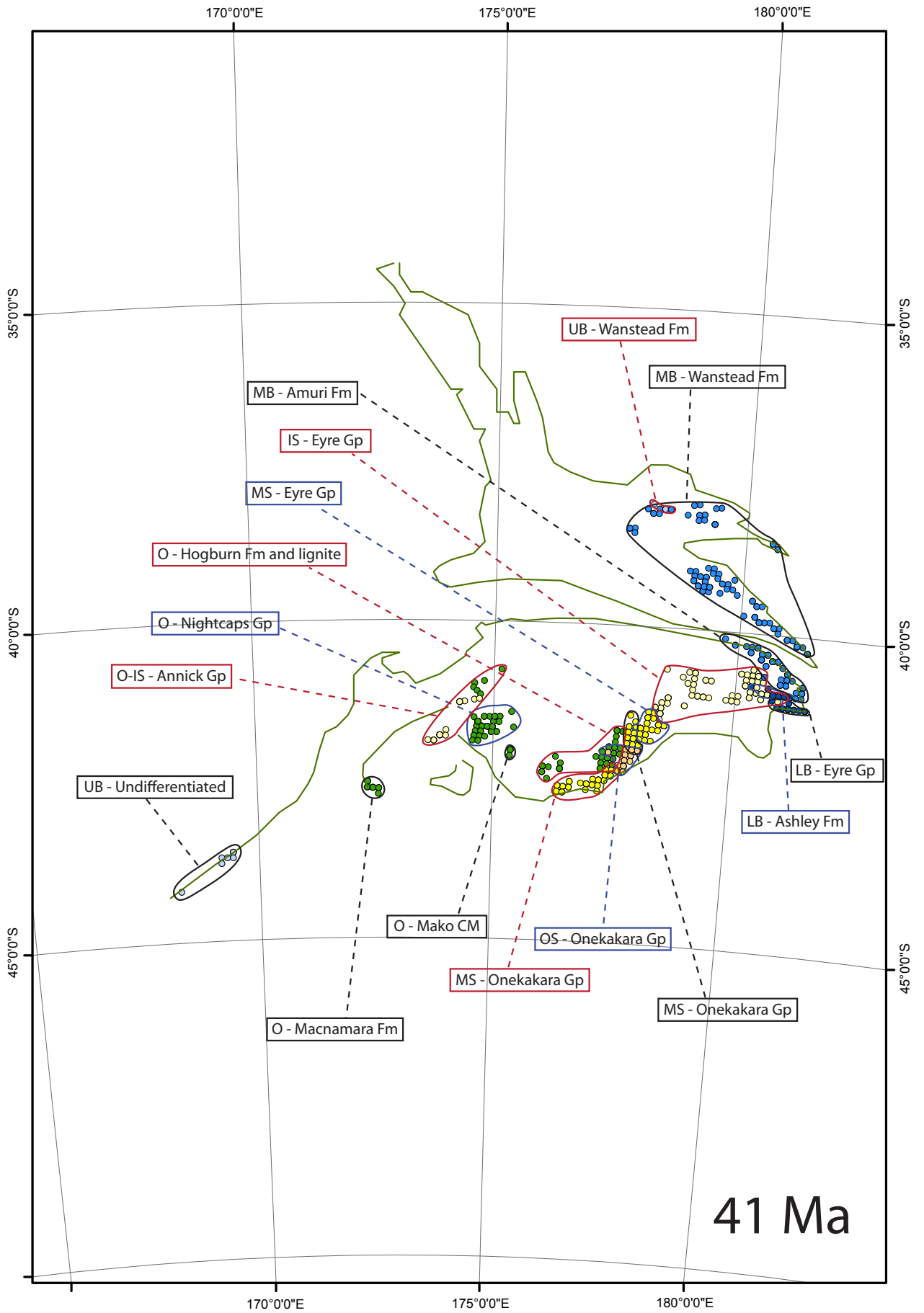




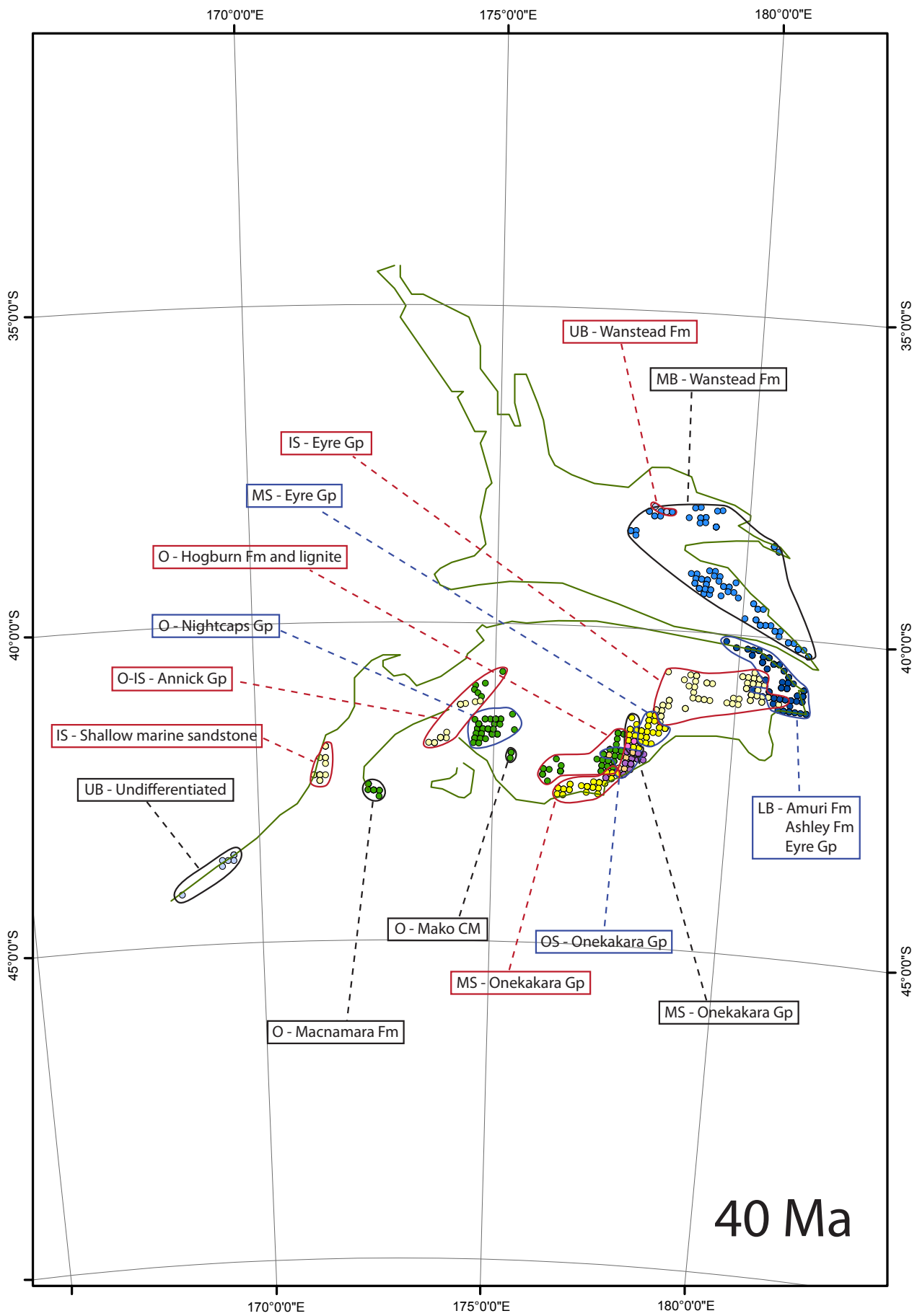


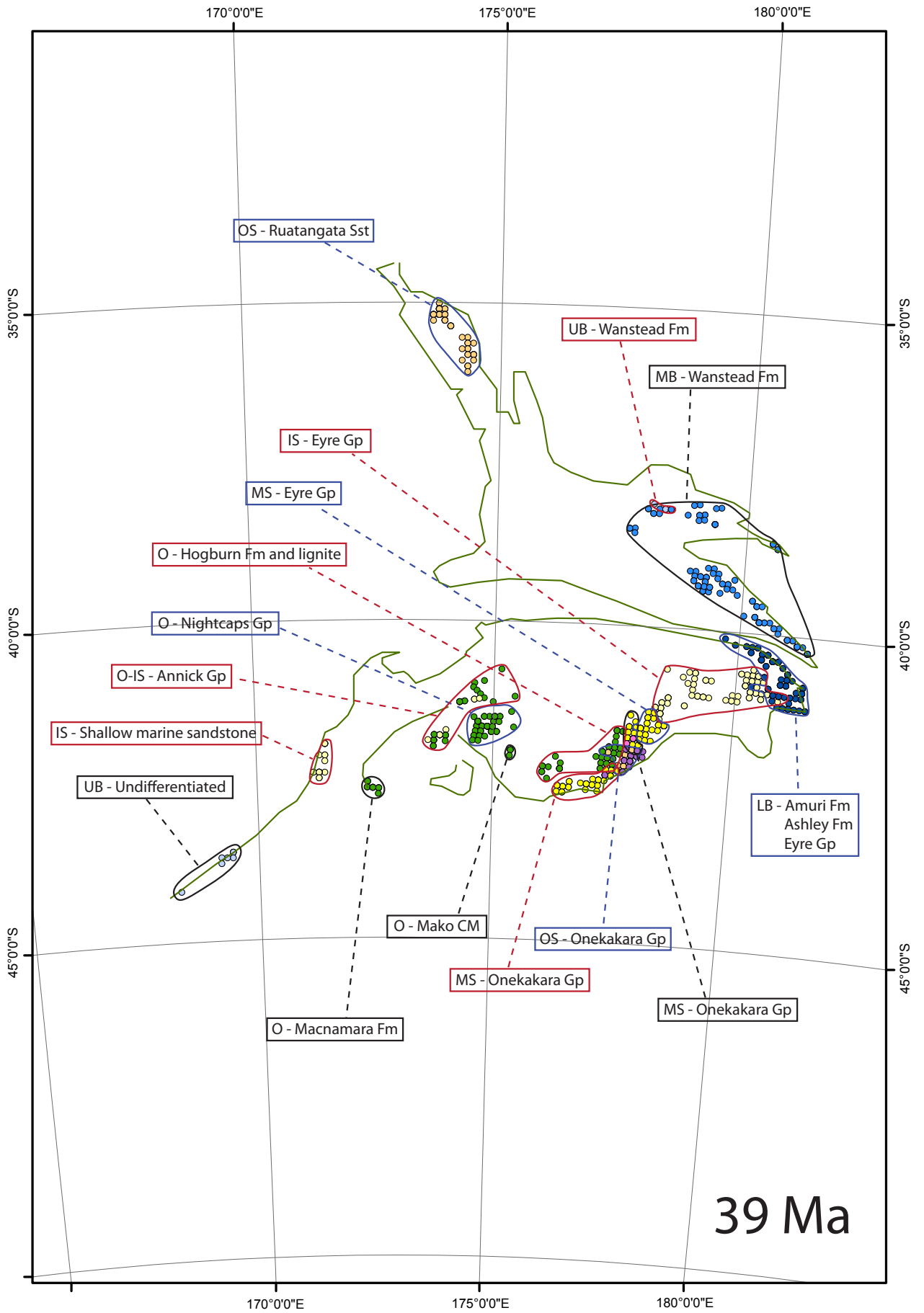


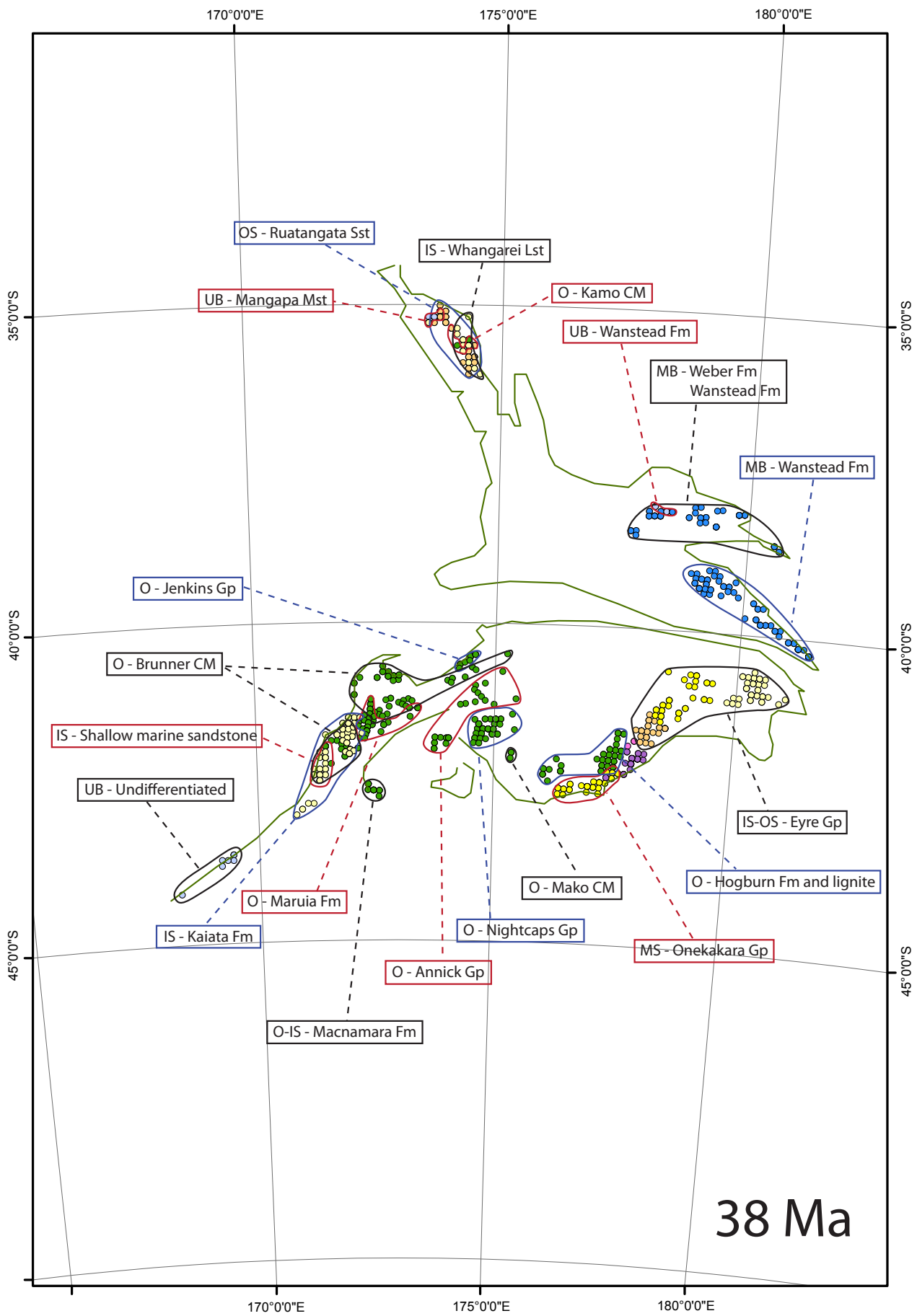


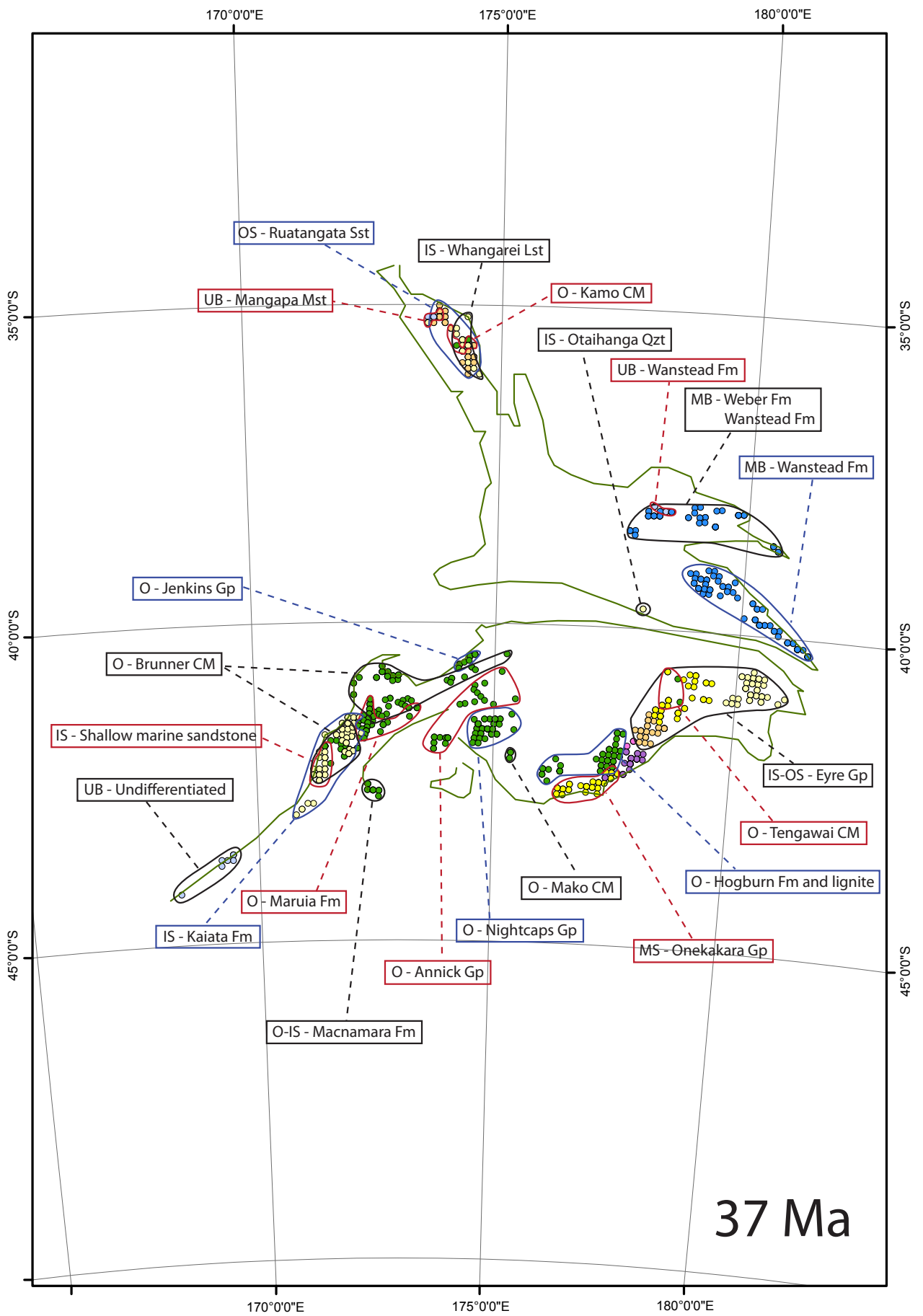


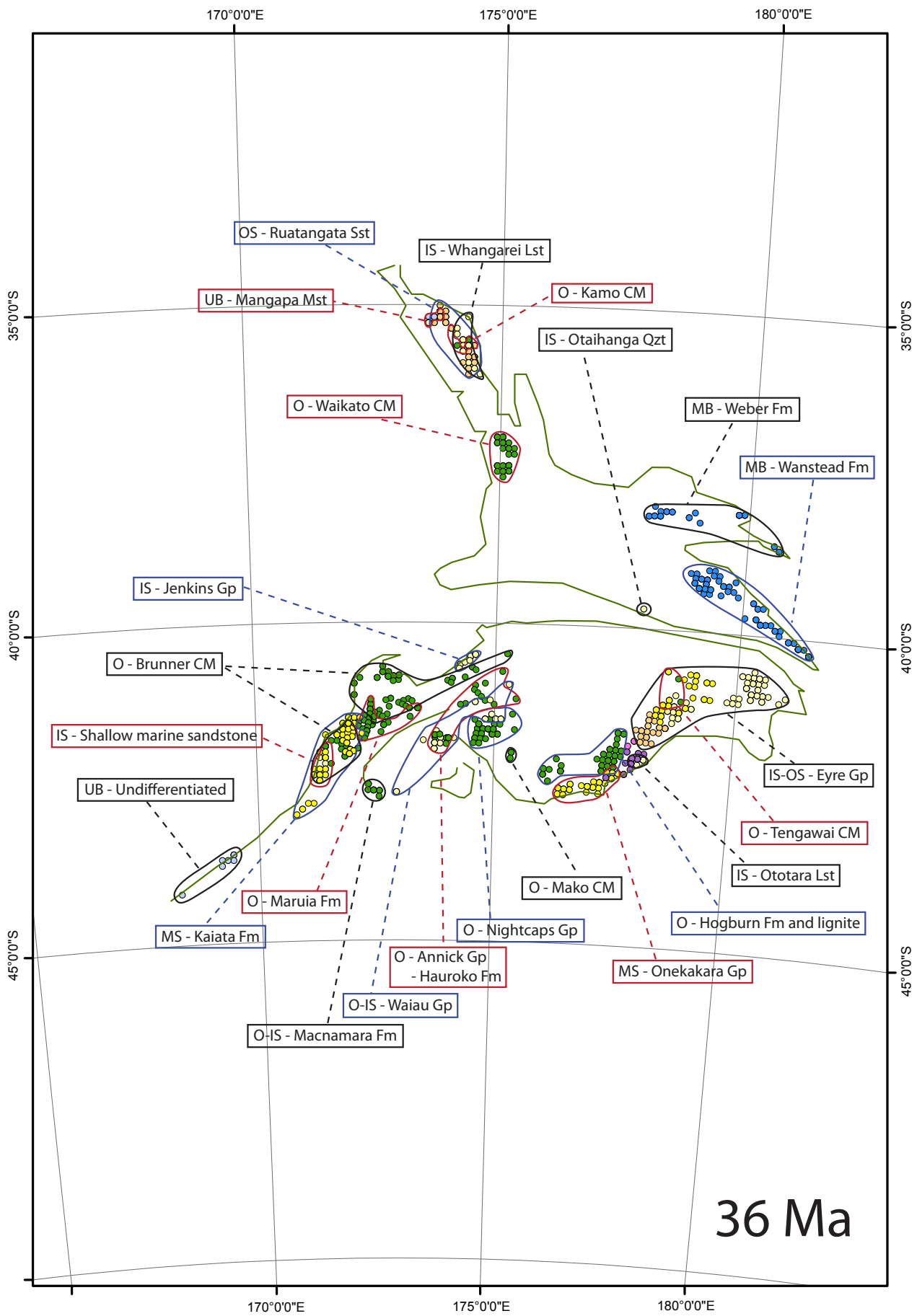


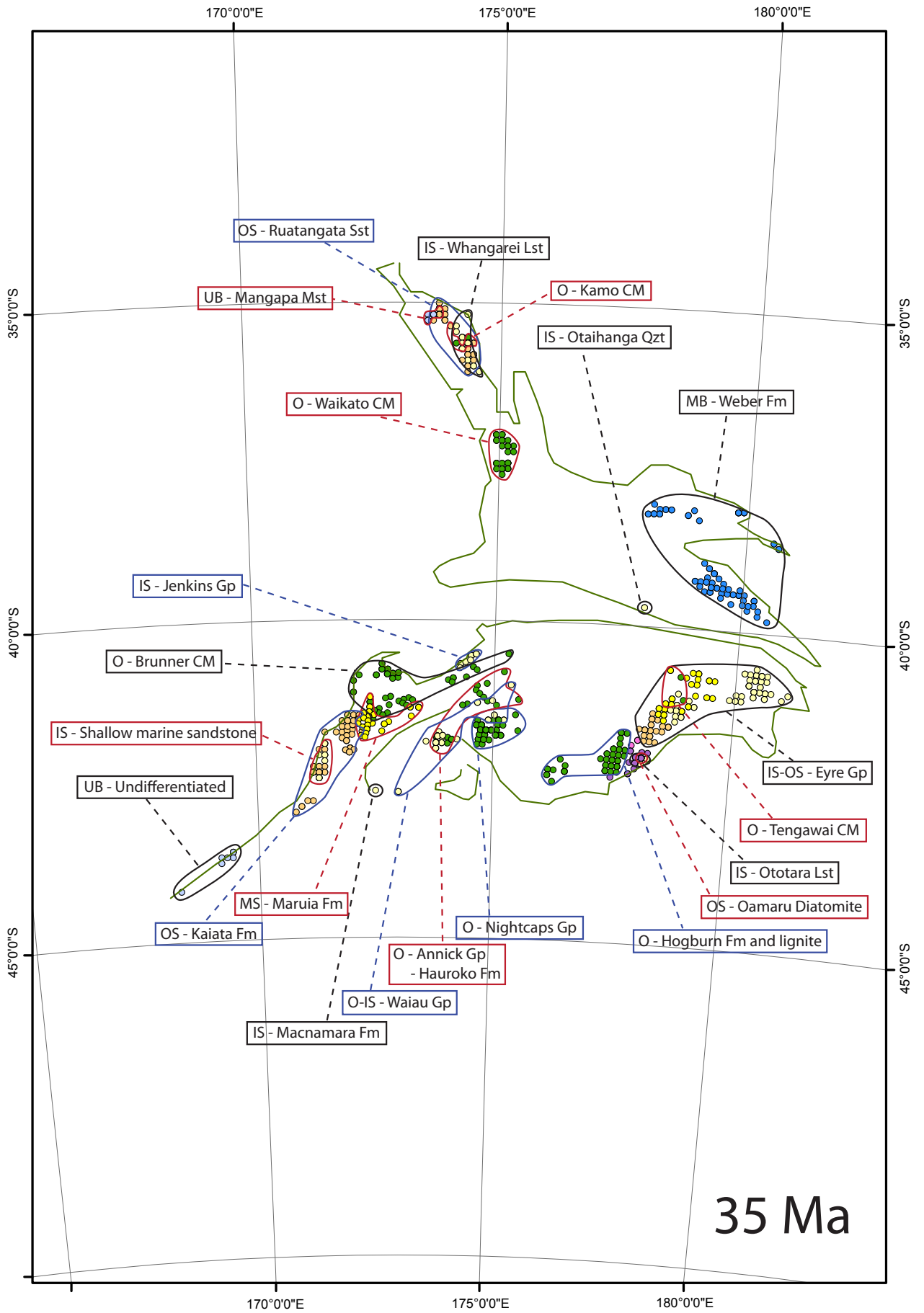


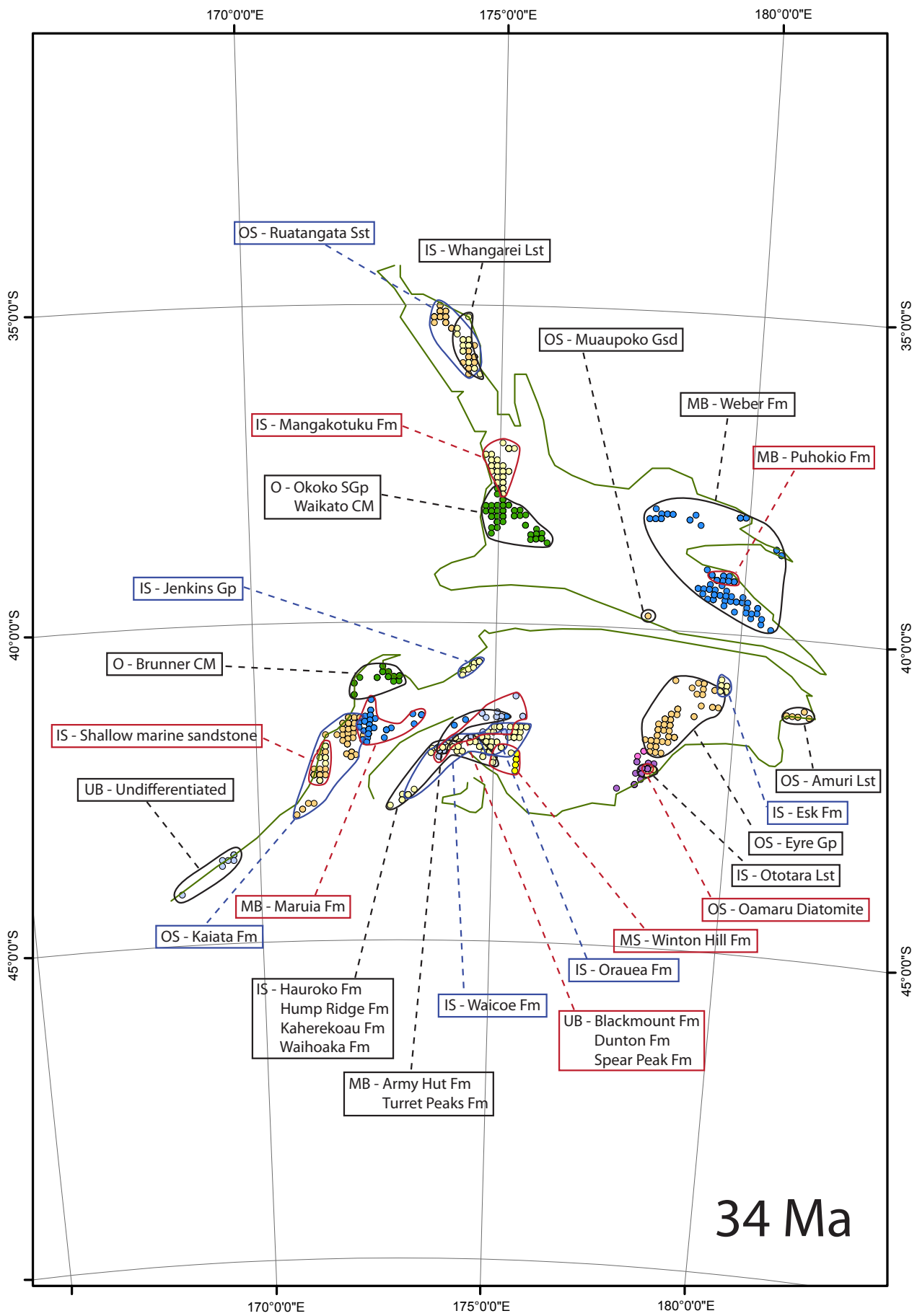


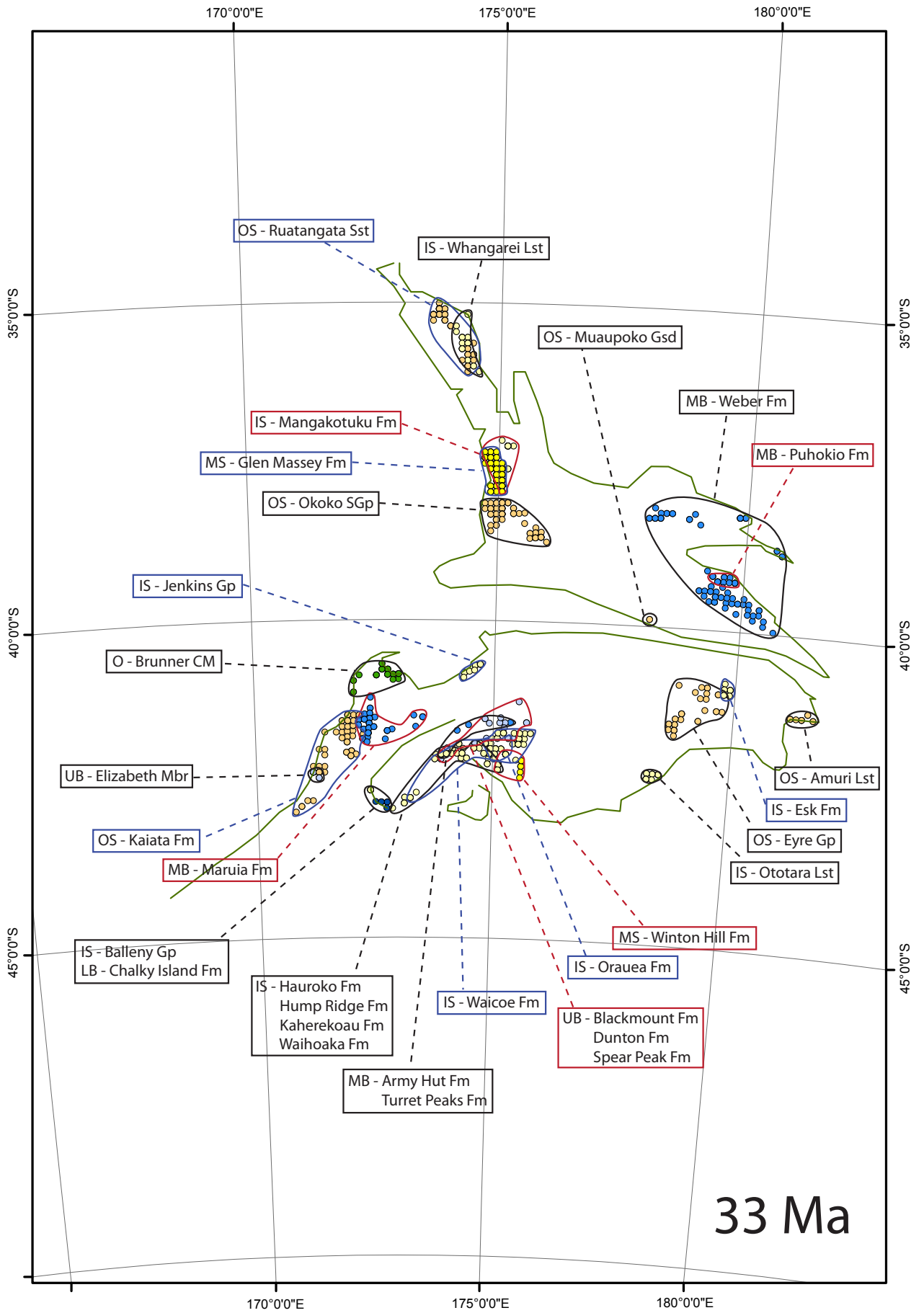




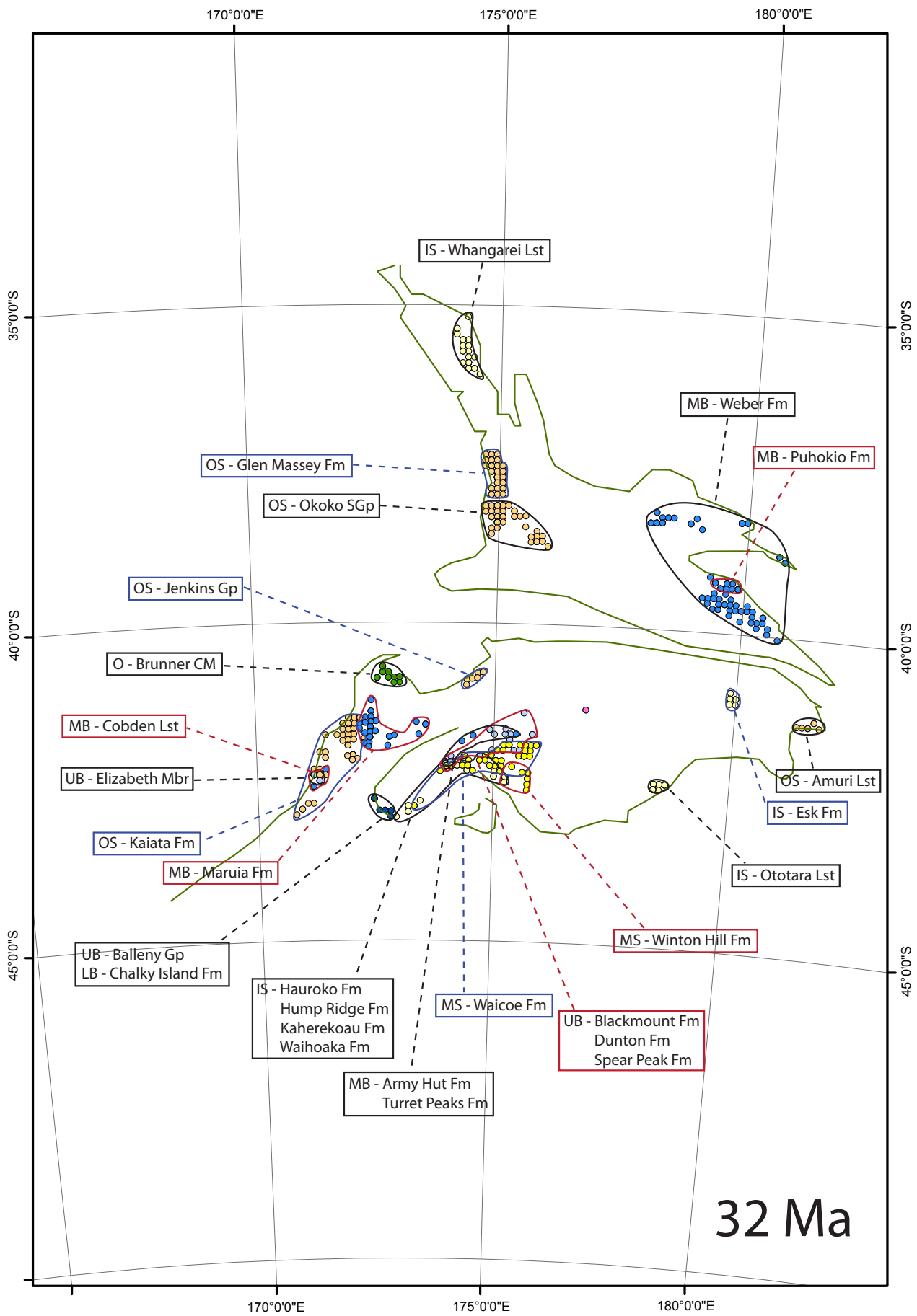


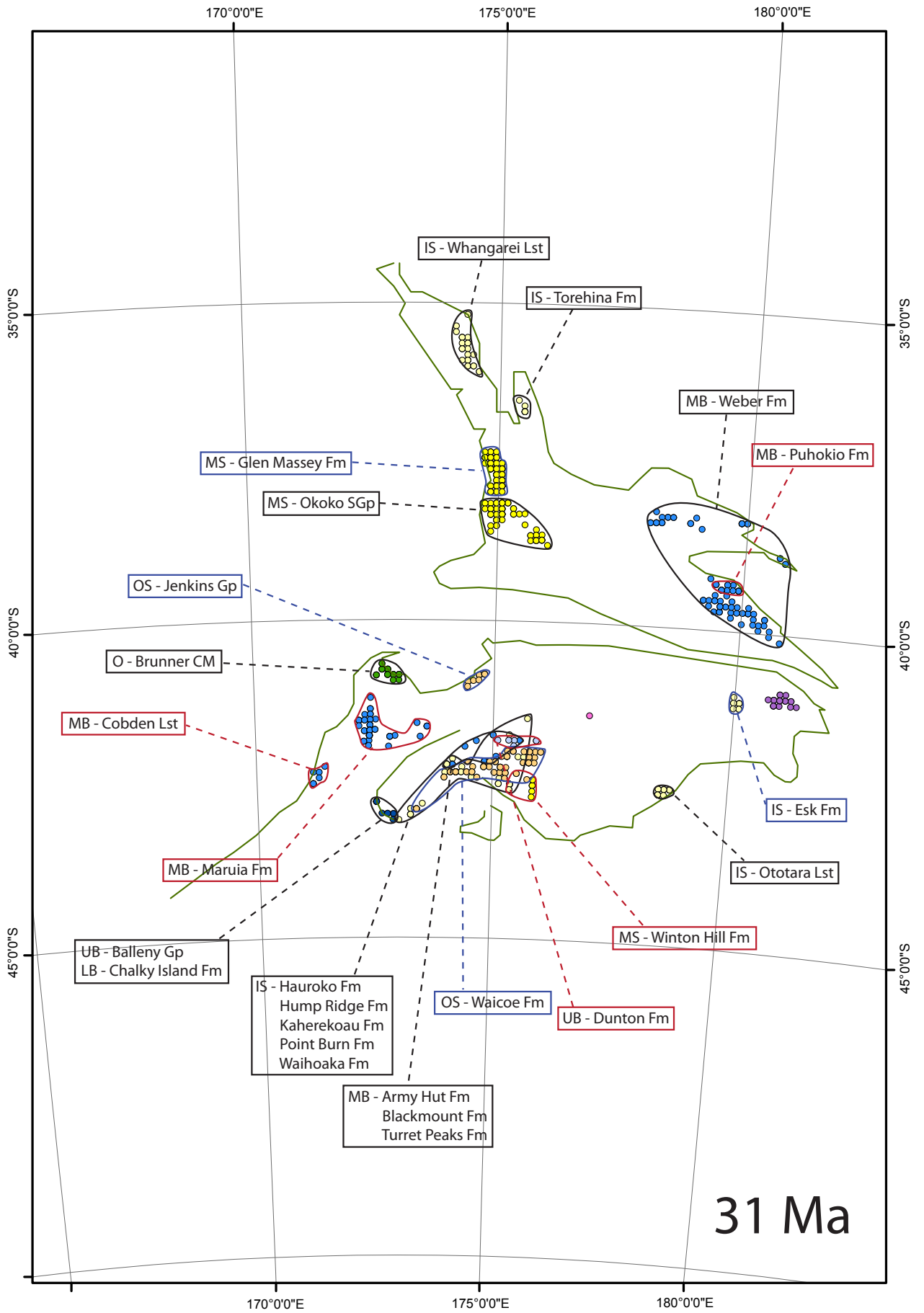


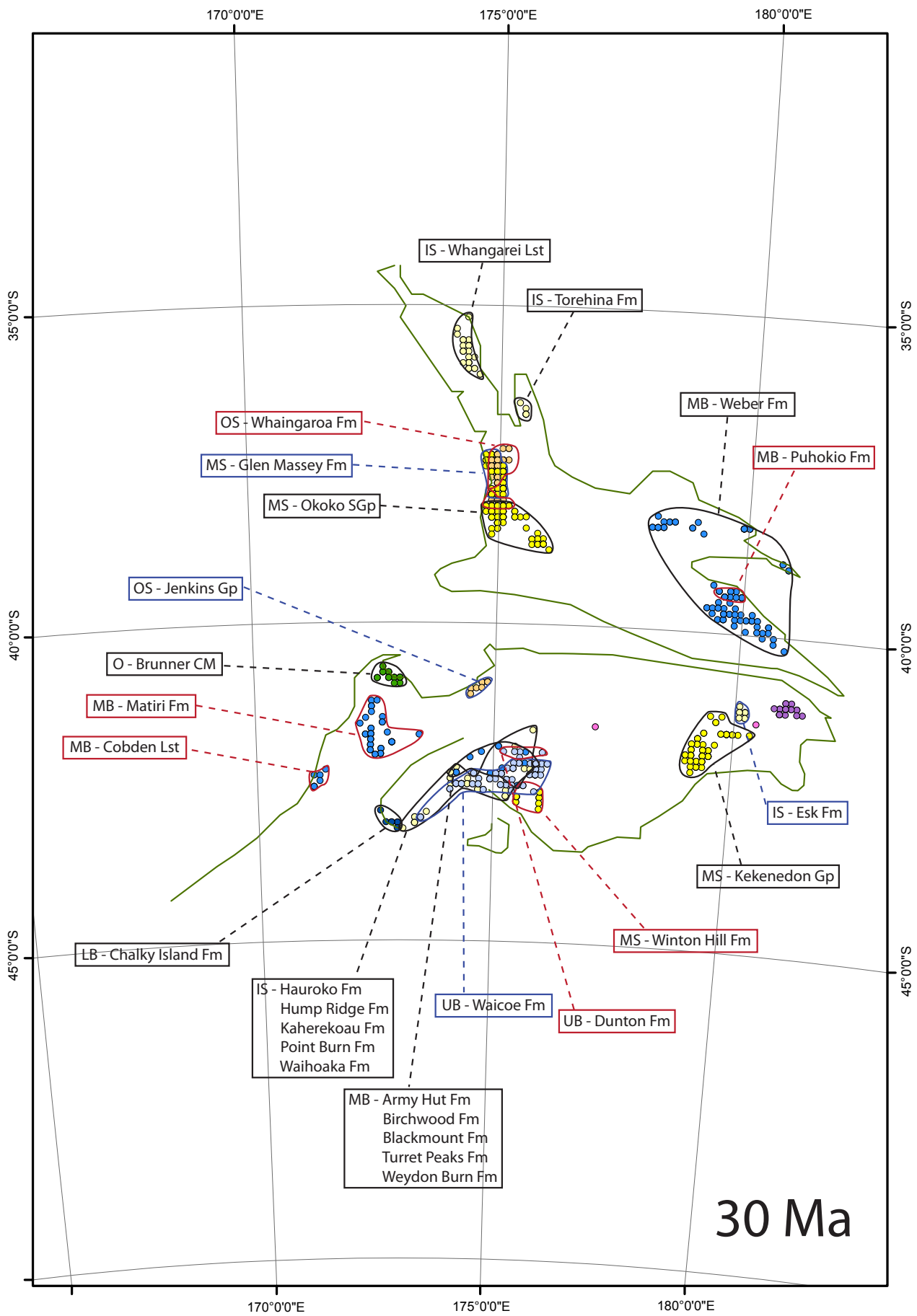


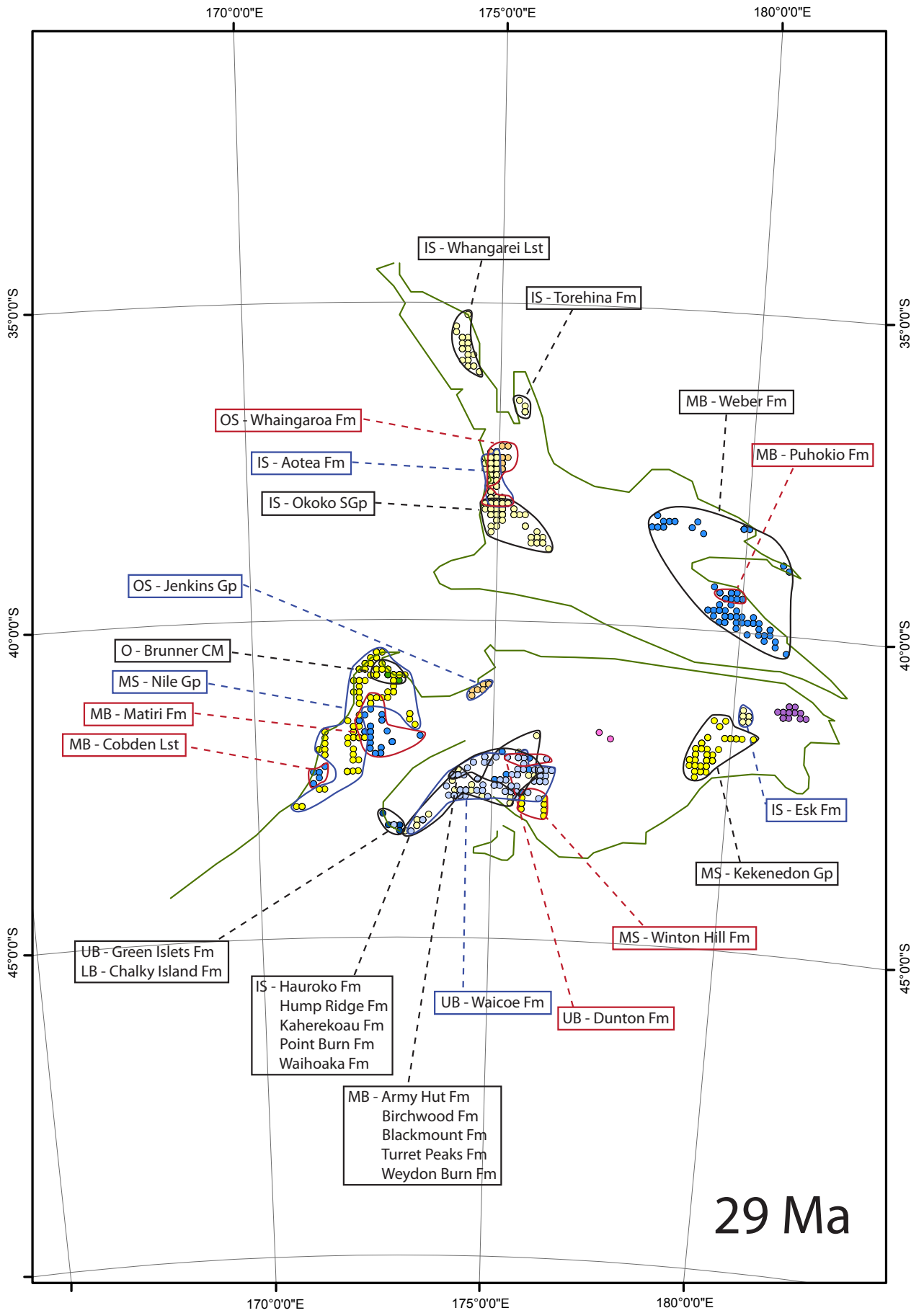


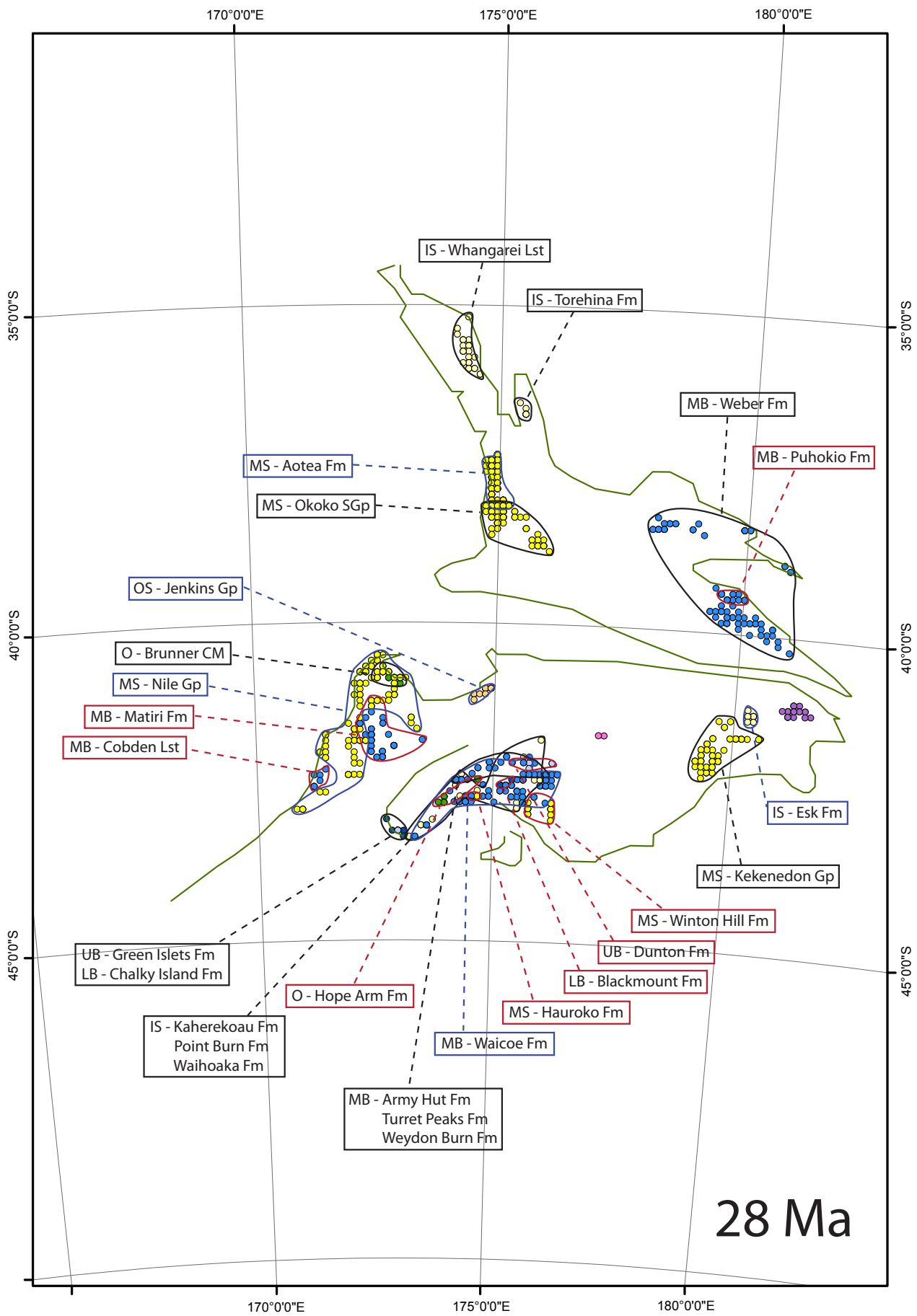


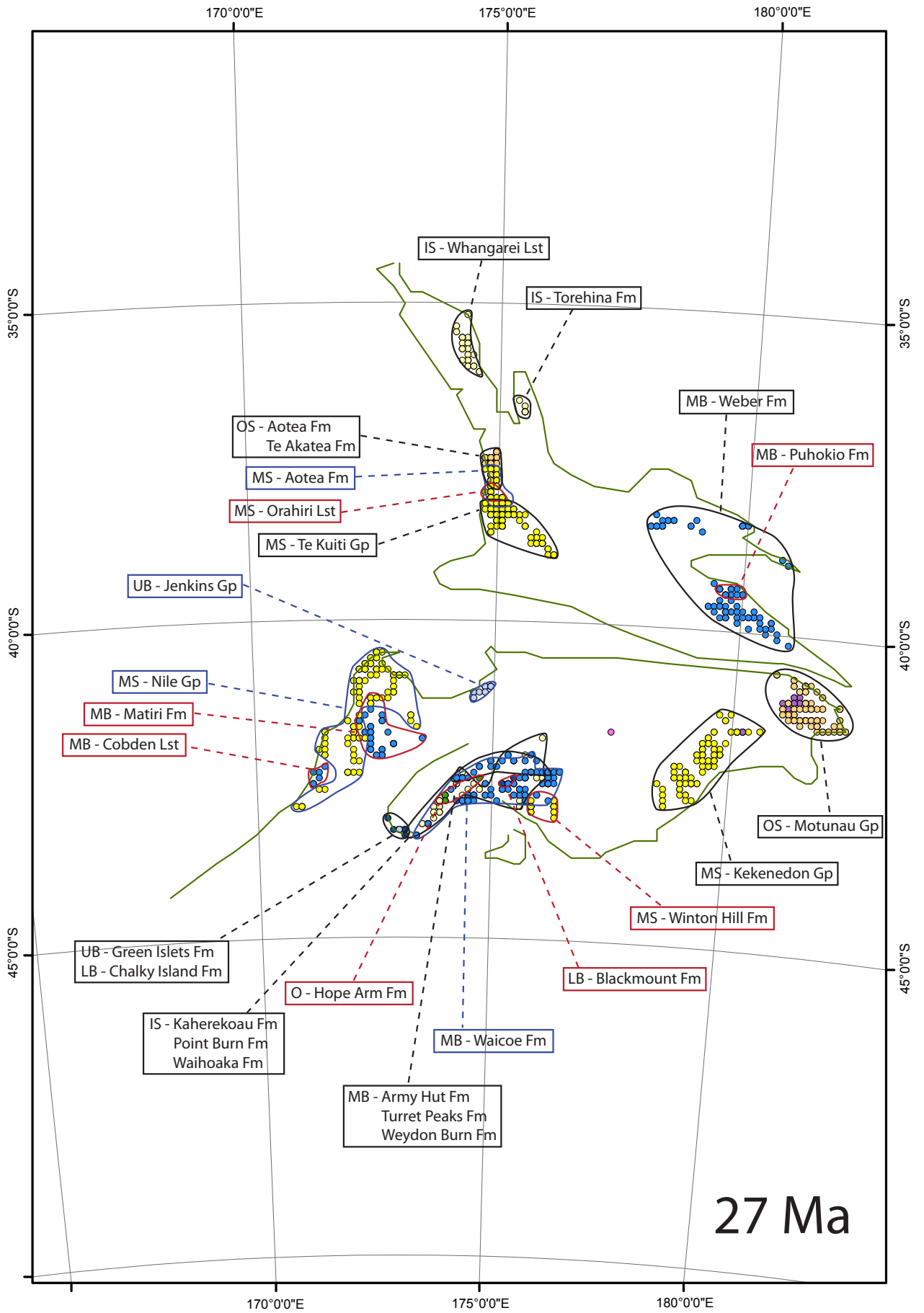


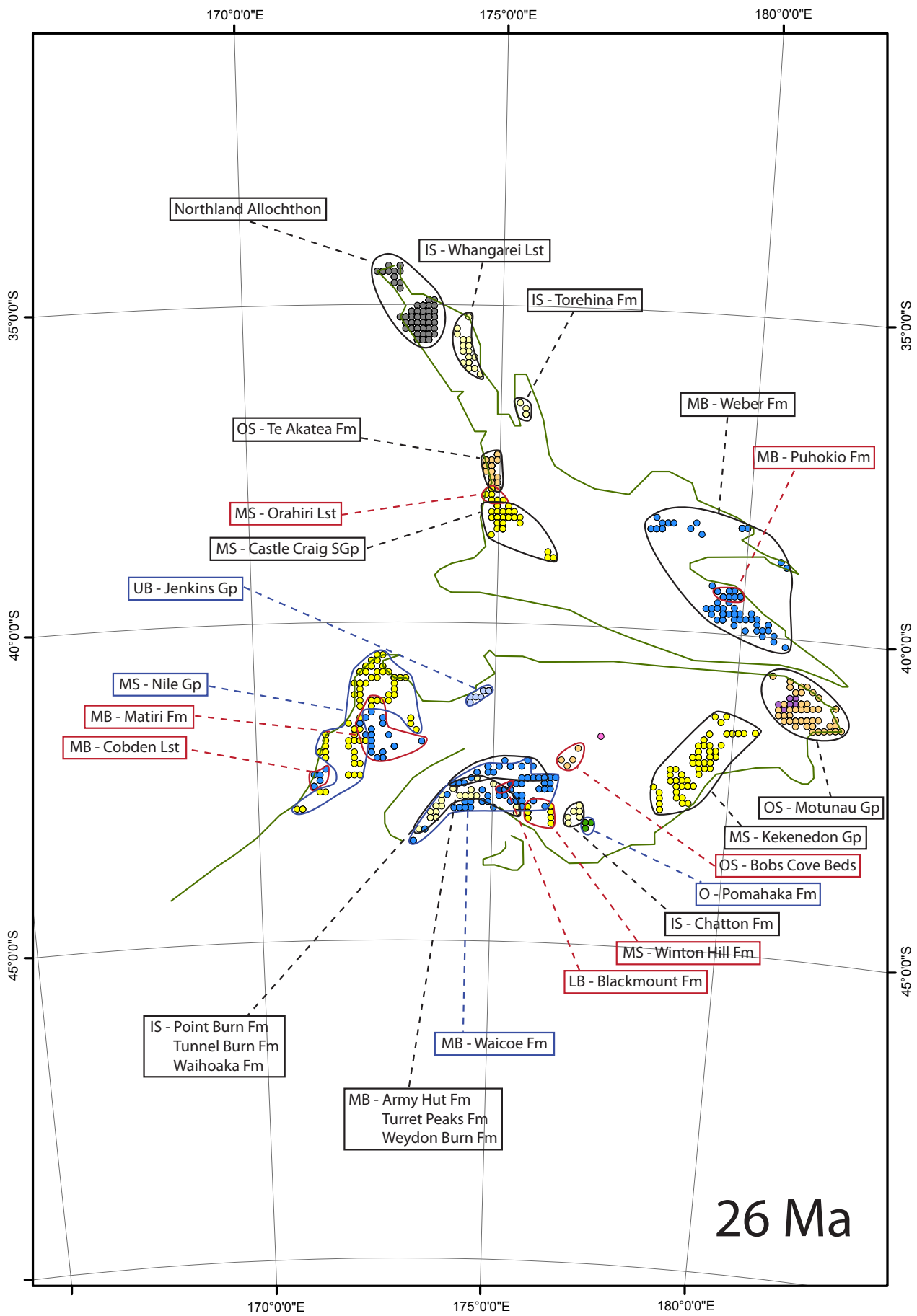


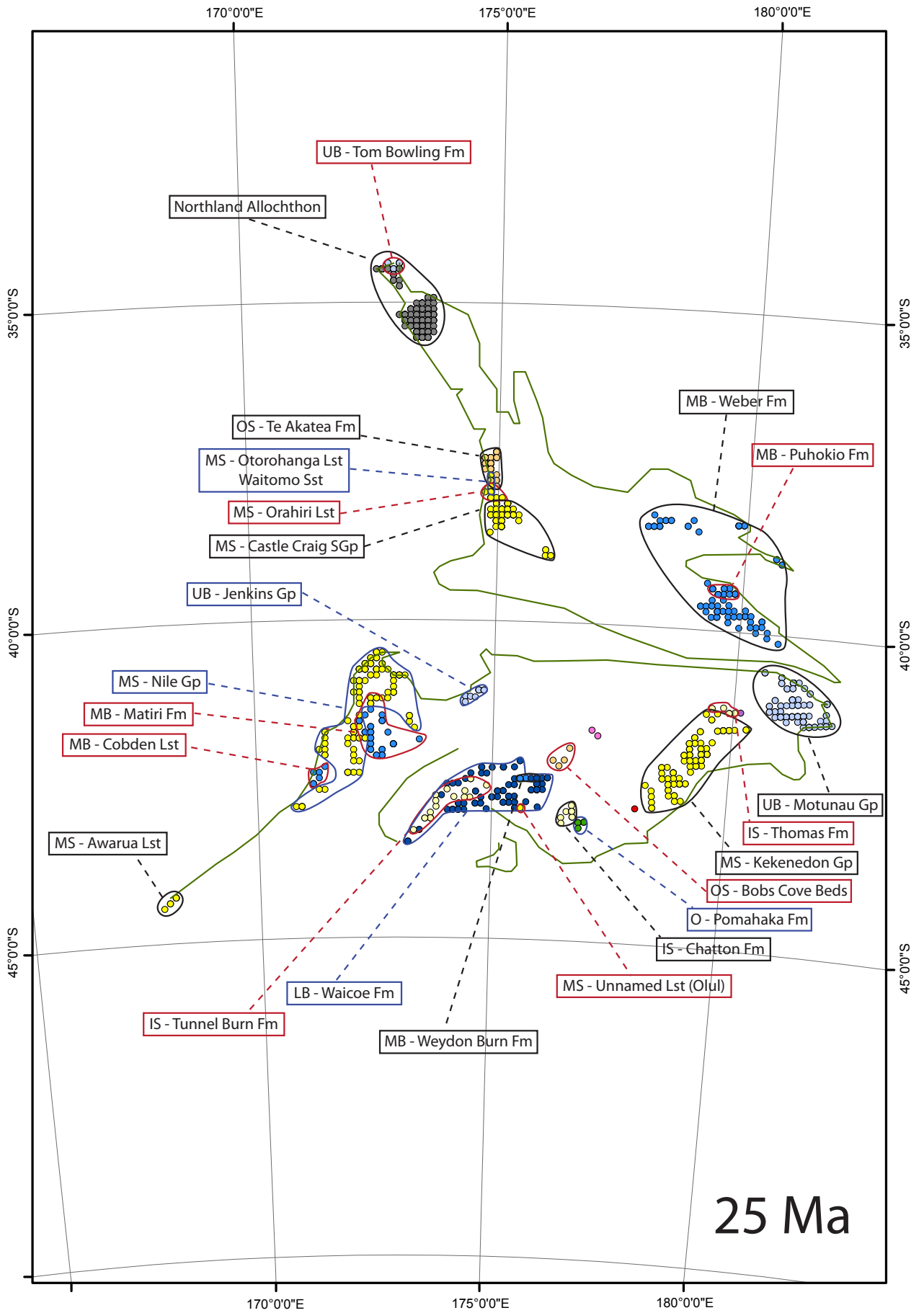




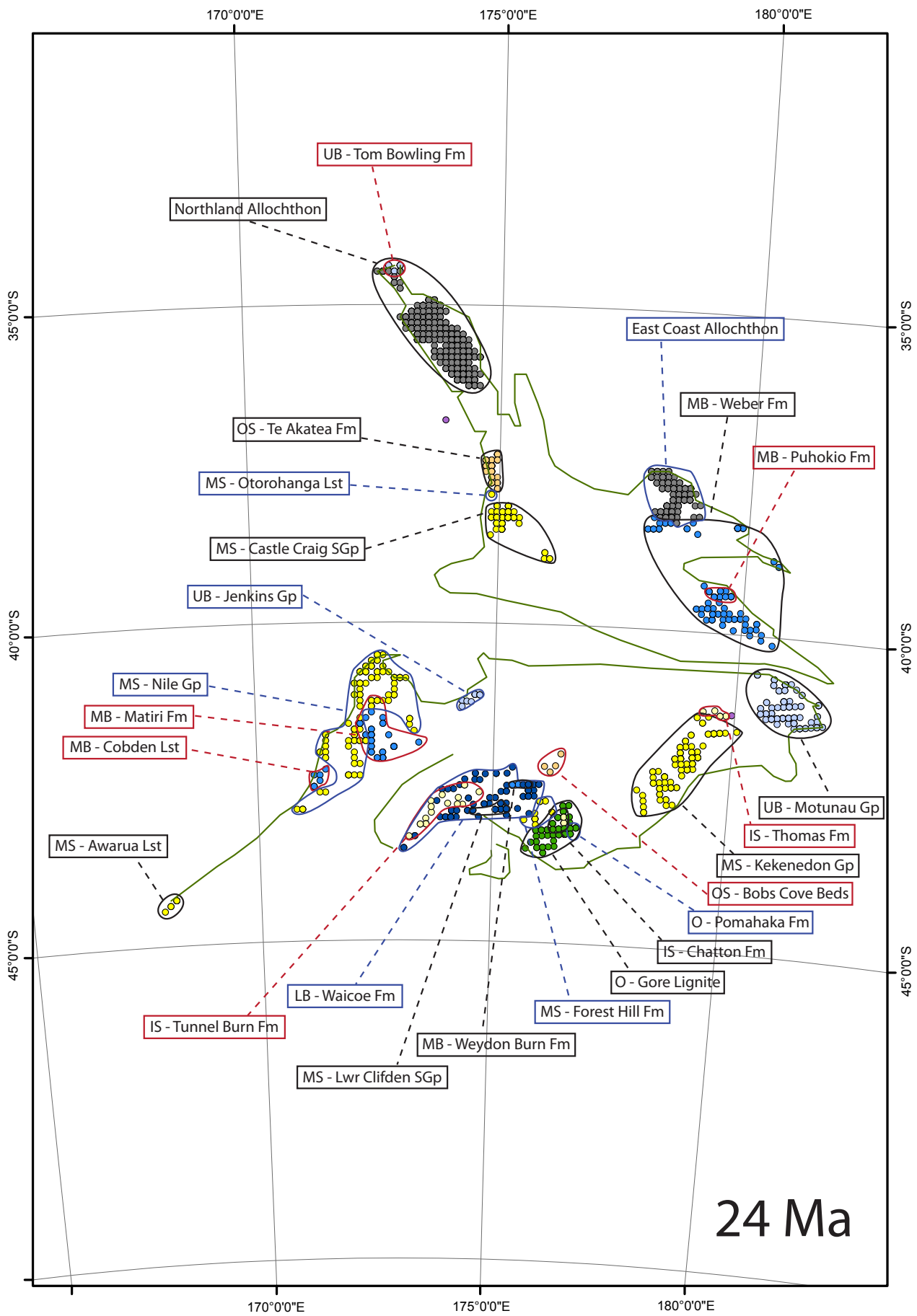


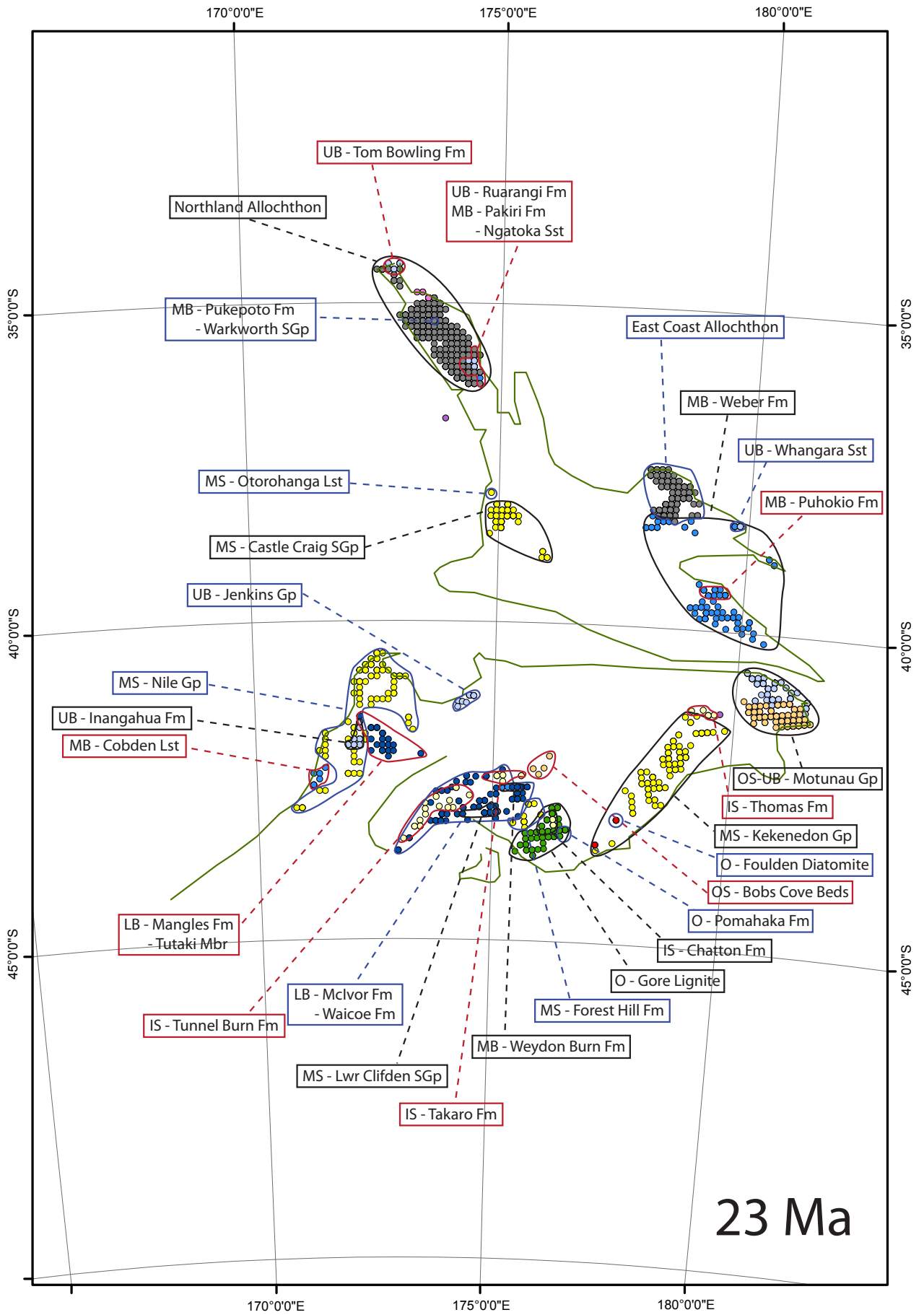


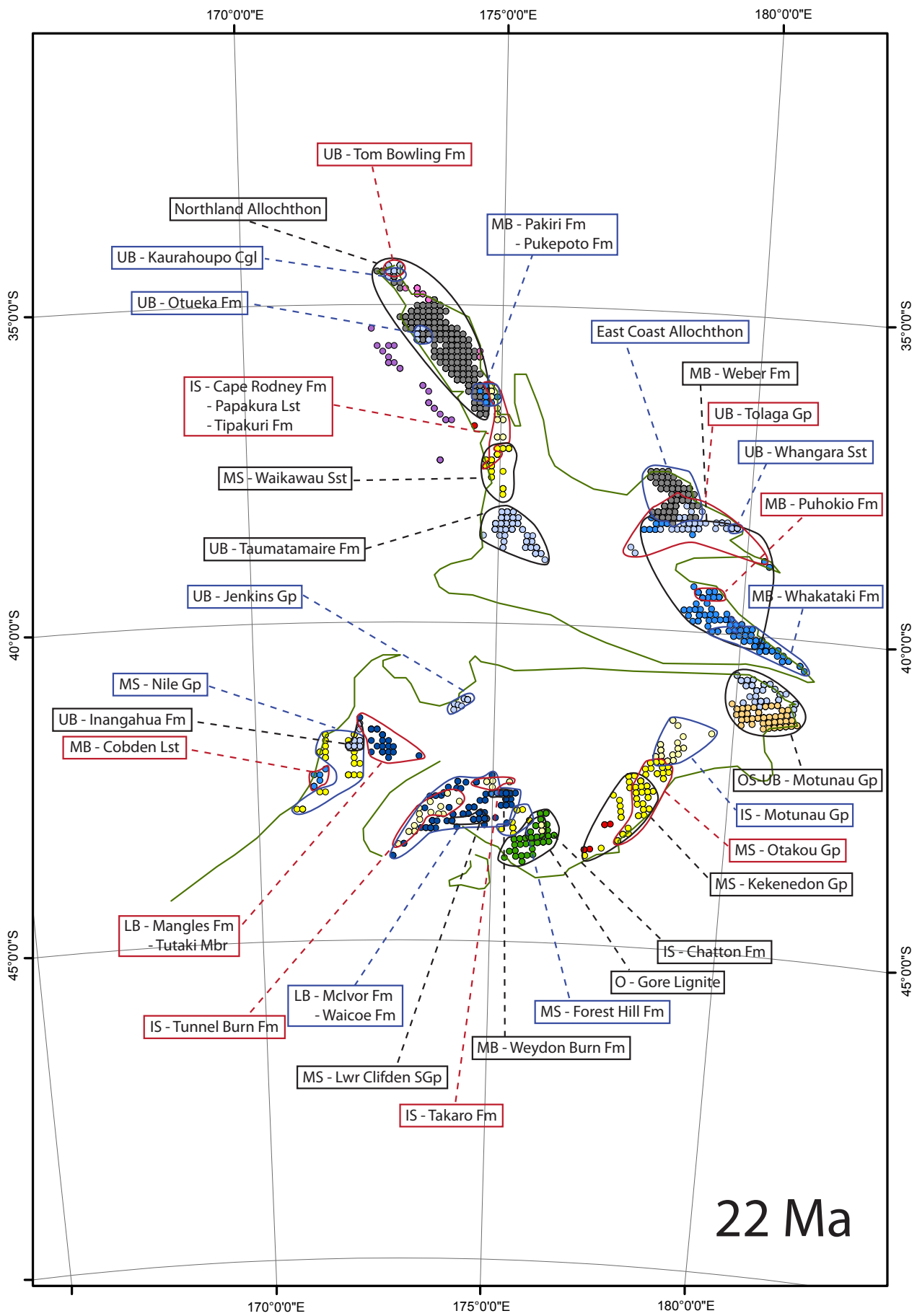


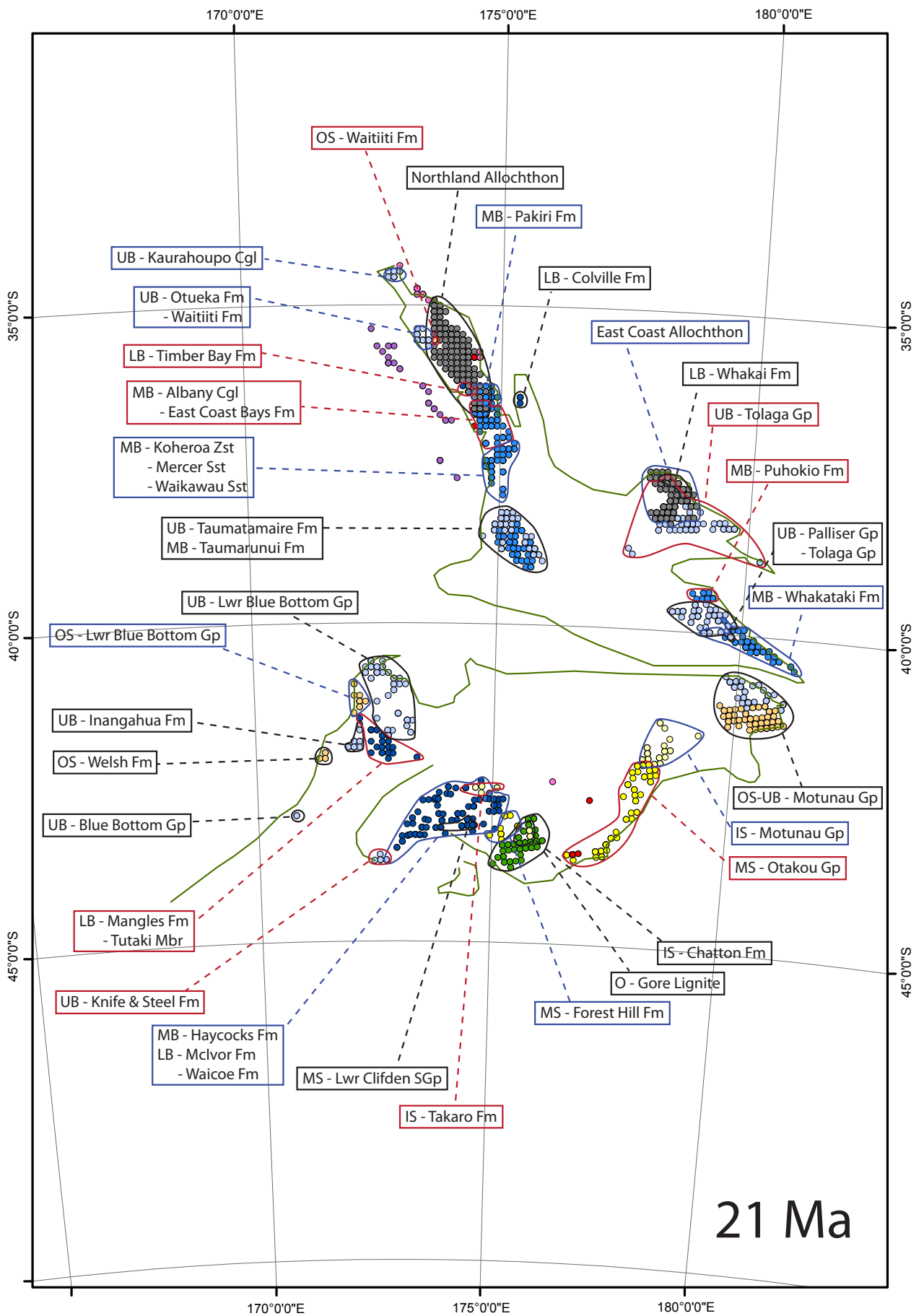


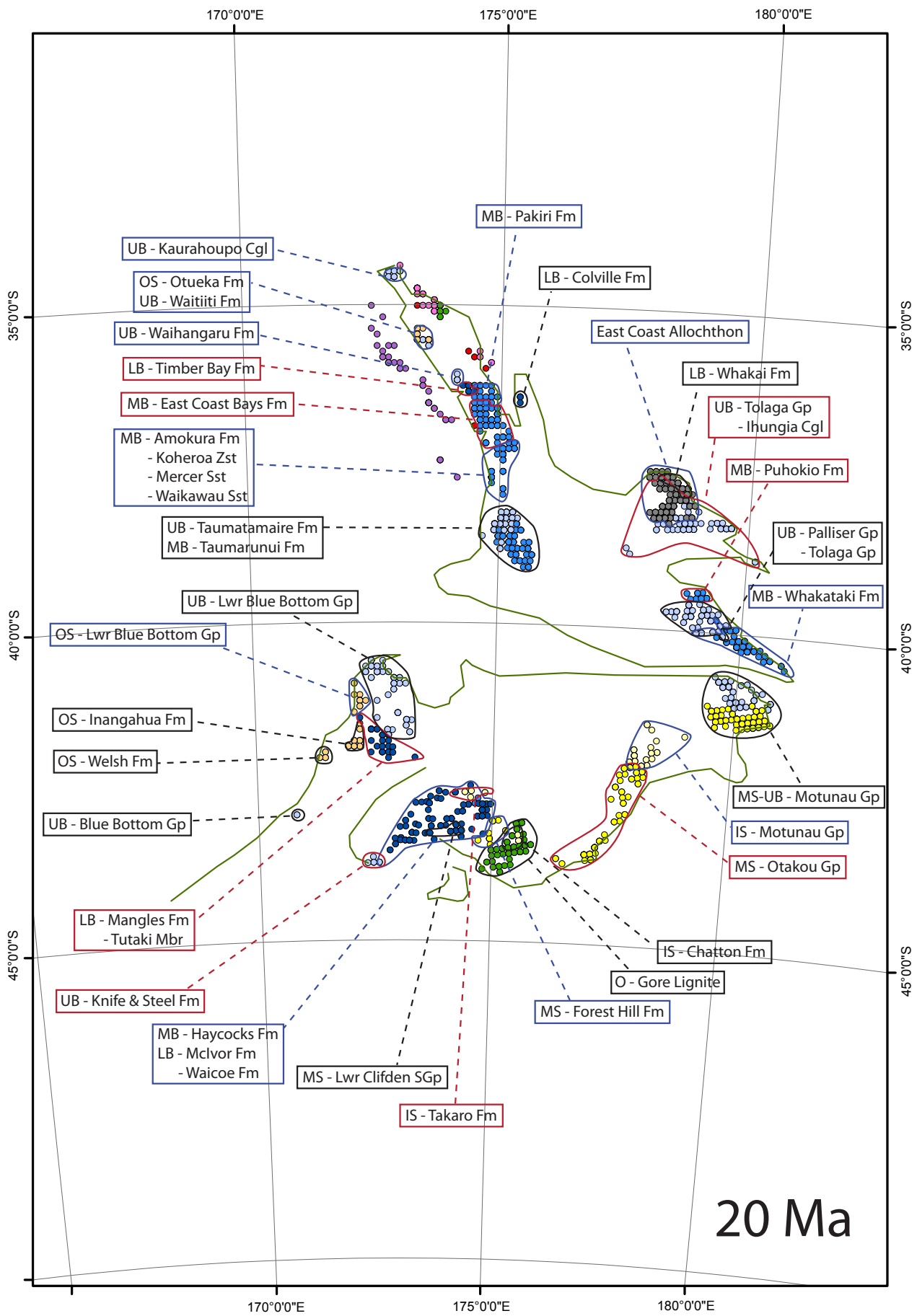


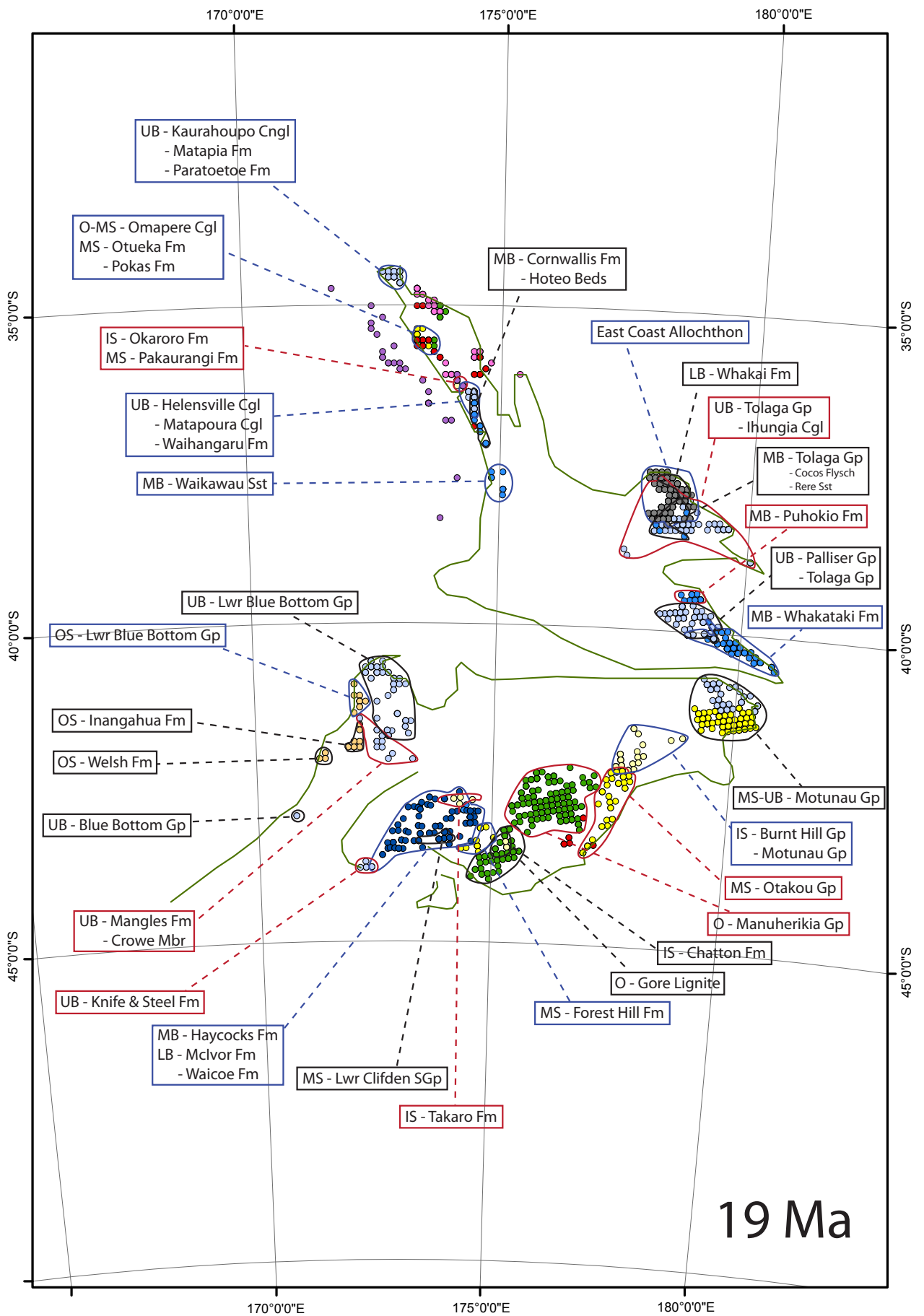


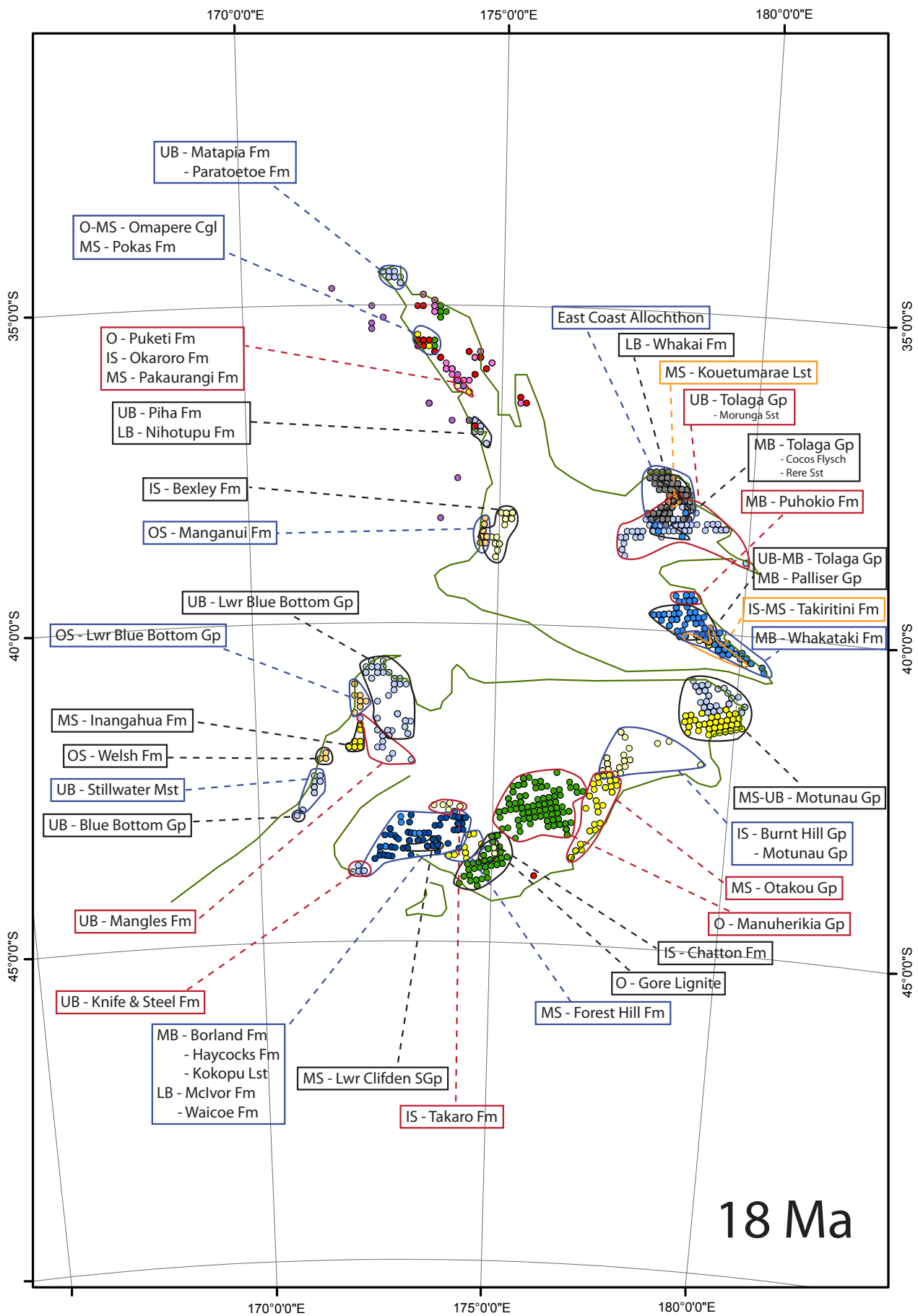


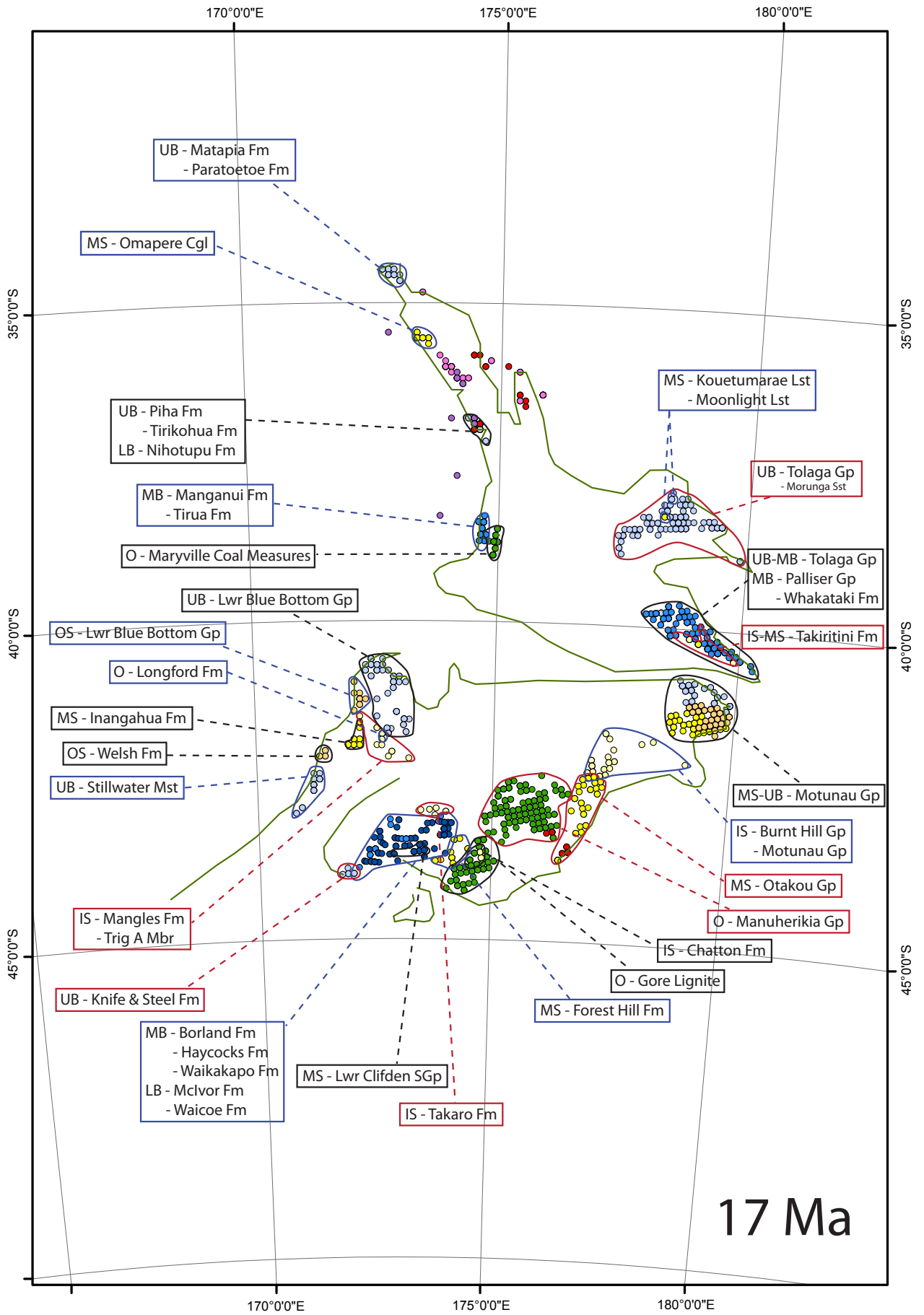




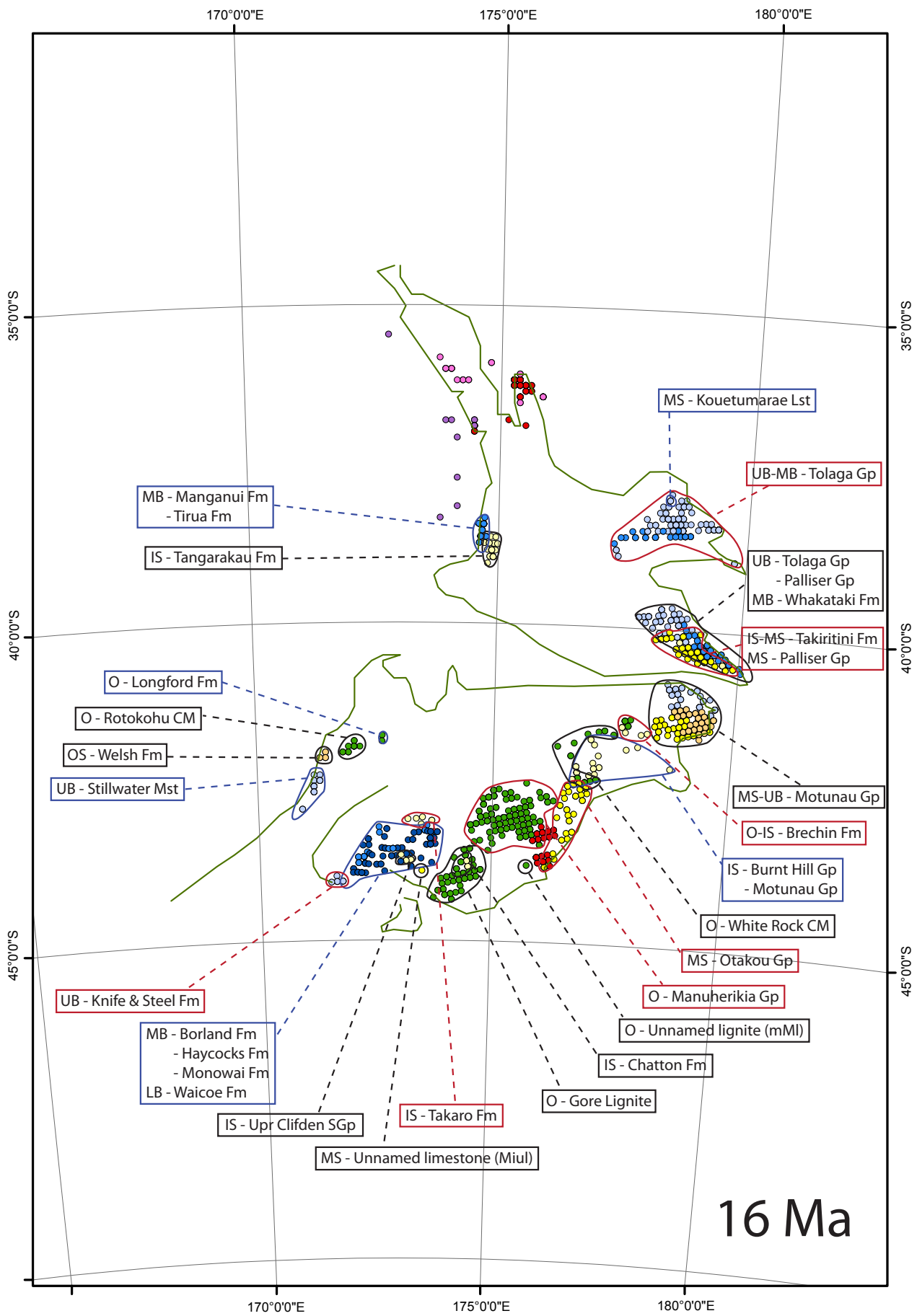


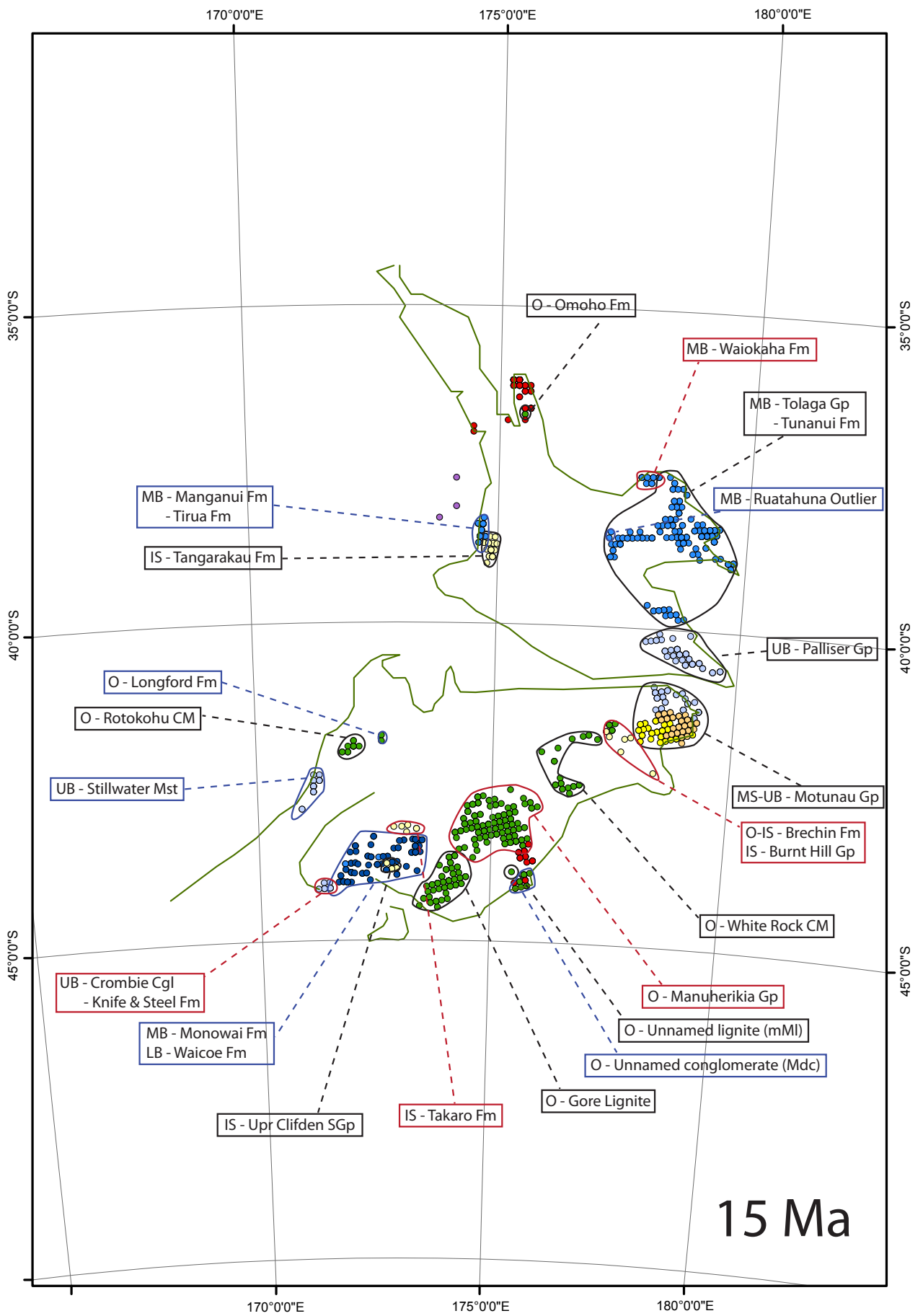


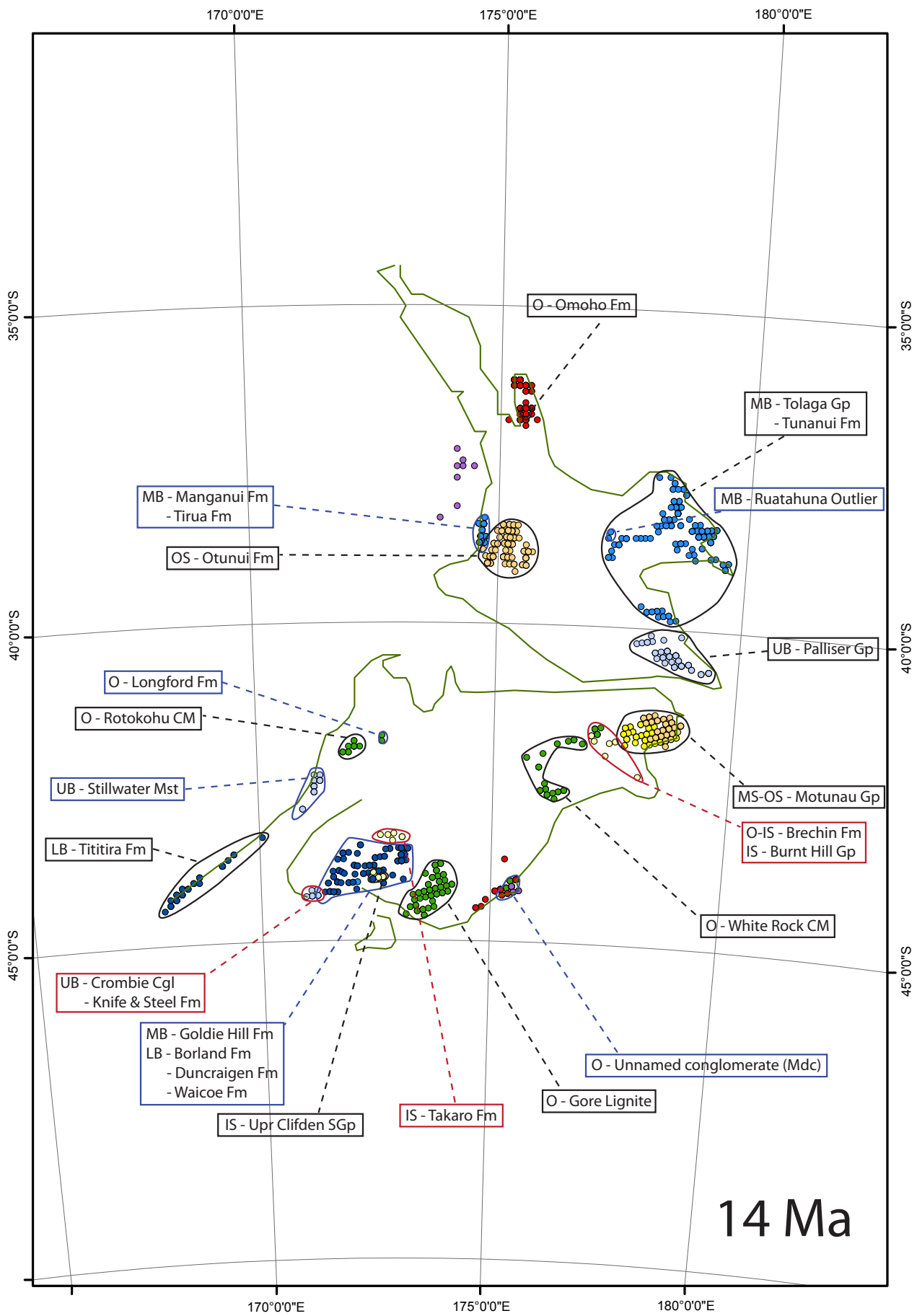


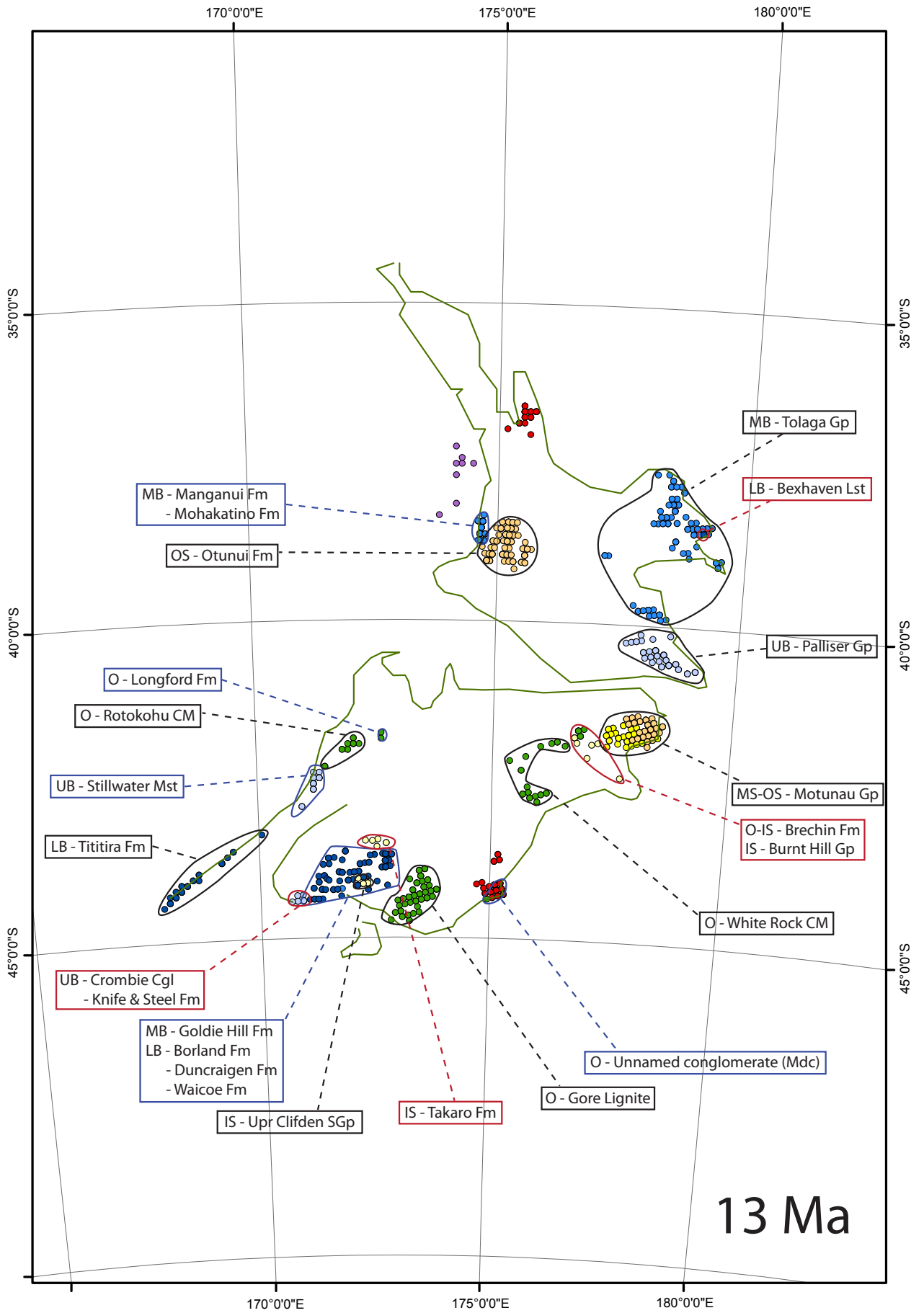


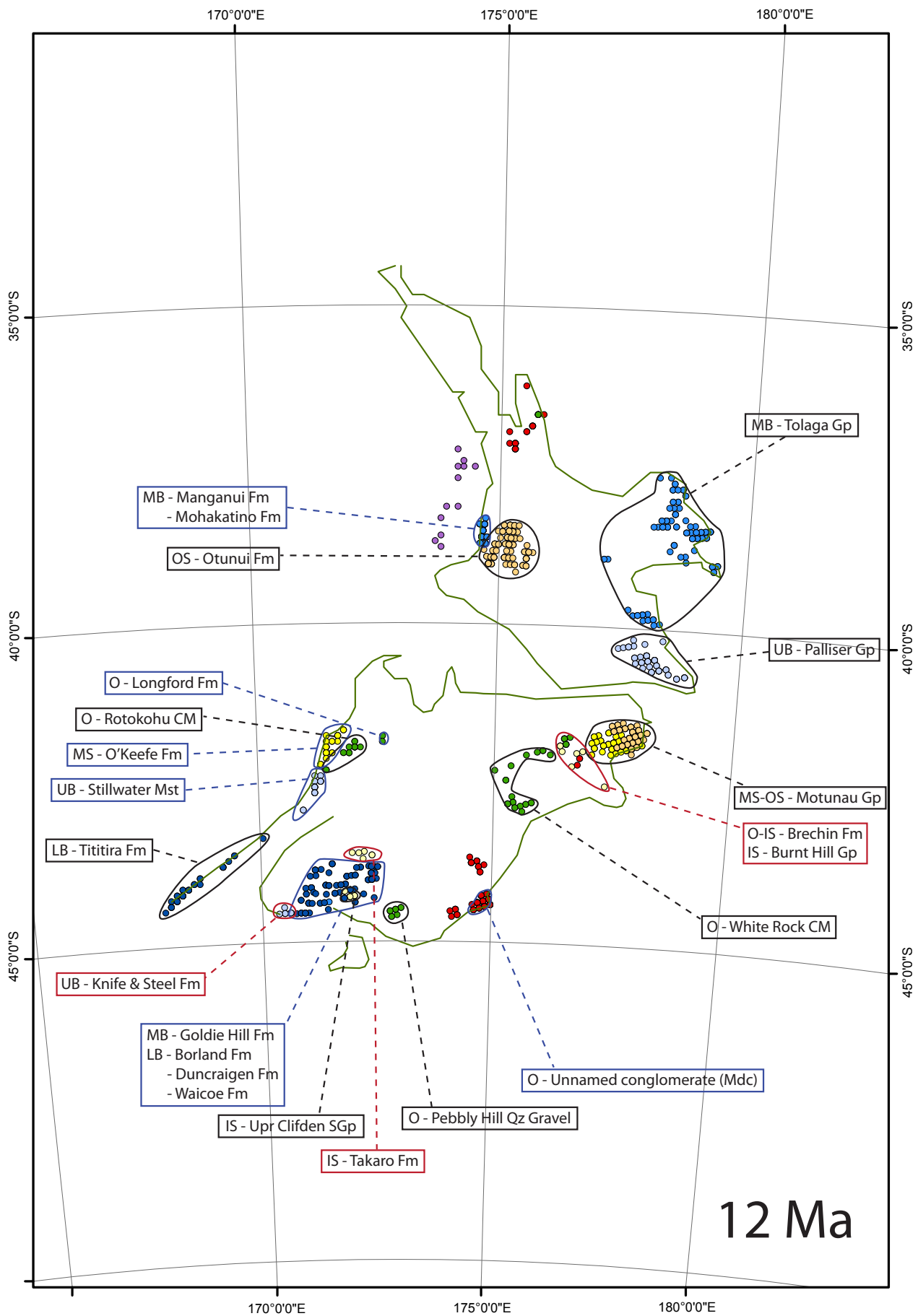


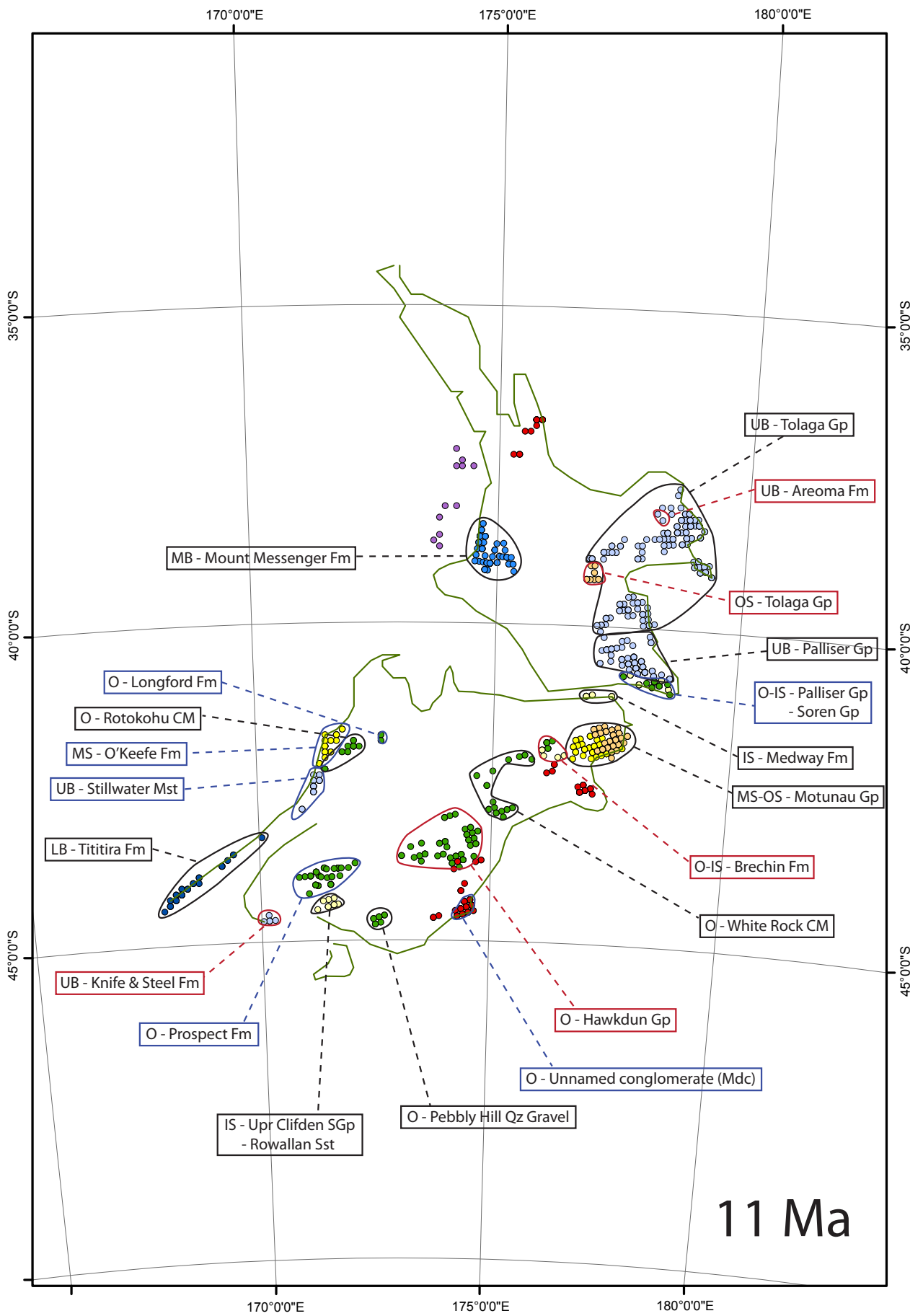


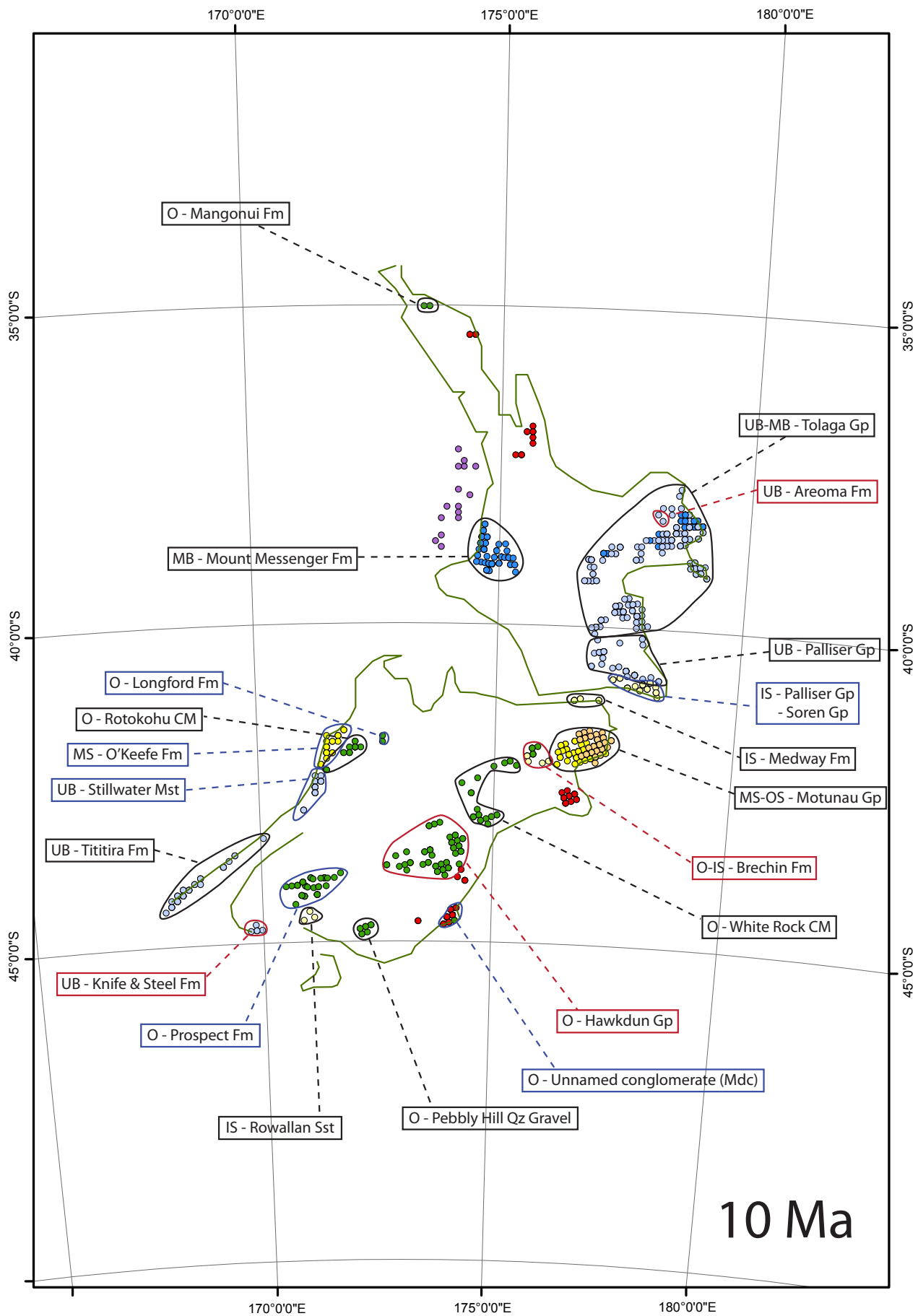


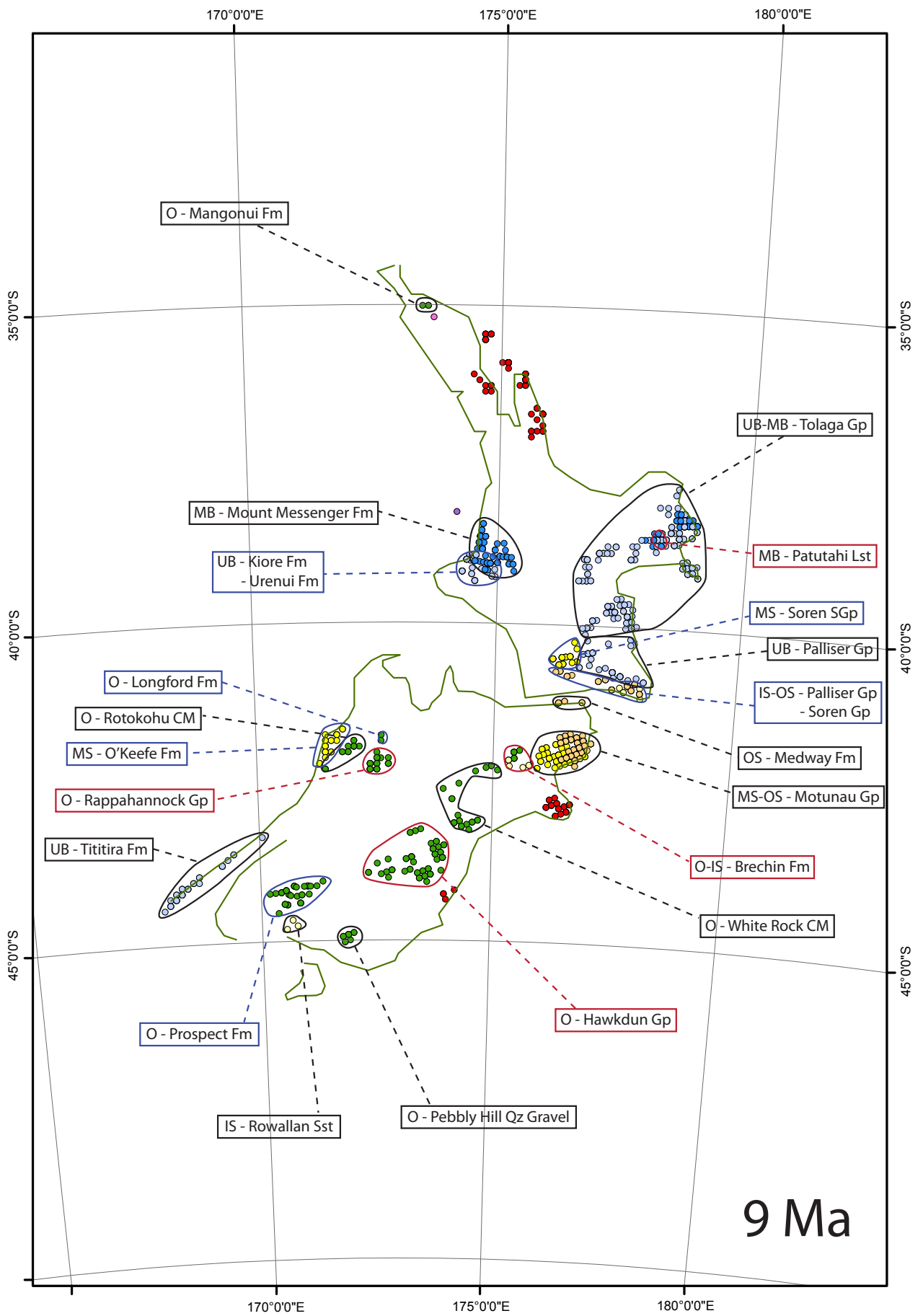




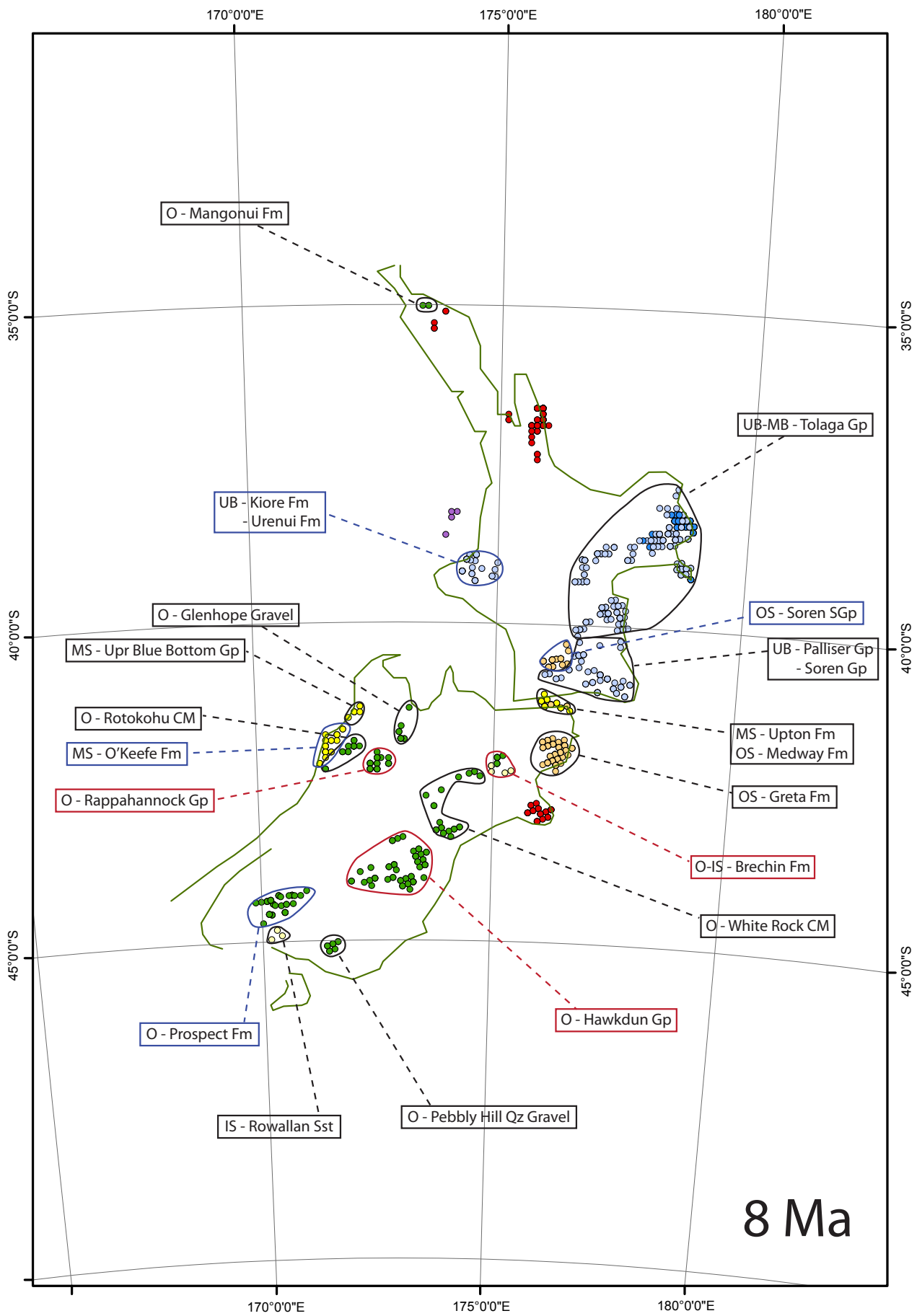


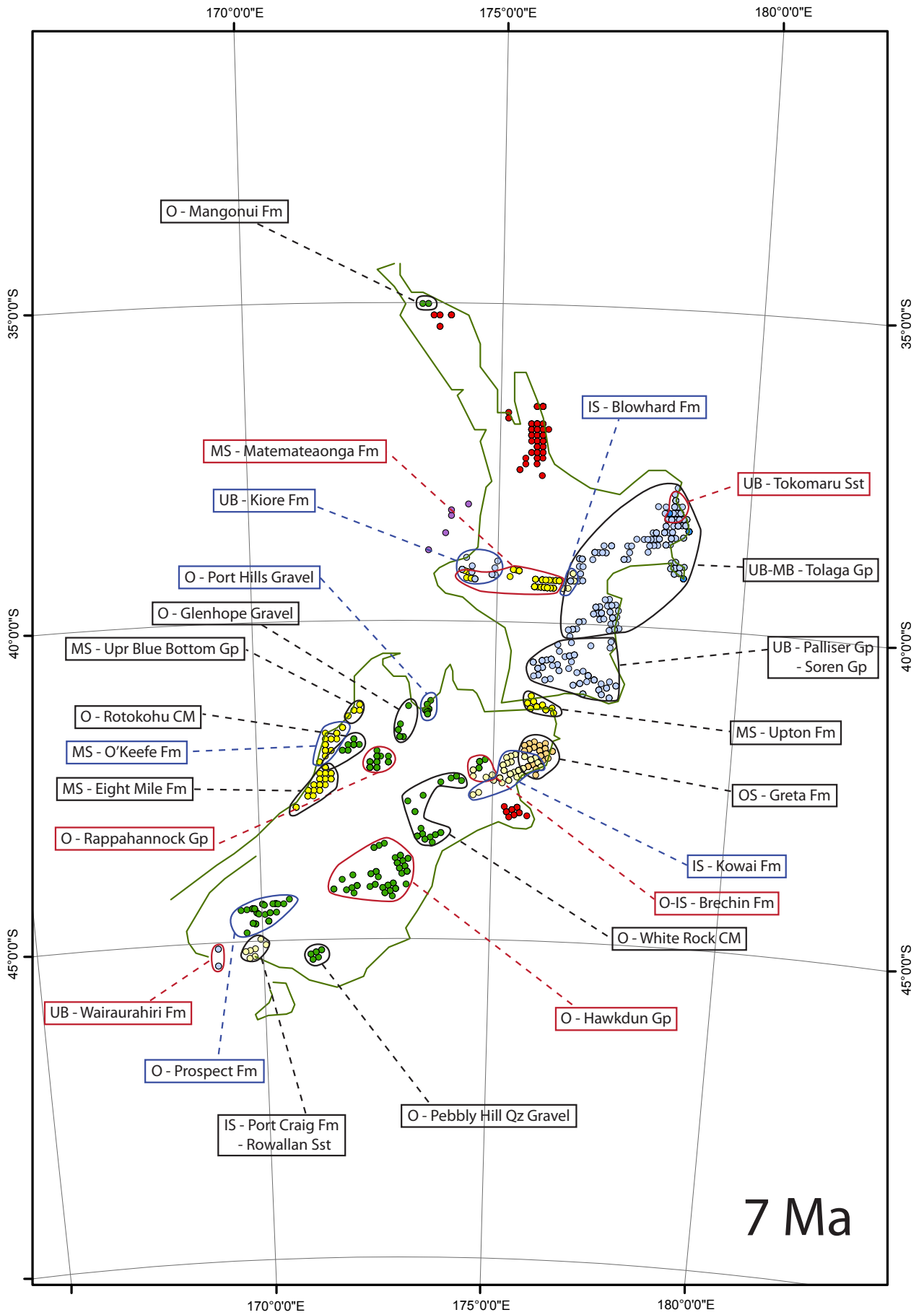


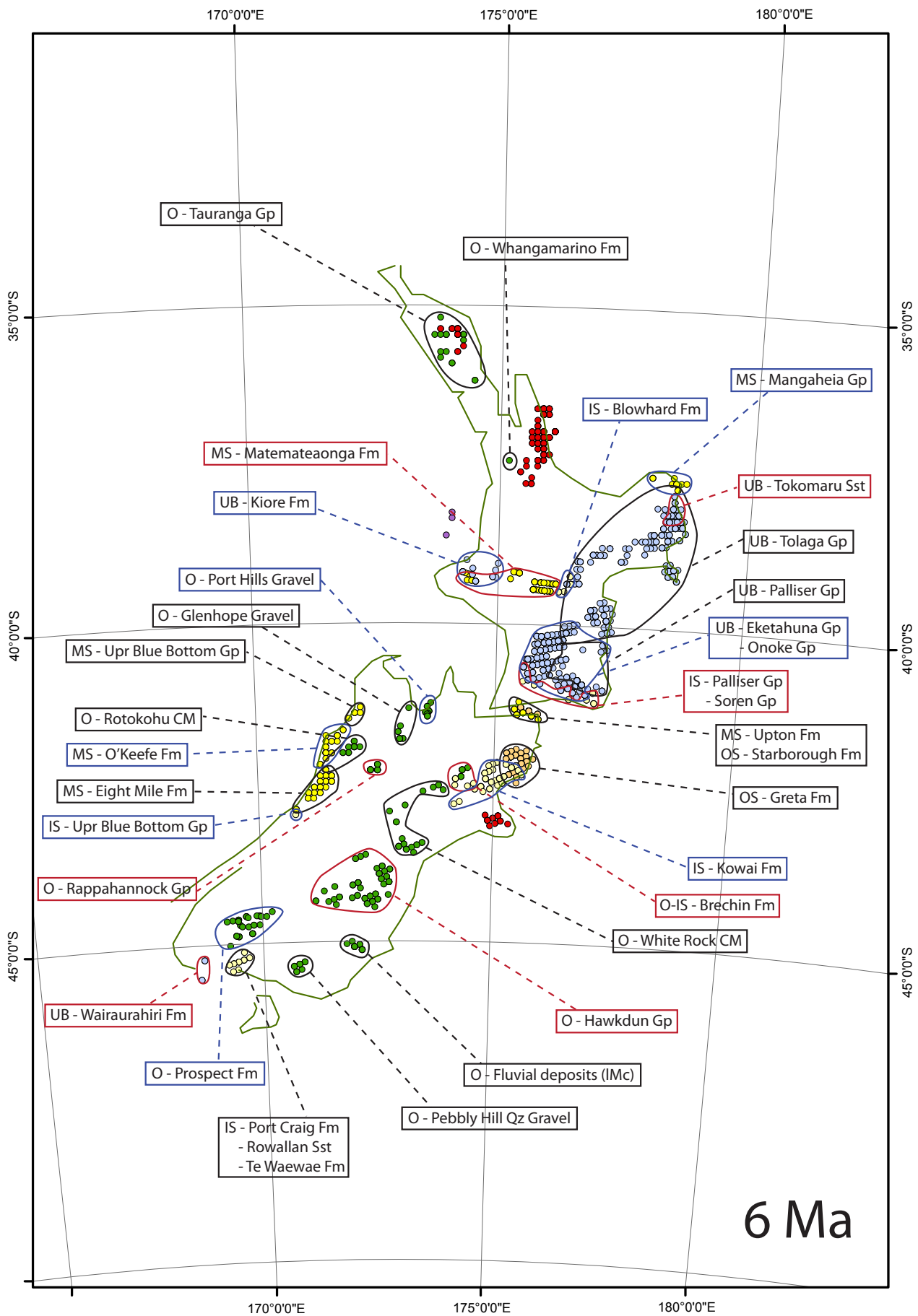


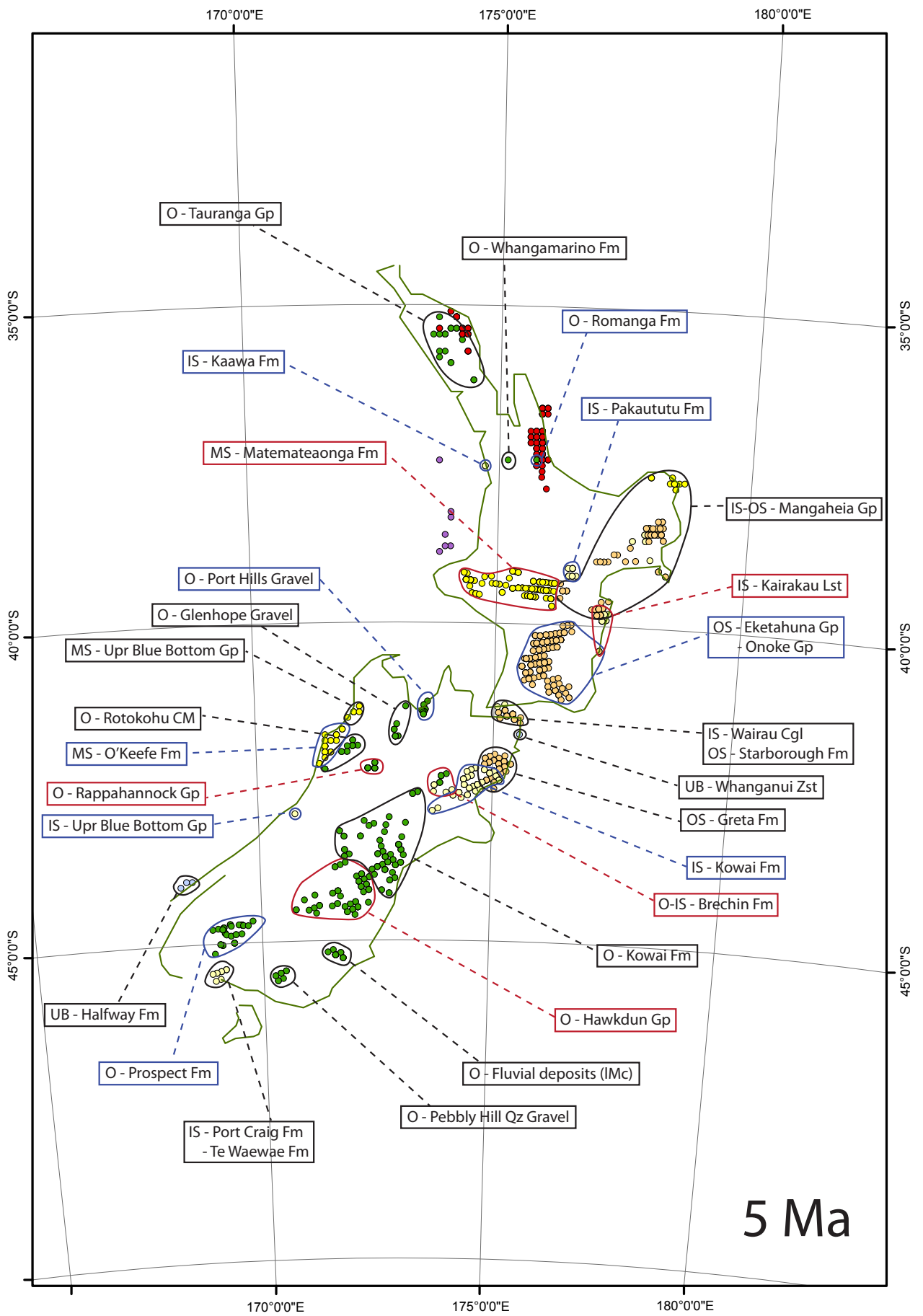


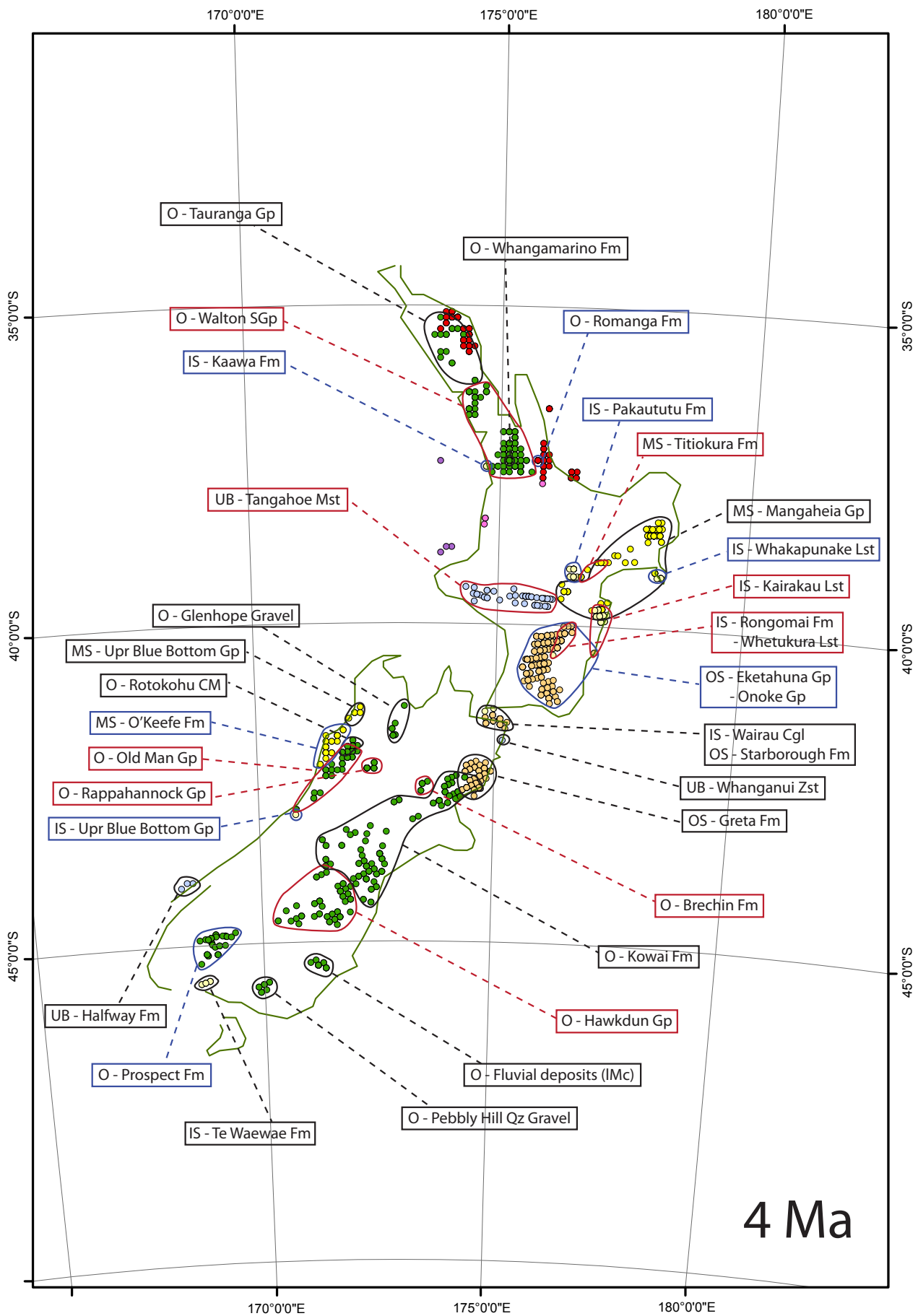


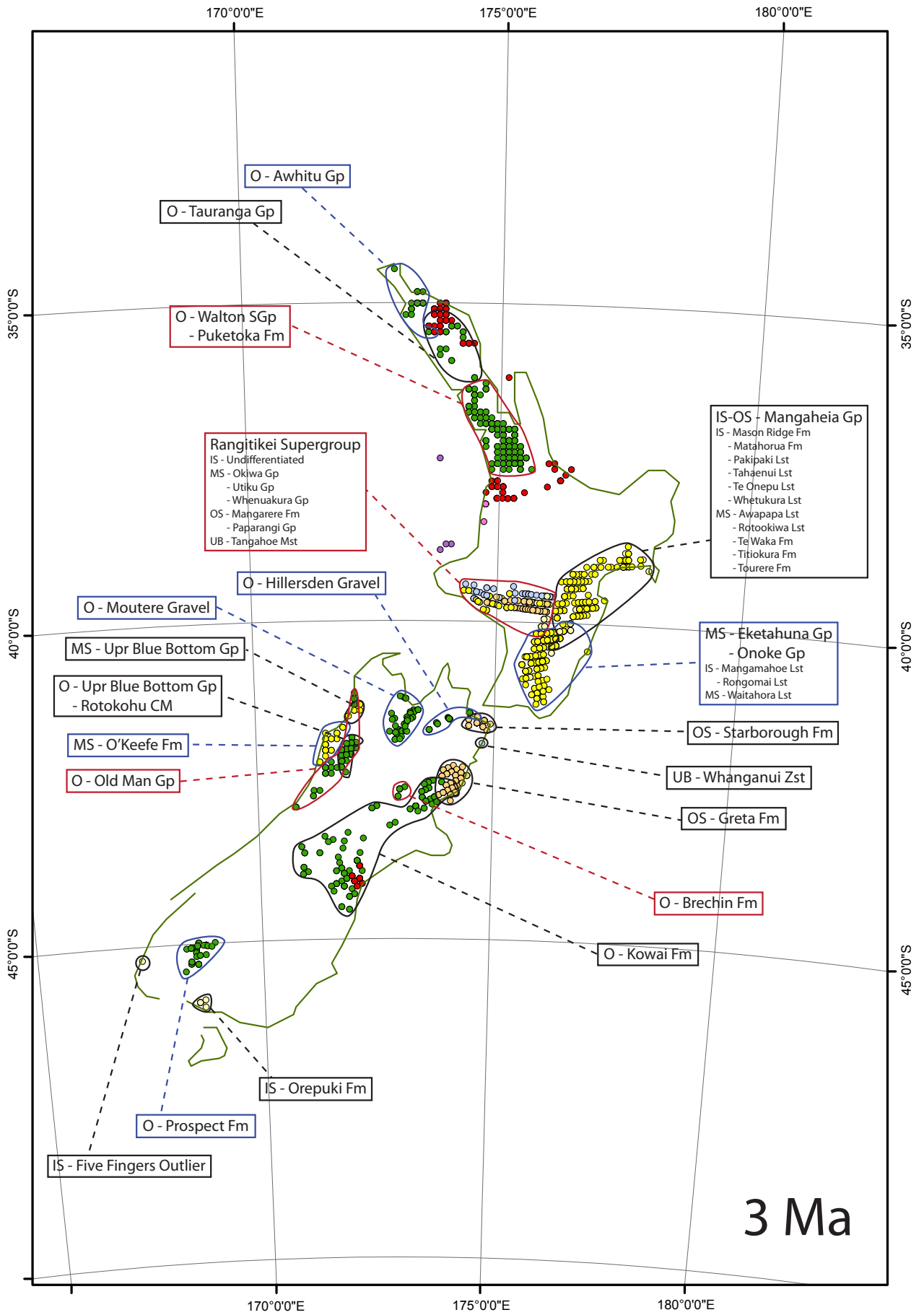


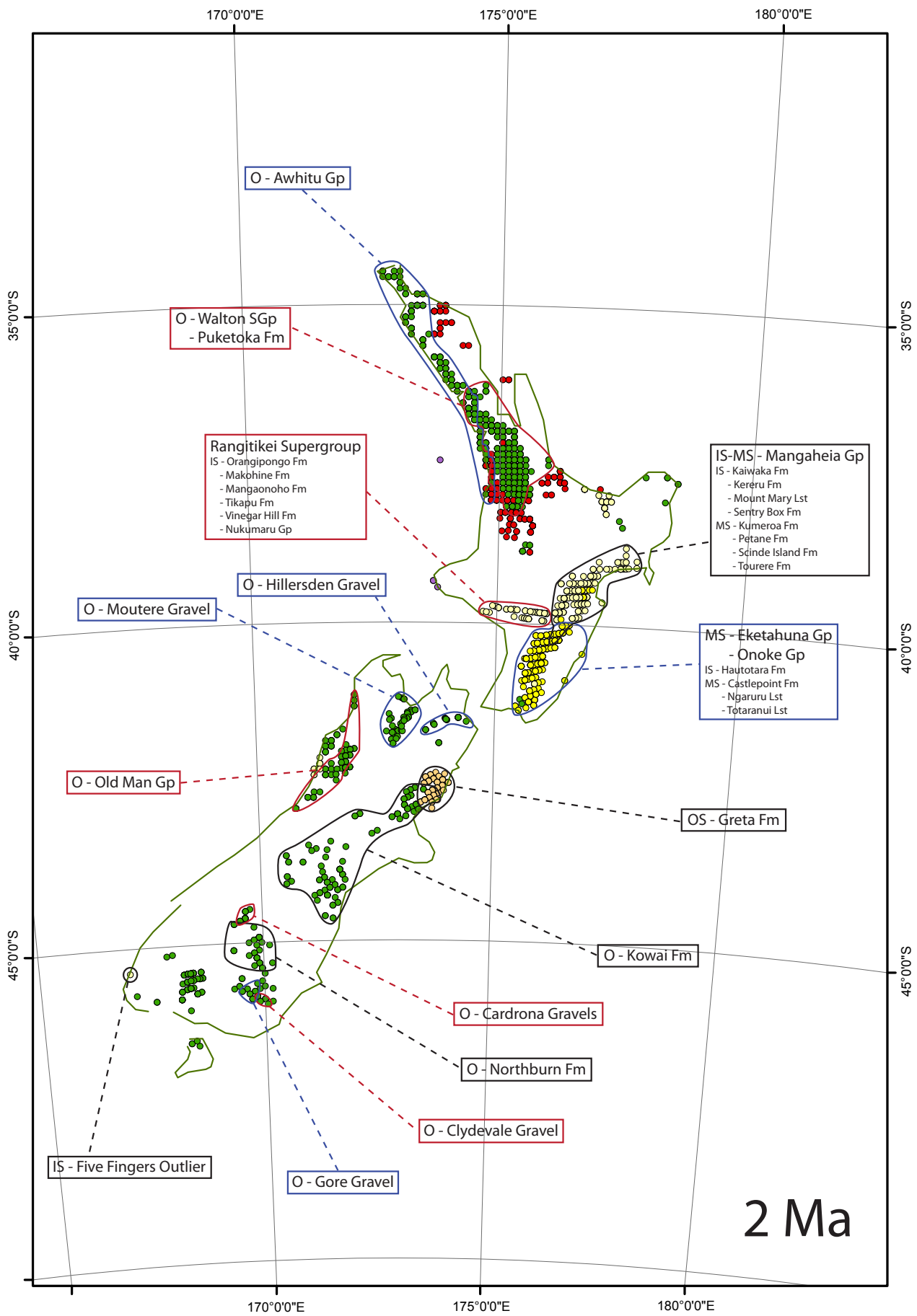


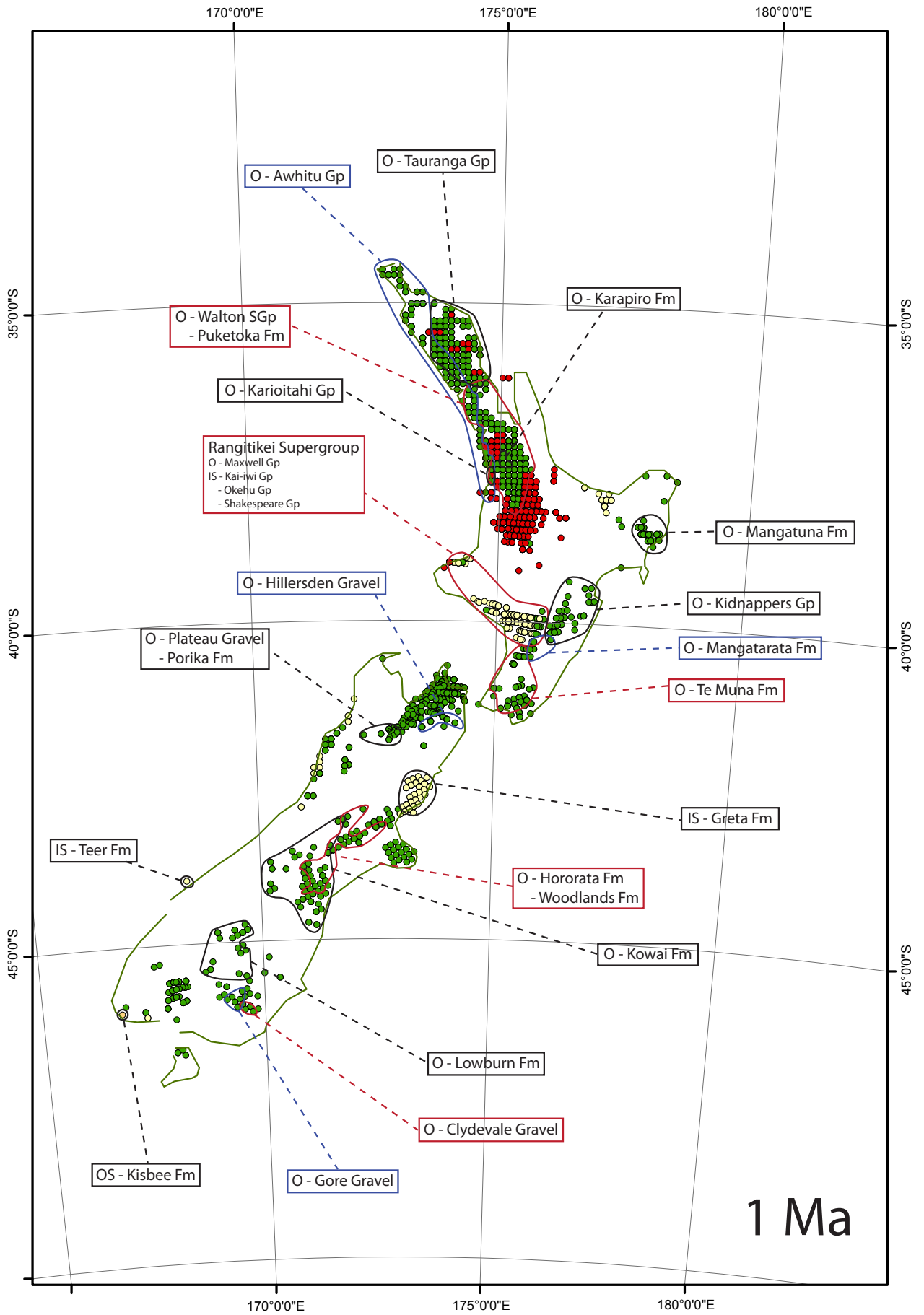














## KAITAIA AREA (Geological Map 1)

### Te Kuiti Group

#### **Ruatangata Sandstone (Etr)**

**Inferred age:** 38-36 Ma (Boyes et al., 2011b)

**EoD:** outer shelf

**Basis for interpretation:** Main\_Rock = sandstone; Description = Poorly bedded, fossiliferous, dark green, calcareous glauconitic sandstone (QMAP database). "Foraminifera indicate deposition in a **range of shelf** environments" (Edbrooke and Brook, 2009) – "*shelf*" is narrowed down to *outer shelf* here. Refer to "Ruatangata Sandstone (Etr)" on the Whangarei map area for further information.

#### **Mangapa Mudstone (Etm)**

**Inferred age:** 38-36 Ma (Boyes et al., 2011b)

**EoD:** upper shelf

**Basis for interpretation:** Main\_Rock = mudstone; Description = Massive blue-grey calcareous mudstone (QMAP database). "...was deposited at **mid shelf to upper bathyal** depths..." (Isaac, 1996) – the map unit is defined here as *upper bathyal*, but a greater range of environments is also likely, including *mid-shelf to mid-bathyal* (Evans and Hayward, 1990). Refer to "Mangapa Mudstone (Etm)" on the Whangarei map area for further information.

#### **Whangarei Limestone (Otw)**

**Inferred age:** 38-36 Ma (Boyes et al., 2011b)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = biosparite; Description = Bryozoan-molluscan-echinoid-foraminiferal-algal limestone (QMAP database). "Although Whangarei Limestone accumulated mainly at **shelf** depths..." (Isaac, 1996) – the depth range for the in place units is here narrowed down to an *innermost shelf* EoD, based on paleogeography maps in Isaac et al. (1994). Refer to "Whangarei Limestone (Otw)" on the Whangarei map area for further information.

### Otaua Group

#### **Pukepoto Formation (Mop)**

**Inferred age:** 23-22 Ma (Isaac, 1996)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone, breccia; Description = Calcareous mudstone with intercalated sandstone and breccia derived from the Northland Allochthon (QMAP database). "The [Whangarei] limestone is sharply and concordantly overlain by an erosional remnant of Otaua Group conglomerate and sandstone of earliest Miocene age (Mop...). Although the Whangarei Limestone accumulated mainly at shelf depths, foraminiferal show that overlying Otaua Group beds were deposited at **mid to lower bathyal depths (1000-4000 m)**..." (Isaac, 1996). "[For the Pukepoto Formation:] The high planktic percentages indicate oceanic water overhead. The sparse benthic faunas contain common *Oridorsalis umbonatus*, *Cassidulina laevigata*, *Cibicides vortex*, *Stilostomella*, *Cibicides mediocris*, and *Pullenia bulloides*, consistent with **bathyal, possibly mid-bathyal depths or deeper (1000-3000 m)**" (Evans and Hayward, 1990) – EoD is based on the *mid-bathyal* interpretation for the formation in Evans and Hayward (1990) and is supported by the *mid- to lower bathyal* EoD interpreted for the Otaua Group (of which the Pukepoto Formation is a part of) in Isaac (1996). A *lower bathyal* EoD is an alternative interpretation. Pukepoto Formation also occurs on the Whangarei map area (Mwx) where it is mapped as an allochthonous unit.

### Northland Allochthon (various unit codes)

Includes Tangihua Complex (Kt, Surville Serpentinite (Kts), Murimotu Intrusives (Ktm), Ktg, Ktb, Ktp), Tupou Complex (Ku), Mangakahia Complex (Kk), Motukaraka Sandstone (Kkm), Punakitere Sandstone (Kkp), Hukerenui Mudstone (Kkh), Whangai Formation (Kkw), Omahuta Sandstone (Emo), Taipa Mudstone (Emt), Mahurangi Limestone (Omm).

**Inferred age:** 26-22 Ma (Boyes et al., 2011b)

**EoD:** allochthonous

**Basis for interpretation:** Terrane = **Northland Allochthon** (QMAP database) – *EoD is based on the QMAP definition of the map units as part of the Northland Allochthon. These units are entirely allochthonous on the Kaitaia map area.*

## Coromandel Group

### **Wairakau Volcanics (Mcw)**

**Inferred age:** 20-18 Ma (Hayward et al., 2001; Edbrooke and Brook, 2009)

**EoD:** onshore intermediate eruptives

**Basis for interpretation:** Main\_Rock = breccia; Sub\_Rocks = agglomerate; Description = **Andesitic** breccia and agglomerate (QMAP database). “Only a small area of proximal volcanoclastics and flow rocks (Wairakau Volcanics, Mcw) lies within the Kaitaia map area...” (Isaac, 1996). “The strata are interpreted as deeply eroded remnants of the proximal, **subaerial** portions of an **andesitic** composite volcano ring-plain (Hayward 1990)” (Isaac et al., 1994) – *EoD is based on the QMAP description and Isaac et al. (1994). The main rock type of breccia may represent laharic deposits which could indicate an onshore EoD based on the classification in this report. Refer to “Whangaroa Subgroup” on the Whangarei map area for further information.*

### **Karikari Plutonics**

- **Mck, PMeMsi**

**Inferred age:** 23-17 Ma (Hayward et al., 2001)

**EoD:** silicic intrusives

**Basis for interpretation:** Main\_Rock = **granitoid**; Sub\_Rocks = monzodiorite, monzonite granite, diorite, andesite; Description = Plutons of quartz monzonite to adamellite and diorite to quartz monzodiorite. Microdiorite near North Cape (QMAP database). “At Karikari Peninsula the northwest-southeast elongate Karikari Plutonics (Mck...) include an older pluton of quartz monzodiorite... and a younger pluton of quartz monzonite to granite” (Isaac, 1996) – *given the main rock type of granitoid the Karikari Plutonics are here defined as silicic intrusives.*

- **PMeMii**

**Inferred age:** 23-18 Ma (Hayward et al., 2001)

**EoD:** intermediate intrusives

**Basis for interpretation:** Main\_Rock = diorite; Sub\_Rocks = andesite (after Hayward et al., 2001). “...the northwest-trending Karikari acidic **plutonic** complex and numerous northwest-trending **andesite**, dacite, and basaltic andesite dikes are the subvolcanic remains...” (Hayward et al., 2001) – *these polygons were created from original QMAP polygons based on samples dated and cited in Hayward et al. (2001). The description is based on information given in Table 1 of Hayward et al. (2001).*

- **Maungataniwha Massif (PMeMii)**

**Inferred age:** 20 Ma (Whattam et al., 2006)

**EoD:** intermediate intrusives

**Basis for interpretation:** Main\_Rock = diorite; Sub\_Rocks = andesite dike (after Whattam et al., 2006). “The **andesite** samples (04-MAU-3.1, 5.1) are from fresh **dikes** that intrude ophiolite pillow basalts at Coopers Beach and Mangonui on the eastern coast of Northland and represent the southern segment of the Whangaroa Miocene arc-type volcanic centre” (Whattam et al., 2006) – *these polygons were created from original QMAP polygons based on samples dated in Whattam et al. (2006). The EoD is based on the description of andesite dikes.*

## Parengarenga Group

### **Tom Bowling Formation (Mpt)**

**Inferred age:** 25-22 Ma (Isaac, 1996; Boyes et al., 2011b)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone, breccia, ‘lapilli tuff’; De-

scription = Basal shelly breccia overlain by mudstone and muddy sandstone, with minor tuff and lapilli tuff (QMAP database). “The Tom Bowling Formation is of earliest Miocene age, and structural relationships suggest it may have accumulated in a “piggy-back” basin on the still-moving and deforming upper surface of the Northland Allochthon...” (Isaac, 1996). “...a basal shelly breccia 1-20 m thick unconformably overlies, and contains clasts derived from, subaerially weathered Tangihua rocks... The conformably overlying 50-400 m thick sequence of **bathyal mudstone and muddy very fine sandstone** includes andesitic (and rarely, rhyolitic) tuff beds... Pelagic and hemipelagic sedimentation subsequently became predominant, with mud and fine sand accumulating as the area subsided to **mid to upper bathyal** depth...” (Isaac et al., 1994) – *the mid- to upper bathyal interpretation is narrowed down to upper bathyal based on the relatively coarse nature of the formation which may favour a more proximal deposit. A mid-bathyal depositional depth is an alternative explanation.*

### ***Kaurahoupo Conglomerate (Mpk)***

**Inferred age:** 22-19 Ma (Isaac, 1996; Boyes et al., 2011b)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = conglomerate; Sub\_Rocks = sandstone; Description = Poorly bedded sandstone and conglomerate derived from Coromandel Group volcanoes (QMAP database). “Most Kaurahoupo Conglomerate accumulated at **mid to upper bathyal depths**, but with time the basin shallowed, and in places upper parts of the unit were deposited in **shelf, estuarine, and fluvial environments...**” (Isaac, 1996) – *Isaac (1996) considers most of the Kaurahoupo conglomerate to be a mid- to upper bathyal deposit and is narrowed here to upper bathyal. Mid-bathyal is an alternative interpretation, as could be shelfal to onshore for the upper portion of this sequence.*

### ***Paratoetoe Formation (Mppp)***

**Inferred age:** 19-17 Ma (Isaac, 1996; Boyes et al., 2011b)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = conglomerate, mudstone; Description = Muddy fine-grained sandstone with pebble to boulder conglomerate, pebbly sandstone and pebbly mudstone (QMAP database). “The main rock type is poorly bedded, muddy fine-grained sandstone with lesser centimetre- to decimetre- scale well bedded sandstone, channelled pebble to boulder conglomerate, pebbly sandstone, and pebbly mudstone” (Isaac, 1996). “The fauna [of the Paratoetoe Formation, sandstone member, shell lens 1] is again viewed to probably indicate marginally tropical conditions and a depth in the order of **200 m**; that is, in the region of the continental shelf – slope break” (Grenfell, 1984) – *the 200 m depositional depth estimate in Grenfell (1984) could indicate either an outer shelf or upper bathyal EoD for the map unit. An upper bathyal depth of accumulation is assigned here based on the occurrence of well bedded sandstone and channelled coarse grained lithologies (Isaac, 1996) which may represent upper submarine fan deposits of upper bathyal depth (Fig. 3).*

### ***Matapia Formation (Mppm)***

**Inferred age:** 19-17 Ma (Isaac, 1996; Boyes et al., 2011b)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = conglomerate; Sub\_Rocks = sandstone; Description = Poorly to moderately bedded sandstone, pebbly and bouldery sandstone, and conglomerate at Matapia Island (QMAP database) – *on this geological map sheet, the Matapia Formation is grouped with Paratoetoe Formation. Consequently, the EoD for Paratoetoe Formation is extended to the Matapia Formation map unit here.*

## ***Otaua Group continued***

### ***Waititi Formation (Mot)***

(QMAP database spelling: Waititi Formation)

**Inferred age:** 21-20 Ma (Isaac, 1996)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone; Description = Massive

to poorly bedded mudstone and muddy sandstone (QMAP database). “The early Miocene age is determined from foraminifera, which also show that the Waititi Formation was deposited at **bathyal depths**” (Isaac, 1996). “Further west in the Waimamaku Valley, the lowest and more western faunas are moderately rich in planktics (50-70%) and have benthic faunas dominated by *Stilostomella*, *Cibicides*, *Uvigerina miozea*, and *Bolivina* with occasional deep-water restricted *Osangularia* and *Pleurostomella*. These indicate a range of **upper bathyal** depths (c. 200-1000 m) for these faunas. Higher and more eastern Waititi faunas from the Waimamaku Valley contain 15-60% planktics, have benthic faunas dominated by *Cibicides mediocris*, *C. vortex*, *Haeuslerella*, *Astrononion*, *Bulimina pupula*, *Cassidulina*, and *Discorbis*, and lack any deepwater restricted taxa. These faunas indicate **mid to outer shelf** depths (c. 50-100 m) with some minor mixing from shallower depths” (Evans, 1994) – *the bathyal interpretation given in Isaac (1996) is narrowed down to upper bathyal based on the interpretation in Evans (1994). Evans (1994) also indicates that the formation was partly deposited in mid- to outer shelf conditions, but more so in the east of the formation, which is taken to be the Whangarei map area in this project.*

### **Waiwhatawhata Cgl, Otueka Fmn (Mow)**

“The lowest foraminiferal fauna [in Waiwhatawhata Conglomerate] (O06/f17) contains 80% large planktics and deep-water benthics like *Buliminella grata* and *Oridorsalis*. It apparently accumulated at **upper bathyal** depths (c. 400-1000 m). The two higher faunas (O06/f18, f22) indicate a shallowing succession (planktics decrease through 70% to 30%), up to **mid-shelf** depths (c. 50-100 m)... Both faunas are dominated by a combination of *Cibicides*, *Bolivina*, *Trifarina*, *Cassidulina*, and *Sphaeroidina*, with occasional *Elphidium* and *Amphistegina*. This association is suggestive of **mid to outer shelf** depths (Hayward 1986)” (Evans, 1994).

**Inferred age:** 22-19 Ma (Isaac, 1996)

**EoD breakdown:** 22-21 Ma: upper bathyal  
 20 Ma: outer shelf  
 19 Ma: mid-shelf

**Basis for interpretation:** Main\_Rock = conglomerate; Sub\_Rocks = sandstone; Description = Conglomerate and sandstone derived from the Northland Allochthon (QMAP database) – *the paleo-environmental interpretations of Evans (1994) for the base (upper bathyal) and top (mid-shelf) of the map unit are used here. The paleoenvironments through the middle portion of the map unit are inferred from the shallowing upwards trend noted in Evans (1994).*

### **Omapere Conglomerate (Moo)**

**Inferred age:** 19-17 Ma (Isaac, 1996)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = conglomerate; Sub\_Rocks = mudstone; Description = Cobble and pebble conglomerate derived mainly from Tangihua Complex. Locally interfingered with Waipoua basalt flows (QMAP database). “The sequence is regressive, for upper parts of the Omapere Conglomerate were deposited in **shelf and nonmarine** environments” (Isaac, 1996). “West of the Waipoua plateau, microfaunas indicate an Otaian age and **mid to outer shelf** environment of deposition” (Evans, 1994) – *combining the interpretations of Isaac (1996) and Evans (1994) gives a depositional depth range of outer shelf to non-marine. The map unit lies to the west of the Waipoua plateau so the mid- to outer shelf interpretations for the Omapere Conglomerate in this area (Evans, 1994) are favoured here. A mid-shelf EoD is assigned to the map unit but an outer shelf depositional environment is an alternative interpretation.*

## **Waitakere Group**

### **Waipoua Subgroup (Mtw, PMeMme)**

**Inferred age:** 19-18 Ma (Hayward et al., 2001)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = **basalt**; Sub\_Rocks = tuff, ‘lapilli tuff’; Description = Plateau-forming basalt, tuff and lapilli derived from the offshore Waipoua volcano; in many places very deeply weathered (QMAP database). “Waipoua Subgroup basalts are the only parts of the voluminous Early Miocene western belt volcanics to outcrop onshore in the Kaitaia map area...”

The plateau is formed of numerous extensive **subaerial** basalt lava flows..." (Isaac, 1996). "They form a partly eroded plateau, which is tilted gently to the southwest... The numerous extensive aa and pahoehoe lava flows are 2-25 m thick, with thin, red-baked and oxidised tuff and lapilli tuff fall deposits between flows (Hayward 1975a; Wright 1980). Mantle bedding of the fall deposits also indicates **subaerial** deposition... In the far north between the mouths of the Waimamaku River and Waiwhatawhata Stream, four thick flows thin rapidly northwards within a regressive sequence of **shallow marine deltaic to terrestrial**, log-bearing conglomerate (Omapere Conglomerate, Hayward 1973a)" (Isaac et al., 1994). "...the large Waipoua shield volcano, is composed mainly of **andesitic basalt**" (Herzer, 1995) – *EoD is based on the main rock type (QMAP database) and the evidence of subaerial deposition, even though most of the unit is currently offshore (Isaac et al., 1994). This is also based on the paleogeography maps in Isaac et al. (1994). Submarine (at mid-shelf depth) may be an appropriate EoD for deposits in the far north of its extent (after Isaac et al., 1994) where it occurs within the mid-shelf Omapere Conglomerate (Moo).*

## Reinga Group

### **Mangonui Formation (IMm)**

**Inferred age:** 10-7 Ma (Isaac et al., 1996)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = conglomerate; Sub\_Rocks = sandstone, mudstone, lignite; Description = Conglomerate, pebbly sandstone, mudstone and lignite (QMAP database). "South of Doubtless Bay, a gullied erosion surface cut on Tangihua Complex rocks is overlain by weakly indurated Mangonui Formation (IMm)" (Isaac, 1996). "The lower conglomerate dominated beds pass upwards into fluviatile and marginal marine carbonaceous sandstones" (Isaac et al., 1994) – *the main rock type of the map unit is conglomerate but the specific EoD of the conglomeratic portion of the Mangonui Formation is not mentioned in the cited references. Its association with an underlying erosion surface and overlying fluviatile and marginal marine lithologies implies that it is possibly the product of fluvial or shallow marine erosion and sedimentation. An onshore EoD is assigned to the map unit here but innermost shelf is an alternative interpretation.*

## Awhitu Group

- **Pad**

**Inferred age:** 2-1 Ma (Isaac et al., 1994)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = sand; Sub\_Rocks = lignite, mudstone; Description = Cemented **dune sands and associated facies** (QMAP database). "Moderately to poorly consolidated, large-scale cross-bedded, quartzofeldspathic to quartzose **dune sand** and minor, parallel-laminated sandstone, **paleosols, lignite**, and carbonaceous mudstone outcrop in the inland part of the North Kaipara Barrier, at Karikari Peninsula, and to northern Aupouri Peninsula (Awhitu Group, Pad...)" (Isaac, 1996) – *EoD is based on the terrestrial facies and lithologies described in Isaac (1996).*

- **Pat**

**Inferred age:** 3-1 Ma (Isaac et al., 1994)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone, peat, gravel; Map\_Unit = higher **alluvial** terraces; Description = Partly consolidated sandstone and mudstone of high terraces (QMAP database). "The deposits (shown as Pat where mappable at this scale) probably accumulated in a range of **fluvial, estuarine, and marine** environments..." (Isaac, 1996) – *EoD is based on the terrestrial facies described in Isaac (1996) and the map unit's definition as "alluvial terraces" in the QMAP database.*

## Kerikeri Volcanic Group (Qvb)

**Inferred age:** 3-0 Ma (Smith et al., 1993)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = basalt; Description = Basalt flows (QMAP database). "Mid-

dle Miocene to Holocene volcanics of Northland collectively known as Kerikeri Volcanics (Qvb; Bell & Clarke 1909) are mainly **basalts** of intraplate character (Smith et al. 1993). No eruption centres are known within the Kaitaia map area..." (Isaac, 1996). "The Late Cenozoic Kerikeri Volcanics are present mainly in eastern Northland; they too erupted **subaerially**" (Isaac et al., 1994) – *EoD is based on the main rock type and the subaerial environment interpretation of the volcanics in Isaac et al. (1994). Refer to Pvbb and Qvbb on the Whangarei map area for further information.*

## Quaternary – Sedimentary deposits

- All Q deposits

*EoD: onshore*

**Basis for interpretation:** Based on the QMAP database which includes alluvial, dune, estuarine, landslide, rock fall, and swamp sediments in the Quaternary deposits.

## Northland Volcanic Arc (PMeMis)

*Inferred age:* 22-16 Ma (Herzer, 1995)

*EoD: submarine intermediate eruptives*

**Basis for interpretation:** Main\_Rock = andesite; Sub\_Rocks = basaltic andesite; Description = submarine andesite and basaltic andesite volcanoes (after Herzer, 1995; Hayward et al., 2001). "**Andesitic** volcanoes erupted onshore and offshore of Northland in Early Miocene time. Tracing of seismic reflectors in the Northland Basin demonstrates that allochthon emplacement was closely followed by and partly contemporaneous with volcanism (Herzer 1995; Isaac et al. 1994). There are five major volcanoes of 15-40 km radius (Ninety Mile, Ahipara, Whangape, Hokianga, and Waipoua), and many smaller ones in the western offshore area covered by the Kaitaia map" (Isaac, 1996). "The Early Miocene (Waitakian to Altonian; Aquitanian to Burdigalian) rocks of western offshore Northland are almost entirely of volcanic and volcanoclastic origin; they are a part of the Waitakere Group (Hayward 1976c; Ballance et al. 1977). To the east and north, they abut, interfinger with and onlap the Northland Allochthon. To the west, volcanoclastics grade into probable volcanopelagic sediments... More than 50 volcanoes have been identified from the seismic reflection profiles (Herzer in prep.)... The volcanoes form a belt 350 km long that extends up to 95 km offshore between Manukau Heads... and Tauroa Knoll..., the most northerly volcano so far identified. The belt of volcanoes trends northwest (315°), subparallel to both the Northland peninsula (325°), and to the northeastern edge of the continental shelf (305°)... The volcanism evidently took place largely in a **submarine** setting, **becoming subaerial** as volcanoes built up to and above sea level" (Isaac et al., 1994). "Laterally, the volcanic sequences may pinch out, onlap, downlap or interfinger with other volcanic sequences, with **terrigenous** sequences, or with **basinal hemipelagic** sequences... For any one volcano, the stratigraphic level at which the oldest internal reflector downlaps should approximately define the time of its first activity. In practice, the oldest internal reflectors are hidden in the larger volcanoes and volcanic massifs, so the time of first activity of the large volcanoes can only be approximated if other evidence is available. Likewise, the stratigraphic level at which the youngest (or top bounding) reflector downlaps defines the time of its last activity. This works for all volcanoes, no matter what their size... Wave planation and **shallow marine** explosive activity commonly occurred in the case of the Northland massifs (Hayward, 1976; 1993)..." (Herzer, 1995) – *these polygons and ages are based on the summarised eruptive history in Figures 2 and 11 of Herzer (1995). The ages are largely based on stratigraphic relationships as determined through seismic reflection profiles. K-Ar and biostratigraphic ages exist for edifices which have present day outcrops onshore (i.e. Waipoua). The EoD of these now buried volcanoes is defined as submarine, as they are described in Isaac et al. (1994) as taking place "largely in a submarine setting". Onshore intermediate eruptives may be appropriate in minor instances.*

## WHANGAREI AREA (Geological Map 2)

### Te Kuiti Group

#### ***Te Kuiti Group (Ot)***

(QMAP database spelling: Undifferentiated)

Partly allochthonous (Sequence = Northland Allochthon), partly autochthonous.

“The oldest in-place rocks overlying basement are Eocene and Oligocene rocks of the Te Kuiti Group... The group is a predominantly transgressive sequence of coal measures with overlying marginal marine to outer shelf calcareous sandstone, calcareous mudstone and limestone. It unconformably overlies Mesozoic basement rocks and is divided into four formations: the Kamo Coal measures, Ruatangata Sandstone, Mangapa Mudstone and Whangarei Limestone. The formations are not differentiated (Ot) on the cross sections and in places on the map” (Edbrooke and Brook, 2009).

**Inferred age:** 39-26 Ma (Boyes et al., 2011b)

**EoD allochthonous units:** allochthonous

**EoD breakdown in place units:**

39 Ma:	<u>outer shelf</u> (Ruatangata Sandstone)
38-35 Ma:	<u>outer shelf</u> (Kamo Coal Measures, Ruatangata Sandstone, Mangapa Mudstone, Whangarei Limestone)
34-33 Ma:	<u>outer shelf</u> (Ruatangata Sandstone, Whangarei Limestone)
32-26 Ma:	<u>innermost shelf</u> (Whangarei Limestone)

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone limestone; Description = ‘Calcareous sandstone, calcareous mudstone and limestone’ (QMAP database) – *the in place unit consists of undifferentiated Kamo Coal Measures, Ruatangata Sandstone, Mangapa Mudstone, and Whangarei Limestone. The EoD is therefore broken down into time intervals based on the EoD of the dominant or average lithology at the time.*

#### ***Kamo Coal Measures (Etk)***

**Inferred age:** 38-35 Ma (Boyes et al., 2011b)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone, conglomerate, coal; Description = ‘Carbonaceous mudstone, sandstone, quartz pebble conglomerate and coal seams.’ (QMAP database). “The coal measures are lithologically variable, ranging from carbonaceous mudstone, sandstone and quartz pebble conglomerate to carbonaceous shale” (Edbrooke and Brook, 2009). “Waipapa-derived Kamo Coal Measures conglomerate and sandstone overlying Waipapa Terrane basement are succeeded by 112 m of calcareous glauconitic Ruatangata Sandstone, in turn overlain by a further interval of coal measures, with intercalated **inner shelf** to **shoreface** and **estuarine** facies... The geographically restricted and locally conglomeratic Late Eocene **fluvial** and **marginal marine** Kamo Coal Measures” (Isaac et al., 1994) – *the map unit is defined here as onshore, based on Isaac et al.’s (1994) description of fluvial, and the paleogeographic maps therein.*

#### ***Ruatangata Sandstone (Etr)***

Partly allochthonous (Sequence = Northland Allochthon), partly autochthonous.

**Inferred age:** 39-33 Ma (Boyes et al., 2011b)

**EoD allochthonous units:** allochthonous

**EoD in place units:** outer shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = limestone, conglomerate; Description = ‘Slightly calcareous, glauconitic, muddy, fine-grained sandstone.’ (QMAP database). “Foraminifera indicate deposition in a **range of shelf** environments” (Edbrooke and Brook, 2009). “South of the Waipapa Horst, the facies include algal limestone, conglomerate, and glauconitic sandstone, are laterally variable over short distances, and are consistent with deposition in a range of **inner to outer shelf** environments... North of the Waipapa Horst... the foraminiferal faunas indicate deposition in **inner to mid shelf** environments... Autochthonous Te Kuiti Group strata of onshore Northland demonstrate gradual subsidence or relative rise of sea level in the Middle to Late Eocene. In northern and northwestern Northland, the Ruatangata Sandstone accumulated at

**shelf** depths...” (Isaac et al., 1994). “The common occurrence of taxa such as *Bulimina pupula*, *Cibicides parki*, *Plectofrondicularia whaingaroica*, *Vaginulinopsis hochstetteri*, *Arenodosaria antipoda*, and diverse nodosariids is suggestive of **outer shelf** depths (100-200 m) for the lower sample. The increased planktic percentage, increased agglutinated taxa, and increased diversity of deeper water calcareous benthics indicates probable **upper bathyal** depths (c. 200-500 m) for the higher sample” (Evans and Hayward, 1990) – *some of the map unit is considered part of the Northland Allochthon in the QMAP database and consequently is defined as allochthonous here. The range of depths indicated in the literature for the in place units is here restricted to outer shelf, based on the presence of glauconite and the QMAP description. Inner to mid shelf may be appropriate for units north of the Waipapa Horst in the north of this map area (Isaac et al., 1994). Upper bathyal may be appropriate for the upper part of the sequence (Evans and Hayward, 1990).*

### **Mangapa Mudstone (Etm)**

Partly allochthonous (Sequence = Northland Allochthon), partly autochthonous.

**Inferred age:** 38-35 Ma (Boyes et al., 2011b)

**EoD allochthonous units:** allochthonous

**EoD in place units:** upper bathyal

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = limestone; Description = ‘Massive to poorly stratified, calcareous, blue-grey mudstone.’ (QMAP database). “Foraminiferal faunas suggest deposition at **mid shelf to upper bathyal** depths... Autochthonous Te Kuiti Group strata of onshore Northland demonstrate gradual subsidence or relative rise of sea level in the Middle to Late Eocene. In northern and northwestern Northland, the Ruatangata Sandstone accumulated at shelf depths and was succeeded conformably by **outer shelf to bathyal** Mangapa Mudstone” (Isaac et al., 1994). “The moderately high planktic content indicates **marginal oceanic** water overhead. The overall benthic composition of the mudstone faunas, together with the presence of largely bathyally restricted *Osangularia culter*, *Pleurostomella*, *Tritaxilina zealandica*, *Glomospira charoides*, *Oridorsalis umbonatus*, *Anomalina aotea*, *Vulvulina*, *Karreriella*, and *Cibicides collinsi*, suggests bathyal, probably **mid bathyal**, depths (c. 500-2000 m)” (Evans and Hayward, 1990) – *some of the map unit is considered part of the Northland Allochthon in the QMAP database and consequently is defined as allochthonous here. The EoD for the in place units is defined here as upper bathyal, but a greater range of environments is also likely, including mid-shelf to mid-bathyal (Evans and Hayward, 1990).*

### **Whangarei Limestone (Otw)**

Partly allochthonous (Sequence = Northland Allochthon), partly autochthonous.

**Inferred age:** 38-26 Ma (Boyes et al., 2011b)

**EoD allochthonous units:** allochthonous

**EoD in place units:** innermost shelf

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = conglomerate, sandstone; Description = ‘Stylolitic, bioclastic limestone with conglomerate and calcareous sandstone beds.’ (QMAP database). “Oligocene Whangarei Limestone is a stylolitic, bioclastic, so-called “crystalline” limestone. Here it is mostly a bryozoan calcarenite grainstone with 50% bryozoan fragments, 20% echinoid and 20% benthic foraminifera... It is considered to be autochthonous **inner shelf** deposit within an *in-situ* Late Eocene – Oligocene sedimentary sequence sitting on an irregular Waipapa Terrane greywacke basement” (Hayward et al., 2002). “Abundant bryozoans and echinoid detritus and the benthic foraminifera are consistent with accumulation at **inner to mid shelf** depths... However, deposition was probably in a greater range of environments, as the broken bioclasts indicate transport. Those limestones rich in planktic foraminifera suggest the depth of accumulation increased with time” (Isaac et al., 1994). “These bathyal faunas are atypical for most autochthonous Whangarei Limestone, which generally contains **inner shelf** assemblages” (Evans and Hayward, 1990) – *some of the map unit is considered part of the Northland Allochthon in the QMAP database and consequently is defined as allochthonous here. The depth range for the in place units is here narrowed down to an innermost shelf EoD, based on the description of conglomerate and the paleogeography maps in Isaac et al. (1994). Mid-shelf (or possibly outer shelf) may be an alternative EoD for the upper part of the unit.*



## Northland Allochthon (various unit codes)

Includes Waipapa Group (TJw), Tangihua Complex (Kt, Kts), Tupou Complex (Ku), Mangakahia Complex (Kk, Punakitere Sandstone (Kkp), Whangai Formation (Kkw), Hukerenui Mudstone (Kkh)), Motatau Complex (Om, Taipa Mudstone (Emt), Omahuta Sandstone (Emo), Mahurangi Limestone (Omm)), Avoca Coal Measures (Ea), Te Kuiti Group (Ot, Ruatangata Sandstone (Etr), Mangapa Mudstone (Etm), Whangarei Limestone (Otw)), Undifferentiated mélange (KOm), Waitemata Group (Puriri Mudstone (Mwf), Onemama Formation (Mwz), Ruarangi Formation (Mwg), Pukepoto Formation (Mwx), Pakiri Formation (Mwp), and Timber Bay Formation (Mwb)).

**Inferred age:** 24-21 Ma (Boyes et al., 2011b)

**EoD:** allochthonous

**Basis for interpretation:** Sequence = **Northland Allochthon** (QMAP database) – EoD is based on the QMAP definition of the map units as part of the Northland Allochthon.

## Waitemata Group

### Bream Subgroup

#### Ruarangi Formation (Mwg)

Partly allochthonous (Sequence = Northland Allochthon), partly autochthonous.

**Inferred age:** 23 Ma (Edbrooke and Brook, 2009)

**EoD allochthonous units:** allochthonous

**EoD in place units:** upper bathyal

**Basis for interpretation:** Main\_Rock = siltstone; Sub\_Rocks = sandstone; Description = ‘Laminated to thin-bedded, calcareous siltstone with rare, interbedded shelly sandstone.’ (QMAP database). “The Ruarangi Formation... was deposited on a topographically irregular and faulted surface. The Otaika Fault... was a major paleo-topographic feature, marked by downthrow to the west, prior to and/or during deposition of the Ruarangi Formation. The formation east of the fault comprises laterally continuous lenses, up to 40 m thick, of weakly bedded calcareous sandstone, muddy sandstone and less common mudstone. By contrast, to the west and south of the fault the formation is thicker and more extensive, and is generally dominated by mudstone, with or without intercalated sandstone beds and **turbidite** units... Locally, thick beds of redeposited bioclastic-lithic pebbly sandstone and glauconitic sandstone are present. Foraminiferal assemblages indicate deposition at **outer shelf to bathyal** depths, with shelf foraminifera being common in the redeposited shelly and glauconitic sediments” (Edbrooke and Brook, 2009) – *some of the map unit is considered part of the Northland Allochthon in the QMAP database and consequently is defined as allochthonous here. To the south and west of the Otaika Fault the Ruarangi Formation consists of finer grained lithologies and turbidites whereas to the east of the fault the formation consists of comparatively coarser grained lithologies and there is an absence of turbidite units (Edbrooke and Brook, 2009). This implies that Ruarangi Formation to the south and west of the fault are bathyal deposits and Ruarangi Formation to the east of the fault are outer shelf deposits, based on the depositional depth range given in Edbrooke and Brook (2009). The majority of the map unit is located to the south and west of the Otaika Fault, which implies a bathyal depth of deposition for the map unit. An upper bathyal EoD is assigned to the map unit due to its proximity to the Otaika Fault, which may approximate the shelf-slope break. A mid-bathyal EoD is an alternative interpretation.*

#### Ngatoka Sandstone (Mwn)

**Inferred age:** 23 Ma (Edbrooke and Brook, 2009)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Description = ‘Thick-bedded, bioclastic sandstone.’ (QMAP database). “It consists of poorly bedded to massive, concretionary, calcareous sandstone, concordantly overlying and overlain by Ruarangi Formation mudstones. The unit... is here redefined as a member of the Ruarangi Formation...” (Edbrooke and Brook, 2009) – *the Ngatoka Sandstone is a member of the Ruarangi Formation (Edbrooke and Brook, 2009) and so a bathyal environment is appropriate.*

## **Warkworth Subgroup**

### **Pakiri Formation (Mwp)**

Partly allochthonous (Sequence = Northland Allochthon), partly autochthonous.

**Inferred age:** 23 Ma (Edbrooke and Brook, 2009)

**EoD allochthonous units:** allochthonous

**EoD in place units:** mid-bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = siltstone; Description = 'Alternating thick-bedded, volcanic-rich, graded sandstone and siltstone.' (QMAP database). "The volcanic-rich **flysch** consists mainly of 10-30 m thick packets of graded medium- to coarse-grained sandstone beds (typically 1-4 m thick), alternating with thinner intervals of laminated siltstone and fine-grained sandstone (beds typically 5-20 cm thick)... Foraminiferal assemblages indicate that the Pakiri Formation was deposited at **bathyal** depths, but foraminifera characteristic of shelf environments are present in the redeposited sandstones" (Edbrooke and Brook, 2009) – *some of the map unit is considered part of the Northland Allochthon in the QMAP database and consequently is defined as allochthonous here. The in place units are defined here as mid-fan sediments deposited at mid-bathyal depths.*

### **Warkworth Subgroup (Mwd)**

**Inferred age:** 23 Ma (Edbrooke and Brook, 2009)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone; Description = Alternating graded sandstone and mudstone (QMAP database). "Warkworth Subgroup... includes Early Miocene **flysch-dominated** sequences that underlie, or are incorporated within, the Northland Allochthon... undifferentiated Warkworth Subgroup (Mwd)" (Edbrooke and Brook, 2009) – *the dominance of flysch in the map unit implies a mid-bathyal EoD (Fig. 3). The map unit is interpreted here as mid-fan sediment deposited at mid-bathyal depths.*

## **Kaipara Subgroup**

### **Waihangaru Formation (Mwi)**

**Inferred age:** 20-19 Ma (Edbrooke and Brook, 2009)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = siltstone, sandstone; Description = "Thin-bedded mudstone, sandy siltstone and rippled muddy fine-grained sandstone." (QMAP database). "The upper part of the formation consists of poorly bedded, massive, and muddy very fine-grained sandstone with sparse thin beds of redeposited volcanoclastic sandstone... Foraminifera indicate deposition at **bathyal** depths..." (Edbrooke and Brook, 2009). "Matapoura Conglomerate, and possibly Hoteo beds, are conformably overlain and enclosed by thin-bedded mudstone, sandy siltstone and rippled, muddy, fine grained sandstone of the Waihangaru Formation (Mwi; Ballance 1976; Brook 1983). It outcrops in the central Kaipara Harbour area, north of Glorit, and locally contains channelised pebbly sandstone beds... Waihangaru Formation and associated Matapoura Conglomerate are inferred to have accumulated on an elongate submarine fan, within a SSE-trending depression that developed in the Kaipara Harbour area in late Otaian time. Sediment from the Kaipara area was funnelled southward through the depression, into central areas of the Waitemata basin..." (Edbrooke, 2001) – *based on the lithologic descriptions of Waihangaru Formation in the QMAP database, Edbrooke and Brook (2009), and Edbrooke (2001) the map unit is interpreted as upper bathyal hemipelagic background sediment with thin ?levee turbidity current deposits. A lower bathyal EoD, with thin distal redeposited sandstone beds, is an alternative interpretation (Fig. 3).*

## **Otaua Group**

### **Waititi Formation (Mot)**

**Inferred age:** 21 Ma (Edbrooke and Brook, 2009)

**EoD:** outer shelf

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone; Description = Massive to poorly bedded mudstone and muddy fine-grained sandstone (QMAP database). "Lower parts of

the Waititi Formation accumulated at **bathyal** depths while the upper part accumulated at **middle to outer shelf depths** (Evans 1994). The formation is inferred to have been deposited in a “piggyback” basin on top of the Northland Allochthon, during and following allochthon emplacement” (Edbrooke and Brooke, 2009). “Macrofaunas and microfaunas of Upper Waitakian, Upper Waitakian-Otaian, Otaian, and Upper Otaian age indicate an **upper bathyal to shelf environment** of deposition... Higher and more eastern Waititi faunas from the Waimamaku Valley contain 15-60% planktics, have benthic faunas dominated by *Cibicides mediocris*, *C. vortex*, *Haeuslerella*, *Astrononion*, *Bulimina pupula*, *Cassidulina*, and *Discorbis*, and lack any deepwater restricted taxa. These faunas indicate **mid to outer shelf** depths (c. 50-100 m) with some minor mixing from shallower depths” (Evans, 1994) – *this formation is shallower in the east of its extent than the west (i.e. Kaitaia map area), where it has been defined as upper bathyal. Therefore it is defined here in the east as outer shelf.*

## Waitakere Group

### *Hukatere Subgroup*

“Products of the Hukatere satellite volcanic centre are preserved within the shallow marine, Early Miocene sedimentary sequences on Hukatere Peninsula in the Kaipara Harbour. The 4 km diameter Hukatere Volcano is a 150 m high shield, mostly composed of basaltic andesite pillow lavas intruded by a number of feeder dikes (Brook 1983; Hayward 1993). Nearby to the north are narrow nephelinite dikes at Te Ruruku and ?intrusive basalt forming small Stony Hill... Hukatere Volcano’s age is poorly constrained within the range of 19-16 Ma” (Hayward et al., 2001). “Between Tokatoka and Dargaville, about 140 small basaltic, andesitic and dacitic necks, dikes, sills, laccoliths and pyroclastic breccia pipes (Mts) intrude Northland Allochthon strata (Black 1966, 1967)... K-Ar ages and biostratigraphic dates from included sedimentary rocks indicate that the subvolcanic rocks of the Tokatoka centre were emplaced between 19 and 16.5 Ma (Hayward et al. 2001), and were probably accompanied by surface eruptions” (Edbrooke and Brook, 2009).

- **Mtsb**

*Inferred age:* 18-16 Ma (Hayward et al., 2001)

*EoD:* mafic intrusives

*Basis for interpretation:* Main\_Rock = breccia; Sub\_Rocks = **basalt**; Description = Pyroclastic **dikes** and **breccia pipes** (QMAP database). “The pyroclastic dikes and breccia pipes are filled with tuff breccia dominated by **olivine and pyroxene basalt** clasts, and some include blocks of **andesite** and Northland Allochthon sedimentary rocks (Black 1966)” (Edbrooke and Brook, 2009) – *EoD is based on the QMAP lithologic description. Intermediate or onshore eruptives could be alternative interpretations.*

- **Mtsi**

*Inferred age:* 19-16 Ma (Hayward et al., 2001)

*EoD:* intermediate intrusives

*Basis for interpretation:* Main\_Rock = **andesite**; Sub\_Rocks = basalt, dacite; Description = ‘Basaltic, andesitic and dacitic **necks, dikes, sills and laccoliths.**’ (QMAP database). “Scattered **intrusions** are also present near Waihue, Hukatere and elsewhere. They are probably the feeders and related subvolcanic intrusions of volcanoes that erupted mainly above the present erosion level” (Edbrooke and Brook, 2009) – *EoD is based on the QMAP lithologic description and the main rock type of andesite. The intrusive equivalent of andesite (diorite) is used here.*

### **Pakaurangi Formation (Mtk)**

*Inferred age:* 19-18 Ma (Edbrooke and Brook, 2009)

*EoD:* mid-shelf

*Basis for interpretation:* Main\_Rock = volcanic sandstone; Sub\_Rocks = mudstone; Description = “Thick-bedded, muddy volcanoclastic sandstone and mudstone.” (QMAP database). “On Hukatere Peninsula in northern Kaipara Harbour, pillow lava, breccias and tuff of the satellite Hukatere Volcanic Centre... are present within a **shallow marine** sedimentary sequence of thick-bedded, muddy volcanoclastic sandstone and fossiliferous mudstone mapped as Pakaurangi Formation (Mtk...)” (Edbrooke and Brook, 2009) – *EoD is based on the shallow marine interpretation for the formation in Edbrooke and Brook (2009). An innermost shelf EoD is an alternative interpretation.*

### ***Pupuia Formation (Mti)***

***Inferred age:*** 19-17 Ma (Edbrooke and Brook, 2009)

***EoD:*** submarine mafic eruptives

***Basis for interpretation:*** Main\_Rock = **basaltic** andesite; Sub\_Rocks = basalt; Description = Basaltic andesite **flows** and **pillow lavas** intruded by feeder dikes (QMAP database). “...**basaltic andesite flows** and **pillow lavas**” (Edbrooke and Brook, 2009). “The type section for the Pupuia Formation, a 150+ m-thick pile of **pillow lavas**, flows, and dikes of basaltic to andesitic composition is on the Hukatere coast southeast of Pupuia Island (Fig. 2.2). **Pillows** are common, very well-formed... The pillow pile at this site was possibly fed by a dike that can be seen on the NE end of Pupuia Island” (Grant-Mackie and Gregory, 2002) – *EoD is based on the main rock type and presence of “common” submarine effusive eruptive products (i.e. pillow lavas) mentioned in Grant-Mackie and Gregory (2002) as well as in the QMAP and Edbrooke and Brook (2009) lithologic descriptions. An onshore intermediate or mafic eruptives EoD is an alternative interpretation.*

### ***Okaroro Formation (Mtr)***

***Inferred age:*** 19-18 Ma (Edbrooke and Brook, 2009)

***EoD:*** innermost shelf

***Basis for interpretation:*** Main\_Rock = volcanic sandstone; Sub\_Rocks = volcanic breccia; Description = ‘**Proximal, marine** volcanoclastic sandstone and breccia.’ (QMAP database). “...**proximal, marine** volcanoclastic sandstone and breccia (Okaroro Formation, Mtr...)...” (Edbrooke and Brook, 2009) – *EoD is based on the proximal marine environment interpretation in Edbrooke and Brook (2009).*

### ***Puketi Formation (Mtu)***

***Inferred age:*** 18 Ma (Edbrooke and Brook, 2009)

***EoD:*** onshore

***Basis for interpretation:*** Main\_Rock = volcanic breccia; Sub\_Rocks = pyroclastics tuff; Description = ‘**Laharic andesite tuff-breccia**, pumiceous pyroclastic flow deposits and tuff, with lignite and soil horizons.’ (QMAP database). “...**terrestrial to marginal marine** laharic, andesite tuff-breccia, pumiceous pyroclastic flow deposits, air fall tuff and lapilli-tuff, with **intercalated lignite and soil horizons**...” (Edbrooke and Brook, 2009). “The Puketi Formation consists of a sequence of **shallow-water deposits with numerous subaerial erosion breaks**. Laminated-bedding and cross-bedding in the Yellow Point Sandstone probably formed as a somewhat localised deposit from a moderately rapid stream. The other members of the Puketi Formation are dominantly **shallow-water** deposits, and since they contain no fossils they were probably deposited in a **non-marine lagoonal** environment... The andesitic grits and Waititi Tuff Breccia probably entered the area of deposition as **mudflows** from the volcanic chain to the west... Numerous **subaerial** erosional breaks are present in the Puketi Formation” (Jones, 1972) – *the main rock type of volcanic breccia appears to be associated with laharic deposits (QMAP database); consequently an onshore EoD is assigned to the map unit.*

### ***Waipoua Subgroup***

#### ***Pokas Formation (Mta)***

***Inferred age:*** 19-18 Ma (Edbrooke and Brook, 2009)

***EoD:*** mid-shelf

***Basis for interpretation:*** Main\_Rock = sandstone; Sub\_Rocks = mudstone, e grit; Description = “Thin bedded sandstone and mudstone, locally with thick coarse-grained sandstone and grit beds.” (QMAP database). “Microfaunas indicate an **outer shelf to uppermost bathyal** environment in the lower part, a **mid to outer shelf** environment in the upper part of the unit, and a Upper Otaian age” (Evans, 1994) – *the depositional depth range for the entire Pokas Formation given in Evans (1994) is mid-shelf to uppermost bathyal. This is narrowed down to a mid-shelf EoD based on the main rock type of sandstone, although mudstone lithologies may indicate outer shelf to upper bathyal deposition (Fig. 3).*

#### ***Omapere Conglomerate (Mtm)***

***Inferred age:*** 19-18 Ma (Edbrooke and Brook, 2009)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = conglomerate; Sub\_Rocks = mudstone; Description = 'Massive to crudely bedded, cobble and pebble conglomerate with thin bedded mudstone.' (QMAP database). "West of the Waipoua plateau, microfaunas indicate an Otaian age and a **mid to outer shelf** environment of deposition. East of the Waipoua plateau, sandstone and carbonaceous mudstone interbedded within the top of the formation (in the Te Kapinga Stream, at Taumatawhauwhau, and at Waimatenui) indicate shallowing to **estuarine and terrestrial** conditions. Pollens from a sample taken at Taumatawhauwhau indicate **terrestrial and/or fluvial** conditions (P06/f71, Appendix 1). Three metres of weakly consolidated (**alluvial?**) fine gravels, coarse sandstones, and conglomerate exposed in a landslip scarp at the head of Otatau Valley (P06/710293), which conformably underlie Waipoua Basalt and unconformably overlie Northland Allochthon, are also correlated with the Omapere Conglomerate. The variation in depth and facies suggests that the formation was deposited in a sloping and emergent coastal plain and marine shelf environment" (Evans, 1994) – *the map unit sits to the east of the Waipoua plateau so the estuarine, fluvial, alluvial, and terrestrial interpretations for the Omapere Conglomerate in this area (Evans, 1994) are applied to the map unit. The descriptions do not mention whether the onshore facies of the Omapere Conglomerate are dominant in the east. If marine facies are in fact dominant then a shelf EoD could be inferred.*

### **Waipoua Subgroup (Mtw)**

**Inferred age:** 19-18 Ma (Hayward et al., 2001)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = **basalt**; Sub\_Rocks = tuff lapilli, tuff, conglomerate; Description = Basalt lava flows and thin interbedded tuff and lapilli (QMAP database). "...numerous extensive **subaerial** lava flows of the Waipoua Basalt (Mtw...)... Individual lava flows are up to 25 m thick and separated by thin beds of airfall tuff and lapilli. The flows and pyroclastic rocks are cut by basalt dikes up to 10 m wide. Both flows and dikes are of uniformly glomeroporphyritic plagioclase-augite-olivine **basalt** (Wright 1980)... The gently southwest-tilted Tutamoe Range is the onshore remnant of a large **submarine** shield volcano, mapped offshore by geophysical methods (Davey 1974; Hayward 1979; Herzer 1995)" (Edbrooke and Brook, 2009) – *EoD is based on the subaerial environment and the main rock type. The description of air fall tuff also supports a subaerial environment. Refer to "Waipoua Subgroup" on the Kaitaia map area for further information.*

### **Coromandel Group**

"Early Miocene igneous rocks are present in two 350 km long, northwest-trending belts... on either side of Northland peninsula... The eastern belt (Coromandel Group...) comprises three major centres (Whangaroa Subgroup...; Taurikura Subgroup...; and Kuaotunu Subgroup...), each of which produced complex stratovolcanoes with several individual cones. Eruptions were **subaerial**, and composite cones surrounded by **terrestrial laharc ring-plains** were formed; the Whangaroa and Kuaotunu sequences include **fluvial and lacustrine** volcaniclastic sediments. Domes of rhyolite and dacite... are a minor component of the Coromandel Group" (Isaac et al., 1994).

### **Whangaroa Subgroup**

"...a southern area of laharc ring plain remnants and associated subvolcanic intrusives... The southern part (Wairakau Volcanics) of the elongate Whangaroa centre around Whangaroa Harbour (Fig. 6C), contains extensive outcrops of weakly stratified, laharc, andesitic tuff breccia and minor gully-confined flows (Bell & Clarke 1909; Brook & Hayward 1989), inferred to be the remnants of the proximal portions of a subaerial ring plain (Hayward 1991)" (Hayward et al., 2001).

### **Wairakau Volcanic Centre (Mcwi)**

**Inferred age:** 20-18 Ma (Hayward et al., 2001)

**EoD:** intermediate intrusives

**Basis for interpretation:** Main\_Rock = **andesite**; Sub\_Rocks = dacite; Description = 'Subvolcanic **intrusive** andesite; andesite, diorite and porphyry **dikes**.' (QMAP database) – *EoD is based on the QMAP lithologic description and the main rock type of andesite. The intrusive equivalent of andesite (diorite) is used here.*

### **Wairakau Volcanic Centre (PMeMii)**

**Inferred age:** 19-18 Ma (Hayward et al., 2001)

**EoD:** intermediate intrusives

**Basis for interpretation:** Main\_Rock = **diorite**; Sub\_Rocks = weathered cpx andesite, andesite dike (after Hayward et al., 2001). “Six dacite and **andesite dikes** and **intrusions** in the Taupo Bay to Cone Rock area, north of Whangaroa Harbour, produced ages within the range 19.7-17.7 ± 0.5 Ma...” (Hayward et al., 2001) – *these polygons were created from original QMAP polygons based on samples dated in Hayward et al. (2001). The EoD is based on the description of samples at these locations as being andesite dikes.*

### **Wairakau Volcanic Centre (Mcvv)**

**Inferred age:** 20-18 Ma (Hayward et al., 2001)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = volcanic breccia; Sub\_Rocks = andesite tuff; Description = ‘**Laharic** and minor vent-filling andesitic breccia, lava flows, fluvial and lacustrine sandstone and mudstone.’ (QMAP database). “Here the rocks are **predominantly of laharic origin** and with associated subvolcanic intrusive constitute the Wairakau Volcanic Centre (Mcv...)” (Edbrooke and Brook, 2009) – *the main rock type of volcanic breccia appears to be associated with laharic deposits (QMAP database). Laharic deposits are considered in this report to be reworked, rather than primary volcanic material deposited onshore. Consequently an onshore EoD is assigned to the map unit. Primary volcanic deposits such as lava flows and tuff also feature in the formation (QMAP database) and thus the map unit could alternatively be classified as onshore intermediate eruptives.*

### **Taurikura Subgroup**

“The Taurikura Subgroup is dominated by **andesitic volcanoclastics and flows, and dacite domes**, but it also includes **andesite, diorite and granodiorite subvolcanic intrusions**, and **andesite and diorite dikes**” (Edbrooke and Brook, 2009). “Onshore outcrops and offshore seismic and magnetic studies (Thrasher 1986) indicate the former presence of a 50 km long belt of stratovolcanoes (Taurikura Subgroup) in the Whangarei Heads to Hen and Chickens Islands area... Around Whangarei Heads, Taurikura Complex igneous rocks intrude and overlie Northland Allochthon sedimentary rocks that were emplaced into this region in the earliest Miocene (in the Upper Waitakian) c. 23-22 Ma (Hayward et al. 1989; Hayward 1993). This was followed by block faulting, uplift, and considerable erosion to produce a plain upon which the Whangarei Heads stratovolcanoes were built. It is unlikely, therefore, that igneous activity in this area could have been older than 21 Ma... On Hen Island, Taurikura Complex volcanic rocks overlie Northland Allochthon rocks... The ages available indicate that volcanic and intrusive activity in the Hen and Chickens centre occurred within the range 19.5-15.5 ± 0.6 Ma. It would appear that igneous activity started earlier in the Whangarei Heads centre than it did in the Hen and Chickens, that both areas may have been active together c. 19-16 Ma, and that activity in the eastern Chickens Islands may have continued later than elsewhere in the Taurikura Complex” (Hayward et al., 2001).

- **Mcrd**

**Inferred age:** 20-18 Ma (Hayward et al., 2001)

**EoD:** onshore silicic eruptives

**Basis for interpretation:** Main\_Rock = **dacite**; Sub\_Rocks = rhyodacite, volcanic breccia; Description = ‘Dacite domes and vent-filling breccia, locally altered to halloysitic clay.’ (QMAP database) – *EoD is based on the main rock type. Hayward et al. (2001) states that “block faulting, uplift, and considerable erosion to produce a plain” took place upon which the Whangarei Heads stratovolcanoes were built. This supports an onshore EoD.*

- **Mcri**

**Inferred age:** 22-16 Ma (Hayward et al., 2001)

**EoD:** intermediate intrusives

**Basis for interpretation:** Main\_Rock = **andesite**; Sub\_Rocks = diorite granodiorite; Description = ‘Andesite, diorite and granodiorite **intrusions**.’ (QMAP database) – *EoD is based on the QMAP litho-*

logic description and the main rock type of andesite. The intrusive equivalent of andesite (diorite) is used here.

- **Mcrv**

**Inferred age:** 21-17 Ma (Hayward et al., 2001)

**EoD:** onshore intermediate eruptives

**Basis for interpretation:** Main\_Rock = volcanic breccia; Sub\_Rocks = andesite tuff; Description = 'Weakly stratified to massive, rubbly **andesitic** breccia, andesite flows and minor tuff.' (QMAP database). "Hen Island and Sail Rock are composed of weakly stratified andesitic rubbly breccias, andesite flows, autobrecciated flows, minor tuff and lapilli tuff, interpreted as **subaerial facies of a cone** more than 8 km in diameter, the vent of which was south of Hen Island" (Isaac et al., 1994) – *EoD is based on the subaerial interpretation of the volcanic breccia lithologies and the suggestion that they form part of a volcanic cone. The main rock type of volcanic breccia may have a laharcic origin, which in this report is considered to be reworked (rather than primary) volcanic material deposited onshore. Consequently, an onshore EoD is an alternative interpretation.*

### ***Kuaotunu Subgroup***

Refer to "*Kuaotunu Subgroup (Mcu)*" on the Auckland area.

"Simpson Rock, south of the Mokohinau Islands, is the only outcrop of the subgroup in the Whangarei map area, and it is composed of dacite K-Ar dated at 16.5 Ma (Nicholson 1996)" (Edbrooke and Brook, 2009) – *this unit appears on both the Whangarei and Auckland map areas. In the database it belongs to the Auckland area so its EoD is discussed there.*

### **Whitianga Group**

#### ***Minden Rhyolite Subgroup (Mhm)***

**Inferred age:** 9 Ma (Edbrooke and Brook, 2009)

**EoD:** onshore silicic eruptives

**Basis for interpretation:** Main\_Rock = **rhyolite**; Sub\_Rocks = volcanic breccia tuff; Description = Rhyolite flow and dome complexes with associated breccia and tuff; extensive hydrothermal alteration (QMAP database). "Late Miocene to Early Pleistocene Whitianga Group (Schofield 1959) rocks of the Coromandel Volcanic Zone include widespread **ignimbrite sheets and rhyolite dome** complexes. They include the rocks of the Poor Knights (Fig. 43) and Mokohinau islands in the Whangarei map area. Both island groups represent the **emergent** parts of extensive, igneous submarine plateaux composed of Late Miocene rocks of the Minden Rhyolite Subgroup (Mhm...)" (Edbrooke and Brook, 2009) – *EoD is based on the main rock type and the emergent (subaerial) interpretation of the volcanic rocks of the Poor Knights and Mokohinau islands. Minden Rhyolite Subgroup also occurs throughout the eastern Coromandel Peninsula (Auckland map area) and further south in the Tauranga Volcanic Centre (Rotorua map area).*

#### **Ti Point Group (Mvt)**

**Inferred age:** 9 Ma (Edbrooke and Brook, 2009)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = olivine **basalt**; Description = Olivine basalt flow remnants (QMAP database). "Small, isolated outcrops of olivine **basalt** near Te Arai and Brynderwyn, of the Late Miocene Ti Point Group (Mvt; Hopgood 1961), are the remnants of lava **flows, plugs or dikes** (Heming 1980)" (Edbrooke and Brook, 2009) – *EoD is based on the main rock type and the subaerial interpretation in Edbrooke and Brook (2009). Refer to "Ti Point Group (Mvt)" on the Auckland map area for further information.*

### **Kerikeri Volcanic Group**

"The Kerikeri Volcanic Group (Bell & Clarke 1909; Kear et al. 1961) is a Late Miocene to Quaternary, predominantly **basaltic, volcanic** association that includes the rocks of the Kaikohe-Bay of Islands Volcanic Field and the Puhipuhi-Whangarei Volcanic Field, as well as an isolated flow remnant near

Mangawhai. The volcanic fields contain numerous monogenetic volcanoes, mainly of small volume, that are regarded as being of intraplate type (Smith 1989; Smith et al. 1993). The age and style of volcanism is similar across the fields, and common igneous units are recognised throughout the group" (Edbrooke and Brook, 2009). "The Late Cenozoic Kerikeri Volcanics are present mainly in eastern Northland; they too erupted **subaerially**" (Isaac et al., 1994).

### ***Kaikohe-Bay of Islands Volcanic Field***

"The Kaikohe-Bay of Islands Volcanic Field covers almost 500 km<sup>2</sup> from the Kawakawa valley north to Matauri Bay, and from Kaikohe east to the Bay of Islands. The younger Pleistocene volcanic centres include **basalt lava flows** (Qvb) and **scoria cones** (Qvs), mostly in the vicinity of Kaikohe and between Kerikeri and Waitangi. Older, Late Miocene and Pliocene flows (Pvb) and associated scoria cones (Pvs), are more extensive, particularly in the north of the field... Some of the oldest rocks of the Kaikohe-Bay of Islands field form small **intrusive plugs** or isolated ridge-top remnants, mainly in the northwest... Rocks of the Kaikohe-Bay of Islands field are mainly **basaltic** and include hawaiite, highly porphyritic tholeiites and some transitional basalts (Ashcroft 1986). Te Pua and Pukekauri volcanoes, east of Lake Omapere, are composed of **basaltic andesite** flows (Pva). Several alkaline and peralkaline **rhyolite** domes (Pvr), locally with obsidian, are also present in the north..." (Edbrooke and Brook, 2009).

- **Pvba**

**Inferred age:** 7-4 Ma (Edbrooke and Brook, 2009)

**EoD:** onshore intermediate eruptives

**Basis for interpretation:** Main\_Rock = basaltic **andesite**; Description = Cone-forming basaltic andesite flows (QMAP database) – *EoD is based on the main rock type and the subaerial interpretation of the Kerikeri Volcanics in Isaac et al. (1994).*

- **Pvbb**

**Inferred age:** 8-2 Ma (Smith et al., 1993)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = **basalt**; Sub\_Rocks = basanite; Description = 'Basalt lava, volcanic plugs and minor tuff.' (QMAP database) – *EoD is based on the main rock type and the subaerial interpretation of the Kerikeri Volcanics in Isaac et al. (1994).*

- **Pvbr**

**Inferred age:** 8-3 Ma (Smith et al., 1993)

**EoD:** onshore silicic eruptives

**Basis for interpretation:** Main\_Rock = **rhyolite**; Sub\_Rocks = obsidian; Description = Alkaline and peralkaline rhyolite domes and local obsidian (QMAP database) – *EoD is based on the main rock type and the subaerial interpretation of the Kerikeri Volcanics in Isaac et al. (1994).*

- **Pvbs**

**Inferred age:** 3 Ma (Smith et al., 1993)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = **scoria**; Sub\_Rocks = **basalt**; Description = Basalt scoria (QMAP database) – *EoD is based on the main rock type and the subaerial interpretation of the Kerikeri Volcanics in Isaac et al. (1994).*

- **Intrusive plug (PMIMmi)**

**Inferred age:** 9 Ma (Smith et al., 1993)

**EoD:** mafic intrusives

**Basis for interpretation:** Main\_Rock = **basalt**; Sub\_Rocks = quartz tholeiite plug (after Smith et al., 1993). "Te Rahui, Papuke-Mangapa Road, **plug**... The oldest rocks form small intrusive plugs or isolated ridge-top outliers capping basement rocks and lower Tertiary sediments on the northwestern side of the field. Dates on these rocks are 7-9 Ma" (Smith et al., 1993) – *this polygon was created from original QMAP polygons based on a sample dated in Smith et al. (1993). The EoD is based on the description of the Tertiary basalts.*



- **Qvbb**

**Inferred age:** 2-0 Ma (Smith et al., 1993)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = **basalt**; Sub\_Rocks = basanite; Description = Basalt lava and volcanic plugs. (QMAP database) – *EoD is based on the main rock type and the subaerial interpretation of the Kerikeri Volcanics in Isaac et al. (1994).*

- **Qvbs**

**Inferred age:** < 0.5 Ma (Smith et al., 1993)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = **scoria**; Sub\_Rocks = **basalt**; Description = Basalt scoria commonly forming steep-sided cones. (QMAP database) – *EoD is based on the main rock type and the subaerial interpretation of the Kerikeri Volcanics in Isaac et al. (1994).*

### **Puhipuhi-Whangarei Volcanic Field**

“The Puhipuhi-Whangarei Volcanic Field extends from just south of the Bay of Islands to Maungakaramea, south of Whangarei City... The mainly youthful, well-preserved, volcanic features include shield volcanoes built up of thin **lava flow** sequences, steep-sided **scoria cones** with well-developed craters (Qvs) that are commonly breached by lava, and lava flows up to 80 m thick and 15 km in length that fill former valleys (Qvb). Older, eroded flows (Pvb) usually pre-date the present topography and scoria cones (Pvs) are rarely preserved... Bedded hydrothermal breccia and siliceous sinter (Pvh) at Puhipuhi are overlain by basalt flows of Pliocene and younger age. **Basalt** is the dominant rock type in the field and includes hawaiite, alkali basalt, tholeiite and transitional basalt, with minor **intermediate** rock types (Ashcroft 1986). The field also includes the **dacite** domes of Parakiore, Hikurangi and Opuawhanga, and a **rhyolite** remnant on Paremata Hill, inland from Helena Bay (Qvd)...” (Edbrooke and Brook, 2009).

- **Pvpb**

**Inferred age:** 10-1 Ma (Smith et al., 1993)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = **basalt**; Sub\_Rocks = basanite; Description = ‘Basalt lava, volcanic plugs and minor tuff.’ (QMAP database) – *EoD is based on the main rock type and the subaerial interpretation of the Kerikeri Volcanics in Isaac et al. (1994).*

- **Pvph**

**Inferred age:** 6-5 Ma (Edbrooke and Brook, 2009)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = breccia; Map\_Unit = Sinter deposits; Description = Bedded hydrothermal breccia and siliceous sinter. (QMAP database) – *EoD is based on the subaerial interpretation of the Kerikeri Volcanics in Isaac et al. (1994). The map unit is a geothermal deposit so no volcanic compositional classification is assigned to the map unit.*

- **Pvps**

**Inferred age:** 3 Ma (Smith et al., 1993)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = **scoria**; Sub\_Rocks = **basalt**; Description = **Basalt scoria** (QMAP database) – *EoD is based on the main rock type and the subaerial interpretation of the Kerikeri Volcanics in Isaac et al. (1994).*

- **Qvpb**

**Inferred age:** 2-0 Ma (Smith et al., 1993)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = **basalt**; Sub\_Rocks = basanite; Description = Basalt lava and volcanic plugs. (QMAP database) – *EoD is based on the main rock type and the subaerial interpretation of the Kerikeri Volcanics in Isaac et al. (1994).*

- **Qvpd**

**Inferred age:** 4-1 Ma (Smith et al., 1993; Takagi, 1995)

**EoD:** onshore silicic eruptives

**Basis for interpretation:** Main\_Rock = **dacite**; Sub\_Rocks = rhyodacite; Description = Dacite and rhyodacite domes with minor flows and tuff. (QMAP database) – *EoD is based on the main rock type and the subaerial interpretation of the Kerikeri Volcanics in Isaac et al. (1994).*

- **Qvps**

**Inferred age:** < 0.5 Ma (Smith et al., 1993)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = **scoria**; Sub\_Rocks = **basalt**; Description = Basalt scoria commonly forming steep-sided cones. (QMAP database) – *EoD is based on the main rock type and the subaerial interpretation of the Kerikeri Volcanics in Isaac et al. (1994).*

- **Qvtb**

**Inferred age:** 1 Ma (Smith et al., 1993)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = **basalt**; Sub\_Rocks = basanite; Description = Basalt lava and volcanic plugs. (QMAP database). “Olivine basalt flow remnants (Qvb) near Mangawhai were previously mapped as part of the Ti Point Group (Thompson 1961; Heming 1980), but more recent age determinations and geochemistry link them with the younger Kerikeri Volcanic Group” (Edbrooke and Brook, 2009) – *EoD is based on the main rock type and the subaerial interpretation of the Kerikeri Volcanics in Isaac et al. (1994).*

## **Tauranga Group (Plal)**

**Inferred age:** 6-3 Ma (Edbrooke and Brook, 2009)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone, conglomerate, lignite; Map\_Unit = **alluvium**; Description = “Thin-bedded, carbonaceous sandstone and carbonaceous mudstone with intercalated conglomerate and lignite.” (QMAP database). “Pliocene to Holocene, **fluvial, lake and estuarine** sediments of the Tauranga Group...” (Edbrooke and Brook, 2009) – *EoD is based on the fluvial, lake and estuarine interpretation of the Tauranga Group in the QMAP database and Edbrooke and Brook (2009).*

## **Quaternary – Sedimentary deposits**

- **All Q deposits**

**EoD:** onshore

**Basis for interpretation:** Based on the QMAP database which includes alluvial, beach, colluvial, construction fill, dune, estuarine, fluvial, landslide, lignite, and swamp sediments in the Quaternary deposits.

## AUCKLAND AREA (Geological Map 3)

### Te Kuiti Group

#### *Waikato Coal Measures (Etw)*

**Inferred age:** 36-35 Ma (Tripathi et al., 2008; Kamp et al., 2014d)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = claystone, coal, sandstone, conglomerate, 'carbonaceous shale', iron; Description = Carbonaceous mudstone and claystone with coal seams, minor sandstone and rare conglomerate (QMAP database). "...a **predominantly terrestrial** Late Eocene (Ar) environment in which the Waikato Coal Measures accumulated..." (Edbrooke et al., 1998). "The WCM were deposited in paleovalleys and faulted sub-basins... the **terrestrial sub-basins** opened eastward into a coastal plain evident from an increase in the degree of marine influence in the coal measures" (Tripathi et al., 2008). "The Waikato Coal Measures accumulated in **fluvial** and overbank depositional environments, marking the start of regional onlap onto basement... The fine-grained lithofacies dominating the Waikato Coal Measures were sourced from deeply weathered basement regolith (Nelson & Hume 1987), transported south to north via a **fluvial** system (Edbrooke et al. 1994) and deposited in meandering **river and floodplain environments** in the northern Waikato region between basement ridges to the west and east" (Kamp et al., 2014a) – *the unit is defined here as onshore based on the paleogeographic maps in Isaac et al. (1994) and Kamp et al. (2014a). Refer to "Waikato Coal Measures (Etw)" on the Waikato map area for further information.*

#### *Mangakotuku Formation (Otm)*

Includes Glen Afton Claystone, Pukemiro Sandstone, Rotowaro Siltstone, and Waikaretu Sandstone members.

"Predominantly **marine** formation... consisting of unbedded, typically non-calcareous siltstone and claystone, with glauconitic, muddy sandstone interbeds usually present in the lower part. Hard, siderite-cemented siltstone lenses are commonly present near the base" (Edbrooke, 2001). "The degree of marine influence within the formation increases up-sequence, as suggested by plentiful benthic foraminifera, ostracods, and echinoderms in upper parts of the formation, although foraminiferal species are very rare (Hornibrook, in Kear & Schofield 1978)" (Tripathi et al., 2008).

- **Glen Afton Claystone**

"...contains fragments of the brachiopod *Lingula*, indicating accumulation in a **shallow marine** environment... light grey non-calcareous claystone..." (Tripathi et al., 2008).

- **Pukemiro Sandstone**

"The presence of abundant ostracods and rare foraminifera (Kear & Schofield 1978) in the glauconite-rich Pukemiro Sandstone Member... probably indicates restricted neritic conditions" (Tripathi et al., 2008).

- **Rotowaro Siltstone**

"dark greyish, massive carbonaceous mudstone" (Kamp et al., 2008).

- **Waikaretu Sandstone**

"...this study suggests that it is mainly a lateral correlative of Rotowaro Siltstone... up to 8 m of dark grey siltstone interbedded with fine to coarse sandstone... The member is unconformably overlain by the Elgood Limestone Member of Glen Massey Formation. The sharp and abrupt nature of this contact is due to erosion, possibly marine planation" (Tripathi et al., 2008).

**Inferred age:** 34-33 Ma (Tripathi et al., 2008; Kamp et al., 2014d)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = siltstone; Sub\_Rocks = mudstone, claystone, greensand; Description = Massive siltstone, mudstone and claystone, with interbedded glauconitic muddy fine sandstone (QMAP database) – *the unit is defined here as innermost shelf, particularly for the oldest*

part of the formation. Refer to “Mangakotuku Formation (Otm)” on the Waikato map area for further information.

### **Glen Massey Formation (Otg)**

Includes Elgood Limestone, Dunphail Siltstone, and Ahirau Sandstone members.

“Glen Massey Formation usually consists of three distinct facies in vertical succession. A thin, flaggy, sandy limestone [Elgood Limestone] and/or calcareous, glauconitic sandstone (greensand) at the base grades up into calcareous siltstone [Dunphail Siltstone], which in turn grades up into massive, calcareous fine- to medium-grained sandstone [Ahirau Sandstone]... The upper sandstone dominates the formation...” (Edbrooke, 2001). “Foraminifera are difficult to extract from the well-cemented lithology of Glen Massey Formation, however the microfaunal assemblage indicates **deepening from shelfal to upper bathyal** water depths” (Kamp et al., 2014b). “Significant marine flooding across the basin marked the onset of accumulation of the Glen Massey Formation. In the Elgood Limestone Member, **inner shelf** high-energy limestone lithofacies (L1-L3) grade eastward into horizontally bedded to massive grainstone/packstone facies (L4-L5) deposited in **mid to outer shelf** environments (Fig. 12). These facies in turn grade into calcareous siltstone/sandstone (sandy marl) with relatively high concentrations of glauconite (Lithofacies C2, C3) (Fig. 12), which also developed across the top of the member” (Kamp et al., 2014c).

- **Elgood Limestone**

“...is the lowermost unit in the formation and comprises flaggy bioclastic limestone... laps onto a weathered and wave-planed basement surface with remnant relief” (Tripathi et al., 2008). “Near shore to **innermost shelf**, adjacent to rocky shoreline... Subaqueous dunes migrating parallel to shore... **Lower inner to mid-outer shelf**, wave (storm) dominated setting” (Kamp et al., 2008).

- **Dunphail Siltstone**

“...is the middle unit, composed of massive calcareous siltstone...” (Tripathi et al., 2008). “**Mid to outer shelf**, between fair weather and storm wave base... **Outer shelf to upper bathyal**” (Kamp et al., 2008).

- **Ahirau Sandstone**

“...is silty fine sandstone forming the uppermost member...” (Tripathi et al., 2008). “**Inner to mid shelf** with moderate to strong bottom currents driven by wind and/or tides interacting with the inherited topography... Moderate energy in **mid to outer shelf** depths below fair-weather but above storm wave base” (Kamp et al., 2008).

**Inferred age:** 33-30 Ma (Tripathi et al., 2008; Kamp et al., 2014d)

**EoD breakdown:** 33 Ma: mid-shelf (Elgood Limestone, Dunphail Siltstone)  
32 Ma: outer shelf (Dunphail Siltstone, Ahirau Sandstone)  
31-30 Ma: mid-shelf (Ahirau Sandstone)

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = siltstone limestone greensand; Description = Calcareous fine sandstone, siltstone and basal glauconitic, sandy limestone or greensand (QMAP database) – the EoD is based on the cited literature. Refer to “Glen Massey Formation (Otg)” on the Waikato map area for further information.

### **Whaingaroa Formation (Oti)**

Includes Kotuku Siltstone, and Waikorea Sandstone members.

“...is a massive, light olive- to blue-grey, glauconitic, calcareous siltstone with a thin, basal, very glauconitic muddy fine-grained sandstone to sandy siltstone” (Edbrooke, 2001). “Large numbers of planktic foraminifera, particularly *Globigerina euapertura* and *G. labiacrassata*, are abundant and indicate **fully oceanic** environments probably at **mid to outer shelf or upper bathyal** depths” (Tripathi et al., 2008). “The Whaingaroa Formation in our lithostratigraphic framework (Tripathi et al. 2008) comprises basal TST limestone facies in places (Awaroa Limestone Member), HST deposits (Kotuku Siltstone Member) and FSST deposits (Waikorea Sandstone Member) and hence conforms to a typical mixed carbonate – siliciclastic sequence” (Kamp et al., 2014a).

- **Kotuku Siltstone**

“...is a featureless blue-grey calcareous siltstone” (Tripathi et al., 2008). “**Mid-outer shelf to possibly upper bathyal**” (Kamp et al., 2008).

- **Waikorea Sandstone**

“Along the northwestern margin, the top one or so metres of the formation comprise bedded silty sandstone named Waikorea Sandstone Member... The member is easily distinguished by its moderately to strongly bedded nature and sandy texture... The lower contact between the Waikorea Sandstone Member and Kotuku Siltstone Member is usually gradational. The member is generally abruptly overlain in the west by cross-stratified Waimai Limestone Member of Aotea Formation...” (Tripathi et al., 2008).

**Inferred age:** 30-29 Ma (Tripathi et al., 2008; Kamp et al., 2014d)

**EoD:** outer shelf

**Basis for interpretation:** Main\_Rock = siltstone; Sub\_Rocks = sandstone, greensand; Description = Massive, glauconitic, calcareous siltstone, locally with a thin basal greensand (QMAP database) – the EoD of the formation is narrowed down here to outer shelf, based on the descriptions in Kamp et al. (2008) and Tripathi et al. (2008), and the main rock type of siltstone (QMAP database, Fig. 3). The Waikorea Sandstone Member may have been deposited at a shallower depth (i.e. mid-shelf) based on its lithology, but it is only shown as a minor component of the Whaingaroa Formation in the chronostratigraphic panel in Fig. 5 of Tripathi et al. (2008). The Whaingaroa Formation includes different members on the Waikato map area.

### **Aotea Formation (Ota)**

Includes Waimai Limestone, Mangiti Sandstone, and Patikirau Siltstone members.

“Cross-bedded, flaggy, crystalline limestone... The 6-15 m thick limestone grades upward and eastward into grey, calcareous, concretionary medium-grained sandstone, grey siltstone and hard glauconitic sandstone, with a total thickness of up to 30 m. The sandstones become finer-grained further east, grading into siltstone... Aotea Formation probably accumulated in current-swept, **inner to mid shelf** environments” (Edbrooke, 2001).

- **Waimai Limestone**

“...in the vicinity of Port Waikato (e.g. PW-1), Aotea Formation comprises limestone (Waimai Limestone) and overlying glauconitic sandstone with a combined thickness of less than 5 m... The limestone commonly grades through silty limestone into Patikirau Siltstone Member. In the vicinity of Port Waikato, Waimai Limestone forms most of the formation and comprises thin (2-3 m), variably glauconitic limestone grading rapidly upward into fossiliferous glauconitic sandstone... **Shelf** water depths developed over most of the northern region following transgressive onlap of Waimai Limestone. The accumulation of cross-bedded limestone (Waimai Limestone Member) reflects **shallow marine** (less than about **60 m**) high current energy depositional environments (Anastas 1997), but the water depth rapidly increased during Waimai Limestone accumulation judging from the accumulation of glauconitic sandstone to mudstone in its uppermost parts in Port Waikato sections” (Tripathi et al., 2008). “High energy **inner to mid shelf** dominated by strong offshore-directed storm and/or tidal induced currents... **Lower inner to mid-outer shelf**; wave (storm) dominated setting... Sediment starved **inner to mid shelf**” (Kamp et al., 2008). “The limestone lithofacies accumulated in **inner- to mid-shelf** water depths” (Kamp et al., 2014d).

- **Mangiti Sandstone**

“...calcareous sandstone with thin siltstone interbeds... Waimai Limestone Member grades laterally into, or interfingers with, [Mangiti Sandstone]” (Tripathi et al., 2008). “**Inner to mid** wave dominated **shelf**... Moderate energy **mid shelf** depths below fair-weather but above storm wave base” (Kamp et al., 2008).

- **Patikirau Siltstone**

“...massive siltstone... Mangiti Sandstone generally fines upward into variably muddy and calcareous siltstone (Patikirau Siltstone)” (Tripathi et al., 2008). “**Mid-outer shelf** to possibly **upper**

**bathyal**" (Kamp et al., 2008; Kamp et al., 2014d).

**Inferred age:** 29-27 Ma (Tripathi et al., 2008; Kamp et al., 2014b)

**EoD breakdown:** 29 Ma: innermost shelf (Waimai Limestone, Mangiti Sandstone)  
28 Ma: mid-shelf (Waimai Limestone, Mangiti Sandstone, Patikirau Siltstone)  
27 Ma: outer shelf (Patikirau Siltstone)

**Basis for interpretation:** Main\_Rock = siltstone; Sub\_Rocks = sandstone limestone greensand; Description = Calcareous sandy siltstone with interbedded concretionary sandstone and basal, cross-bedded or flaggy, glauconitic limestone (QMAP database) – *sedimentary lithofacies as observed in stratigraphic sections by A. Tripathi are detailed in Table 1.1 of Kamp et al. (2008). The EoD of the Aotea Formation is broken down into time intervals based on the EoD of the dominant or average lithology at the time. The Aotea Formation includes different members on the Waikato map area.*

### ***Te Akatea Formation (Ott)***

Includes Carter Siltstone Member.

"...a light grey or white, very calcareous, massive or weakly bedded siltstone to silty fine-grained sandstone. It commonly has a very calcareous, concretionary sandy siltstone to sandy limestone at the base" (Edbrooke, 2001). "...Te Akatea Formation accumulated in an open marine setting, probably at **outer shelf to upper bathyal** water depths, in the northern part of the basin" (Kamp et al., 2014e).

#### **• Carter Siltstone**

"The lower bedded siltstone passes upward into massive siltstone with occasional concretionary bands... The microfauna identified by Hornibrook (Kear & Schofield 1978) in Carter Siltstone are dominated by planktics (*Globigerina*) and benthics such as *Cibicides thiara* and *Karreriella novozealandica*, indicating an **outer shelf to upper bathyal** depositional environment" (Tripathi et al., 2008).

**Inferred age:** 27-24 Ma (King et al., 1999; Tripathi et al., 2008; Kamp et al., 2014e)

**EoD:** outer shelf

**Basis for interpretation:** Main\_Rock = siltstone; Sub\_Rocks = sandstone, limestone; Description = Massive calcareous sandy siltstone to silty fine sandstone, locally with a thin basal muddy limestone (QMAP database) – *based on the stratigraphic columns in Kamp et al. (2008) Carter Siltstone is the only member of this formation that occurs in the Auckland Map area. The EoD is narrowed down here to outer shelf, but upper bathyal may be an appropriate alternative. The Te Akatea Formation includes different members on the Waikato map area.*

### ***Torehina Formation (Oth)***

**Inferred age:** 31-26 Ma (Dix and Nelson, 2004)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = siltstone sandstone coal conglomerate; Description = Flaggy limestone, calcareous siltstone, and carbonaceous siltstone and sandstone with thin coal seams and lenticular conglomerate (QMAP database). "...it comprises up to 15 m of basal conglomerate, carbonaceous sandstone and siltstone, 46 m of calcareous siltstone and shelly sandstone, 31 m of glauconitic, bioclastic limestone, and 23 m of sandy limestone... calcareous sandstone underlying the limestone yielding a Late Oligocene, **inner shelf** foraminifera fauna..." (Edbrooke, 2001). "Microfossil dating of the coral bearing horizon and overlying limestone has so far proved elusive, but the marly sandstone several metres lower has an **inner shelf** foraminiferal fauna (S10/f9512) of Late Oligocene age (Duntroonian or Lower Waitakian, probably Duntroonian - *Notorotalia spinosa*, *Globigerina euapertura*)" (Hayward et al., 1990). "The Torehina Formation is an isolated lithostratigraphic equivalent to the geographically widespread terrestrial and shallow-marine transgressive deposits of the mid-Tertiary Te Kuiti Group of central western North Island..." (Dix and Nelson, 2003). "It contains two major transgressive sequences that record successive onlap of a once emergent landmass. The first sequence records marine flooding of **non-marine to marginal marine fan delta/estuarine facies**, followed by deepening upward and

formation of a low-energy, **deep (100+ m)** muddy carbonate ramp” (Dix and Nelson, 2004) – *an innermost shelf EoD is inferred based on the facies descriptions in Dix and Nelson (2004). Mid- to outer shelf may be appropriate for higher in the sequence based on the finer-grained lithology.*

## **Northland Allochthon (various unit codes)**

Includes Tangihua Complex (Kt), Mangakahia Complex (Kk, Whangai Formation (Kkw), Hukerenui Mudstone (Kkh)), Motatau Complex (Om, Mahurangi Limestone (Omm), and Puriri Mudstone (Omp)).

**Inferred age:** 22-21 Ma (King et al., 1999)

**EoD:** allochthonous

**Basis for interpretation:** *EoD is based on the allochthonous interpretation of the map units on the Edbrooke (2001) geological map sheet.*

## **Waitemata Group**

### **Kawau Subgroup**

“**Shallow marine** facies of the Kawau Subgroup... lap on to, and partly bury, an irregular paleo-shoreline of Waipapa basement in the north and east, and unconformably overlies eroded Te Kuiti Group in the south... Kawau Subgroup consists of up to 60 m of heterogeneous sediments that accumulated at **intertidal through to uppermost bathyal** depths, although **most are inner to mid shelf...**” (Edbrooke, 2001).

### **Cape Rodney Formation (Mwr)**

**Inferred age:** 22 Ma (Edbrooke, 2001)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = conglomerate; Sub\_Rocks = breccia grit sandstone; Description = Greywacke conglomerate and breccia with associated grit, pebbly medium to coarse sandstone, carbonaceous siltstone and shelly, (QMAP database). “...is prevalent in the north, comprising most of the Kawau Subgroup north of Waiheke Island. It occurs as conformable lenses up to 40 m thick within Kawau Subgroup and is the lowest unit in many places” (Edbrooke, 2001) – *the description of the Kawau Subgroup in Edbrooke (2001) indicates a transgressive sequence, with shallow marine facies occurring at the base of the subgroup. The Cape Rodney Formation sits at the base of the Kawau Subgroup, implying a shallow marine environment for the map unit. This interpretation is narrowed down to an innermost shelf EoD based on the main rock type of conglomerate and descriptions of the formation in Edbrooke (2001) which indicate a near shore depositional environment.*

### **Tipakuri Formation (Mwt)**

**Inferred age:** 22 Ma (Edbrooke, 2001)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = siltstone; Description = Macrofossiliferous, massive or weakly bedded, calcareous sandstone (QMAP database). “Shelly calcareous sandstone with local thin interbedded siltstone... occurs as conformable lenses up to 20 m thick, in the area between Orewa (in drillholes) and the coast south of Port Waikato” (Edbrooke, 2001) – *EoD is based on the lithologic descriptions in Edbrooke (2001) and the QMAP database, and Fig. 3.*

#### **• Mwt+Mwr**

**Inferred age:** 22 Ma (Edbrooke, 2001)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = conglomerate, siltstone, breccia, grit; Description = Macrofossiliferous, massive or weakly bedded, calcareous sandstone (QMAP database) – *based on the unit codes, the map unit appears to consist of Tipakuri Formation (Mwt) and Papakura Limestone (Mwu), both of which are interpreted here as innermost shelf sediments. Additionally, the QMAP lithologic description used in conjunction with Fig. 3 indicates an innermost shelf depositional environment.*

- **Papakura Limestone (Mwu)**

**Inferred age:** 22 Ma (Edbrooke, 2001)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = sandstone, conglomerate, breccia; Description = Pebbly, gritty, shelly or sandy, bioclastic, crystalline or semicrystalline limestone, and local limestone breccia (QMAP database). "...are sporadically distributed throughout the area of Kawau Subgroup outcrop" (Edbrooke, 2001). "Lenses of pebbly, gritty, shelly or sandy bioclastic limestone or rarely limestone breccia; sometimes glauconitic, usually crystalline or semicrystalline, flaggy (Fig. 4) or poorly flaggy. Lithic clasts are usually greywacke and quartz; bioclasts are primarily bryozoans and bivalves with subsidiary algae, corals, foraminifera, and echinoderms; 55-90% CaCO<sub>3</sub> overall. The limestone is often laminated, occasionally with cross-bedded horizons and rarely with small-scale scour and fill structures. The majority of Papakura Limestone lenses are clean sediments with foraminiferal faunas dominated by the large **shallow-water** benthic *Amphistegina* and with fewer than 10% planktics... The shelly sand of these lenses is inferred to have originated at shelf depths, together with other Kawau Subgroup sediment, and to have been transported as subaqueous mass flows down into the deeper water sequence" (Hayward and Brook, 1984) – *EoD is based on the lithologic descriptions in Edbrooke (2001) and the QMAP database, and Fig. 3.*

### **Meremere Subgroup**

"...a lateral equivalent of the Warkworth Subgroup... Weakly stratified, fine- to medium-grained sandstone and sandy siltstone of the Meremere Subgroup... conformably overlies Kawau Subgroup or unconformably overlies eroded Te Kuiti Group or Waipapa (composite) terrane basement in the Waikato area... It consists of three formations that are inferred to represent **bathyal submarine fan and basin floor facies**" (Edbrooke, 2001).

### **Waikawau Sandstone (Mww)**

"The basal Waikawau Sandstone (Mww...) is a massive to well bedded, grey, calcareous, glauconitic fine- to medium-grained sandstone commonly with calcareous concretionary beds near the base. It is up to 70 m thick, tuffaceous in places, and may contain siltstone interbeds" (Edbrooke, 2001). "A **cross-bedded coarse shelly sandy limestone** (Waikawau Limestone Member) is separated from Carter Siltstone by a sharp planar surface. Waikawau Limestone grades abruptly into bedded Waikawau Sandstone" (Tripathi et al., 2008). "The abundance of *Notorotalia* suggests a **shelf** environment" (Hornibrook and Schofield, 1963). "The Waikawau Limestone is only known to crop out on the coast at the well-documented Kaawa section (grid ref.\* N51/272800 to 272804, Fig. 2) where it rests unconformably on Te Akatea Siltstone... The limestone represents a very local basal facies of the Waikawau Sandstone (Otaian Stage, Lower Miocene), the lowest formation of the Waitemata Group in west Auckland... The sequence of events leading to the present form of the Waikawau Limestone seems to have been as follows: (1) The deposition, in a **shallow Early Miocene sea**, of a lens of foraminiferal-bryozoan carbonate sand with about 38% of siliciclastic grains and allochthonous glauconite. (2) The beginning of glauconite formation, contemporaneously with deposition, in bioclast cavities where mildly reducing micro-environments were available in an otherwise oxidising environment" (Ballance and Nelson, 1969).

**Inferred age:** 22-21 Ma (Edbrooke, 2001; Tripathi et al., 2008)

**EoD breakdown:** 22 Ma: mid-shelf

21 Ma: mid-bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = siltstone tuff limestone; Description = Calcareous, glauconitic fine to medium sandstone with minor siltstone and tuff: locally concretionary near base (QMAP database) – *the base of the Waikawau Sandstone appears to consist of shelfal/shallow sea cross-bedded coarse shelly sandy limestone (Tripathi et al., 2008; Hornibrook and Schofield, 1963; Ballance and Nelson, 1969) with the remainder of the formation inferred to represent bathyal submarine fan and basin floor deposits (Edbrooke, 2001). Alternative interpretations include a basal innermost shelf EoD, grading upsection to lower bathyal. Waikawau Limestone facies are stratigraphically equivalent to Papakura Limestone. Note: If basal Waikawau Formation makes up a relatively small portion of time on the 22 Ma paleomap, with the majority of the period dominated by bathyal Waikawau Formation, then the map unit should instead be classified entirely as mid-bathyal.*



### ***Koheroa Siltstone (Mwk)***

***Inferred age:*** 21 Ma (Edbrooke, 2001)

***EoD:*** mid-bathyal

***Basis for interpretation:*** Main\_Rock = siltstone; Sub\_Rocks = sandstone, tuff; Description = Calcareous, sandy siltstone with minor fine sandstone and tuff beds (QMAP database). "...massive to well bedded, light grey to blue-grey, moderately calcareous sandy siltstone, commonly with interbedded calcareous sandstone and tuffaceous sandstone up to 2 m thick. Koheroa Siltstone is up to 75 m thick and commonly contains fine carbonaceous fragments" (Edbrooke, 2001). "...Koheroa Siltstone, which is likely to have been deposited in **deeper water**, and suggests that *dissimilis* is an **open-sea** species occurring only sporadically in relatively shallow deposits" (Hornibrook and Schofield, 1963) – *the description in Edbrooke (2001) implies a submarine fan deposit at bathyal depths. Upper or lower bathyal paleoenvironments are alternative interpretations, perhaps for different parts of the formation.*

### ***Mercer Sandstone (Mwm)***

***Inferred age:*** 21-20 Ma (Edbrooke, 2001)

***EoD:*** mid-bathyal

***Basis for interpretation:*** Main\_Rock = sandstone; Sub\_Rocks = mudstone; Description = Massive, non-calcareous, fine to coarse sandstone and thin sandy mudstone, with carbonaceous fragments and abundant volcanic glass (QMAP database). "Mercer Sandstone (Mwm...) is a massive to thick-bedded (0.3-8 m thick), brown, fine- to coarse-grained, poorly sorted, non-calcareous sandstone with interbedded light grey, sandy mudstone up to 0.6 m thick, and rare conglomerate beds..." (Edbrooke, 2001) – *the bathyal submarine fan and basin floor, and deeper water depositional environments suggested in Edbrooke (2001) and Hornibrook and Schofield (1963) infer an upper to lower bathyal depositional environment. The lithologic descriptions of the map unit in Edbrooke (2001) and the QMAP database suggest that Mercer Sandstone sediments are mass emplaced deposits. The map unit is interpreted as a mid-fan deposit at mid-bathyal depths. An alternative interpretation is that the unit is a basin floor fan deposited at lower bathyal depths.*

### ***Warkworth Subgroup***

"Following the rapid, early Otaian deepening of the Waitemata basin, it filled with up to 1000 m... of interbedded turbidite sandstone and pelagic mudstone, with associated laminated mudstone and muddy sandstone, redeposited conglomerate, and intercalated volcanoclastic diamictite (Warkworth Subgroup...). These sediments accumulated in **bathyal submarine fan and basin floor** settings..." (Edbrooke, 2001).

### ***East Coast Bays Formation (Mwe, Mwe~)***

***Inferred age:*** 21-20 Ma (Edbrooke, 2001)

***EoD:*** mid-bathyal

***Basis for interpretation:*** Main\_Rock = turbidite; Sub\_Rocks = sandstone mudstone grit; Description = Alternating sandstone and mudstone with variable volcanic content and interbedded volcanoclastic grits (QMAP database). "The characteristic alternating, decimetre-bedded, graded sandstone and laminated mudstones of East Coast Bays Formation..." (Edbrooke, 2001) – *EoD is based on the bathyal submarine fan and basin floor interpretation of the Warkworth Subgroup (Edbrooke, 2001), of which the East Coast Bays Formation is a part, the map unit's definition as turbidity current deposits (QMAP database), and Fig. 3. The map unit is interpreted as a mid-fan deposit at mid-bathyal depths, but alternatively could be a basin floor fan emplaced at lower bathyal depths.*

### ***Albany Conglomerate (Mwy)***

***Inferred age:*** 21 Ma (Edbrooke, 2001)

***EoD:*** mid-bathyal

***Basis for interpretation:*** Main\_Rock = conglomerate; Sub\_Rocks = sandstone; Description = Conglomerate composed mainly of pebble- and boulder-size clasts of dolerite and spilitic basalt with less common sedimentary clasts (QMAP database). "Bedding is indistinct and often masked by clast imbrications. Both normal and reverse grading are common... Albany Conglomerate clasts are inferred to have been derived from the western Kaipara area and transported south and south-

east into the northwestern part of the Waitemata basin as **channelized turbidity currents...**" (Edbrooke, 2001) – *EoD is based on the bathyal submarine fan and basin floor interpretation of the Warkworth Subgroup (Edbrooke, 2001), of which the Albany Conglomerate is part, and Fig. 3.*

### **Pakiri Formation (Mwp)**

**Inferred age:** 22-20 Ma (Edbrooke, 2001)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = turbidite; Sub\_Rocks = 'volcanic sandstone', siltstone grit; Description = Alternating, thick-bedded, volcanic-rich, graded sandstone and siltstone, with volcanoclastic grit beds (QMAP database). "...typically volcanic-rich, thick-bedded **turbidites** of the Pakiri Formation (Mwp...)... Pakiri Formation is dominated by 10-30 m thick packets of graded, medium- to coarse-grained sandstone (beds typically 1-4 m thick), alternating with thinner intervals of laminated siltstone and fine-grained sandstone (beds typically 0.05-0.2 m thick)..." (Edbrooke, 2001) – *EoD is based on the bathyal submarine fan and basin floor interpretation of the Warkworth Subgroup (Edbrooke, 2001), of which the Pakiri Formation is a part. The map unit is interpreted as a mid-fan deposit at mid-bathyal depths, but alternatively could be a basin floor fan emplaced at lower bathyal depths.*

### **Amokura Formation (Mwa)**

**Inferred age:** 20 Ma (Edbrooke, 2001)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = turbidite; Sub\_Rocks = sandstone, mudstone, grit; Description = Alternating, graded sandstone and mudstone, with interbedded, thin volcanoclastic grits (QMAP database). "**Bathyal** turbidites poor in volcanic detritus (Amokura Formation, Mwa...)... consists predominantly of alternating 0.2-1.0 m thick graded sandstone and 0.05-0.2 m thick laminated mudstone" (Edbrooke, 2001) – *EoD is based on the bathyal submarine fan and basin floor interpretation of the Warkworth Subgroup (Edbrooke, 2001), of which the Amokura Formation is a part, the map unit's definition as turbidity current deposits (QMAP database), and Fig. 3. The map unit is interpreted as a mid-fan deposit at mid-bathyal depths, but alternatively could be a basin floor fan emplaced at lower bathyal depths.*

### **Colville Formation (Mwv)**

**Inferred age:** 21-20 Ma (Edbrooke, 2001)

**EoD:** lower bathyal

**Basis for interpretation:** Main\_Rock = turbidite; Sub\_Rocks = sandstone, siltstone, grit; Description = Alternating lithic-volcanic sandstone and mudstone with andesitic grit (QMAP database). "Thin-bedded distal turbidites at northern Coromandel Peninsula (Colville Formation, Mwv...)... regarded as a distal lateral equivalent of the Pakiri Formation" (Edbrooke, 2001) – *EoD is based on the bathyal submarine fan and basin floor interpretation of the Warkworth Subgroup (Edbrooke, 2001), of which the Colville Formation is a part, the map unit's definition as distal turbidity current deposits (Edbrooke, 2001), and Fig. 3. The map unit is interpreted as a lower fan deposit at lower bathyal depths, but alternatively could be mid-fan emplaced at mid-bathyal depths, where the main depocentre of the fan has moved away from the depositional site leading to deposition of distal turbidites.*

### **Timber Bay Formation (Mwb)**

**Inferred age:** 21-20 Ma (Edbrooke, 2001)

**EoD:** lower bathyal

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone, siltstone; Description = Thin-bedded mudstone, sandy siltstone and rippled muddy fine sandstone, with minor graded, medium to fine sandstone (QMAP database). "Volcanic-rich, centimetre-bedded mudstone, sandy siltstone and rippled, muddy fine-grained sandstone of the Timber Bay Formation (Mwb...)... include occasional beds of graded, medium- to fine-grained turbidite sandstone 0.1-0.7 m thick. The formation accumulated on the northwestern slopes of the Waitemata basin, probably in north-east-trending fault angle basins developed on the top of the Northland Allochthon..." (Edbrooke, 2001) – *EoD is based on the bathyal submarine fan and basin floor interpretation of the Warkworth Subgroup (Edbrooke, 2001), of which the Timber Bay Formation is a part, the description of the map*

unit which implies distal turbidity current deposition (Edbrooke, 2001; QMAP database), and Fig. 3. The map unit is interpreted as a lower fan deposit at lower bathyal depths, but alternatively could be mid-fan emplaced at mid-bathyal depths, where the main depocentre of the fan has moved away from the depositional site leading to deposition of distal turbidites.

### **Cornwallis Formation (Mwc, Mwc~)**

**Inferred age:** 19 Ma (Edbrooke, 2001)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = volcanic sandstone; Sub\_Rocks = siltstone; Description = Thick-bedded, graded, pebbly and gritty volcanic sandstone and thin-bedded fine sandstone and siltstone (QMAP database). “Cornwallis Formation (Mwc...) consists of thick, graded **turbidite** sandstone, typically 0.5-3 m thick, interbedded with laminated siltstone and fine-grained sandstone, typically 0.05-0.2 m thick... Sandstone are generally thicker and coarser-grained than those of the East Coast Bays Formation...” (Edbrooke, 2001) – *EoD is based on the bathyal submarine fan and basin floor interpretation of the Warkworth Subgroup (Edbrooke, 2001), of which the Cornwallis Formation is a part, the interpretation of the unit as turbidity current deposits (Edbrooke, 2001), and Fig. 3. The map unit is interpreted as a mid-fan deposit at mid-bathyal depths, but alternatively could be basin floor fan emplaced at lower bathyal depths.*

### **Helensville Conglomerate (Mwl)**

**Inferred age:** 19 Ma (Edbrooke, 2001)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = conglomerate; Sub\_Rocks = sandstone; Description = Conglomerate, composed mainly of well-rounded, boulder-, cobble- and pebble-size clasts of andesite, with less microdiorite (QMAP database). “[Helensville Conglomerate, Mwl] is locally present within the Cornwallis Formation north of Waimauku... Lenses of Helensville Conglomerate, up to 100 m thick in the north, are interpreted as **submarine channel or canyon fill deposits**, while thinner (1-30 m) sheet-like bodies with channelized lenses further south are probably **submarine fan** deposits...” (Edbrooke, 2001) – *EoD is based on the bathyal submarine fan and basin floor interpretation of the Warkworth Subgroup (Edbrooke, 2001), of which the Helensville Conglomerate is a part, and the interpretation of the unit as submarine channel and fan deposits within the Cornwallis Formation (Edbrooke, 2001). The map unit is interpreted as upper bathyal channel fill deposits (Fig. 3).*

### **Matapoura Conglomerate (Mwo)**

**Inferred age:** 19 Ma (Edbrooke, 2001)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = conglomerate; Sub\_Rocks = sandstone; Description = Conglomerate, composed of well-rounded, cobble- and pebble-size clasts of andesite, microdiorite, spilitic basalt, limestone (QMAP database). “...probably accumulated in submarine canyons and channels, cut into underlying Timber Bay Formation and Northland Allochthon...” (Edbrooke, 2001) – *EoD is based on the bathyal submarine fan and basin floor interpretation of the Warkworth Subgroup (Edbrooke, 2001), of which the Matapoura Conglomerate is a part, the interpretation of the unit as submarine channel and canyon deposits (Edbrooke, 2001), and Fig. 3. The map unit is interpreted as an upper-submarine fan deposited at upper bathyal depths, but alternatively could represent shifting mid- to lower bathyal feeder channels for a migrating submarine fan depocentre.*

#### **• Hoteo beds (Mwh)**

**Inferred age:** 19 Ma (Edbrooke, 2001)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone; Description = Thick-bedded, graded, calcareous sandstone with minor interbedded mudstone (QMAP database). “Timber Bay Formation is unconformably overlain by up to 50 m of bluff-forming, thick-bedded, graded, calcareous sandstone with minor interbedded mudstone” (Edbrooke, 2001) – *the thick-bedded graded sandstone and minor interbedded mudstone of the Hoteo beds is interpreted here as proximal turbidity current deposits. EoD is based on the bathyal submarine fan and basin floor interpretation of the Warkworth Subgroup (Edbrooke, 2001), of which the Hoteo beds are a part, the interpretation of the unit as turbidite deposits (Edbrooke, 2001), and Fig. 3. The map unit is interpreted to be a mid-*

fan deposit at mid-bathyal depth. Alternatively it may represent a basin floor fan deposited at lower bathyal depths.

### **Waihangaru Formation (Mwi)**

**Inferred age:** 19 Ma (Edbrooke, 2001)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = siltstone, sandstone; Description = Thin-bedded mudstone, sandy siltstone and rippled muddy fine sandstone (QMAP database). “The upper part of the formation consists of poorly bedded, massive, and muddy very fine-grained sandstone with sparse thin beds of redeposited volcanoclastic sandstone... Foraminifera indicate deposition at **bathyal** depths...” (Edbrooke and Brook, 2009). “Matapoura Conglomerate, and possibly Hoteo beds, are conformably overlain and enclosed by thin-bedded mudstone, sandy siltstone and rippled, muddy, fine grained sandstone of the Waihangaru Formation (Mwi; Ballance 1976; Brook 1983). It outcrops in the central Kaipara Harbour area, north of Glorit, and locally contains channelised pebbly sandstone beds... Waihangaru Formation and associated Matapoura Conglomerate are inferred to have accumulated on an elongate submarine fan, within a SSE-trending depression that developed in the Kaipara Harbour area in Upper Otaian time. Sediment from the Kaipara area was funnelled southward through the depression, into central areas of the Waitemata basin...” (Edbrooke, 2001) – *based on the lithologic descriptions of Waihangaru Formation in the QMAP database, Edbrooke and Brook (2009), and Edbrooke (2001) the map unit is interpreted as upper bathyal hemipelagic background sediment with thin ?levee turbidity current deposits. A lower bathyal EoD, with thin distal redeposited sandstone beds, is an alternative explanation (Fig. 3).*

## **Waitakere Group**

### **Manukau Subgroup**

“The mainly offshore Manukau centre (Manukau Subgroup) is a predominantly submarine strato-volcano that was periodically emergent, and only in its final phases produced significant terrestrial flows and pyroclastics, at least on its eastern flanks which now form the Waitakere Ranges of west Auckland (Hayward 1993). A number of offshore satellite volcanoes appear to have been almost entirely submarine... comprises andesite and basaltic andesite, volcanic and volcanoclastic rocks that erupted and were deposited on the eastern flank of the Manukau stratovolcano” (Edbrooke, 2001).

### **Waiatarua Formation (Mtw)**

**Inferred age:** 18-16, 10 Ma (Hayward et al., 2001)

**EoD:** submarine mafic eruptives

**Basis for interpretation:** Main\_Rock = basalt; Sub\_Rocks = andesite; Description = Basalt flows, pillow lava, hyaloclastite and associated intrusives, with minor basic andesite (QMAP database). “The subgroup includes a **submarine eruptive** facies comprising **basalt and basaltic andesite flows, pillow lavas** and massive **hyaloclastite** breccia and associated small intrusions” (Edbrooke, 2001). “It erupted mostly **andesite or basaltic andesite**, and built a large **submarine** volcano capped at times by small islands (Hayward 1979a). The eastern flank deposits that form the Waitakere Ranges consist of an eruptive facies of lava flows, **pillow lavas**, and **hyaloclastite** breccia concentrated in the west (Waiatarua Formation; Hayward 1983)” (Hayward et al., 2001) – *EoD is based on the main rock type, the presence of hyaloclastite and pillow lavas, and the submarine interpretation of the formation in Edbrooke (2001). Submarine intermediate eruptives may be an alternative interpretation.*

### **Piha Formation (Mtp, Mtp~)**

**Inferred age:** 18-17 Ma (Edbrooke, 2001)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = volcanic conglomerate; Sub\_Rocks = grit, ‘volcanic sandstone’, siltstone; Description = Stratified, submarine andesitic breccio-conglomerate with minor grit, sandstone and siltstone (QMAP database). “The eruptive facies [Waiatarua Formation] is largely enclosed within a **proximal submarine slope** facies of coarse volcanoclastics, dominated

by stratified, andesitic boulder-bearing, cobble-pebble breccia and conglomerate, locally interbedded with volcanoclastic granular sandstone, and rarely, volcanoclastic sandstone and siltstone. The coarse volcanoclastics are interpreted as debris flow lag deposits that accumulated on the **bathyal** slopes of the volcano" (Edbrooke, 2001) – *the paleoenvironmental interpretation of the Piha Formation as a bathyal proximal submarine slope facies (Edbrooke, 2001) implies an upper bathyal EoD.*

### ***Nihotupu Formation (Mtn)***

***Inferred age:*** 18-17 Ma (Edbrooke, 2001)

***EoD:*** lower bathyal

***Basis for interpretation:*** Main\_Rock = volcanic sandstone; Sub\_Rocks = grit siltstone; Description = Submarine volcanoclastic grit, sandstone and siltstone (QMAP database). "[the coarse volcanoclastics of the Piha Formation] pass outward into a **distal, base of slope**, fine-grained facies, dominated by planar-bedded, volcanoclastic sandstone and siltstone... Bed types range from thin-bedded traction deposits to graded, thick-bedded turbidites" (Edbrooke, 2001). "These deposits are interpreted as **turbidites** that were emplaced at **bathyal** water depths within an inter-arc basin on the lower eastern flanks of the west Northland volcanic arc" (MacEachern et al., 2007). "...a distal, base-of-slope, fine volcanoclastic facies..." (Isaac et al., 1994) – *the distal, base of slope interpretation of the Nihotupu Formation in Edbrooke (2001) implies a lower bathyal EoD for the map unit. The generally coarse grain size of the map unit, and occurrence of thick bedded turbidites (Edbrooke, 2001) may alternatively indicate more proximal mid-bathyal conditions. The map unit represents a submarine fan deposited at lower bathyal depths, or alternatively, a mid-fan deposited at mid-bathyal depths.*

- **Mtn+Mtp**

***Inferred age:*** 18-17 Ma (Edbrooke, 2001)

***EoD:*** lower bathyal

***Basis for interpretation:*** Main\_Rock = volcanic sandstone; Sub\_Rocks = grit, siltstone; Description = Submarine volcanoclastic grit, sandstone and siltstone (QMAP database) – *based on the unit code the map unit appears to include Nihotupu and Piha Formations, giving an interpreted depth of deposition ranging from upper to lower bathyal. However, because the main and sub rock types and QMAP lithologic description are identical to the Nihotupu Formation map unit, the same lower bathyal EoD is inferred. As with the Nihotupu Formation, a mid-bathyal EoD is also an alternative interpretation.*

### ***Tirikohua Formation (Mtt)***

***Inferred age:*** 17 Ma (Edbrooke, 2001)

***EoD:*** upper bathyal

***Basis for interpretation:*** Main\_Rock = volcanic conglomerate; Sub\_Rocks = 'volcanic sandstone'; Description = Local channel-fill volcanic conglomerate and sandstone (QMAP database). "Submarine channels and canyons cut in Piha and Nihotupu formations south of Muriwai are up to 1.5 km across, and filled with scoured, lenticular, cross-bedded, or structureless mass flow deposits of volcanic conglomerate, breccia, sandstone and minor siltstone..." (Edbrooke, 2001). "The contact with the overlying Tirikohua Formation is sharp and erosional, and exhibits visible relief... Hayward (1976) interpreted the erosional discontinuity as a **submarine canyon** wall, excavated into bathyal to neritic inter-arc sediment gravity-flow deposits as a result of basin margin tectonic uplift... Colonization of the canyon walls by the firmground tracemakers preceded the gradual burial of the canyon margins by **neritic turbidite** deposits of the Tirikohua Formation. The infill of the submarine canyon probably corresponds to late-stage relative sea-level lowstand and early transgression" (MacEachern et al., 2007) – *MacEachern et al. (2007) considers the Tirikohua Formation to be composed of neritic turbidites. The EoD is based on the main rock type of conglomerate and its occurrence in a channel system.*

### ***Lone Kauri Formation (Mtl)***

***Inferred age:*** 22-15 Ma (Hayward et al., 2001)

***EoD:*** onshore intermediate eruptives

***Basis for interpretation:*** Main\_Rock = **andesite**; Sub\_Rocks = dacite; Description = Andesite flows and pyroclastics, plugs, diatremes, clastic dikes, shallow intrusives and crater-fills, with minor flow-banded dacite (QMAP database). "The submarine volcanics and associated marine sediments

are overlain by **predominantly terrestrial andesite** flows and minor pyroclastic sediments that were formed during the last phases of eruption, and cap central and western parts of the Waitakere Ranges (Lone Kauri Formation, Mtl; Hayward 1976c). Shallow intrusive rocks are also present locally. Lone Kauri Formation rocks are predominantly strongly porphyritic andesite, but include local flow-banded dacite near Karekare (Hayward 1983) (Edbrooke, 2001). "...a sequence of **sub-aerial andesite** flows (Lone Kauri Formation)..." (Hayward et al., 2001) – *EoD is based on the main rock type and the terrestrial interpretation of the formation in Edbrooke (2001). Silicic or intrusive may be alternative environments locally.*

### **Hukatere Subgroup**

"The offshore Kaipara Volcano is inferred to have a submarine lower part that grew (or was uplifted) into a substantial terrestrial stratovolcano. Eroded remnants of its small eastern satellite volcanoes are preserved onshore in the central Kaipara area (Hukatere Subgroup)... Pillow lava, breccia and tuff of two satellite volcanic centres east of the offshore Kaipara Volcano outcrop on Hukatere, Puketotara and Okahukura peninsulas in central Kaipara (Hukatere Subgroup, Hayward 1976c)" (Edbrooke, 2001).

### **Pakaurangi Formation (Mtk)**

**Inferred age:** 18 Ma (Edbrooke, 2001)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = volcanic sandstone; Sub\_Rocks = mudstone; Description = Thick-bedded, muddy, volcanoclastic sandstone and fossiliferous mudstone (QMAP database). "[Volcanic rocks of the Hukatere Subgroup] are associated with a **shallow marine** sedimentary sequence of thick-bedded, muddy volcanoclastic sandstone and fossiliferous mudstone" (Edbrooke, 2001). "Two eruptive centres extruded basaltic andesite into a **shallow marine** setting...; fine-grained volcanoclastic **shelf** sediments (Pakaurangi Formation; Jones 1969a, 1970; Carter 1971) accumulated between them" (Isaac et al., 1994) – *the shallow marine and shelfal interpretation of the formation is narrowed down to a mid-shelf depositional environment.*

### **Oruawharo Hyaloclastite (Mto)**

**Inferred age:** 18 Ma (Edbrooke, 2001)

**EoD:** submarine mafic eruptives

**Basis for interpretation:** Main\_Rock = volcanic breccia; Sub\_Rocks = 'vitric tuff', 'basaltic andesite'; Description = **Basaltic andesite, hyaloclastite breccia** and tuff with minor basaltic **pillow lava** (QMAP database). "...~150 m thick, massive, unsorted hyaloclastite breccia, with common hyaloclastites and minor **basaltic pillow lava**, transacted in places by numerous basaltic andesite dikes..." (Edbrooke, 2001) – *EoD is based on the composition mentioned in the QMAP lithologic description and the presence of hyaloclastite.*

### **Motuouhi Formation (Mth)**

**Inferred age:** 18 Ma (Edbrooke, 2001)

**EoD:** submarine intermediate eruptives

**Basis for interpretation:** Main\_Rock = vitric tuff; Description = Hard, fine-grained, brown **hyaloclastic** tuff (QMAP database). "Using the refractive index curves of George (in Williams et al., 1954) the glass is estimated to contain 55%-56% SiO<sub>2</sub> (n 1.540-1.545) which places it just in the **andesite** field... The tuffs of the Motuouhi Formation were deposited in a **marine environment** as indicated by the presence of glauconite and foraminifers. Calm water conditions are necessitated by the fragile forms of the glass shards, which are unlikely to have survived reworking by waves or currents" (Carter, 1971) – *EoD is based on the depositional environment and composition proposed for the formation in Carter (1971).*

### **Pupuia Formation (Mti)**

**Inferred age:** 19-17 Ma (Edbrooke and Brook, 2009)

**EoD:** submarine mafic eruptives

**Basis for interpretation:** Main\_Rock = **basalt**; Description = Basalt flows, **pillow lavas** and associ-

ated intrusives. (QMAP database). “The sequence consists of **basaltic andesite** flows and **pillow lavas**” (Edbrooke, 2001) – *EoD is based on the main rock type and presence of submarine effusive eruptive products. Refer to “Pupua Formation (Mti)” on the Whangarei map area for further information.*

### **Okaroro Formation (Mtr)**

**Inferred age:** 19-18 Ma (Edbrooke and Brook, 2009)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = volcanic sandstone; Sub\_Rocks = ‘volcanic breccia’; Description = Volcaniclastic sandstone and breccia (QMAP database). “...**proximal, marine** volcaniclastic sandstones and breccias...” (Edbrooke, 2001) – *EoD is based on the proximal marine interpretation of the formation in Edbrooke (2001).*

### **Puketi Formation (Mtu)**

**Inferred age:** 18 Ma (Edbrooke and Brook, 2009)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = volcanic breccia; Sub\_Rocks = tuff; Description = Andesitic tuff-breccia, tuff, pumiceous tuff and lignite (QMAP database). “...laharic, andesite tuff-breccia, pumiceous pyroclastic flow deposits, air fall tuff, lapilli-tuff, lignite and soil horizons... **Terrestrial and marginal marine** volcaniclastics of the Puketi Formation accumulated during late-phase pyroclastic eruptions from breccias pipes on Hukatere Peninsula” (Edbrooke, 2001) – *the main rock type of volcanic breccia appears to be associated with laharic deposits (QMAP database); consequently an onshore EoD is assigned to the map unit. Refer to “Puketi Formation (Mtu)” on the Whangarei map area for further information.*

## **Coromandel Group**

“The **subaerial** Coromandel Group... is dominated by pyroxene or pyroxene-hornblende andesite, with dacite and rhyodacite being less common. Plutonic rocks are present on Cuvier Island and in the north of Coromandel Peninsula, and the group also includes volcanogenic sedimentary deposits. Regional subdivision of the group into four unconformable subgroups (Kuaotunu, Waiwawa, Omahine, Kaimai) is based mainly on the recognition of significant volcanic hiatuses (Skinner 1986)” (Edbrooke, 2001).

### **Kuaotunu Subgroup (Mcu)**

**Inferred age:** 18-6 Ma (Adams et al., 1994; Takagi, 1995)

**EoD:** onshore intermediate eruptives

**Basis for interpretation:** Main\_Rock = **andesite**; Sub\_Rocks = dacite; Description = Basaltic andesite, andesite and dacite intrusives, flows, volcaniclastites and volcanic epiclastites (QMAP database). “Kuaotunu Subgroup (Mcu; Skinner 1986) includes **andesite and dacite intrusives, flows** (Fig. 45), volcaniclastites and volcanic epiclastites of Great Barrier Island and northern and central Coromandel Peninsula, north of Thames. They are the oldest Coromandel Group rocks, ranging in age from Early Miocene (~18 Ma) to late Middle Miocene (~11 Ma)” (Edbrooke, 2001). “Kuaotunu Subgroup rocks (of the Kuaotunu Volcanic Complex) at the northern end of this Coromandel chain (Fig. 1) were **intruded** and **erupted** in the Early and Middle Miocene, partly contemporaneous with activity on nearby Northland... Within the Kuaotunu Complex, the north Great Barrier Volcanic Centre consists of numerous andesite and dacite dikes that intrude greywacke (Moore & Kenny 1985) and are inferred to be the subvolcanic evidence of a stratovolcano that has been completely removed by erosion (Hayward 1993)” (Hayward et al., 2001) – *EoD is based on the subaerial interpretation for Coromandel Group rocks of which Kuaotunu Subgroup is a part (Edbrooke, 2001). Both extrusive and intrusive volcanic products have been included in the QMAP description of the map unit. The map unit is defined as extrusive here based on the main rock type being andesite. Two polygons on Great Mercury Island are defined as Late Miocene onshore silicic eruptives after Takagi (1995). There are a few dikes on Great Barrier Island which are defined as Early Miocene intermediate and silicic intrusives after Adams et al. (1994) and Hayward et al. (2001) (PMeMii, PMeMsi).*

### ***Omoho Formation (Mcm)***

***Inferred age:*** 15 Ma (Edbrooke, 2001)

***EoD:*** onshore

***Basis for interpretation:*** Main\_Rock = tuff; Sub\_Rocks = breccia; Description = Rhyodacitic within **lithic-volcanic to lithic sedimentary deposits** (QMAP database). “An unusual sheet-like formation of bedded, rhyodacite tuff and breccia with intercalated lithic-sedimentary and carbonaceous material... There are other occurrences of iron sulphides in carbonaceous **lacustrine** sediments of the Omoho Formation at Colville, and beneath ignimbrite at Neavesville” (Edbrooke, 2001). “The intercalated Omoho Formation rhyodacitic ignimbrite may have erupted from a large dike on Tokatea Hill (Skinner 1976)” (Isaac et al., 1994). “...a sheet-like formation of **tuffaceous coal measures, rhyolite** flows (hypersthene-biotite-oligoclase) and rhyolitic fragmentals... rhyolite (s.s.) makes up only a relatively small, although characteristic, part of the content of the formation...” (Skinner, 1967) – *based on the Auckland QMAP legend the Omoho Formation appears to be a sedimentary deposit so an onshore EoD is assigned here. However due to the (“relatively small, although characteristic” (Skinner, 1967)) rhyolitic component of the formation, onshore silicic eruptives may be an alternative EoD. The age of the formation is poorly defined but appears to be older than the oldest known silicic eruptives of the Coromandel Volcanic Zone (c. 12 Ma, Carter et al., 2003).*

### ***Waitaia Sinter (Mct)***

***Inferred age:*** 13-12 Ma (Edbrooke, 2001)

***EoD:*** onshore

***Basis for interpretation:*** Main\_Rock = sinter; Description = Quartz sinter, forming terraces and plugs. (QMAP database). “Bedded, volcanogenic quartz sinter, including chert with **plant remains** and associated **lacustrine** sediments (Waitaia Sinter, Met...), forms plugs and sheets resting on Manaia Hill Group basement east of Kuaotunu” (Edbrooke, 2001) – *descriptions of the Waitaia Sinter in Edbrooke (2001) indicate that the sinter formed onshore within a lake.*

### ***Paritu Plutonics (Mcp)***

***Inferred age:*** 18-16 Ma (Adams et al., 1994; Hayward et al., 2001)

***EoD:*** intermediate intrusives

***Basis for interpretation:*** Main\_Rock = quartz **diorite**; Sub\_Rocks = granodiorite aplite; Description = Quartz diorite to granodiorite, with minor aplite and pegmatite (QMAP database). “A pluton composed of granodiorite and quartz-diorite with marginal biotite-rich tonalite, aplites and pegmatoid drus (Paritu Plutonics, Mcp; Black 1972; Skinner 1975), intrudes Manaia Hill Group basement at the northern end of Coromandel Peninsula (Fig. 46). It intrudes early Kuaotunu Subgroup andesite on Mt Moehau and is locally associated with penecontemporaneous andesite-dacite dike swarms. The pluton probably represents a subvolcanic, differentiated reservoir (Black 1972)” (Edbrooke, 2001) – *EoD is based on the main rock type (QMAP database). Silicic intrusives may be an alternative EoD.*

### ***Cuvier Plutonics (Mcc)***

***Inferred age:*** 17-16 Ma (Edbrooke, 2001)

***EoD:*** intermediate intrusives

***Basis for interpretation:*** Main\_Rock = **granodiorite**; Sub\_Rocks = diorite, aplite; Description = Granodiorite to diorite, with minor aplite and pegmatite. (QMAP database). “On Cuvier Island to the northeast of Coromandel Peninsula, gabbro, diorite and granodiorite with andesite-dacite dike swarms (Cuvier Plutonics, Mcc; Thompson 1960; Black 1967) intrude possible Waipapa Group basement. The Cuvier pluton is also a composite, high level intrusive, contemporaneous with the Paritu pluton (Black 1967), but major element chemistry suggests the rocks were not cogenetic (Adams et al. 1994)” (Edbrooke, 2001) – *EoD is based on the main rock type (QMAP database). Mafic or silicic intrusives may be appropriate in minor cases.*

### ***Waiwawa Subgroup (Mci)***

***Inferred age:*** 10-6 Ma (Adams et al., 1994; Takagi, 1995; Brathwaite and Christie, 1996; Krippner, 2000)

***EoD:*** onshore intermediate eruptives



**Basis for interpretation:** Main\_Rock = **andesite**; Sub\_Rocks = dacite, rhyodacite, tuff, breccia; Description = Andesite, dacite and rhyodacite flows and domes with intercalated tuff, tuff breccia and volcanoclastic sediments. Local, non-we (QMAP database). “The subgroup includes andesite, dacite and rhyodacite flows and domes with intercalated tuff, tuff breccia and volcanoclastic sediments. In some areas non-welded to partially welded, dacitic, pumice-rich ignimbrites, with associated tuffs and sediments, are intercalated with andesite flows and breccias” (Edbrooke, 2001) – *EoD is based on the subaerial interpretation for Coromandel Group rocks, and the QMAP database and Edbrooke’s (2001) descriptions of the map unit which mention mostly subaerial, and few phreatomagmatic, extrusive volcanic products.*

### ***Omahine Subgroup (Mco)***

**Inferred age:** 8-6 Ma (Adams et al., 1994; Takagi, 1995; Brathwaite and Christie, 1996; Krippner, 2000)

**EoD:** onshore intermediate eruptives

**Basis for interpretation:** Main\_Rock = **andesite**; Sub\_Rocks = dacite, tuff, breccia; Description = Andesite and dacite intrusives and lava flows with minor intercalated tuff and tuff breccias (QMAP database). “Two-pyroxene andesite and dacite intrusive, lava flows and agglomerate (residual volcanic necks) with minor intercalated tuff and tuff breccias (Omahine Subgroup, Mco...)” (Edbrooke, 2001) – *the lithologic descriptions of the map unit in Edbrooke (2001) and the QMAP database indicates both extrusive and intrusive processes emplaced the unit. The map unit is defined as extrusive here based on the main rock type being andesite, which is an extrusive igneous rock. The EoD is defined as onshore based on the subaerial interpretation for Coromandel Group rocks, of which Omahine Subgroup is a part (Edbrooke, 2001), and the QMAP database and Edbrooke’s (2001) descriptions of the map unit which mention mostly subaerial, and few submarine, extrusive volcanic products.*

### ***Kaimai Subgroup (Mca)***

**Inferred age:** 6-4 Ma (Takagi, 1995; Brathwaite and Christie, 1996; Vincent, 2012)

**EoD:** onshore intermediate eruptives

**Basis for interpretation:** Main\_Rock = **andesite**; Sub\_Rocks = dacite; Description = Andesitic and dacitic lava flows and domes, intrusives, tuff and tuff breccias, volcanoclastic sediments, and welded dacitic ignimbrite (QMAP database). “Latest Miocene and Early Pliocene **andesitic** and dacitic, volcanic and volcanoclastic rocks of southern Coromandel Peninsula, mainly south of Waihi, and the Kaimai Range are included in the Kaimai Subgroup (Mca; Houghton & Cuthbertson 1989; Brathwaite & Christie 1996). They comprise predominantly two-pyroxene andesite and dacite **intrusives, lava flows and domes**, and tuff and tuff breccias with intercalated **volcanoclastic sediments** (Fig. 48). Welded, dacitic ignimbrite is present locally northeast of Waihi. Tuff breccias with interbedded crystal and lithic tuffs are the most common lithology. Tuff breccias are interpreted as products of **lahars and reworked pyroclastic material** deposited on the flanks of a series of stratovolcanoes (Brathwaite & Christie 1996). Lava flows and domes are more common near the top of the subgroup” (Edbrooke, 2001) – *the QMAP description of the map unit indicates both extrusive and intrusive processes emplaced the unit. The map unit is defined as extrusive here based on the main rock type being andesite, which is an extrusive igneous rock. The EoD is defined as onshore based on the subaerial interpretation of the Coromandel Group. Onshore or intermediate intrusives may be minor alternative EoDs. One polygon is defined as onshore mafic eruptives, and five others are defined as onshore silicic eruptives after Takagi (1995), Brathwaite and Christie (1996), and Vincent, 2012.*

### **Whitianga Group**

“**Rhyolitic** caldera eruptions in the Coromandel Volcanic Zone began in the Late Miocene... They produced widespread ignimbrite sheets and rhyolite dome complexes... The **rhyolitic rocks and ignimbrites** of CVZ are subdivided into three subgroups (Coroglen, Minden Rhyolite and Ohinemuri)...” (Edbrooke, 2001).

### ***Coroglen Subgroup (Mhc)***

**Inferred age:** 11-5 Ma (Adams et al., 1994; Takagi, 1995; Krippner, 2000; Vincent, 2012)

**EoD:** onshore silicic eruptives

**Basis for interpretation:** Main\_Rock = **ignimbrite**; Sub\_Rocks = rhyolite tuff breccia; Description

= Ignimbrite flow sheets and local rhyolitic and obsidian-rich pumice breccia deposits and tuff (QMAP database). "...includes Late Miocene to mid Pliocene, lithic- and pumice-rich **ignimbrite** (Fig. 49), bedded tuff breccia and associated airfall and phreatomagmatic tephra, and intercalated volcanogenic sediments. Basal fluvial and lacustrine beds are commonly present in the Coroglen Subgroup..." (Edbrooke, 2001) – *EoD is based on the rhyolitic nature of the Coroglen Subgroup (Edbrooke, 2001) and the QMAP descriptions of the map unit which mention mostly subaerial extrusive volcanic products.*

### **Romanga Formation (Phr)**

**Inferred age:** 5-4 Ma (Edbrooke, 2001)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = siltstone; Sub\_Rocks = mudstone, sandstone conglomerate; Description = **Lacustrine** siltstone, mudstone, tuffaceous sandstone and conglomerate (QMAP database). "The subgroup includes an extensive unit of **lacustrine** siltstone, mudstone, tuffaceous sandstone and conglomerate..." (Edbrooke, 2001) – *EoD is based on the lacustrine interpretation of the map unit in the QMAP description.*

### **Minden Rhyolite Subgroup (Mhm)**

**Inferred age:** 9-3 Ma (Adams et al., 1994; Takagi, 1995; Brathwaite and Christie, 1996; Krippner, 2000; Vincent, 2012)

**EoD:** onshore silicic eruptives

**Basis for interpretation:** Main\_Rock = **rhyolite**; Sub\_Rocks = 'volcanic breccia', tuff; Description = Rhyolite flow and dome complexes with associated breccias and tuffs (QMAP database). "Late Miocene to Late Pliocene, **rhyolite** flow and dome complexes with associated breccias and tuffs..." (Edbrooke, 2001). "[regarding the Coroglen and Minden Rhyolite subgroups] In late Miocene time violent eruptions of **acidic** volcanic debris blanketed the Hahei area in a sequence of ash and breccia deposits. **Sub-aerial** erosion during the deposition of these volcanic sediments carved narrow, steep-sided ravines in a landscape where lowland beech forest managed to become temporarily established. Some ash was probably redeposited by streams along valley floors, and perhaps in small lakes. After a short interval, insufficient for deep weathering to occur, lava was extruded from a number of separate fissures to form complex rhyolite domes" (Moore, 1983) – *EoD is based on the main rock type, and the onshore environment of the Minden Rhyolite Subgroup described in Moore (1983). Minden Rhyolite Subgroup also occurs to the north on Poor Knights and Mokohinau islands (Whangarei map area) and further south in the Tauranga Volcanic Centre (Rotorua map area).*

### **Ohinemuri Subgroup (Pho)**

(QMAP database spelling: Subgroup)

**Inferred age:** 4 Ma (Hoskin et al., 1998; Vincent, 2012)

**EoD:** onshore silicic eruptives

**Basis for interpretation:** Main\_Rock = **ignimbrite**; Sub\_Rocks = 'vitric tuff'; Description = Welded, pumice-rich ignimbrite (QMAP database). "They comprise non- to strongly welded, predominantly pumice-rich ignimbrite, with local intercalated pumice breccia and near basal, tuffaceous and carbonaceous sediments" (Edbrooke, 2001) – *EoD is based on the rhyolitic nature of the Ohinemuri Subgroup (Edbrooke, 2001) and the QMAP descriptions of the map unit which mention subaerial extrusive volcanic products. This also includes the Owharoa Ignimbrite.*

### **Mercury Basalts Subgroup (Mvm)**

**Inferred age:** 9-4 Ma (Adams et al., 1994; Takagi, 1995)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = **basalt**; Sub\_Rocks = 'basaltic andesite'; Description = Olivine and olivine-augite basalt to pyroxene basalt and basaltic andesite flows, pyroclastites, dikes and sills (QMAP database). "Mercury Basalts are locally at least 270 m thick on the Mercury Islands, consisting of individual flows, separated by basaltic **scoria**, **spatter**, lapilli and tuff, and minor rhyolitic ash... Lopolithic sills and plugs with remnant **scoria** mounds define at least 10 eruptive centres" (Edbrooke, 2001) – *the QMAP description of the map unit indicates both extrusive and intrusive processes emplaced the unit. The map unit is defined as extrusive here based on the main rock type*

being basalt, which is an extrusive igneous rock, and the majority of deposits reflecting a subaerial environment. The EoD is defined as onshore based on QMAP description of the map unit which mention mostly subaerial extrusive volcanic products. Five polygons are defined as onshore intermediate eruptives after Adams et al. (1994) and Takagi (1995).

### **Woody Hill Basalt (PMePme)**

**Inferred age:** 5 Ma (Adams et al., 1994)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = **basalt**; Description = Basaltic andesite flow (after Adams et al., 1994). "Mercury Basalts also intrude and overlie eroded and paleoweathered Mahinapua Andesite on the eastern Kuaotunu Peninsula, and form a skeletal volcanic neck and dike swarm intruding Ruahine Rhyolite (and ignimbrite) at Woody Hill" (Adams et al., 1994). "The Woody Hill Basaltic Andesite is a dark grey porphyritic **basalt**... Woody Hill itself appears to be the remains of a basaltic andesite lava flow... The 'cone' of Woody Hill itself appears to be the last remaining sample of this lava flow, the rest having been eroded away" (Karl, 1996) – *Woody Hill is a prominent basaltic andesite cone that has intruded and overlies older rhyolite units of the Ruahine Rhyolite, Minden Rhyolite Subgroup.*

### **Kiwitahi Volcanic Group**

"The middle to Late Miocene Kiwitahi Volcanic Group (Mk...) includes the isolated remnants of several former small, **subaerial** andesitic stratovolcanoes or composite cones..." (Edbrooke, 2001).

#### **Waiheke unit (Mkw)**

**Inferred age:** 16-14 Ma (Black et al., 1992)

**EoD:** onshore intermediate eruptives

**Basis for interpretation:** Main\_Rock = **andesite**; Sub\_Rocks = 'volcanic breccia', agglomerate; Description = Pyroxene andesite and hornblende andesite agglomerate and breccia (QMAP database). "...an oldest group of agglomerates and volcanic breccias at northeastern Waiheke, containing pyroxene and hornblende **andesites**..." (Black et al., 1992) – *EoD is based on the subaerial interpretation of the Kiwitahi Volcanic Group, of which the Waiheke unit is a part, and the main rock type.*

#### **Miranda unit (Mkm)**

**Inferred age:** 13-10 Ma (Black et al., 1992)

**EoD:** onshore intermediate eruptives

**Basis for interpretation:** Main\_Rock = basaltic **andesite**; Sub\_Rocks = andesite, dacite, 'volcanic breccia', tuff; Description = Pyroxene basaltic andesite, pyroxene andesite, hornblende andesite and hornblende dacite breccia, agglomerate, tuff, lava and di (QMAP database). "Volcanic breccias, agglomerates, tuffs, and the eroded remnants of lava flows are preserved in fault-angle depressions in the Ruaotehuia valley and near Miranda and Maramarua. They have been previously described by Holmes (1971), Schofield (1976), and Dewes (1991), and comprise pyroxene **basaltic andesite**, pyroxene and hornblende **andesite**, and hornblende **dacite**" (Black et al., 1992) – *EoD is based on the subaerial interpretation of the Kiwitahi Volcanic Group, of which the Miranda unit is a part, and the main rock type.*

#### **Tahuna unit (Mkt)**

**Inferred age:** 6-7 Ma (Black et al., 1992)

**EoD:** onshore intermediate eruptives

**Basis for interpretation:** Main\_Rock = basaltic **andesite**; Sub\_Rocks = andesite, 'volcanic breccia'; Description = Pyroxene basaltic andesite and pyroxene andesite lava and breccia (QMAP database). "The Tahuna unit (Mkt) includes eroded remnants of lava flows and volcanic breccias in the vicinity of Tahuna, composed of pyroxene **basaltic andesite** and pyroxene **andesite**..." (Edbrooke, 2001) – *EoD is based on the subaerial interpretation of the Kiwitahi Volcanic Group and the main rock type. Refer to "Kiwitahi Volcanic Group (IMk)" on the Rotorua map area for further information.*

## Ti Point Group (Mvt)

(QMAP database spelling: Ti Point Volcanic Group)

**Inferred age:** 9-7 Ma (Black et al., 1992; Smith et al., 1993)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = **basalt**; Sub\_Rocks = 'basaltic andesite'; Description = Olivine basalt and olivine basaltic andesite flow remnants and dikes. (QMAP database). "The existing outcrops are thought to be residual outliers of a once more extensive **subaerial basaltic** volcanic field..." (Edbrooke, 2001). "The major occurrence of volcanics in the Ti Point area is a **lava-flow** remnant at Ti Point. Two other substantial outcrops (Barrow Hill and Sugar Loaf) and several smaller outcrops in the Leigh-Mangawhai area are the eroded remnants of volcanic **plugs or dikes** (Heming 1980c)" (Smith et al., 1993) – *EoD is based on the main rock type and the subaerial interpretation in Edbrooke (2001). Mafic intrusives may be an alternative interpretation in some places.*

## Hauturu Volcanic Group

"Little Barrier Island is the emergent part of a large, subduction-related, **subaerial dacite-rhyodacite** stratovolcano (Hauturu Volcanic Group) formed during two periods of eruption in the Late Pliocene and Early Pleistocene" (Edbrooke, 2001). "Two volcanic episodes are recognised: Waimaomao Formation was emplaced as a **rhyodacite** dome at 3 Ma, whereas the more extensive **dacitic** lavas of Haowhenua Formation were erupted between 1.2 and 1.6 Ma" (Lindsay et al., 1999).

### Waimaomao Formation (Pvw)

**Inferred age:** 3 Ma (Takagi, 1995)

**EoD:** onshore silicic eruptives

**Basis for interpretation:** Main\_Rock = **rhyodacite**; Description = Flow-banded rhyodacite lava (QMAP database). "The Waimaomao Formation (Pvw; Lindsay et al. 1999)... emplaced during the first period of activity and dated at 3.0 Ma" (Edbrooke, 2001). "Waimaomao Formation is a distinctive pinkish, strongly porphyritic rhyodacite with phenocrysts of plagioclase, hornblende, and traces of orthopyroxene that crops out along the northeastern coastline of the island" (Lindsay et al., 1999) – *EoD is based on the subaerial interpretation of the Hauturu Volcanic Group in Edbrooke (2001).*

### Haowhenua Formation (Qvhl)

**Inferred age:** 2-1 Ma (Takagi, 1995)

**EoD:** onshore silicic eruptives

**Basis for interpretation:** Main\_Rock = dacite; Description = Porphyritic dacite lava flows and dikes. (QMAP database). "More extensive dacitic lavas of the Haowhenua Formation (Qvh; Kear 1961c; Lindsay et al. 1999) were produced during a second eruption phase between 1.2 and 1.6 Ma. Haowhenua Formation comprises a series of lava flows, exposed at the base of coastal cliffs and in the centre of the island, and a widespread breccia forming the lower flanks of the cone (Fig. 54)" (Edbrooke, 2001). "Haowhenua Dacite is a dark grey, strongly porphyritic lava bearing phenocrysts of plagioclase, orthopyroxene, and traces of hornblende and augite. Flows of the dacite crop out at the base of cliffs along the western, northwestern, and eastern coast of the island" (Lindsay et al., 1999) – *EoD is based on the subaerial interpretation of the Hauturu Volcanic Group in Edbrooke (2001) and composition description from Lindsay et al. (1999).*

### Haowhenua Formation (Qvhb)

**Inferred age:** 2-1 Ma (Takagi, 1995)

**EoD:** onshore silicic eruptives

**Basis for interpretation:** Main\_Rock = volcanic breccia; Sub\_Rocks = dacite; Description = Debris flow-derived dacite breccia. (QMAP database). "More extensive dacitic lavas of the Haowhenua Formation (Qvh; Kear 1961c; Lindsay et al. 1999) were produced during a second eruption phase between 1.2 and 1.6 Ma. Haowhenua Formation comprises a series of lava flows, exposed at the base of coastal cliffs and in the centre of the island, and a widespread breccia forming the lower flanks of the cone (Fig. 54)" (Edbrooke, 2001). "Haowhenua Breccia crops out along most of the

coastline and along incised stream valleys on the lower flanks of the cone... All clasts were derived from Haowhenua Dacite, but adjacent clasts show different degrees of alteration (Fig. 4), suggesting that they were derived from more than one area... we interpret the breccia as a stacked succession of stream-flood and debris-flow deposits" (Lindsay et al., 1999) – *EoD is based on the subaerial interpretation of the Hauturu Volcanic Group in Edbrooke (2001) and composition description from Lindsay et al. (1999).*

## **Kerikeri Volcanic Group**

"A Late Miocene to Holocene, dominantly **basaltic** volcanic association in the Northland and Auckland regions includes the Kaikohe/Bay of Islands, Puhipuhi, Whangarei, Auckland, South Auckland and Ngatutura volcanic fields. Each field contains numerous, small volume, monogenetic volcanoes composed of basaltic lava flows, scoria cones and maars. These volcanics, collectively known as the Kerikeri Volcanic Group, are generally regarded as having a back-arc continental intraplate setting (Smith 1989; Smith et al. 1993). The earliest Pleistocene to Holocene Ngatutura Basalts and the South Auckland and Auckland volcanic fields are within the Auckland map area" (Edbrooke, 2001).

### **Ngatutura Basalts (Qvn)**

**Inferred age:** 2 Ma (Briggs et al., 1989)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = basalt; Sub\_Rocks = hawaiite, 'volcanic breccia', scoria; Description = Fine-grained, porphyritic olivine hawaiite **lavas**, dikes, volcanic breccias and **scoria cones** (QMAP database). "The Ngatutura Basalts consist of 16 small volume monogenetic volcanic centres situated south of Port Waikato on the west coast of the North Island (Fig. 1,3). They are comprised of alkali **basaltic** lavas, dikes, volcanic breccias, and scoria cones, produced by **strombolian** eruptions (Utting 1986), and a diatreme at Ngatutura Point (Heming 1980c)... The Ngatutura Basalt lavas are fine-grained porphyritic olivine **basalts** of hawaiite and nepheline hawaiite compositions and commonly contain ultramafic xenoliths" (Briggs et al., 1989) – *EoD is based on the composition and products mentioned in Briggs et al. (1989).*

### **South Auckland Volcanic Field**

"Early Pleistocene **basalts** of the South Auckland Volcanic Field (Qvs; Rafferty & Heming 1979) cover an area of about 300 km<sup>2</sup> in the Waiuku-Pukekohe-Bombay-Tuakau-Pukekawa-Onewhero area of South Auckland. The field includes at least 97 **subaerial**, mainly monogenetic volcanic centres. These are either magmatic or effusive centres that have produced scoria cones and associated basalt lava flows, or phreatomagmatic or explosive centres that have mainly formed tuff rings and maars, with or without a nested scoria cone (Rafferty 1977; Briggs et al. 1994)... Rock types are mainly basanite and hawaiite with nepheline hawaiite, transitional basalt and *ol*-tholeiitic basalt, and minor nephelinite, alkali basalt, *Q*-tholeiitic basalt and nepheline mugearite (Briggs et al. 1994). The lavas are fine- to medium-grained, vesicular and porphyritic, with common quartz and ultramafic xenoliths" (Edbrooke, 2001).

- **Qvsl**

**Inferred age:** 2-1 Ma (Briggs et al., 1994)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = **basalt**; Sub\_Rocks = basanite, hawaiite; Description = Fine-grained and coarse-grained, porphyritic, olivine basalt, basanite and hawaiite **lava flows** (QMAP database) – *EoD is based on the subaerial interpretation of the South Auckland Volcanic Field in Edbrooke (2001).*

- **Qvss**

**Inferred age:** 1 Ma (Briggs et al., 1994)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = **basalt**; Sub\_Rocks = scoria basanite, hawaiite; Description = Red or red-brown to dark grey, poorly-sorted, vesicular, pebble- to boulder-sized **ejecta** of basaltic, basanitic or hawaiitic com (QMAP database) – *EoD is based on the subaerial interpretation of the South Auckland Volcanic Field in Edbrooke (2001).*

- **Qvst**

**Inferred age:** 1 Ma (Briggs et al., 1994)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = tuff; Sub\_Rocks = 'lapilli tuff'; Description = Lithic tuff, comprising comminuted pre-volcanic materials with **basaltic** fragments, and unconsolidated ash and lapilli deposits (QMAP database) – *EoD is based on the subaerial interpretation of the South Auckland Volcanic Field in Edbrooke (2001).*

### **Auckland Volcanic Field**

“The potentially active, Late Pleistocene to Holocene Auckland Volcanic Field (Qva; Kermode 1992) consists of at least 48 eruption centres... Eruption styles ranging from lava effusion to **phreatomagmatic** and **Strombolian-Hawaiian** eruptive activity have produced a wide range of volcanic landforms including lava fields, scoria cones, tuff rings, and ash and lapilli mantles (Searle 1981; Homer et al. 2000). Individual centres show a consistent pattern of eruption from initial explosive phreatomagmatic and/or Strombolian activity, to less violent effusive activity (Hawaiian) later in the eruption sequence (Heming & Barnet 1986)... The lavas are predominantly fine-grained alkali basalt and basanite, with minor transitional basalt, tholeiitic basalt and nephelinite” (Edbrooke, 2001).

- **Qval**

**Inferred age:** < 0.5 Ma (Lindsay et al., 2011)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = **basalt**; Sub\_Rocks = basanite; Description = Grey to very dark grey, dense, fine grained olivine basalt or basanite **lava flows** (QMAP database) – *EoD is based on the eruption styles and products of the Auckland Volcanic Field mentioned in Edbrooke (2001). However, based on the mention of phreatomagmatic and Strombolian activity, submarine may be appropriate at times.*

- **Qvas**

**Inferred age:** < 0.5 Ma (Lindsay et al., 2011)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = **basalt**; Sub\_Rocks = scoria, basanite; Description = Red or red-brown to dark grey, poorly-sorted, vesicular, pebble- to boulder-sized **ejecta** of basaltic or basanitic composition (QMAP database) – *EoD is based on the eruption styles and products of the Auckland Volcanic Field mentioned in Edbrooke (2001). However, based on the mention of phreatomagmatic and Strombolian activity, submarine may be appropriate at times.*

- **Qvat**

**Inferred age:** < 0.5 Ma (Lindsay et al., 2011)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = tuff; Sub\_Rocks = 'lapilli tuff'; Description = Lithic tuff, comprising comminuted pre-volcanic materials with **basaltic** fragments, and unconsolidated ash and lapilli deposits (QMAP database) – *EoD is based on the eruption styles and products of the Auckland Volcanic Field mentioned in Edbrooke (2001). However, based on the mention of phreatomagmatic and Strombolian activity, submarine may be appropriate at times.*

### **Mayor Island Group**

“The Late Quaternary (c. 1000 – 50 000 years) peralkaline **rhyolite extrusive** rocks of Mayor Island (Mayor Island Group, Qvm) form a composite cone built up of thick lava flows of the Tutaretare Rhyolite Formation, and pyroclastic deposits of the Oira Pyroclastite Formation (Buck et al. 1981)” (Edbrooke, 2001). “The peralkaline extrusive rocks of Mayor Island are collectively named the Mayor Island Group (new) and are divided into two formations depending on whether they are dominantly lava flows (the Tutaretare Rhyolite Formation) or pyroclastic deposits (the Oira Pyroclastite Formation)” (Buck et al., 1981).

### ***Tutaretare Rhyolite Formation (Qvmt)***

***Inferred age:*** < 0.5 Ma (Buck et al., 1981)

***EoD:*** onshore silicic eruptives

***Basis for interpretation:*** Main\_Rock = **rhyolite**; Description = Peralkaline rhyolite **lava flows** and domes (QMAP database). “The cone consists mainly of flow-banded, vesicular rhyolite flows up to 40 m thick, with obsidian selvages on their upper and lower surfaces. They are dominantly pantellerites with minor comendites” (Edbrooke, 2001). “The Tutaretare Rhyolite Formation (new) includes all the peralkaline lava flows on the island” (Buck et al., 1981) – *EoD is based on comments in Edbrooke (2001) and Buck et al. (1981).*

### ***Oira Pyroclastite Formation (Qvmo)***

***Inferred age:*** < 0.5 Ma (Buck et al., 1981)

***EoD:*** onshore silicic eruptives

***Basis for interpretation:*** Main\_Rock = pyroclastics; Description = Pyroclastic pumice deposits (QMAP database). “Pyroclastic deposits up to 100 m thick mantle the outer slopes of the cone and some of the fault blocks within the central, ring-fractured caldera. Thinner deposits are intercalated with lava flows. The pyroclastic deposits are dominated by fragments of lithoidal and glassy pantellerite, obsidian, pumice, glass shards, accretionary lapilli and free crystals (Buck et al. 1981; Houghton et al. 1985)” (Edbrooke, 2001). “The Oira Pyroclastite Formation (new) includes all pyroclastic deposits of both airfall and pyroclastic flow origin on Mayor Island” (Buck et al., 1981) – *EoD is based on comments in Edbrooke (2001) and Buck et al. (1981).*

### ***Kaawa Formation (Pk)***

***Inferred age:*** 5-4 Ma (Edbrooke, 2001)

***EoD:*** innermost shelf

***Basis for interpretation:*** Main\_Rock = sandstone; Sub\_Rocks = ‘shell beds’, clay; Description = Pumiceous, shelly, calcareous sandstone, overlain by pumiceous, carbonaceous sandstone with andesite and basalt pebbles, and lignite (QMAP database). “The Kaawa Formation accumulated in **shallow marine and estuarine** environments” (Edbrooke, 2001) – *EoD is based on the interpretation of the formation in Edbrooke (2001).*

## **Tauranga Group**

### ***Whangamarino Formation (Puw)***

***Inferred age:*** 6-4 Ma (Edbrooke, 2001)

***EoD:*** onshore

***Basis for interpretation:*** Main\_Rock = clay; Sub\_Rocks = silt, sand, gravel, **lignite**, pumice; Description = Slightly pumiceous clays, with b, gravel and some pure pumice silt and sand. (QMAP database). “The oldest known Tauranga Group sediments in the map area are massive or lenticularly bedded mudstone and siltstone with sandy and gravelly mud, thinly bedded pumiceous sand and common **lignite** (Whangamarino Formation, Puw; Kear & Schofield 1978)... Several drillholes near Huntly encountered a thin, muddy shell bed containing pebbles of basement rocks within Whangamarino Formation, indicating a brief Pliocene **marine** incursion” (Edbrooke, 2001) – *EoD is based on the presence of lignite. However there is also record of a brief marine incursion, so innermost shelf may be appropriate but is too minor to be of significance here.*

### ***Puketoka Formation (Pup)***

***Inferred age:*** 3-1 Ma (Edbrooke, 2001)

***EoD:*** onshore

***Basis for interpretation:*** Main\_Rock = sand; Sub\_Rocks = mud, gravel, **peat**, **lignite**, tephra pumice; Description = Pumiceous mud, sand and gravel with muddy peat and lignite: rhyolite pumice, including non-welded ignimbrite, tephra and alluvial sediment (QMAP database). “Late Pliocene to Early Pleistocene **non-marine** sediments of the Puketoka Formation (Pup; Battey 1949; Kear & Schofield 1978) are widespread around the Waitemata and Manukau harbours, in the Lower Waikato and Hamilton lowlands, and probably at depth beneath the Hauraki Plains” (Edbrooke, 2001) – *EoD is based on the presence of peat and lignite.*

## Quaternary – Sedimentary deposits

- All Q deposits

**EoD:** onshore

**Basis for interpretation:** Based on the QMAP database which includes alluvial, beach, colluvial, construction fill, dune, estuarine, landslide, lignite, mine waste, peat, refuse landfill, rock fall, and swamp sediments in the Quaternary deposits.

## Northland Volcanic Arc (PMIOeMis, PMeMis)

**Inferred age:** 24-16 Ma (Herzer, 1995)

**EoD:** submarine intermediate eruptives

**Basis for interpretation:** Main\_Rock = andesite; Sub\_Rocks = basaltic andesite; Description = submarine andesite and basaltic andesite volcanoes (after Herzer, 1995; Hayward et al., 2001). “Early Miocene andesite volcanoes of the Northland Arc erupted offshore north of the present Manukau Harbour mouth (Herzer 1995). The large Manukau and Kaipara stratovolcanoes and their satellites produced thick sequences of lavas and volcanoclastic sedimentary rocks (Akarana Super-group)” (Edbrooke, 2001). “The Early Miocene (Waitakian to Altonian) rocks of western offshore Northland are almost entirely of volcanic and volcanoclastic origin; they are a part of the Waitakere Group (Hayward 1976c; Ballance et al. 1977). To the east and north, they abut, interfinger with and onlap the Northland Allochthon. To the west, volcanoclastics grade into probable volcanopelegic sediments. In the southeast, the volcanoclastics interfinger with the Waitemata Group of the Auckland region (Ballance et al. 1977). More than 50 volcanoes have been identified from seismic reflection profiles...The volcanoes form a belt 350 km long that extends up to 95 km offshore between Manukau Heads... and Tauroa Knoll..., the most northerly volcano so far identified. The belt of volcanoes trends northwest (315°), subparallel to both Northland peninsula (325°), and to the northeastern edge of the continental shelf (305°)... The volcanism evidently took place largely in a **submarine** setting, **becoming subaerial** as volcanoes built up to and above sea level” (Isaac et al., 1994). “Laterally, the volcanic sequences may pinch out, onlap, downlap or interfinger with other volcanic sequences, with **terrigenous** sequences, or with **basinal hemipelagic** sequences... For any one volcano, the stratigraphic level at which the oldest internal reflector downlaps should approximately define the time of its first activity. In practice, the oldest internal reflectors are hidden in the larger volcanoes and volcanic massifs, so the time of first activity of the large volcanoes can only be approximated if other evidence is available. Likewise, the stratigraphic level at which the youngest (or top bounding) reflector downlaps defines the time of its last activity. This works for all volcanoes, no matter what their size... Wave planation and **shallow marine** explosive activity commonly occurred in the case of the Northland massifs (Hayward, 1976; 1993)... Both these intermediate-sized cones [D12-S1 and D10/750] have flat, probably erosional tops, suggesting that the sea at the time was between **1.75 and 2 km** deep (Herzer, 1993)” (Herzer, 1995) – *these polygons and ages are based on the summarised eruptive history in Figures 2 and 11 of Herzer (1995). The ages are largely based on stratigraphic relationships as determined through seismic reflection profiles. K-Ar and biostratigraphic ages exist for edifices which have present day outcrops onshore (i.e. Kaipara and Manukau). The EoD of these now buried volcanoes is defined as submarine, as they are described in Isaac et al. (1994) as taking place “largely in a submarine setting”. The depth indicated in Herzer (1995) of 1.75 to 2 km corresponds to lower bathyal, so it is interpreted that most of the eruptions took place at bathyal depths, and that some of the larger edifices may have built up to shelf depths and even become subaerial at some stage. Onshore intermediate eruptives may be appropriate in minor instances.*

## Manukau Volcano (PMeMis)

**Inferred age:** 22-16 Ma (Herzer, 1995)

**EoD:** submarine intermediate eruptives

**Basis for interpretation:** Main\_Rock = andesite; Sub\_Rocks = basaltic andesite; Description = submarine andesite and basaltic andesite volcanoes (after Hayward et al., 2001). “The mainly offshore Manukau centre (Manukau Subgroup) is a predominantly **submarine** stratovolcano that was **periodically emergent**, and only in its final phases produced significant terrestrial flows and pyroclastics, at least on its eastern flanks which now form the Waitakere Ranges of west Auckland (Hayward



1993). A number of offshore satellite volcanoes appear to have been almost entirely submarine” (Edbrooke, 2001). “It erupted mostly **andesite** or **basaltic andesite**, and built a large **submarine** volcano capped at times by small islands (Hayward 1979a)” (Hayward et al., 2001) – *these polygons and ages are based on the summarised eruptive history in Figures 2 and 11 of Herzer (1995). The ages are largely based on stratigraphic relationships as determined through seismic reflection profiles. K-Ar and biostratigraphic ages exist for edifices which have present day outcrops onshore, e.g. Manukau Volcanic Complex. Onshore intermediate eruptives (or even mafic) may be appropriate in minor instances.*

## **Mohakatino Volcanic Arc (PMmMIMis)**

***Inferred age:*** 14-10 Ma (Strogen, 2011)

***EoD:*** submarine intermediate eruptives

***Basis for interpretation:*** Main\_Rock = andesite; Sub\_Rocks = basaltic andesite; Description = submarine andesite and basaltic andesite volcanoes (after Edbrooke, 2001). “**Andesite** volcanoes of the Mohakatino Arc erupted **offshore** south of Manukau Harbour mouth during the Middle and Late Miocene, as volcanism migrated southward” (Edbrooke, 2001) – *these polygons and ages were created based on paleogeographic maps in Strogen (2011). The ages are largely based on stratigraphic relationships as determined through seismic reflection profiles.*

## **Awhitu Volcano (PMPeQms)**

***Inferred age:*** 5-2 Ma (Strogen, 2011)

***EoD:*** submarine mafic eruptives

***Basis for interpretation:*** Main\_Rock = basalt; Description = submarine basalt (after Edbrooke, 2001). “A buried Pliocene offshore volcanic centre (Awhitu Volcano; Stagpoole 1999) is present in the southwest corner of the map (cross section B-B’). It is inferred to be of **basaltic** composition and may be related to onshore Pliocene-Pleistocene Alexandra Volcanics of the Waikato” (Edbrooke, 2001) – *this polygon was created based on paleogeographic maps in Strogen (2011). The age is based on stratigraphic relationships as determined from seismic reflection profiles.*

## WAIKATO AREA (Geological Map 4)

### Te Kuiti Group

#### *Waikato Coal Measures (Etw)*

**Inferred age:** 36-34 Ma (Tripathi et al., 2008; Edbrooke et al. 1998)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = claystone, coal, sandstone, conglomerate, carbonaceous shale, ironstone; Description = Carbonaceous mudstone with muddy quartzose sandstone, carbonaceous shale, coal seams and rare conglomerates; siderite concretion (QMAP database). “The coal measures south of the Hakarimata Range [i.e., on the Waikato map area] are inferred to have accumulated in an inland **alluvial plain predominantly terrestrial** setting, remote from marine influence, whereas those to the north [that is, on the Auckland map area] exhibit a marked **marine** influence and are inferred to have accumulated in a more **coastal setting** (Edbrooke et al. 1994)” (Edbrooke, 2005). “The WCM were deposited in paleovalleys and faulted sub-basins... the **terrestrial sub-basins** opened eastward into a coastal plain evident from an increase in the degree of marine influence in the coal measures” (Tripathi et al., 2008). “The Waikato Coal Measures accumulated in **fluvial** and overbank depositional environments, marking the start of regional onlap onto basement... The fine-grained lithofacies dominating the Waikato Coal Measures were sourced from deeply weathered basement regolith (Nelson & Hume 1987), transported south to north via a **fluvial** system (Edbrooke et al. 1994) and deposited in meandering **river and floodplain environments** in the northern Waikato region between basement ridges to the west and east” (Kamp et al., 2014a). “This deposition was driven by the start of regional subsidence of the underlying lithosphere and led to gradual marine incursion into the Waikato Basin” (Kamp et al., 2014b) – *the unit is defined here as onshore, but innermost shelf may be an alternative environment for upper parts of the formation. It is Runangan (36-35 m.y.) in age to the north of Raglan Harbour, and earliest Whaingaroan (34 m.y.) to the south.*

#### *Mangakotuku Formation (Otm)*

Includes Glen Afton Claystone, Pukemiro Sandstone, Rotowaro Siltstone, and Waikaretu Sandstone members.

“Predominantly **marine** formation... is inferred to have been deposited in **shallow marine** environments, ranging from **tidal flats** to an **inner shelf** sheltered gulf” (Edbrooke, 2005). “Deposition of Mangakotuku Formation began with marine transgression... Dinoflagellate assemblages from the two Mangakotuku Formation samples (500-504 and 527-532 m) contain a large variety of species, dominated by *Spiniferites* spp. [which has] previously used to indicate **inner to outer neritic** water masses (Brinkhuis 1994), but the low number of *Impagidinium* forms suggests conditions were not fully open oceanic (Brinkhuis 1994). Land was probably not far away, as miospores are moderately abundant and a probable specimen of *Deflandrea phosphoritica* may indicate deposition in a **coastal nearshore** environment (Pocknall 1985). The rather poor foraminiferal faunas obtained from the Mangakotuku and Glen Massey Formations suggest deposition in a **mid-outer shelf** environment; obvious inner shelf taxa are not present” (Edbrooke et al., 1998). “The degree of marine influence within the formation increases up-sequence, as suggested by plentiful benthic foraminifera, ostracods, and echinoderms in upper parts of the formation, although foraminiferal species are very rare (Hornibrook, in Kear & Schofield 1978)” (Tripathi et al., 2008).

- **Glen Afton Claystone**

“...contains fragments of the brachiopod *Lingula*, indicating accumulation in a **shallow marine** environment... light grey non-calcareous claystone...” (Tripathi et al., 2008).

- **Pukemiro Sandstone**

“The presence of abundant ostracods and rare foraminifera (Kear & Schofield 1978) in the glauconite-rich Pukemiro Sandstone Member... probably indicates restricted neritic conditions” (Tripathi et al., 2008).

- **Rotowaro Siltstone**

“dark greyish, massive carbonaceous mudstone” (Kamp et al., 2008).

- **Waikaretu Sandstone**

“...this study suggests that it is mainly a lateral correlative of Rotowaro Siltstone... up to 8 m of dark grey siltstone interbedded with fine to coarse sandstone... The member is unconformably overlain by the Elgood Limestone Member of Glen Massey Formation. The sharp and abrupt nature of this contact is due to erosion, possibly marine planation” (Tripathi et al., 2008).

**Inferred age:** 34-33 Ma (Tripathi et al., 2008)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = siltstone; Sub\_Rocks = mudstone, claystone, sandstone, greensand; Description = Massive siltstone and mudstone, with glauconitic, muddy sandstone beds; common siderite concretions near base (QMAP database) – *the unit is defined here as innermost shelf, particularly for the oldest part of the formation. Mid-shelf may be an alternative environment for the upper part of the formation.*

### **Glen Massey Formation (Otg)**

Includes Elgood Limestone, Dunphail Siltstone, and Ahirau Sandstone members.

“Glen Massey Formation typically comprises three distinct facies in vertical succession. A thin, flaggy, sandy limestone and/or calcareous, glauconitic sandstone (greensand) at the base is overlain by grey, calcareous siltstone, which grades up into massive, calcareous fine- to medium-grained sandstone... The upper sandstone dominates the formation...” (Edbrooke, 2005). “The upper boundary, between Mangakotuku Formation and Glen Massey Formation, marks significant marine inundation, probably the earliest that can be defined regionally across the basin. This upper boundary is usually well defined where it involves the basal limestone member (Elgood Limestone) of the Glen Massey Formation...” (Tripathi et al., 2008). “Foraminifera are difficult to extract from the well-cemented lithology of Glen Massey Formation, however the microfaunal assemblage indicates **deepening from shelfal to upper bathyal** water depths” (Kamp et al., 2014b). “Although the Glen Massey Formation does not comprise the earliest marine facies of the Te Kuiti Group ... it does represent the first occurrence of **fully marine** environments across much of the basin from Port Waikato in the north to Awakino in the south... Significant marine flooding across the basin marked the onset of accumulation of the Glen Massey Formation. In the Elgood Limestone Member, **inner shelf** high-energy limestone lithofacies (L1-L3) grade eastward into horizontally bedded to massive grainstone/packstone facies (L4-L5) deposited in **mid to outer shelf** environments (Fig. 12). These facies in turn grade into calcareous siltstone/sandstone (sandy marl) with relatively high concentrations of glauconite (Lithofacies C2, C3) (Fig. 12), which also developed across the top of the member. Overall, the depositional setting is interpreted to have been a low-gradient shelf, with shallow water areas to the west and deeper water areas to the east (Kamp et al. 2014b). The strong development of limestone lithofacies in the northwest compared with the central and southern areas (Fig. 2) suggests that it was more distant from siliciclastic sediment input or within an area of siliciclastic sediment bypass... Lithofacies S1 and S2 accumulated in an **inner to mid shelf** environment and occur in the upper parts of the Ahirau Sandstone Member. These vertical facies transitions and their inferred depositional paleoenvironments imply that the Glen Massey Formation is made up generally of **lower deepening and upper shoaling** components” (Kamp et al., 2014c).

- **Elgood Limestone**

“...is the lowermost unit in the formation and comprises flaggy bioclastic limestone... laps onto a weathered and wave-planed basement surface with remnant relief” (Tripathi et al., 2008). “Near shore to **innermost shelf**, adjacent to rocky shoreline... Subaqueous dunes migrating parallel to shore... **Lower inner to mid-outer shelf**, wave (storm) dominated setting” (Kamp et al., 2008). “The Elgood Limestone Member is mainly composed of skeletal material derived from **shallow water** epibenthic communities living on rocky, gravelly and coarse shelly sea bottoms around ridges, banks and islands that provided stable firm substrates (Nelson 1978a)” (Kamp et al., 2014c).

- **Dunphail Siltstone**

“...is the middle unit, composed of massive calcareous siltstone...” (Tripathi et al., 2008). “**Mid to outer shelf**, between fair weather and storm wave base... **Outer shelf to upper bathyal**” (Kamp et al., 2008).

- **Ahirau Sandstone**

“...is silty fine sandstone forming the uppermost member...” (Tripathi et al., 2008). “**Inner to mid shelf** with moderate to strong bottom currents driven by wind and/or tides interacting with the inherited topography... Moderate energy in **mid to outer shelf** depths below fair-weather but above storm wave base” (Kamp et al., 2008).

**Inferred age:** 33-30 Ma (Tripathi et al., 2008)

**EoD breakdown:** 33 Ma: mid-shelf (Elgood Limestone, Dunphail Siltstone)  
32 Ma: outer shelf (Dunphail Siltstone, Ahirau Sandstone)  
31-30 Ma: mid-shelf (Ahirau Sandstone)

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = siltstone limestone greensand; Description = Massive, calcareous fine sandstone and siltstone with a basal flaggy glauconitic limestone or greensand (QMAP database) – *sedimentary lithofacies as observed in stratigraphic sections by A. Tripathi are detailed in Table 1.1 of Kamp et al. (2008). The EoD of the Glen Massey Formation is broken down into time intervals based on the EoD of the dominant or average lithology at the time. The Elgood Limestone Member is an innermost shelf deposit, however it is only a minor component of the 33 Ma interval, so the EoD of the Dunphail Siltstone is preferred for this time.*

### **Whaingaroa Formation (Oti)**

Includes Awaroa Limestone, Ngapaenga Siltstone, Kotuku Siltstone, and Waikorea Sandstone members.

“Large numbers of planktic foraminifera, particularly *Globigerina euapertura* and *G. labiacrassata*, are abundant and indicate **fully oceanic** environments probably at **mid to outer shelf or upper bathyal** depths” (Tripathi et al., 2008). “The Whaingaroa Formation in our lithostratigraphic framework (Tripathi et al. 2008) comprises basal TST limestone facies in places (Awaroa Limestone Member), HST deposits (Kotuku Siltstone Member) and FSST deposits (Waikorea Sandstone Member) and hence conforms to a typical mixed carbonate – siliciclastic sequence” (Kamp et al., 2014a).

- **Awaroa Limestone**

“...a transgressive limestone (Awaroa Limestone Member) accumulated in **inner to mid-shelf** environments, followed by accumulation of shelfal siltstone facies... moderately to poorly flaggy to blocky in appearance, and includes abundant rounded to subrounded glauconite coated pebbles and grit” (Tripathi et al., 2008).

- **Ngapaenga Siltstone**

“...generally massive and variably calcareous, with common thin sandy siltstone interbeds in the middle portion. In places the formation is condensed and comprises a highly glauconitic sandstone overlying thin pebbly gritty limestone... The contact between Awaroa Limestone and overlying Ngapaenga Siltstone Member corresponds to a gradational but distinct up-sequence increase in the content of terrigenous clastics” (Tripathi et al., 2008).

- **Kotuku Siltstone**

“...is a featureless blue-grey calcareous siltstone” (Tripathi et al., 2008). “**Mid-outer shelf to possibly upper bathyal**” (Kamp et al., 2008).

- **Waikorea Sandstone**

“Along the northwestern margin, the top one or so metres of the formation comprise bedded silty sandstone named Waikorea Sandstone Member... The member is easily distinguished by its moderately to strongly bedded nature and sandy texture... The lower contact between the Waikorea Sandstone Member and Kotuku Siltstone Member is usually gradational. The member is generally abruptly overlain in the west by cross-stratified Waimai Limestone Member of Aotea Formation...” (Tripathi et al., 2008).

**Inferred age:** 30-29 Ma (Tripathi et al., 2008)

**EoD:** outer shelf

**Basis for interpretation:** Main\_Rock = siltstone; Sub\_Rocks = sandstone, greensand, limestone; Description = Massive, calcareous siltstone, commonly glauconitic, with rare, thin sandstone and

muddy limestone beds; near basal sandy limestone (QMAP database) – the EoD of the formation is narrowed down here to outer shelf, based on the descriptions in Kamp et al. (2008) and Tripathi et al. (2008), and the main rock type of siltstone (QMAP database, Fig. 3). The Waikorea Sandstone Member may have been deposited at a shallower depth (i.e. *mid-shelf*) based on its lithology, but it is only shown as a minor component of the Whaingaroa Formation in the chronostratigraphic panel in Fig. 5 of Tripathi et al. (2008). The Whaingaroa Formation only includes the Kotuku Siltstone and Waikorea Sandstone members on the Auckland map area.

### **Aotea Formation (Ota)**

Includes Waimai Limestone, Mangiti Sandstone, Hauturu Sandstone, Patikirau Siltstone, and Kihi Sandstone members.

“The base of the Aotea Formation is marked by a significant erosional unconformity, which probably formed initially through subaerial erosion but was subsequently modified by wave planation that gave rise to the sharp planar surface observed in most areas (Tripathi et al. 2008)” (Kamp et al., 2014d).

#### **• Waimai Limestone**

“**Shelf** water depths developed over most of the northern region following transgressive onlap of Waimai Limestone. The accumulation of cross-bedded limestone (Waimai Limestone Member) reflects **shallow marine** (less than about **60 m**) high current energy depositional environments (Anastas 1997), but the water depth rapidly increased during Waimai Limestone accumulation judging from the accumulation of glauconitic sandstone to mudstone in its uppermost parts in Port Waikato sections” (Tripathi et al., 2008). “The limestone lithofacies accumulated in **inner- to mid-shelf** water depths” (Kamp et al., 2014d).

#### **• Mangiti Sandstone**

“...calcareous sandstone with thin siltstone interbeds... Waimai Limestone Member grades laterally into, or interfingers with, [Mangiti Sandstone]... Mangiti Sandstone is a correlative of Hauturu Sandstone” (Tripathi et al., 2008). “**Inner to mid** wave dominated **shelf**... Moderate energy **mid shelf** depths below fair-weather but above storm wave base” (Kamp et al., 2008). “However, we prefer a deeper-water **middle to outer shelf** environment of deposition characterised by high-energy storm deposition of sandstone alternating with low-energy background accumulation of burrowed hemipelagic sandy siltstone” (Kamp et al., 2014d).

#### **• Hauturu Sandstone**

“The sandstone is moderately well sorted with occasional thin gritty bands and shell hash layers. Small- to medium-scale cross-stratification is evident in places. The sandstone fines upward into massive to crudely bedded fine muddy sandstone (Kihi Sandstone Member)... The accumulation of the Hauturu Sandstone lithofacies represented an abrupt increase in the supply of sand to the basin” (Tripathi et al., 2008). “The variably calcareous fine to medium sandstone was deposited in a wave, tide and storm-dominated **inner to mid shelf** environment. The common occurrence of trough cross-stratification indicates high-energy conditions (e.g. Dott & Bourgeois 1982; Swift et al. 1983; Walker 1984). The abundance of burrows indicates that there were also fair-weather conditions between storm events” (Kamp et al., 2014d).

#### **• Patikirau Siltstone**

“...massive siltstone... Mangiti Sandstone generally fines upward into variably muddy and calcareous siltstone (Patikirau Siltstone)” (Tripathi et al., 2008). “**Mid-outer shelf** to possibly **upper bathyal**” (Kamp et al., 2008). “The regional extent of this fine-grained facies implies a quiet depositional environment, probably at **outer shelf** water depths. However, the presence of thin sandy siltstone interbeds indicates that the seafloor was supplied with sandstone during storm action. The presence of *Sphaeroidina bulloides*, *Cibicides novozelandicus*, *Sipholina australis* and *Haeuslerella textilariformis* indicates that the water depth may have been in the range **outer shelf to possibly upper bathyal**, with transport of inner and mid shelf faunas (e.g. *Arenodosaria antipoda*, *Bulimina pupula*, *Melonis maorica* in R14/f92-94) into deeper water (e.g. Hayward 1986; Van Markhoven et al. 1986)” (Kamp et al., 2014d).

- **Kihi Sandstone**

“...bioturbated fine muddy sandstone with thin siltstone interbeds” (Tripathi et al., 2008). “The Kihi Sandstone differs in having higher silt content and in being a silty fine to very fine sandstone (Lithofacies S4). This facies grades into Hauturu Sandstone (S1) but it also stratigraphically overlies it, especially in the Aotea and Kawhia areas... The high density of burrows and the fine texture suggests a moderate to low energy **mid to outer shelf** depositional environment” (Kamp et al., 2014d).

**Inferred age:** 29-27 Ma (Tripathi et al., 2008)

**EoD breakdown:** 29 Ma: innermost shelf (Waimai Limestone, Mangiti Sandstone, Hauturu Sandstone)  
28 Ma: mid-shelf (Waimai Limestone, Mangiti Sandstone, Hauturu Sandstone, Patikirau Siltstone, Kihi Sandstone)  
27 Ma: mid-shelf (Patikirau Siltstone, Kihi Sandstone)

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = siltstone limestone greensand; Description = Massive or banded, calcareous muddy sandstone and sandy calcareous siltstone, commonly glauconitic; basal, flaggy or cross bedded (QMAP database) – *EoD is based on the shallow marine nature of the members of this formation (e.g. Tripathi et al., 2008; Kamp et al., 2014d). The EoD of the Aotea Formation is broken down into time intervals based on the EoD of the dominant or average lithology at the time. The Aotea Formation only includes Waimai Limestone, Mangiti Sandstone, and Patikirau Siltstone members on the Auckland map area.*

### ***Te Akatea Formation (Ott)***

Includes Raglan Limestone and Carter Siltstone members.

“...Te Akatea Formation accumulated in an open marine setting, probably at **outer shelf to upper bathyal** water depths, in the northern part of the basin” (Kamp et al., 2014e).

- **Raglan Limestone**

“...fine grained foraminiferal limestone with thin interbeds of calcareous siltstone, which are commonly extensively burrowed. The members grades upward through silty limestone into calcareous siltstone of the Carter Siltstone Member... In the vicinity of Raglan Harbour, Raglan Limestone Member aggraded the depositional slope and represents a transition between the neritic platform carbonate facies (Orahiri Formation) to the south and the upper bathyal Carter Siltstone facies to the north” (Tripathi et al., 2008). “The common occurrence of highly fragmented skeletal debris intermixed with planktic foraminifera probably resulted from storm-induced currents originating on the shelf with **redemption into outer shelf-upper bathyal** depths. In most modern cool-water carbonate systems, the carbonate mud and marl accumulation occurs only at depths greater than 200 m (Nelson et al. 1988a; James et al. 1992; Boreen et al. 1993)... Raglan Limestone in effect represents a transition between shelf carbonates (L1-L7) to the south of Aotea Harbour and outer shelf to upper bathyal marls (Z1-Z2) to the north” (Kamp et al., 2014e).

- **Carter Siltstone**

“The microfauna identified by Hornibrook (Kear & Schofield 1978) in Carter Siltstone are dominated by planktics (*Globigerina*) and benthics such as *Cibicides thiara* and *Karreriella novozealandica*, indicating an **outer shelf to upper bathyal** depositional environment” (Tripathi et al., 2008). “The medium bedded calcareous siltstone lithofacies (Z1) represents deposition in **outer shelf to upper bathyal** environments... The massive calcareous siltstone lithofacies Z2 accumulated in **outer shelf to upper bathyal** water depths... The presence of rare benthic foraminifera *Amphistegina*, which are intermixed with the outer shelf to upper bathyal fauna, suggests seaward **reworking** of these shallow shelfal fauna. Clear physical evidence of mass-emplacment is lacking. Bottom currents probably introduced the allochthonous components. Overall, deposition was dominated by hemipelagic settling of background sedimentation” (Kamp et al., 2014e).

**Inferred age:** 27-24 Ma (Tripathi et al., 2008)

**EoD:** outer shelf

**Basis for interpretation:** Main\_Rock = siltstone; Sub\_Rocks = sandstone, limestone; Description = Massive or weakly bedded, very calcareous sandy siltstone to silty fine-grained sandstone, locally

with a sandy or muddy limestone (QMAP database) – *EoD is based on the descriptions of the members in Tripathi et al. (2008) and Kamp et al., (2014e) and is narrowed down to outer shelf for the entire formation. Upper bathyal may be an appropriate alternative, particularly in the upper part of the formation.*

### **Orahiri Limestone (Otr)**

Includes Mangaotaki Limestone, Te Anga Limestone, and Waitomo Sandstone members.

“The Orahiri Limestone is inferred to have accumulated in a **shallow marine** setting subject to strong current action...” (Edbrooke, 2005). “From the facies associations it is clear that the Orahiri Formation and Otorohanga Limestone accumulated in **shoreline and shelf marine** paleoenvironments under strong wave and tidal influence (Nelson 1973, 1978a; Anastas 1997)” (Kamp et al., 2014e).

- **Mangaotaki Limestone**

“...massive sandy limestone, its fine to medium terrigenous sandstone content typically varying from 5-30 %” (Tripathi et al., 2008). “This facies [L4] is inferred to have accumulated on a moderate to high energy wave dominated **inner to mid shelf**... the sediment emplaced across a carbonate shelf producing an interbedded succession of limestone conglomerate (L7) and sandy limestone lithofacies (L4) (Nelson et al. 1994)” (Kamp et al., 2014e).

- **Te Anga Limestone**

“It is up to 12 m thick and comprises irregularly to wavy, flaggy limestone with common disarticulated oyster shells...is distinguished by the presence of large oyster shells averaging 15 cm across...” (Tripathi et al., 2008). “This facies [L4] is inferred to have accumulated on a moderate to high energy wave dominated **inner to mid shelf**... Lithofacies L6 with its oyster biostromes/banks and abundant pebble lags accumulated in a current-swept **inner to mid shelf** depositional paleoenvironment (Nelson 1978b; Nelson et al. 1983)” (Kamp et al., 2014e).

- **Waitomo Sandstone**

“...variably calcareous and glauconitic, burrowed, massive fine sandstone” (Tripathi et al., 2008).

**Inferred age:** 27-25 Ma (Tripathi et al., 2008)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = shell beds, sandstone; Description = Limestone, ranging from massive sandy to glauconitic and pebbly varieties through to pure flaggy bioclastic limestone and thick (QMAP database) – *the main rock type of sandy, pebbly, glauconitic, or pure bioclastic limestone indicates a dominantly innermost to mid-shelf EoD for the map unit (Fig. 3). The EoD is narrowed down here to mid-shelf, but innermost shelf may be an alternative EoD.*

### **Waitomo Sandstone (Oto)**

**Inferred age:** 25 Ma (Tripathi et al., 2008)

**EoD:** mid-shelf (see above)

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = shell beds; Description = Brown-grey, massive to poorly bedded, calcareous, muddy, glauconitic fine sandstone with scattered shells and shell fragments (QMAP database). “Scattered macrofossils, including thin oyster beds, and a rich microfauna indicate latest Oligocene deposition in **mid- to outer shelf** depths...” (Edbrooke, 2005). “The sandstone lithofacies vary from sparsely fossiliferous to highly fossiliferous, with a diverse range of macrofaunal taxa. They are either overlain by horizontally to cross-stratified grainstone or occur at the very top of the thick limestone succession, possibly associated with an **increase in water depth**... The massive fine-grained character of this lithofacies suggests moderate energy in the environment of deposition. Bioturbation was able to continuously keep pace with the slow rate of sediment accumulation, leading to the massive and homogenised character of the facies. The restricted occurrence of facies S1 may be the result of locally increased terrigenous sediment input, possibly associated with active faulting in the vicinity. It may also represent localised subsidence associated with fault movement or changes in the hydrodynamic regime” (Kamp et al., 2014e) – *EoD is based on the mid- to outer shelf depositional depth range given in Edbrooke*

(2005), which is narrowed down to a mid-shelf depositional environment based on the QMAP lithologic description of the map unit as “muddy, glauconitic fine sandstone with scattered shells and shell fragments”, and Fig. 3.

### **Otorohanga Limestone (Otn)**

Includes Pakeho Limestone, Waitanguru Limestone, and Piopio Limestone members.

“...thick accumulations of Otorohanga Limestone represent dispersal to eastern areas of carbonate sand from carbonate factories probably located along a rocky shoreline in the west (Herangi Range)” (Tripathi et al., 2008). “Facies L8 reflects increasing water depths in the upper part of Otorohanga Limestone, reflecting a retrogradational stratal pattern... From the facies associations it is clear that the Orahiri Formation and Otorohanga Limestone accumulated in **shoreline and shelf marine** paleoenvironments under strong wave and tidal influence (Nelson 1973, 1978a; Anastas 1997)” (Kamp et al., 2014e).

#### • **Pakeho Limestone**

“...well developed flaggy limestone. Cross-bedding up to a few metres thick (e.g. at the type locality of Waitomo Valley, C-32) is common” (Tripathi et al., 2008). “This facies [L4] is inferred to have accumulated on a moderate to high energy wave dominated **inner to mid shelf**” (Kamp et al., 2014e).

#### • **Waitanguru Limestone**

“...invariably falls in the pure carbonate end with calcium carbonate content as high as 98% (Nelson 1978a). In outcrop, the member is distinguished by its blocky, knobby, and cavernous weathering appearance” (Tripathi et al., 2008). “This lithofacies accumulated in a **high energy shelf** setting with substantial wave and/or current agitation indicated by the presence of isopachous sea floor cements (Nelson & James 2000)” (Kamp et al., 2014e).

#### • **Piopio Limestone**

“...includes well developed pure flaggy limestone having higher calcium carbonate content compared with the underlying flaggy Pakeho Limestone Member... The very top of the formation comprises a metre or so of massive or thickly flagged silty limestone alternating with thin mudstone interbeds that rapidly thicken upward over a few metres into massive Mahoenui Group mudstone” (Tripathi et al., 2008). “This facies [L4] is inferred to have accumulated on a moderate to high energy wave dominated **inner to mid shelf**” (Kamp et al., 2014e).

**Inferred age:** 25-23 Ma (Tripathi et al., 2008)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = shell beds; Description = Light-grey to white, flaggy, pure bioclastic limestone with local shell hash lenses (QMAP database) – EoD is based on the shallow marine interpretation of the Otorohanga Limestone in Kamp et al. (2014e), the QMAP lithologic description, and Fig. 3.

### **Okoko Subgroup (Otl)**

“[The Te Kuiti Group] is a predominantly transgressive sequence of basal coal measures overlain by **marginal marine to outer shelf** calcareous mudstone, calcareous sandstone and limestone... It is dominated by siltstone and mudstone in the north (north of Pirongia) with a transition to sandstone-dominated sequences in the south; limestones are present throughout but are thicker in the south... In some areas, particularly in the southern part of the map area where the Te Kuiti Group is thin, it is not possible to show individual formations as the scale of this map and the group is subdivided into lower and upper subgroups” (Edbrooke, 2005). “The two-fold subdivision of the Te Kuiti Group is extended here to the central and northern regions. The lower five formations (Waikato Coal Measures, Mangakotuku, Glen Massey, Whaingaroa, and Aotea) are assigned to the Okoko Subgroup, and the three upper formations (Orahiri, Otorohanga, and Te Akatea) are assigned to the Castle Craig Subgroup” (Tripathi et al., 2008).

**Inferred age:** 34-27 Ma (Tripathi et al., 2008)

**EoD breakdown:** 34 Ma: onshore (Waikato Coal Measures, Mangakotuku Formation)  
33-32 Ma: outer shelf (Mangakotuku Formation, Glen Massey Formation)



31-30 Ma: mid-shelf (Glen Massey Formation, Whaingaroa Formation)  
29 Ma: innermost shelf (Whaingaroa Formation, Aotea Formation)  
28-27 Ma: mid-shelf (Aotea Formation)

**Basis for interpretation:** Main\_Rock = siltstone; Sub\_Rocks = sandstone, mudstone, limestone, coal; Description = Siltstone and sandstone with local limestone conglomerate and coal; calcareous in upper part (QMAP database) – *the Te Kuiti Group is defined by Edbrooke (2005) as being marginal marine to outer shelf. The EoD of the Okoko Subgroup is broken down into time intervals based on the EoD of the dominant or average formation at the time. The Okoko Subgroup has previously been referred to as the Lower Te Kuiti Subgroup (Tripathi et al., 2008).*

### **Castle Craig Subgroup (Otu)**

**Inferred age:** 27-23 Ma (Tripathi et al., 2008)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = sandstone, siltstone, conglomerate; Description = Sandy and pure skeletal limestone with calcareous sandstone and rare conglomerate (QMAP database). “[The Te Kuiti Group] is a predominantly transgressive sequence of basal coal measures overlain by **marginal marine to outer shelf** calcareous mudstone, calcareous sandstone and limestone... It is dominated by siltstone and mudstone in the north (north of Pirongia) with a transition to sandstone-dominated sequences in the south; limestones are present throughout but are thicker in the south... In some areas, particularly in the southern part of the map area where the Te Kuiti Group is thin, it is not possible to show individual formation as the scale of this map and the group is subdivided into lower and upper subgroups...” (Edbrooke, 2005). “The two-fold subdivision of the Te Kuiti Group is extended here to the central and northern regions. The lower five formations (Waikato Coal Measures, Mangakotuku, Glen Massey, Whaingaroa, and Aotea) are assigned to the Okoko Subgroup, and the three upper formations (Orahiri, Otorohanga, and Te Akatea) are assigned to the Castle Craig Subgroup” (Tripathi et al., 2008). “The question around complete mid-Cenozoic marine inundation of the New Zealand platform is topical and has substantial implications for the history of New Zealand flora and fauna (Landis et al. 2008). To date, the Te Kuiti Group record and the paleogeography that can be inferred from it, have not contributed significantly to this debate. Our paleogeographic interpretations and the stratigraphic record upon which they are based, strongly suggest that parts of the Herangi structural high on the western side of the basin and east of the Taranaki Fault, and possibly also local structural highs to the east and southeast of the basin, remained above sea level throughout the Late Oligocene-earliest Miocene interval of peak flooding of the New Zealand platform and would have been a refugia for terrestrial flora and fauna” (Kamp et al., 2014a) – *the formations in this subgroup have an average EoD of mid-shelf. The Castle Craig Subgroup has previously been referred to as the Upper Te Kuiti Subgroup (Tripathi et al., 2008).*

## **Waitemata Group**

### **Meremere Subgroup**

#### **Waikawau Sandstone (Mww)**

“The basal Waikawau Sandstone (Mww...) is a massive to well-bedded, grey, calcareous, glauconitic fine- to medium-grained sandstone, commonly with calcareous concretionary beds near the base. It is up to 50 m thick, tuffaceous in places, and may contain thin siltstone interbeds. The Waikawau Sandstone grades up into the Koheroa Siltstone... The Meremere Subgroup is inferred to have accumulated in **bathyal, submarine fan and basin floor** settings...” (Edbrooke, 2005).

**Inferred age:** 22-19 Ma (Kamp et al., 2008; Tripathi et al., 2008)

**EoD breakdown:** 22 Ma: mid-shelf  
21-19 Ma: mid-bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = siltstone, tuff; Description = Calcareous, glauconitic fine to medium sandstone with minor siltstone and tuff; locally concretionary near base. (QMAP database) – *refer to “Waikawau Sandstone (Mww)” on the Auckland map area for further information.*

## ***Koheroa Siltstone (Mwk)***

***Inferred age:*** 21-20 Ma (Edbrooke, 2005)

***EoD:*** mid-bathyal

***Basis for interpretation:*** Main\_Rock = siltstone; Sub\_Rocks = sandstone, tuff; Description = Calcareous, sandy siltstone with minor fine sandstone and tuff beds (QMAP database). "...a massive to well-bedded, light grey to blue-grey, moderately calcareous sandy siltstone, commonly with calcareous sandstone and tuffaceous sandstone beds up to 2 m thick... The Meremere Subgroup is inferred to have accumulated in **bathyal, submarine fan and basin floor** settings..." (Edbrooke, 2005) – *EoD is based on the bathyal, submarine fan and basin floor interpretation in Edbrooke (2005). Upper or lower bathyal paleoenvironments are alternative interpretations. Refer to "Koheroa Siltstone (Mwk)" on the Auckland map area for further information.*

## ***Mahoenui Group***

"The Mahoenui Group accumulated mostly at **bathyal** depths; no regressive deposits are evident, having been eroded during subsequent uplift... The Mahoenui Group comprises massive mudstone (Taumatamaire Formation) and flysch (Taumarunui Formation) facies (Nelson and Hume 1977)" (Kamp et al., 2002). "The occurrence of turbidites and other mass flow deposits (flysch facies) in the Mahoenui Group are indicative of **submarine fan** deposition and hence a **slope or basin floor** environment" (Bear, 2006).

## ***Taumatamaire Formation (eMt)***

***Inferred age:*** 22-20 Ma (Kamp and Vonk, 2006)

***EoD:*** upper bathyal

***Basis for interpretation:*** Main\_Rock = mudstone; Sub\_Rocks = limestone; Description = Bioturbated, massive to weakly bedded mudstone with local interbedded limestone (QMAP database). "It accumulated in mainly **outer shelf to mid-bathyal** settings, but the limestones deposited marginal to the Herangi High probably reflect periods of **inner shelf** deposition..." (Edbrooke, 2005). "The massive mudstone facies was probably deposited through **hemipelagic** settling of suspended sediment transported seaward in nepheloid (cloudy) layers. It is also possible that much of the massive mud has a muddy **turbidite** origin... It is probable that the faintly bedded mudstone facies were formed by mud **turbidites** or the distal muddy part of turbidites... Both the Awakino and Black Creek Limestone Members were interpreted by Cochrane (1988) to have been deposited through storm reworking and tractional deposition of carbonate sand across a paleoshelf. There are some redeposited turbidites and channelised deposits beyond the shelf edge in mudstone slope deposits" (Bear, 2006) – *an average upper bathyal EoD is assigned to the map unit but outer shelf or mid-bathyal depositional depths are alternative options. An innermost shelf EoD may be appropriate in areas of the map unit dominated by limestone. It is 22-20 m.y. to the north of the Whenuakura Fault, and 22-21 m.y. south of the Whenuakura Fault.*

## ***Taumarunui Formation (eMa)***

***Inferred age:*** 21-20 Ma (Kamp and Vonk, 2006)

***EoD:*** mid-bathyal

***Basis for interpretation:*** Main\_Rock = sandstone; Sub\_Rocks = mudstone; Description = Interbedded, massive or graded sandstone and mudstone (QMAP database). "The Taumarunui Formation (Mea...) is a **flysch** sequence apparently lying within and above Taumatamaire Formation... It consists of up to 900 m of alternating, massive to graded sandstone and mudstone... The sandstone are typically fine- to very fine-grained, up to 3 m thick but generally less than 0.3 m thick, and grade up into mudstone... Some massive fine-grained sandstone beds up to 8 m thick are present locally... The Taumarunui Formation is inferred to have accumulated at **bathyal** depth in a narrow submarine trough formed by local tectonism..." (Edbrooke, 2005). "The Taumarunui Formation comprises alternating sandstone and mudstone beds of around 10-50 cm thickness. The sandstone beds within the **flysch** are either graded or massive sandstone... Overlying the sandstone layers in the flysch is dark grey friable mudstone, exactly the same as the massive mudstone of the Taumatamaire Formation. As with the mudstone found in the north, this was likely to have been deposited by means

of suspension settling” (Bear, 2006) – *the map unit is interpreted as mid-fan sediment deposited at mid-bathyal depths. This is based on the bathyal depositional depth for the map unit and its interpretation as flysch deposits in Kamp et al. (2002), and Fig. 3.*

## **Mokau Group (eMo)**

Includes Bexley Formation, Maryville Coal Measures, and Tangarakau Formation.

**Inferred age:** 18-15 Ma (Kamp and Vonk, 2006)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone, shale, coal; Description = Grey to orange brown fine to medium sandstone with mudstone, carbonaceous shale and thin coal seams (QMAP database). “The Mokau Group (Mu...) comprises **shallow marine** sandstones and mudstones with associated **paralic deposits**, including coal measures” (Edbrooke, 2005) – *although this unit is named Mokau Group, the description most closely matches that of the Maryville Coal Measures so the EoD is based on the interpretation of the Maryville Coal Measures (eMm).*

## **Bexley Formation (eMb)**

**Inferred age:** 18 Ma (Kamp and Vonk, 2006)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone, coal; Description = Massive to metre-bedded, grey to orange-brown, fine to medium sandstone with carbonaceous mudstone beds and rare thin coal seams (QMAP database). “A few shell beds and concretionary horizons are present locally... [The Bexley Formation occurs at the base of the Mokau Group and grades up into the Maryville Coal Measures or Tangarakau Formation]... The Mokau Group (Mu...) comprises **shallow marine sandstones and mudstones** with associated **paralic deposits**, including coal measures” (Edbrooke, 2005) – *the occurrence of coal seams, shell beds, and carbonaceous mudstone beds implies an innermost shelf to marginal marine to onshore EoD for the map unit (QMAP database; Edbrooke, 2005). Based on the main rock type of sandstone, the interpreted shallow marine EoD of sandstone in the Mokau Group (of which the Bexley Sandstone is a part) in Edbrooke (2005), and Fig. 3, an innermost shelf EoD is assigned to the map unit.*

## **Maryville Coal Measures (eMm)**

**Inferred age:** 17 Ma (Kamp and Vonk, 2006)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone, shale, coal; Description = Grey-brown, muddy sandstone, mudstone, carbonaceous shale and thin coal seams (QMAP database). The Mokau Group (Mu...) comprises **shallow marine sandstone and mudstone** with associated **paralic deposits**, including coal measures” (Edbrooke, 2005). “...coal measure, **fluvial** and intervening **shoreface** succession...” (Kamp et al., 2004) – *based on the main rock type of sandstone, the interpreted shallow marine EoD of sandstone in the Mokau Group (of which the Maryville Coal Measures is a part) in Edbrooke (2005), and Fig. 3, an onshore EoD is assigned to the map unit.*

## **Tangarakau Formation (eMn)**

**Inferred age:** 16-15 Ma (Kamp and Vonk, 2006)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = siltstone, shale, shell beds; Description = Grey, massive to well bedded or laminated, fine muddy sandstone with thin siltstone beds and conglomerate; common shell beds and (QMAP database). “The Tangarakau Formation probably accumulated in a range of **inner shelf to shoreline** environments” (Edbrooke, 2005) – *EoD is based on the interpretation of the formation in Edbrooke (2005), the main rock type of sandstone, and Fig. 3.*

## **Wai-iti Group**

### **Manganui Formation (Mmg)**

“The Manganui Formation is Early to Middle Miocene in age and was deposited in an **outer shelf to**

**upper bathyal** setting...” (Edbrooke, 2005). “This was followed by the accumulation of Manganui Formation mudstone, **initially as a shelfal** deposit, but **by the upper Altonian as a mid-bathyal** succession...” (Kamp et al., 2004).

**Inferred age:** 18-12 Ma (Kamp and Vonk, 2006)

**EoD breakdown:** 18 Ma: outer shelf  
17-12 Ma: mid-bathyal

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone, limestone; Description = Blue-grey, calcareous, massive mudstone with concretion layers and some bioclastic sandstone beds (QMAP database) – *the base of the Manganui Formation is assigned an outer shelf EoD and the remainder of the formation an upper bathyal depositional environment based on the interpretations and depositional trends suggested in Edbrooke (2005) and Kamp et al. (2004).*

### **Manganui Formation (eMu)**

(QMAP database spelling: Undifferentiated Mokau Group and)

“The Mokau Group (Mu...) comprises **shallow marine** sandstone and mudstone with associated **paralic deposits**, including coal measures... In the vicinity of Awakino there are transitional areas where the Manganui Formation and Mokau Group are not differentiated. Here, massive or weakly bedded, fine-grained sandy mudstone and fine- to medium-grained sandstone (Muu) overlies basement rocks or the Bexley Formation. The Manganui Formation is Early to Middle Miocene in age and was deposited in an **outer shelf to upper bathyal** setting...” (Edbrooke, 2005).

**Inferred age:** 18-12 Ma (Kamp and Vonk, 2006)

**EoD breakdown:** 18 Ma: outer shelf  
17-12 Ma: mid-bathyal

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone, siltstone; Description = Massive to weakly bedded, sandy mudstone and muddy fine to medium sandstone (QMAP database) – *this unit is assumed to be Manganui Formation and it is assigned the EoD and age of the Manganui Formation (refer to “Manganui Formation (Mmg)”).*

### **Tirua Formation (mMt)**

**Inferred age:** 17-14 Ma

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = limestone, volcanic sandstone; Description = Bioclastic sandstone and sandy limestone with volcanoclastic sandstone layers (QMAP database). “...calcareous sandstone and sandy limestone (Tirua Formation, Mit...), up to 40 m thick, overlies the Manganui Formation... The contact is locally unconformable. Some sandstones exhibit low-angle cross-bedding and include coarse shelly beds and pebbly, volcanoclastic and concretionary horizons. The formation is interpreted as a sequence of **deep water** bioclastic sandstone and limestone containing redeposited shelf faunas...” (Edbrooke, 2005). “Nodder et al. (1990) argue that the Tirua Formation represents the middle to outer reaches of an **upper to mid-slope** carbonate apron, which evolved diachronously across the region from the southwest” (Nodder et al., 1990) – *a mid-bathyal EoD is assigned to the map unit based on the upper to mid-slope depositional environment interpretation proposed in Nodder et al. (1990). Upper bathyal EoD is an alternative interpretation.*

### **Mohakatino Formation (mMm)**

**Inferred age:** 13-12 Ma (Kamp and Vonk, 2006)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = volcanic sandstone; Sub\_Rocks = mudstone, siltstone; Description = Well bedded, graded volcanic sandstone and mudstone (QMAP database). “The formation is dominated by well-bedded, graded volcanic sandstone and mudstone (Fig. 43), locally with massive sandstone beds up to 5 m thick and siltstone beds up to 3 m thick. In some areas, particularly north of Awakino, there are horizons of contorted bedding produced by intraformational slumping... The Mohakatino Formation represents a sequence of **gravity flow deposits** that accumulated on the **outer parts of volcanoclastic fan aprons** formed on the eastern flanks of active volcanoes of the Mohakatino Volcanic Arc...” (Edbrooke, 2005). “The four formations at Waikawau are a record of mainly **hemipelagic** and **gravity flow** deposition in an outer shelf to more typically

**slope** setting located between basement Herangi High to the east and evolving andesitic volcanic massifs offshore to the west” (Nodder et al., 1990) – *the EoD is based on the interpretation of the Mohakatino Formation in Edbrooke (2005) and the QMAP lithologic description combined with Fig. 3.*

## Whangamomona Group

### **Otunui Formation (mMo)**

**Inferred age:** 14-12 Ma (Kamp and Vonk, 2006)

**EoD:** outer shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone, conglomerate, limestone; Description = Massive argillaceous, fine- to medium-grained sandstone with some mudstone and conglomerate; basal sandy limestone locally (QMAP database). “...predominantly blue-grey, massive, argillaceous fine- to medium-grained sandstone of the Otunui Formation... Shelly, granule to pebble conglomerate lenses, up to 10 m thick, are present in some areas and shell fragments are common, scattered throughout the formation. Locally the base of the formation is a sandy bioclastic limestone or calcareous sandstone, up to 10 m thick, of early Middle Miocene age (Mangarara Member...)” (Edbrooke, 2005). “During the middle Miocene the whole of the King Country region subsided, resulting in the accumulation of a transgressive **shelf** succession represented by the middle Miocene Otunui Formation...” (Kamp et al., 2002). “Insights into the architecture of the Otunui Sequence in northern parts of the basin can be gained from outcrop in the King Country region... There, the **shelf and upper slope** deposits of the Otunui Sequence form linked depositional systems with bathyal components in northern Taranaki Basin” (Vonk and Kamp, 2008). “The basal facies of the Otunui Formation are heterolithic, commonly characterised by an onlap shellbed known as the Mangarara Formation (Henderson & Ongley 1923)... The Otunui Formation is 100-200 m thick and comprises crudely bedded silty fine sandstone and sandy siltstone, with occasional conglomeratic channels” (Kamp et al., 2004). “In the vicinity of Awakino and Mohakatino valley, these Mangarara carbonate and mixed siliciclastic-carbonate sediments are interpreted as mass-emplaced densites and debrites **deposited at slope depths within different parts of a submarine channel-fan system**... During the middle Miocene (Upper Lillburnian), regional subsidence led to marked marine transgression across the Whangamomona block in the King Country with accumulation of an **inner neritic shellbed** (Mangarara Formation) followed by siliciclastic **shelf and upper bathyal** facies of the Otunui Formation. Redeposited carbonate facies also named Mangarara Formation and of early middle Miocene age, some predating the shellbed facies to the east, accumulated within Manganui Formation to the west...” (Puga-Bernabéu et al., 2009) – *based on interpretations made in Vonk and Kamp (2008) and Puga-Bernabéu et al. (2009) the map unit has depositional environments ranging from innermost shelf (basal Mangarara Member) to upper bathyal. A general outer shelf EoD is assigned to the map unit.*

### **Mount Messenger Formation (IMm)**

**Inferred age:** 11-9 Ma (Kamp and Vonk, 2006)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone, siltstone; Description = Interbedded fine to very fine sandstone and mudstone or siltstone, with some channelized conglomerate horizons; massive mudstone (QMAP database). “Muddy fine- to very fine-grained sandstone is the predominant lithology, commonly with interbedded mudstone or siltstone. Thick-bedded sandstone are common in the lower part, where channelized conglomerate are also present. Locally, north of the Tongaporutu River, the lower beds are contorted by intraformational slumping. The upper part of the formation consists of well-bedded, graded sandstone and siltstone... The lower beds are inferred to represent **bathyal, basin floor** deposits while the upper beds were probably deposited at the **foot of an advancing slope**...” (Edbrooke, 2005). “Lowermost sequences [of Mount Messenger Formation] are composed primarily of early lowstand system tract **basin floor fan** deposits, whereas uppermost cycles consist mainly of mid-lowstand **slope fan deposits**” (King and Thrasher, 1996). “[Lower sandstone unit:] ... is dominated by fine- to coarse grained, medium- to thick-bedded sandstone... The sandstone are massive or occasionally graded and contain water escape structures. Similar characteristics typify high density, non-turbulent (laminar) liquefied flow deposits, and also the upper beds (S3) of high density turbidity current deposits... [Middle siltstone/sandstone interbed unit:] In lower parts of the middle interbed unit, separate horizons

contain upper and lower bathyal faunas in varying proportions. In all probability, background sedimentation was at **lower bathyal** depths, and admixing resulted from downslope re-working... some oscillation of bathymetry is possible... In upper parts of the middle interbed unit, the depocentre **shallowed to mid bathyal** water depths... [Upper sandstone unit:] **Uppermost mid-bathyal** water depths are inferred to the upper sandstone unit of the formation, though a marked upsequence decrease in paleobathymetry is not obvious" (King et al., 1993) – *the Mount Messenger Formation is dominantly a bathyal deposit, which shallowed over time from lower to upper bathyal. Mid-bathyal is inferred to be the dominant EoD; consequently this is the assigned EoD.*

### **Urenui Formation (IMu)**

**Inferred age:** 9-8 Ma (Kamp and Vonk, 2006)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = siltstone; Sub\_Rocks = conglomerate, sandstone; Description = Medium to light grey, weakly bedded, bioturbated siltstone and mudstone with incised, coarse channel-fill sequences (QMAP database). "Urenui Formation is interpreted as the deposits of a **prograding slope** and the included channel-fill deposits as infills of **slope canyon complexes**, down which river- and shelf-derived sediments were transported to the basin floor..." (Edbrooke, 2005). "Large volumes of mainly fine-grained Urenui sediment were subsequently deposited on the **mid-upper slope**, at slightly slower sedimentation rates than the Mount Messenger Formation... Fine-grained sediments were preferentially deposited on the **slope**, whereas coarse-grained sediments were funnelled further into the **basin**, or deposited within isolated slope channel complexes" (King et al., 1993) – *EoD is based on the slope interpretation of the Urenui Formation, as well as the occurrence of channel-fill deposits (King et al., 1993), combined with Fig. 3. Refer to "Urenui Formation (Mgu)" on the Taranaki map area for further information.*

### **Mohakatino Volcanic Arc (PMeMmMis, PMeMlMis, PMmMlMis, PmlMis, PmlMePis, PMPis)**

**Inferred age:** 21-3 Ma (Strogen, 2011)

**EoD:** submarine intermediate eruptives

**Basis for interpretation:** Main\_Rock = andesite; Sub\_Rocks = basaltic andesite; Description = submarine andesite and basaltic andesite volcanoes (after Edbrooke, 2005). "The Mohakatino Volcanic Arc is a NNE-trending chain of **submarine andesite** stratovolcanoes and associated **intrusive** complexes in the northeast of Taranaki Basin, identified from seismic surveys and gravity and magnetic anomalies (King & Thrasher 1996). The cone- or dome-shaped volcanic piles are up to 1 km thick and 25 km across (Bergman et al. 1992). Petroleum exploration wells have penetrated several of the volcanoes, providing information on their petrology, age and lithofacies. The Mohakatino volcanoes are largely composed of calc-alkaline **andesite, basaltic andesite and minor basalt**. They range in age from Middle to Late Miocene, but most activity occurred in the Middle Miocene (14-11 Ma)... The Mohakatino Arc represents the southernmost part of a 400 km-long chain of buried Miocene andesitic magmatic complexes located offshore from Northland to Taranaki, and partly onshore in Northland (Isaac et al. 1994; King & Thrasher 1996). There is some overlap in age but in general, Mohakatino volcanism began after volcanism in Northland had ceased... Middle and Late Miocene eruption of the Mohakatino Volcanic Arc produced submarine volcanic edifices (now buried) and deep-water volcanoclastic deposits (Mohakatino Formation)" (Edbrooke, 2005) – *these polygons and ages were created based on paleogeographic maps in Strogen (2011). The ages are largely based on stratigraphic relationships as determined through seismic reflection profiles.*

### **Kiwitahi Volcanic Group**

#### **Tahuna unit (Mkt)**

(QMAP database spelling: Tahuna volcanic centre)

**Inferred age:** 7-6 Ma (Black et al., 1992)

**EoD:** onshore intermediate eruptives

**Basis for interpretation:** Main\_Rock = basaltic andesite; Sub\_Rocks = volcanic breccia; Description = Olivine basaltic andesite lava and breccia (QMAP database). "...includes the isolated remnants of

several former small, **subaerial andesitic** stratovolcanoes... Only a few small remnants of volcanic cones are present in the Waikato map area, overlying basement greywacke of the Hangawera Hills northeast of Hamilton” (Edbrooke, 2005) – *EoD is based on the subaerial interpretation of the Kiwitahi Volcanic Group and the main rock type. Refer to “Kiwitahi Volcanic Group (IMk)” on the Rotorua map area for further information.*

## Orangiwhao Intrusive Group

“The Orangiwhao Intrusive Group (Po; Waterhouse & White 1994, after Kear 1959) comprises near-surface **intrusive** rocks (hypabyssal) clustered at three centres between Kawhia Harbour and Waikawau. They are the deeply weathered and eroded remnants of dikes, sills, necks and plutons now exposed within uplifted basement rocks of the Murihiku terrane. The intrusive rocks are coarse-grained, porphyritic, medium to highly potassic **andesite and dacite** with large phenocrysts of plagioclase and amphibole (Smith 1986)... Rocks of the Otauanui centre cover over 4 km<sup>2</sup> west of Kawhia Harbour. The Pehimatea centre comprises two small areas near Kiritehere, and the Whareorino centre is about 7 km further south” (Edbrooke, 2005).

### **Otauanui Intrusive Formation (Poo)**

**Inferred age:** 3 Ma (Edbrooke, 2005)

**EoD:** intermediate intrusives

**Basis for interpretation:** Main\_Rock = **andesite**; Sub\_Rocks = dacite; Description = Coarse-grained, medium to high potassium, andesitic to dacitic **intrusives** (dikes, sills, plugs, necks and plutons) (QMAP database) – *EoD is based on the QMAP description. The map unit is defined as diorite here because it is the intrusive equivalent of andesite (the main rock type of the map unit).*

### **Pehimatea Intrusive Formation (Pop)**

**Inferred age:** 4 Ma (Edbrooke, 2005)

**EoD:** intermediate intrusives

**Basis for interpretation:** Main\_Rock = **andesite**; Sub\_Rocks = dacite; Description = Coarse-grained, medium to high potassium, andesitic to dacitic **intrusives** (dikes, sills, plugs, necks and plutons) (QMAP database) – *EoD is based on the QMAP description. The map unit is defined as diorite here because it is the intrusive equivalent of andesite (the main rock type of the map unit).*

### **Whareorino Intrusive Formation (Pow)**

**Inferred age:** 4-3 Ma (Edbrooke, 2005)

**EoD:** intermediate intrusives

**Basis for interpretation:** Main\_Rock = **andesite**; Sub\_Rocks = dacite; Description = Coarse-grained, medium to high potassium, andesitic to dacitic **intrusives** (dikes, sills, plugs, necks and plutons) (QMAP database) – *EoD is based on the QMAP description. The map unit is defined as diorite here because it is the intrusive equivalent of andesite (the main rock type of the map unit).*

## Alexandra Volcanic Group

“The Alexandra Volcanics include the volcanoes of Karioi, Pirongia, Kakepuku, and Te Kawa which show a northwesterly (300°) alignment. Volcanism was predominantly **basaltic** and produced approximately 55 km<sup>3</sup> of lava, volcanic breccia, and scoria from at least 40 centres... The Pirongia, Karioi, Kakepuku, and Te Kawa Volcanics form large low-angle composite cones constructed of thick lava flows and volcanic breccias, with minor dikes, scoria, tuff and lahars. They are composed of tholeiitic or subalkaline coarse-grained **basalts, basaltic andesites, with rare andesites**... Geomorphological evidence suggests the volcanoes of Karioi, Pirongia, Kakepuku, and Te Kawa become progressively younger to the southeast. The Okete Volcanics intercalate stratigraphically with lavas from Pirongia and Karioi, and show no distinct temporal relationships” (Briggs, 1983).

### **Karioi Volcanic Formation (Pvlk)**

**Inferred age:** 2 Ma (Briggs et al., 1989)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = **basalt**; Sub\_Rocks = basaltic andesite, volcanic breccia; Description = Basalt, basaltic andesite and andesite **lava**, tuffs and volcanic breccia; andesite dikes (QMAP database). “Karioi is a stratovolcano consisting of **basalt, basaltic andesite and andesite lavas**, volcanic breccias and tuffs, lahar deposits, and epiclastic sediments, and is described in detail by Matheson (1981). The bulk of the 756 m high cone has been produced by **strombolian** eruptions from a central summit vent and later from a parasitic flank vent at Te Toto Gorge” (Briggs, 1983) – *EoD is based on the QMAP and Briggs (1983) lithologic descriptions which do not mention pillow basalts or a phreatomagmatic eruption style.*

### ***Pirongia Volcanic Formation (Pvlp)***

**Inferred age:** 3-2 Ma (Briggs et al., 1989)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = **basalt**; Sub\_Rocks = basaltic andesite, volcanic breccia; Description = Basalt and basaltic andesite lava, volcanic breccia and tuffs (QMAP database). “Pirongia is a composite low-angle cone rising to 959 m which has reached the end of the planeze stage of erosion (Kear & Schofield 1978) and is built up of a succession of **basaltic flows**, volcanic breccias, and minor tuffs” (Briggs, 1983) – *EoD is based on the description in Briggs (1983).*

### ***Takepuku Volcanic Formation (Pvlu)***

**Inferred age:** 3-2 Ma (Briggs et al., 1989)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = **basalt**; Sub\_Rocks = tuff; Description = Basalt lava and minor tuff. (QMAP database). “The 440 m high cone of Takepuku is composed principally of **basalt lava**, but is generally poorly exposed” (Briggs, 1983) – *EoD is based on the description in Briggs (1983).*

### ***Te Kawa Volcanic Formation (Pvlt)***

**Inferred age:** 3-2 Ma (Briggs et al., 1989)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = **basalt**; Sub\_Rocks = basaltic andesite, scoria tuff; Description = Basalt and basaltic andesite lava with minor scoria and tuff (QMAP database). “Te Kawa is a low, 214 m high, semicircular cone, breached to the southwest by erosion... It is the only volcano in the Alexandra Volcanics where a crater feature is preserved... Basalt boulders are exposed at Tokanui, where a small mound rises about 30 m through the surrounding gently rolling hills of the Puketoka and Karapiro Formations” (Briggs, 1983) – *EoD is based on the description in Briggs (1983).*

### ***Okete Volcanic Formation (Pvlo)***

**Inferred age:** 3-2 Ma (Briggs et al., 1989)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = olivine **basalt**; Sub\_Rocks = basanite scoria tuff; Description = **Scoria**, tuff and lava with compositions including basanite, alkali-olivine basalt and rare hawaiiite; most lavas contain ultramaf (QMAP database). “... the eroded **scoria cones, basalt flows and tuff rings** of Kirikiripu, Mangatawhiri, Houchens Hill, Waimaori, Whataipu, Haroto Bay, Wharauoa, Koponui, Karamu, Turitea and many other small volcanic centres in the region” (Briggs, 1983) – *EoD is based on the description in Briggs (1983).*

## **Kerikeri Volcanic Group**

### ***Ngatutura Basalts (Qvn)***

**Inferred age:** 2 Ma (Briggs et al., 1989)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = **basalt**; Sub\_Rocks = hawaiiite; Description = Fine-grained porphyritic olivine **basalt (hawaiiite) lava** (QMAP database). “The Ngatutura Basalts consist of 16 small volume monogenetic volcanic centres situated south of Port Waikato on the west coast of the North Island (Fig. 1,3). They are comprised of alkali **basaltic** lavas, dikes, volcanic breccias, and



scoria cones, produced by **strombolian** eruptions (Utting 1986), and a diatreme at Ngatutura Point (Heming 1980c)" (Briggs et al., 1989) – *EoD is based on the composition and products mentioned in Briggs et al. (1989).*

### ***Karewa Volcanic Formation (Qvk)***

***Inferred age:*** 1 Ma (Briggs et al., 1997)

***EoD:*** onshore mafic eruptives

***Basis for interpretation:*** Main\_Rock = vitric tuff; Sub\_Rocks = tuff olivine nephelinite volcanic breccia; Description = Vitric lapilli tuff and ash tuff dominated by vesicular scoriaceous **basalt** (olivine nephelinite) (QMAP database). "Gannet (Karewa) Island, 22 km northwest of Kawhia Harbour, consists of well-indurated, palagonitic and lapilli tuff with scoriaceous **basalt** (olivine nephelinite) bombs and blocks of the Karewa Volcanic Formation (Qvk; Briggs et al. 1997)" (Edbrooke, 2005) – *EoD is based on the composition and products mentioned in Edbrooke (2005).*

## **Taupo Volcanic Zone**

### ***Pakaumanu Group***

***Inferred age:*** 2-1 Ma (Houghton et al., 1995)

"Voluminous and widespread deposits of the older Pakaumanu Group (Kear 1960) are the major landscape forming ignimbrites in the Waikato area (Fig. 7). The group includes a series of welded ignimbrites and at least two large phreatomagmatic fall plus non-welded ignimbrite deposits. They are inferred to have been erupted from the Mangakino Volcanic Centre between 1.68 Ma and 1.0 Ma (Houghton et al. 1995)" (Edbrooke, 2005). Includes the following onshore silicic eruptives: Ngaroma Formation (eQpn Includes Ignimbrite A, Rangitoto Ignimbrite, Ngaroma Lenticulite, and Ngaroma Ignimbrite), Ongatiti Formation (eQpo Includes Waipari Ignimbrite and Ongatiti Ignimbrite), Mangaokewa Formation (eQpa Includes Unit D, Ahuroa Ignimbrite, and Ranginui Lenticulite), Raepahu Formation (eQpr Includes Potaka Tephra, Unit E, Kidnappers Ignimbrite, and Rocky Hill Ignimbrite). Refer to "Pakaumanu Gorup" on the Rotorua map area for further information.

### ***Whakamaru Group (Q9w)***

***Inferred age:*** < 0.5 Ma (Houghton et al., 1995)

"The Middle Pleistocene Whakamaru Group consists of widespread, voluminous welded ignimbrites that outcrop along the western and eastern margins of the TVZ. They are the most voluminous TVZ ignimbrites and include the products of at least three eruptive phases from a large, single source caldera in the northern Taupo-Maroa area (Wilson et al. 1986; Brown et al. 1998). Several, as yet undefined formations representing the deposits of different eruption phases are likely to be present within the Whakamaru Group... Whakamaru Group ignimbrites are variably welded and crystal-rich, typically with large resorbed quartz crystals and conspicuous biotite" (Edbrooke, 2005). Includes the following onshore silicic eruptives: Whakamaru Group (Q9w Includes Manunui and Whakamaru ignimbrites). Refer to "Whakamaru Group" on the Rotorua map area for further information.

### ***Taupo Group***

***Inferred age:*** < 0.5 Ma (references in Lowe et al., 2008)

"The term "Taupo Volcanic Centre" encompasses the eruptive vents of the Taupo area" (Leonard et al., 2010). "The Oruanui eruption generated widespread, thick airfall deposits and a voluminous non-welded ignimbrite... Taupo Formation (Q1v; Grindley 1960; Wilson & Walker 1985) comprises the deposits of the 1.8 ka Taupo eruption, which in the map area include primary, non-welded, fine-grained ignimbrite and secondary reworked materials" (Edbrooke, 2005). Includes the following onshore silicic eruptives: Oruanui Formation (Q2o Includes Aokautere Ash, Scinde Island Ash, Wairakei Breccia, Wairakei Formation, Kawakawa Tephra, Oruanui fall deposit, and Oruanui Ignimbrite), Taupo Pumice Formation (Q1ati). Refer to "Taupo Volcanic Centre" on the Rotorua map area for further information.

## Volcanic Ash Beds

### ***Kauroa Ash Formation (eQu)***

***Inferred age:*** 2-1 Ma (Edbrooke, 2005)

***EoD:*** onshore silicic eruptives

***Basis for interpretation:*** Main\_Rock = tephra; Sub\_Rocks = clay; Description = Weathered, clay-rich, multiple tephra deposits and associated **paleosols** (QMAP database). “The Kauroa Ash Formation (eQu; Ward 1967) comprises a sequence of extremely weathered, clay-rich, multiple rhyolitic tephra deposits and associated paleosols, mapped around Kawhia Harbour and further north... Possible sources of the Kauroa Ash are the younger volcanic centres in the southern Coromandel Volcanic Zone and older volcanic centres in the TVZ (Mangakino)” (Edbrooke, 2005) – *the Kauroa Ash Formation is defined here as a primary volcanic product.*

### ***Hamilton Ash Formation (mQh)***

***Inferred age:*** < 0.5 Ma (Edbrooke, 2005)

***EoD:*** onshore silicic eruptives

***Basis for interpretation:*** Main\_Rock = **tephra**; Sub\_Rocks = clay; Description = Strongly weathered, clay-textured, multiple **rhyolitic** tephra deposits and associated paleosols (QMAP database). “The Hamilton Ash Formation (mQh; Ward 1967) consists of up to 6 m of strongly weathered, clay-rich, multiple rhyolitic tephra deposits and associated paleosols. It is present throughout much of the Waikato region as a thin mantle but it is only mapped locally south of Raglan Harbour... The oldest tephtras probably originated from the Whakamaru caldera and later tephtras from younger centres in the Taupo Volcanic Zone” (Edbrooke, 2005) – *the Hamilton Ash Formation is defined here as a primary volcanic product.*

### ***Undifferentiated volcanic ash (Qta)***

***Inferred age:*** 2-0 Ma (Edbrooke, 2005)

***EoD:*** onshore silicic eruptives

***Basis for interpretation:*** Main\_Rock = tephra; Sub\_Rocks = clay; Description = Weathered, clay-rich, multiple tephra deposits of rhyolitic and andesitic origin, and associated **paleosols** (QMAP database). “Undifferentiated volcanic ash (Qtu) includes deposits of Kauroa and Hamilton Ash, and Late Quaternary tephtras. The latter are up to 10 m thick and originated from the Okataina and Taupo volcanic centres, and from Tongariro and Taranaki (Pain 1975)” (Edbrooke, 2005) – *the undifferentiated ashes are defined here as a primary volcanic product.*

## Quaternary – Sedimentary deposits

- **All Q deposits** (except – see below)

***EoD:*** onshore

***Basis for interpretation:*** Based on the QMAP database which includes alluvial, colluvial, dune, lacustrine, lahar, landslide, paleosol, peat, rock fall, and swamp sediments in the Quaternary deposits.

- **Rapanui Terrace (Q5b)**

***EoD:*** innermost shelf

***Basis for interpretation:*** “Uplifted **marine** terrace cover beds” (Edbrooke, 2005).

## ROTORUA AREA (Geological Map 5)

### Tinui Group

#### **Whangai Formation (Kiw)**

**Inferred age:** > 65-60 Ma (Field and Uruski, 1997)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone; Description = hard siliceous, poorly calcareous (lower), calcareous (upper) mudstone or shale (QMAP database). "...it is inferred to have accumulated in a regionally extensive ocean basin, mainly at **bathyal** depths..." (Leonard et al., 2010) – *the EoD for the in place units is defined here as upper bathyal, based on the QMAP description and lithology; however outer shelf and even mid-bathyal may be alternative environments, based on comments in the literature. Refer to "Whangai Formation (Kiw, ?Kiw)" on the Raukumara map area for further information.*

### Mangatu Group

#### **Wanstead Formation (Egw)**

**Inferred age:** 57-37 Ma (Field and Uruski, 1997)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone; Description = mudstone, minor greensand, red/green mudstone (QMAP database). "Microfossils indicate... an **outer shelf to mid-bathyal** environment" (Leonard et al., 2010) – *the in place units are defined here as mid-bathyal, based on the lithology and comments in Field and Uruski (1997). Outer shelf to upper bathyal or even lower bathyal-abyssal may be an alternative EoD. Refer to "Wanstead Formation" on the Raukumara map area for further information.*

#### **Weber Formation (Ogw)**

**Inferred age:** 38-22 Ma (Field and Uruski, 1997)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = mudstone; Description = calcareous mudstone, greensand, sandstone, minor conglomerate, limestone (QMAP database). "Foraminifera indicate an Oligocene age (34-25 Ma), and deposition mainly at **mid-bathyal** depths..." (Leonard et al., 2010) – *EoD is based on the Field and Uruski (1997) mid-bathyal interpretation for the Weber Formation. Based on the mention of minor conglomerate in the QMAP description, and Fig. 3, some parts of the map unit may have been deposited in an upper-bathyal depth. There is evidence that shelf deposits have been reworked downslope (Field and Uruski, 1997). Refer to "Weber Formation" on the Raukumara map area for further information.*

### Tolaga Group

#### **Early Miocene Tolaga Group (eMts)**

(QMAP database spelling: Early Miocene sandstone)

**Inferred age:** 18-17 Ma (Mazengarb and Speden, 2000)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone; Description = muddy sandstone (QMAP database). "Early Miocene Tolaga Group (Mts) consists of fossiliferous, blue-grey, calcareous sandstone and siltstone with sparse metre-bedded calcareous sandstone, and **alternating** centimetre- to decimetre-bedded sandstone and siltstone sequences" (Leonard et al., 2010). "At Hangaroa River and Mutuera Stream the basal sediments include a thin conglomerate, cross-bedded, shelly, pebbly sandstone (Joass 1987) and muddy fossiliferous sandstone of late Early Miocene (Altonian) age (Mts)" (Mazengarb and Speden, 2000) – *EoD is based on the description in Leonard et al. (2010) of metre-bedded sandstone and thinner bedded units, which implies mass emplacement.*

## ***Middle Miocene Tolaga Group***

- **mMt**

(QMAP database spelling: undifferentiated Middle Miocene)

**Inferred age:** 16-15 Ma (Leonard et al., 2010)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone; Description = mudstone, minor sandstone (QMAP database). “It comprises massive mudstone and alternating, centimetre- to decimetre-bedded very fine-grained sandstone and siltstone... Middle Miocene Tolaga Group (MI) beds of the Ruatahuna outlier comprise a thin basal conglomerate, with overlying slightly calcareous, very fine-grained sandstone and sandy siltstone and massive mudstone, rarely with macrofossils. The uppermost beds preserved are massive mudstone and alternating centimetre- to decimetre-bedded sandstone and mudstone... Foraminifera indicate a Middle Miocene age and **shelf to lower bathyal** depositional environments” (Leonard et al., 2010) – *the lithologic description of the map unit in Leonard et al. (2010) seems to describe a deepening upwards succession, from innermost shelf conglomerate into mid-shelf very fine-grained sandstone and sandy siltstone, then outer shelf to bathyal mudstone, and finally mid- to lower bathyal flysch. The main rock type of mudstone implies an outer shelf to lower bathyal EoD for the map unit. An average mid-bathyal EoD is assigned to the map unit here.*

## ***Tunanui Formation (mMtu)***

**Inferred age:** 15-14 Ma (Field and Uruski, 1997)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone; Description = alternating sandstone/mudstone (QMAP database). “...consists largely of alternating centimetre- to decimetre-bedded, very fine-grained sandstone and siltstone... In the Ruakituri Valley, the unit includes massive siltstone, alternating centimetre- decimetre-bedded sandstone and mudstone and metre-bedded sandstone... Massive, fine-grained, calcareous sandstone underlies an alternating sandstone and siltstone sequence between the Hopuruahine and Mokau streams... Foraminifera are common throughout, and indicate an early Middle Miocene age (Clifdenian to Lillburnian; 15.9-12.7 Ma) and a **bathyal** depositional environment” (Leonard et al., 2010) – *the lithologic descriptions in the QMAP database and Leonard et al. (2010) are assumed here to be describing mid-fan flysch deposits (Fig. 3) which, along with the bathyal interpretation for the map unit in Leonard et al. (2010), indicates a mid-bathyal EoD for the map unit.*

## ***Ruatahuna Outlier (MI)***

(QMAP database spelling: undifferentiated Late Miocene mu)

**Inferred age:** 15-14 Ma (Leonard et al., 2010)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone; Description = mudstone, minor sandstone (QMAP database). “Middle Miocene Tolaga Group (MI) beds of the Ruatahuna outlier comprise a thin basal conglomerate, with overlying slightly calcareous, very fine-grained sandstone and sandy siltstone and massive mudstone, rarely with macrofossils... Foraminifera indicate a Middle Miocene age and **shelf to lower bathyal** depositional environments” (Leonard et al., 2010) – *the main rock type of mudstone implies that the map unit is dominated by its lower, comparatively finer-grained part. The sandstone that occurs within this lower part of the sequence (Leonard et al., 2010) are interpreted here as bathyal submarine fan deposits surrounded by hemipelagic mudstone (the main rock type). Consequently, a mid- to upper bathyal EoD is inferred for the map unit (Leonard et al., 2010) with a mid-bathyal depositional depth assigned to the unit here. An upper bathyal EoD is an alternative interpretation.*

## ***Late Miocene Tolaga Group***

“Undifferentiated Late Miocene Tolaga Group rocks (MI) comprise blue-grey mudstone and mudstone-dominated sequences, coarsening upward into siltstone-dominated units with minor rhyolitic tuff beds... Between the Ruakituri River and Lake Waikareiti, the lower part of the Late Miocene sequence forms two prominent strike ridges. These consist of five discrete centimetre- to

decimetre-bedded, sandstone-dominated horizons (Mla), with minor mudstone. The lowest of these... is overlain by massive or thick-bedded siltstone... Foraminifera indicate a Late Miocene age and **middle to upper bathyal** environments of deposition. The second of the horizons comprises... centimetre- to decimetre-bedded sandstone... The remaining three horizons are discontinuous, less prominent, and comprise **alternating** centimetre to decimetre-bedded, very fine-grained sandstone and siltstone, and intervening massive mudstone. The uppermost horizon is overlain by fossiliferous, sandy siltstone to silty sandstone..." (Leonard et al., 2010).

- **IMt**

(QMAP database spelling: Late Miocene mudstone)

**Inferred age:** 11-6 Ma (Leonard et al., 2010)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone; Description = mudstone, sandstone (QMAP database) – *the main rock type of mudstone implies that the map unit is dominated by its lower, comparatively finer-grained part. The sandstone that occurs within this lower part of the sequence (Leonard et al., 2010) is interpreted here as bathyal submarine fan deposits surrounded by hemipelagic mudstone (the main rock type). Consequently, a mid- to upper bathyal EoD is inferred for the map unit (Leonard et al., 2010) with an upper bathyal depositional depth assigned to the unit here. Mid-bathyal is an alternative interpretation.*

- **IMta**

**Inferred age:** 11-10 Ma (Leonard et al., 2010)

**EoD:** mid-bathyal (3 southern polygons), and upper bathyal (2 northern polygons)

**Basis for interpretation:** "Between the Ruakituri River and Lake Waikareiti, the lower part of the Late Miocene sequence forms two prominent strike ridges. These consist of five discrete centimetre- to decimetre-bedded, sandstone-dominated horizons (Mla), with minor mudstone... Foraminifera indicate a Late Miocene age and **middle to upper bathyal** environments of deposition" (Leonard et al., 2010) – *the unit is interpreted as consisting of mid-fan submarine deposits emplaced at mid-bathyal depths (Fig. 3). Refer to "IMta" on the Hawke's Bay map area for further information.*

## **Early Pliocene Mangaheia Group (ePmz)**

"The base of the Mangaheia Group in the map area is marked by Early Pliocene Opoiti Limestone (Pmo), a shelly, sandy limestone horizon c. 10 m thick that abruptly (and perhaps unconformably) overlies Tolaga Group... The overlying undifferentiated Mangaheia Group (Pmz) consists of shelly sandstone, sandstone and siltstone, with minor rhyolitic ash beds..." (Leonard et al., 2010).

**Inferred age:** 5-4 Ma (Mazengarb and Speden, 2000; Leonard et al., 2010)

**EoD breakdown:** 5 Ma: outer shelf

4 Ma: mid-shelf

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone; Description = siltstone, sandstone, tuff beds (QMAP database) – *EoD is based on the shelf interpretation for the map unit, and that the Mangaheia Group shallows over time. Upper bathyal may be an appropriate initial environment.*

## **Whangamomona Group**

### **Otunui Formation (mMo)**

**Inferred age:** 14-12 Ma (Kamp and Vonk, 2006)

**EoD:** outer shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone, conglomerate, limestone; Description = massive argillaceous, fine- to medium-grained sandstone with some mudstone and conglomerate; basal sandy limestone locally (Mang (QMAP database). "Massive to poorly bedded sandy siltstone and silty sandstone of the Middle Miocene Otunui Formation (Mgo), of the Whangamomona Group (Kamp et al. 2002), crop out southwest of Lake Taupo. Minor lithologies in the formation include thin glauconitic beds and shelly to pebbly conglomerate lenses" (Leonard et al., 2010). "During the middle Miocene (Upper Lillburnian), regional subsidence led to marked marine

transgression across the Whangamomona block in the King Country with accumulation of an **inner neritic shellbed** (Mangarara Formation) followed by siliciclastic **shelf and upper bathyal** facies of the Otunui Formation” (Puga-Bernabéu et al., 2009) – *the unfinished Description from the database is assumed to refer to the basal Mangarara Formation, as does the comment for Otunui Formation on the Taranaki map area. A general outer shelf EoD is assigned to the map unit. Refer to “Otunui Formation (mMo)” in the Waikato map area for further interpretations of the formation.*

## **Kiwitahi Volcanic Group (IMk)**

Includes Maungatapu, Ruru, Maungakawa, and Te Tapui cones.

**Inferred age:** 6 Ma (Black et al., 1992)

**EoD:** onshore intermediate eruptives

**Basis for interpretation:** Main\_Rock = basaltic **andesite**; Sub\_Rocks = volcanic breccia; Description = Olivine pyroxene basaltic andesite - andesite lava and breccia (QMAP database). “The Middle to Late Miocene Kiwitahi Volcanic Group (IMk)... includes the isolated remnants of several small stratovolcanoes... The youngest rocks of this group occur within the map area, as poorly exposed- and pyroxene-phyric, **basalt andesite to andesite** lava and scoria deposits erupted between 5.5 and 6.2 Ma...” (Leonard et al., 2010). “The rounded hill of Maungatapu is an eroded remnant of a volcanic cone... Olivine-bearing two-pyroxene **basaltic andesite** are most common, although two-pyroxene **basaltic andesite** (with no olivine) also occurs. Ruru (482 m), Maungakawa (495 m), and Te Tapui (492 m) are three symmetrical cones in a distinct line which shows a 305° alignment... Lithologies at Ruru, Maungakawa, and Te Tapui are olivine **basaltic andesite**, pyroxene **basaltic andesite**, and pyroxene **andesite**” (Black et al., 1992) – *EoD is based on Black et al. (1992) and Leonard et al. (2010) lithologic descriptions which indicate subaerial intermediate (to mafic) eruption products.*

## **Coromandel Group**

“Coromandel Group is an association of deposits primarily erupted from vents in the Coromandel Peninsula, north of the map area (Coromandel Volcanic Zone; Edbrooke 2001)” (Leonard et al., 2010).

### **Waiwawa Subgroup**

#### **Waipupu Formation (Mcw)**

**Inferred age:** 7 Ma (Brathwaite and Christie, 1996)

**EoD:** onshore intermediate eruptives

**Basis for interpretation:** Main\_Rock = volcanic breccia; Sub\_Rocks = andesite; Description = Pyroxene andesitic massive lensoidal tuff breccia and thick lava (QMAP database). “Waipupu Formation (Mci...) of the Waiwawa Subgroup, **consists predominantly of andesite** breccias, lava flows and minor epiclastic sediments” (Leonard et al., 2010) – *EoD is based on the QMAP and Leonard et al. (2010) lithologic descriptions which do not mention pillow basalts or a phreatomagmatic eruption style. Refer to “Waiwawa Subgroup (Mci)” on the Auckland map area for further information.*

### **Kaimai Subgroup**

#### **Uretara Formation (Mcu)**

**Inferred age:** 5-4 Ma (Takagi, 1995; Brathwaite and Christie, 1996)

**EoD:** onshore intermediate eruptives

**Basis for interpretation:** Main\_Rock = **andesite**; Sub\_Rocks = dacite, volcanic breccia; Description = Pyroxene and amphibole andesitic and dacitic predominantly flow banded and jointed lava; volcanic breccia; volcanoclastic mudstone (QMAP database). “Uretara Formation (Mca) consists of a sequence of alternating andesite-dacite lava flows and subordinate pyroclastic breccias..., epiclastic sediments and agglomerates, cut by minor intrusions/dikes...” (Leonard et al., 2010) – *EoD is based on the QMAP and Leonard et al. (2010) lithologic descriptions which do not mention pillow basalts or a phreatomagmatic eruption style. Refer to “Kaimai Subgroup (Mca)” on the Auckland map area for further information.*

### ***Omahia Formation (Plco)***

***Inferred age:*** 4 Ma (stratigraphic inferences)

***EoD:*** intermediate intrusives

***Basis for interpretation:*** Main\_Rock = **andesite**; Description = Olivine pyroxene **andesite dikes** (QMAP database). "...minor intrusions/dikes..." (Leonard et al., 2010) – *EoD is based on the QMAP description.*

### ***Pukepenga Formation (ePcp)***

***Inferred age:*** 5-4 Ma (Leonard et al., 2010)

***EoD:*** onshore intermediate eruptives

***Basis for interpretation:*** Main\_Rock = **andesite**; Sub\_Rocks = dacite volcanic breccia; Description = Andesite and dacite commonly jointed lava; intervening thin red volcanic breccia (QMAP database). "Pukepenga Formation (Pcp) andesite and dacite lava flows and autobreccias cap Uretara Formation..." (Leonard et al., 2010) – *EoD is based on the QMAP and Leonard et al. (2010) lithologic descriptions which do not mention pillow basalts or a phreatomagmatic eruption style.*

## **Whakamarama Group**

"Whakamarama Group includes rocks temporally and spatially intermediate between Coromandel Group and Whitianga Group in the Tauranga area..." (Leonard et al., 2010).

### ***Aongatete Formation (ePat)***

***Inferred age:*** 4 Ma (Briggs et al., 2005)

***EoD:*** onshore silicic eruptives

***Basis for interpretation:*** Main\_Rock = andesite; Sub\_Rocks = dacite, rhyolite, ignimbrite, tephra; Description = Andesite with subordinate dacite and rhyolite ignimbrite and tuff (QMAP database). "The Aongatete Ignimbrites consist of a >290 m sequence of non-welded to densely welded lenticular **dacitic ignimbrite** and tuff, with evidence (paleosols, intercalated sediments) for their having been erupted over a prolonged period of time (Houghton & Cuthbertson 1989)" (Briggs et al., 2005) – *EoD is based on the formation being an ignimbrite, however as it is dacitic, intermediate may also be an appropriate composition.*

### ***Waiteariki Formation (IPwt)***

***Inferred age:*** 2 Ma (Takagi, 1995; Briggs et al., 2005)

***EoD:*** onshore silicic eruptives

***Basis for interpretation:*** Main\_Rock = **ignimbrite**; Description = Crystal-rich **dacitic welded ignimbrite** (QMAP database). "The partly overlying Waiteariki Formation (Pww) is... a crystal-rich, welded, dacite ignimbrite..." (Leonard et al., 2010) – *EoD is based on the main rock type of the map unit being ignimbrite and the QMAP lithologic description which do not mention pillow basalts or a phreatomagmatic eruption style.*

## **Whitianga Group**

"The Tauranga area was the site of Late Pliocene stratovolcanoes and dome-forming eruptions. Rocks erupted from Tauranga Volcanic Centre are mapped as Whitianga Group" (Leonard et al., 2010).

### ***Otawa Formation (IPov)***

***Inferred age:*** 3 Ma (Stipp, 1968)

***EoD:*** onshore intermediate eruptives

***Basis for interpretation:*** Main\_Rock = **andesite**; Sub\_Rocks = basaltic andesite, dacite volcanic breccia; Description = Hornblende and pyroxene basaltic andesite to dacite lavas and volcanic breccia (QMAP database). "Peaks southwest of Te Puke are remnants of a stratovolcano comprising hornblende- and pyroxene-phyric, basaltic andesite to dacite lava and volcanic breccia. These make up the Ottawa Formation (IPo...)..." (Leonard et al., 2010) – *EoD is based on the QMAP and Leonard et al. (2010) lithologic descriptions which do not mention pillow basalt or a phreatomagmatic eruption style.*

### ***Minden Rhyolite Subgroup (IPlm)***

***Inferred age:*** 3-2 Ma (Takagi, 1995; Briggs et al., 2005)

***EoD:*** onshore silicic eruptives

***Basis for interpretation:*** Main\_Rock = **rhyolite**; Sub\_Rocks = Rhyodacite; Description = Flow-banded rhyolite to rhyodacite lava; often as domes or dome complexes, some highly eroded (QMAP database). "Minden Rhyolite Subgroup (Phm) includes rhyolite to rhyodacite flow-banded lavas erupted in and around the Tauranga area, including Mount Manganui..." (Leonard et al., 2010) – *EoD is based on the QMAP and Leonard et al. (2010) lithologic descriptions which do not mention pillow basalts or a phreatomagmatic eruption style. Minden Rhyolite Subgroup also occurs to the north on Poor Knights and Mokohinau islands (Whangarei map area) and throughout the eastern Coromandel Peninsula (Auckland map area).*

### ***Papamoa Formation (IPva)***

***Inferred age:*** 2 Ma (Briggs et al., 2005)

***EoD:*** onshore silicic eruptives

***Basis for interpretation:*** Main\_Rock = ignimbrite; andesite; Description = **Basaltic andesite to dacite ignimbrite**; Pyroxene andesite lava; minor tephra (QMAP database). "Papamoa Formation (IPp) is composed of multiple flow units of **rhyolite to dacite ignimbrite** forming a gently north-dipping fan" (Leonard et al., 2010) – *EoD is based on the main rock type of the map unit being ignimbrite and the QMAP lithologic description which do not mention pillow basalts or a phreatomagmatic eruption style.*

### ***Matakana Formation (IPlvb)***

***Inferred age:*** 3 Ma (Hollis, 1995)

***EoD:*** onshore mafic eruptives

***Basis for interpretation:*** Main\_Rock = basalt; Sub\_Rocks = scoria, lapilli, tuff; Description = Olivine basalt lava; olivine altered to iddingsite (QMAP database). "...Late Pliocene **basalt** at Matakana Island..." (Leonard et al., 2010) – *EoD is based on the QMAP lithologic description which does not mention pillow basalts or a phreatomagmatic eruption style.*

## **Ungrouped Pliocene volcanic rocks**

### ***Motiti Formation (ePlmo)***

***Inferred age:*** 4 Ma (Henry, 1991)

***EoD:*** onshore intermediate eruptives

***Basis for interpretation:*** Main\_Rock = **andesite**; Sub\_Rocks = volcanic breccia; Description = Pyroxene andesitic jointed lavas; minor volcanic breccia (QMAP database). "Motiti Island is situated 12 km offshore from the Bay of Plenty coast northeast of Tauranga (Fig. 2), and is a flat lying eroded remnant of a Pliocene andesitic composite cone. It has been K-Ar (whole rock) dated by Itaya (in Henry 1991) at  $4.32 \pm 0.68$  (Motiti Formation) and  $3.42 \pm 0.19$  Ma (Orongatea Formation), and has a similar composition to Kaimai Subgroup andesite" (Briggs et al., 2005) – *EoD is based on the QMAP and Briggs et al. (2005) lithologic descriptions which do not mention pillow basalts or a phreatomagmatic eruption style.*

### ***Motiti Formation (Plva)***

***Inferred age:*** 4 Ma (Henry, 1991)

***EoD:*** onshore intermediate eruptives

***Basis for interpretation:*** Main\_Rock = **andesite**; Description = Andesite volcanics (QMAP database). "Undifferentiated Pliocene **andesite** rocks (Pva) include rocks on Motiti Island..." (Leonard et al., 2010) – *EoD is based on the QMAP lithologic description which does not mention pillow basalts or a phreatomagmatic eruption style.*

### ***Orongatea formation (IPlor)***

***Inferred age:*** 3 Ma (Henry, 1991)

***EoD:*** onshore intermediate eruptives



**Basis for interpretation:** Main\_Rock = tuff; Sub\_Rocks = breccia andesite; Description = Pyroxene andesitic and basaltic andesitic agglutinate, ash, volcanic breccia and thin lava (QMAP database) – *EoD is based on the QMAP and Briggs et al. (2005) lithologic descriptions which do not mention pillow basalt or a phreatomagmatic eruption style.*

### **Hauhungaroa Formation (IPlha)**

**Inferred age:** 2-1 Ma (Appendix 1 in Leonard et al., 2010)

**EoD:** onshore intermediate eruptives

**Basis for interpretation:** Main\_Rock = **andesite**; Description = Eroded often weathered pyroxene andesite lava (QMAP database). “Hauhungaroa Formation lava (IPa) is the only ungrouped pre-Quaternary volcanic deposit mapped. It comprises mostly andesite lava lying to the southwest of Lake Taupo” (Leonard et al., 2010) – *EoD is based on the QMAP lithologic description which does not mention pillow basalts or a phreatomagmatic eruption style.*

### **Hauhungaroa Formation (IPlh/mMo, IPlh)**

**Inferred age:** 2-1 Ma (Leonard et al., 2010)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = conglomerate; Sub\_Rocks = gravel tephra; Description = Laharic andesitic bouldery conglomerate and coarse sandy gravel; interbedded andesitic tephra (QMAP database). “Hauhungaroa Formation **lahar** deposits (IPlh) consist of andesitic, boulder-rich conglomerate and coarse sandy gravel, with interbedded pyroclastic deposits” (Leonard et al., 2010) – *EoD is based on the laharic mode of deposition.*

## **Taupo Volcanic Zone**

“TVZ rocks are areally and volumetrically dominated by silicic ignimbrite sheets, with smaller lava domes, minor intermediate-composition stratovolcanoes, and scattered mafic scoria cones and lava flows” (Leonard et al., 2010). “The Taupo Volcanic Zone (TVZ) in the central North Island is the main focus of young volcanism in New Zealand. Andesitic activity started at c. 2 Ma, joined by voluminous rhyolitic (plus minor basaltic and dacitic) activity from c. 1.6 Ma” (Wilson et al., 1995). *The EoDs of the volcanic rocks of the TVZ have been assigned based mostly on the QMAP database, or where this appears to be incorrect, on Leonard et al. (2010) and other literature.*

### **Quaternary stratovolcanoes**

**Inferred age:** 2-0 Ma (Appendix 1 in Leonard et al., 2010)

“Andesite and dacite form prominent stratovolcanoes within the TVZ...” (Leonard et al., 2010). Includes the following units: Maungatautari Formation (eQmt onshore intermediate eruptives), Maungatautari Lahars (eQamt onshore), Hewson Formation (eQvb onshore mafic eruptives), Titirapenga Formation (IPlt onshore intermediate eruptives), Pureora Formation (IPva onshore intermediate eruptives), Rolles Peak Formation (eQvr onshore intermediate eruptives), Manawahe Formation [And Awakaponga Formation] (eQmw onshore intermediate eruptives), Manawahe Formation (Qd onshore intermediate eruptives), Kakaramea Formation (mQka onshore intermediate eruptives), Kakaramea Lahars (mQaka onshore) – *all the Quaternary stratovolcanoes and their associated products are defined as onshore because there is no mention of submarine products, e.g. pillow lavas. Their composition is defined after the QMAP database, or where this appears to be incorrect, Leonard et al. (2010) and other sources have been used.*

## **Mangakino Volcanic Centre**

### **Pakaumanu Group**

**Inferred age:** 2-1 Ma (Appendix 1 in Leonard et al., 2010)

“Voluminous and widespread deposits of the Pakaumanu Group (Kear 1960) dominate the landscape in the westernmost part of the map area... Pakaumanu Group consists mostly of welded **ignimbrites** along with two large phreatomagmatic fall deposits. All are **silicic**, apart from the **andesitic** Pouakani Formation. Most are inferred to have been erupted from the Mangakino caldera or nearby...” (Leonard et al., 2010). Includes the following onshore silicic eruptives: Link Formation

(eQf), Ngaroma Formation (eQn Includes Ignimbrite A, Rangitoto Ignimbrite, Ngaroma Lenticulite, and Ngaroma Ignimbrite), Tolley Formation (eQb), Pouakani Formation (eQc onshore intermediate eruptives), Ongatiti Formation (eQpo Includes Waipari Ignimbrite and Ongatiti Ignimbrite), Mangaokewa Formation (eQpm Includes Unit D, Ahuroa Ignimbrite, and Ranginui Lenticulite), Raepahu Formation (eQpr Includes Potaka Tephra, Unit E, Kidnappers Ignimbrite, and Rocky Hill Ignimbrite), undifferentiated Pakaumanu Group (eQp), Whakaahu Formation (eQwr), Marshall Formation (eQms) – *all products of the Pakaumanu Group are defined as onshore. Their composition is defined after the QMAP database, or where this appears to be incorrect, Leonard et al. (2010) and other sources are used.*

### ***Ungrouped early Quaternary silicic deposits***

***Inferred age:*** 1 Ma (Appendix 1 in Leonard et al., 2010)

“These deposits, mainly **ignimbrite**, are mapped either as undifferentiated or as Waiotapu Formation... Undifferentiated early Quaternary silicic pyroclastic deposits (eQi) comprise up to six previously described formations which individually crop out over small areas; these are briefly described below in stratigraphic order...” (Leonard et al., 2010). Includes the following onshore silicic eruptives: Pukerimu Formation (eQpt), Rahopaka Formation (eQrp), Unit X (eQx), Akatarewa Formation [Rahopaka?] (eQak), Waiotapu Formation (eQwi) – *all the ungrouped early Quaternary silicic products are defined as onshore.*

### **Whakamaru Group**

***Inferred age:*** < 0.5 Ma (Appendix 1 in Leonard et al., 2010)

“The group comprises a widely distributed collection of deposits mapped under various names in the map area (Grindley 1960; Briggs 1976; Keall 1988; Houghton et al. 1995)...” (Leonard et al., 2010). Includes the following onshore silicic eruptives: Whakamaru Group (Q9w, Q9w/Jtk Includes Whakamaru, Rangitaiki, Manunui, and Te Whaiti ignimbrites), Paeroa Formation (Q9wp Includes Te Kopia, Te Weta and Paeroa ignimbrites) – *all products of the Whakamaru Group are defined as onshore. Their composition is defined after the QMAP database.*

### **Ongaroto Group**

***Inferred age:*** 1 Ma (Appendix 1 in Leonard et al., 2010)

“...is comprised mostly of a north-trending complex of **rhyolite** lava domes (Fig. 36; the Western Dome Belt of Wilson et al. 1986)... Some Ongaroto Group lavas are locally flanked and underlain by rhyolite pyroclastic deposits (mQn), which comprise ash fall and block-and-ash flow deposits, with clasts ranging from poorly vesicular pumice to dense lava” (Leonard et al., 2010). Includes the following onshore silicic eruptives: mQvwp, mQvwr – *all products of the Ongaroto Group are defined as onshore because there is no mention of submarine products, e.g. pillow lavas. Their composition is defined after the QMAP database.*

### **Rotorua, Kapenga and Ohakuri Volcanic Centres**

#### ***Ungrouped middle and late Quaternary silicic deposits***

***Inferred age:*** < 0.5 Ma (Appendix 1 in Leonard et al., 2010)

“Some middle and late Quaternary **silicic** deposits are ungrouped because geographic, petrological and chronological association(s) amongst them have not been adequately clarified” (Leonard et al., 2010). Includes the following onshore silicic eruptives: Chimp Formation (Q8c), Pokai Formation (Q7p), Mamaku Plateau Formation (Q7mk), Ohakuri Formation (Q7oh), undifferentiated Rotorua-Kapenga (mQrl, mQvp, mQvr, lQvp, lQvr, Q13vr, Q7vr, Q6vr) – *all ungrouped middle and late Quaternary silicic products are defined as onshore because there is no mention of submarine products, e.g. pillow lavas.*

#### ***Ungrouped middle and late Quaternary basalt volcanoes***

***Inferred age:*** < 0.5 Ma (Appendix 1 in Leonard et al., 2010)

“**Basaltic** volcanic rocks are widely scattered across the TVZ, but comprise <0.1% by volume of TVZ deposits (Wilson et al. 1995a)” (Leonard et al., 2010). Includes the following onshore mafic eruptives: Matapan Formation (mQmb), Johnson Road Formation (mQhb, mQvb), Ongaroto Formation (lQob) – *all ungrouped middle and late Quaternary basaltic volcanoes are defined as onshore because there is no mention of submarine products, e.g. pillow lavas.*

### **Reporoa Volcanic Centre**

**Inferred age:** < 0.5 Ma (Appendix 1 in Leonard et al., 2010)

“Reporoa Volcanic Centre is the source for the Kaingaroa Formation (Q7k; Grindley 1960), which consists of ignimbrite and minor basal fall deposits (Nairn et al. 1994; Beresford & Cole 2000a)” (Leonard et al., 2010). Includes onshore silicic eruptives Kaingaroa Formation (Q7kiu).

### **Maroa Volcanic Centre, Maroa Group**

**Inferred age:** < 0.5 Ma (Appendix 1 in Leonard et al., 2010)

“Maroa Group comprises a complex of dome-forming **rhyolite** lavas with associated pyroclastic flow deposits (mostly ignimbrite)” (Leonard et al., 2010). Includes the following onshore silicic eruptives: Korotai Formation (Q8ko), Orakonui and Putauaki formations (Q8orl, Q8oru), Atiamuri Formation (Q7at), Pukeahua Formation (Q7pke, Q7pkw), Mokai Formation (Q7mo), Tatua and Kakuki formations (mQvb onshore mafic eruptives), Akatarewa Formation Basalt (mQvb onshore mafic eruptives), Puketarata Formation (Q2vmp, Q2vmr), undifferentiated Maroa Group (lQvmp, lQvmr, Q9vmr, Q8vmr, Q7vmp, Q7vmr, Q6vmr, Q5vmr, Q46vmp, Q3vmr) – *all products of the Maroa Group are defined as onshore because there is no mention of submarine products, e.g. pillow lavas.*

### **Taupo Volcanic Centre, Taupo Group**

**Inferred age:** < 0.5 Ma (Appendix 1 in Leonard et al., 2010)

“The term “Taupo Volcanic Centre” encompasses the eruptive vents of the Taupo area” (Leonard et al., 2010). Includes the following units: Tauhara Formation (Q7td onshore silicic eruptives), Karangahape Formation (2 polygons of Qvtp + 1 polygon of eQvb = Q7v on map onshore intermediate eruptives), Ngangiho Formation (Q3vtr onshore silicic eruptives), undifferentiated Taupo Group (Qvtp, lQvtp, lQvtr, Q5vtr, Q1vtr onshore silicic eruptives), undifferentiated (K Trig, Acacia Bay, Ben Lomond, Marotiri and Otaketake formations) (mQvb, mQpb onshore mafic eruptives), Oruanui Formation (Q3or Includes Aokautere Ash, Scinde Island Ash, Wairakei Breccia, Wairakei Formation, Kawakawa Tephra, Oruanui fall deposit, and Oruanui Ignimbrite onshore silicic eruptives), Taupo Pumice Formation (Q1ta onshore silicic eruptives) – *all the products of the Taupo Volcanic Centre are defined as onshore because there is no mention of submarine products, e.g. pillow lavas. Their composition is defined after the QMAP database, or where this appears to be incorrect, Leonard et al. (2010) and other sources are used.*

### **Okataina Volcanic Centre, Okataina Group**

**Inferred age:** < 0.5 Ma (Appendix 1 in Leonard et al., 2010)

“Okataina Group includes the products of Okataina Volcanic Centre (OVC) eruptions, east of Rotorua... Most of the post-61 ka Okataina Group deposits are included within the Mangaone, Haroharo or Tarawera subgroups” (Leonard et al., 2010). Includes the following onshore silicic eruptives: Matahina Formation (Q8ma, Q8ma/Q9w), Pokopoko Formation (Q8pp), Millar Road Formation (Q8mr), Puhipuhi Formation (lQpd), Rotoiti Formation (Q4ro), Earthquake Flat Formation (Q4eq), undifferentiated Okataina Group (mQvd, mQvop, mQvor, lQvor, Q78vp, Q57vp, Q14vor).

### **Mangaone Subgroup**

**Inferred age:** < 0.5 Ma (Appendix 1 in Leonard et al., 2010)

“...includes landscape-forming, gently dipping pyroclastic fan deposits...” (Leonard et al., 2010). Includes the following onshore silicic eruptives: Mangaone Formation (Q3m), Mangaone Formation (no unit code = fall deposit).

### ***Haroharo Subgroup***

***Inferred age:*** < 0.5 Ma (Appendix 1 in Leonard et al., 2010)

“Five silicic formations comprise Haroharo Subgroup” (Leonard et al., 2010). Includes the following onshore silicic eruptives: Te Rere Formation (Q2trp, Q2trr), Rotorua Formation (Q2ror), Rotoma Formation (Q1rmp, Q1rmr, Q1ol), Mamaku Formation (Q1mkp, Q1mkr), Whakatane Formation (Q1wkp, Q1wkr).

### ***Mount Tarawera Subgroup***

***Inferred age:*** < 0.5 Ma (Appendix 1 in Leonard et al., 2010)

“Mount Tarawera Subgroup includes the lavas and pyroclastic deposits forming Mount Tarawera, and comprises five formations. The first four are silicic and were erupted between c. 21,800 and 636 years ago, whereas the most recent is basaltic (Fig. 48)” (Leonard et al., 2010). Includes the following onshore silicic eruptives: Okareka Formation (Q2okp, Q2okr), Rerewhakaaitu Formation (Q2rep, Q2rer), Waiohau Formation (Q2wip, Q2wir), Kaharoa Formation (Q1kap, Q1kar, Q1vop), Tarawera Formation (Q1twp onshore mafic eruptives).

### ***Rotokawau and Edgecumbe formations***

***Inferred age:*** < 0.5 Ma (Appendix 1 in Leonard et al., 2010)

“Rotokawau Formation (Q1z) is associated with four maar craters on the northwestern margin of the Okataina Volcanic Centre, and comprises **basalt** pyroclastic deposits of bedded lapilli-rich and ash-rich scoria beds (Beanland & Houghton 1991). Edgecumbe Formation (Q1z), near Kawerau, includes the deposits of a pyroxene-bearing **andesite to dacite** stratovolcano comprising lava flows, domes and minor pyroclastic block-and-ash flows” (Leonard et al., 2010). Includes: Rotokawau Formation (Q1rb onshore mafic eruptives), Edgecumbe Formation (Q1ed onshore intermediate eruptives).

### ***Volcanic islands***

***Inferred age:*** < 0.5 Ma (Appendix 1 in Leonard et al., 2010)

“Moutohora (Whale) Island (Fig. 54) is dominated by Whale Formation (mQo), comprising **basaltic andesite to dacite lava** domes... White Island is the subaerial tip of an **andesite to dacite** stratovolcano in the Bay of Plenty, mapped as White Island Formation (lQc). It comprises the older, eroded, Ngatoro Cone in the north and the active Central Cone (Fig. 3; Cole et al. 2000)” (Leonard et al., 2010). Includes onshore intermediate eruptives: Whale Formation (mQwh), White Island Formation (lQwc, lQwn).

## **Quaternary – Sedimentary deposits**

- All Q deposits (except – see below)

***EoD:*** onshore

***Basis for interpretation:*** Based on the QMAP database which includes alluvial, beach, colluvial, lacustrine, lahar, landslide, peat, reclaimed land, rock fall, and swamp sediments in the Quaternary deposits.

## **Tauranga Group (eQu, mQu)**

***EoD:*** innermost shelf

***Basis for interpretation:*** “These deposits contain less alluvium than the early Quaternary Tauranga Group alluvium in the west, and **marine** sediments are a significant component” (Leonard et al., 2010) – onshore may also be appropriate.

## RAUKAMARU AREA (Geological Map 6)

### Tinui Group

#### **Whangai Formation (Kiw, ?Kiw)**

(QMAP database spelling: Tinui Gp, Whangai Fm)

Partly allochthonous (Terrane = East Coast Allochthon), partly autochthonous.

Includes Upper Calcareous Member, Porangahau Member, and Te Uri Member.

*Kiw*: Main\_Rock = mudstone; Description = Hard siliceous, poorly calcareous (lower), calcareous (upper) mudstone or shale (QMAP database). *?Kiw*: Main\_Rock = mudstone; Description = Siliceous mudstone (QMAP database). "...a thick, mudstone-dominated unit widely recognised throughout eastern New Zealand (Northland, Raukumara Peninsula, Hawke's Bay-Wairarapa and Marlborough) and in adjacent areas offshore... is inferred to have accumulated in a regionally extensive ocean basin, mainly at **bathyal** depths..." (Mazengarb and Speden, 2000). "The formation typically consists of 300-500 m of non-calcareous and calcareous shale and mudstone of Haumurian-Teurian age; rarely the formation may be up to 600 m thick (Moore 1988b)... Much of the Whangai Formation appears, from foraminiferal assemblages, to have accumulated at **bathyal** depths (...), although **outer shelf to upper bathyal** species have been found in the Upper Calcareous Member. This revises the interpretation given in Moore (1988b) of largely shelf depths for the Whangai. Planktics form generally less than 10% of Upper Calcareous Member foraminiferal assemblages" (Field and Uruski, 1997).

- **Upper Calcareous Member**

"...consists of poorly bedded, medium grey, hard, slightly to moderately calcareous (1-15%), micaceous mudstone, with laminae, bioturbation, sporadic calcareous concretions, pyrite nodules and beds of glauconitic sandstone. It is recognised throughout the region, but in some eastern areas it is partly replaced by the laterally equivalent Porangahau Member... **outer shelf to upper bathyal** species have been found in the Upper Calcareous Member" (Field and Uruski, 1997).

- **Porangahau Member**

"In the Waitahaia River area, centimetre- to decimetre-bedded sandstone, siliceous mudstone with chert nodules and moderately calcareous mudstone are mapped as a part of the Porangahau Member..." (Mazengarb and Speden, 2000). "...is a well-bedded, light grey to white, hard, moderately calcareous mudstone, with common glauconitic sandstone beds" (Field and Uruski, 1997).

- **Te Uri Member**

"The Waipawa Formation is contemporaneous with, at least in part, the upper part of the **mid- to upper bathyal** Te Uri Member" (Field and Uruski, 1997).

**Inferred age:** > 65-60 Ma (Field and Uruski, 1997)

**EoD allochthonous units:** allochthonous

**EoD in place units:** upper bathyal

**Basis for interpretation:** *Some of the map unit is considered part of the East Coast Allochthon in the QMAP database and consequently is defined as allochthonous here. The EoD for the in place units is defined here as upper bathyal, based on the QMAP description and lithology; however outer shelf and even mid-bathyal may be alternative environments based on comments in the literature. The Upper Calcareous Member may be reworked downslope. On the geological map sheet ?Kiw is mapped as Kiw, so is here assumed to be part of Kiw.*

### Mangatu Group

#### **Wanstead Formation**

(QMAP database spelling: Mangatu Gp, Wanstead Fm)

"Deposition of mud-rich sediments continued throughout the Eocene and Oligocene... In the southwest of the Raukumara map area the Waipawa Formation is conformably overlain by Wanstead Formation (Egw), which consists of up to 200 m of poorly bedded, bioturbated, green-grey to blue-grey,

calcareous, glauconitic mudstone, with minor alternating glauconitic sandstone and mudstone, and locally, massive muddy greensand... Wanstead clays accumulated from background sedimentation in a deep ocean basin... Foraminifera suggest deposition was mainly at **mid bathyal** depths” (Mazengarb and Speden, 2000). “The formation is known from all North Island East Coast basins where Paleogene aged strata are recorded... is mainly a poorly bedded, highly bioturbated, green-grey, calcareous mudstone with beds of glauconitic sandstone in places. In parts the formation is highly smectitic, and can be siliceous or brecciated. Other lithofacies included in the formation are the Te Waka Greensand (Black 1980), breccia and conglomeratic units, poorly to well-bedded glauconitic sandstone and mudstone, flysch facies, and siliceous units... At Mangapapa Stream (X17), there is up to 100 m of upper Runangan Wanstead, with paleobathymetry increasing up-section from **outermost shelf to upper bathyal**... The Wanstead Formation is generally considered to represent the deepest depositional environment of the Late Cretaceous-Paleogene of the East Coast, with average paleodepths generally **mid-bathyal**, and **lower bathyal-abyssal** in parts. Nevertheless, there are some instances of **shelf** deposition within the glauconite-dominated Te Waka Greensand facies at Parihohonu Stream, X17, and at Te Weraroa and Ngamangatawa streams” (Field and Uruski, 1997).

- **Egw**

Partly allochthonous (Terrane = East Coast Allochthon), partly autochthonous.

**Inferred age:** 57-37 Ma (Field and Uruski, 1997)

**EoD allochthonous units:** allochthonous

**EoD in place units:** mid-bathyal

**Basis for interpretation:** Main\_Rock = mudstone; Description = Mudstone, minor greensand, red/green mudstone (QMAP database) – *some of the map unit is considered part of the East Coast Allochthon in the QMAP database and consequently is defined as allochthonous here. The in place units are defined here as mid-bathyal, based on the lithology and comments in Field and Uruski (1997). Lower bathyal-abyssal may be an alternative EoD, or for the formation to deepen over time.*

- **Egwg**

Partly allochthonous (Terrane = East Coast Allochthon), partly autochthonous.

**Inferred age:** 57-37 Ma (Field and Uruski, 1997)

**EoD allochthonous units:** allochthonous

**EoD in place units:** upper bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Description = Glauconitic sandstone (greensand) (QMAP database) – *some of the map unit is considered part of the East Coast Allochthon in the QMAP database and consequently is defined as allochthonous here. It is thought that this unit code may represent the Te Waka Greensand of Black 1980 that is mentioned in Field and Uruski (1997). Therefore it may be appropriate to define the in place units as outer shelf, based on the lithology, presence of glauconite, and comments in Field and Uruski (1997).*

## **Weber Formation**

(QMAP database spelling: Mangatu Gp, Weber Fm)

“...rests unconformably on Wanstead Formation, but may overlie it conformably in the east, as in the area of Waerengaokuri... It consists of up to 400 m of calcareous, alternating, glauconitic sandstone and mudstone, and light grey bioturbated, calcareous massive mudstone... foraminifera suggest deposition was mainly at **mid bathyal** depths” (Mazengarb and Speden, 2000). “The paleoecology of the Weber Formation is generally quite uniform, with high percentages of planktic foraminifera indicating oceanic conditions and generally **mid-bathyal** paleodepths. While there is evidence for shallower deposition, most of the shelf faunas are considered to have been **reworked downslope**. The Weber Formation was possibly deposited at slightly shallower depths than some of the preceding Wanstead Formation, suggesting a slight regional regression” (Field and Uruski, 1997).

- **Ogw**

Partly allochthonous (Terrane = East Coast Allochthon), partly autochthonous.

**Inferred age:** 38-22 Ma (Field and Uruski, 1997)

**EoD allochthonous units:** allochthonous

**EoD in place units:** mid-bathyal

**Basis for interpretation:** Main\_Rock = mudstone; Description = Calcareous mudstone, greensand, sandstone, minor conglomerate, limestone (QMAP database) – *some of the map unit is considered part of the East Coast Allochthon in the QMAP database and consequently is defined as allochthonous here. EoD is based on the Field and Uruski (1997) mid-bathyal interpretation. The main rock type of mudstone is consistent with deposition at mid-bathyal depths in an area isolated from submarine fans, although the alternating sandstone and mudstone mentioned in the QMAP description may represent sediment gravity flow deposits. The Weber Formation also occurs as a calc-turbidite facies.*

- ?Ogws

Weber Formation mislabelled as “Tolaga Group” in QMAP database.

**Inferred age:** 38-22 Ma (Field and Uruski, 1997)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = greensand; Sub\_Rocks = mudstone; Description = greensand and mudstone (QMAP database) – *EoD is based on the Field and Uruski (1997) mid-bathyal interpretation for the Weber Formation. The lithologic description of the map unit combined with Fig. 3 could also indicate an outer shelf to upper bathyal depth of deposition for the map unit, but as with Ogw, these may have been reworked down slope. NB: on the geological map sheet ?Ogws is mapped as Ogw sandstone, so is here assumed to be part of Ogw. It is also mislabelled as “Tolaga Group”.*

### **Whangai Fm & Mangatu Gp (Kiw-Egw)**

Partly allochthonous (Terrane = East Coast Allochthon), partly autochthonous.

**Inferred age:** > 65-37 Ma (Field and Uruski, 1997)

**EoD allochthonous units:** allochthonous

**EoD breakdown in place units:**

> 65-60 Ma: upper bathyal (Whangai Formation)

59-58 Ma: upper bathyal (Waipawa Formation)

57-37 Ma: mid-bathyal (Wanstead Formation)

**Basis for interpretation:** Main\_Rock = mudstone; Description = Noncalcareous mudstone, smectitic mudstone, and thin glauconite beds (QMAP database) – *based on the combined unit code, this unit appears to include Whangai, Waipawa and Wanstead Formations. The EoD range for the in place units is based on that which has been determined in this report for the individual formations. Refer to “Whangai Formation (Kiw, ?Kiw)” and “Wanstead Formation” on the Raukumara map area, and “Whangai and Waipawa formations (Kiw, ?Kiw)” on the Hawke’s Bay map area for further interpretations and possible alternative environments.*

### **Whangai Fm & Mangatu Gp (Kiw-Ogw)**

**Inferred age:** > 65-22 Ma (Field and Uruski, 1997)

**EoD breakdown:** > 65-60 Ma: upper bathyal (Whangai Formation)

59-58 Ma: upper bathyal (Waipawa Formation)

57-22 Ma: mid-bathyal (Wanstead Formation, Weber Formation)

**Basis for interpretation:** Main\_Rock = mudstone; Description = Noncalcareous mudstone, smectitic mudstone, and thin glauconite beds, and muddy limestone (QMAP database) – *based on the combined unit code, this unit appears to include Whangai, Waipawa, Wanstead and Weber Formations. The EoD range is based on that which has been determined in this report for the individual formations. Refer to “Whangai Formation (Kiw, ?Kiw)”, “Wanstead Formation” and “Weber Formation” on the Raukumara map area, and “Whangai and Waipawa formations (Kiw, ?Kiw)” on the Hawke’s Bay map area for further interpretations and possible alternative environments.*

### **Waipawa Fm & Mangatu Gp (Piw-Ogw, Piw-Ogw~)**

**Inferred age:** 59-22 Ma (Field and Uruski, 1997)

**EoD breakdown:** 59-58 Ma: upper bathyal (Waipawa Formation)

57-22 Ma: mid-bathyal (Wanstead Formation, Weber Formation)

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = limestone, sandstone; Description = see Waipawa, Wanstead & Weber Fms (QMAP database) – *based on the combined unit code, this unit appears to include Waipawa, Wanstead and Weber Formations. The EoD range is based on that which has been determined in this report for the individual formations. Refer to “Wanstead Forma-*

tion" and "Weber Formation" on the Raukumara map area, and "Whangai and Waipawa formations (Kiw, ?Kiw)" on the Hawke's Bay map area for further interpretations and possible alternative environments.

### **Wanstead and Weber formations (Egw+Ogw, Egw+Ogw~, Egw+Ogws)**

Partly allochthonous (Terrane = East Coast Allochthon), partly autochthonous.

**Inferred age:** 57-22 Ma (Field and Uruski, 1997)

**EoD allochthonous units:** allochthonous

**EoD in place units:** mid-bathyal

**Basis for interpretation:** Sub\_Rocks = mudstone, limestone, sandstone; Description = Mudstone, limestone, sandstone (QMAP database) – based on the combined unit code, this unit appears to include Wanstead and Weber Formations. The EoD range is based on that which has been determined in this report for the individual formations. Refer to "Wanstead Formation" and "Weber Formation" for further interpretations and possible alternative environments.

### **East Coast Allochthon (various unit codes)**

Includes Matakaoa Volcanic Group (Kov, Kog, Kos), Ruatoria Group (Rip Volcanics (eKrr), Mokoivi Formation (eKrm), Taitai Sandstone (eKrt), Tikhore Formation (eKri, eKri~, Kri, lKri, lKri~, lKrib, lKris, lKriv, lKriz), Tapuwaeroa Formation (lKrp, ?lKrp), Whangai Formation (Kiw), Tikhore and Whangai formations (lKri-Kiw), Wanstead Formation (Egw, Egw~, Egwg), Whangai and Wanstead formations (Kiw-Egw, Kiw-Egw~), Waipawa and Wanstead formations (Piw+Egw), Weber Formation (Ogw, Ogwl, Ogw-eMt), Wanstead and Weber formations (Egw+Ogw, Egw+Ogwl), Whakai Formation (?eMtl), and Early Miocene Tolaga Group (eMt, eMts).

**Inferred age:** 24-18 Ma (Boyes et al., 2011a)

**EoD:** allochthonous

**Basis for interpretation:** Terrane = **East Coast Allochthon** (QMAP database) – EoD is based on the QMAP definition of the map units as part of the East Coast Allochthon.

### **Tolaga Group**

"...Early Miocene rocks are terrigenous and much thicker [than underlying Mangatu Group], containing sequences of massive blue-grey mudstone, alternating centimetre- to metre-bedded sandstone and mudstone, and massive sandstone, with lesser conglomerate and tuff" (Mazengarb and Speden, 2000). "...Tolaga Group (Waitakian to upper Tongaporutuan), consisting of marine mudstone with packets of **flysch, thick-bedded sandstone**, and minor limestone, conglomerate and tuff" (Field and Uruski, 1997). "Tolaga Group **deep water** Miocene sandstone units occur in many places on Raukumara Peninsula. At Waiiau River the group includes several **bathyal channel-fill** units of sandstone and grit as well as units of **thin-bedded turbidites**" (Stagpoole et al., 2008).

#### **Early Miocene Tolaga Group**

"The bulk of the Tolaga Group (MI) comprises massive and thinly bedded mudstone" (Mazengarb and Speden, 2000). "The Miocene succession of the region consists mainly of **bathyal** mudstone and **flysch** punctuated with units of paralic conglomerate, and neritic sandstone and limestone... the initial setting for the Otaian for most of the region appears to have been **bathyal**... The record of the Altonian is more complete than that of the Otaian, mainly comprising **deep-water** mudstone, with pulses of **flysch** and a few units of limestone. Sedimentation rates were markedly higher than in the Waitakian or Otaian... Altonian rocks of the Raukumara Peninsula belong to the Tolaga Group and consist mainly of **bathyal** mudstone and **flysch**, with a few units of conglomerate and limestone" (Field and Uruski, 1997).

- **eMt**

Partly allochthonous (Terrane = East Coast Allochthon), partly autochthonous.

**Inferred age:** 22-16 Ma (Mazengarb and Speden, 2000)

**EoD allochthonous units:** allochthonous

**EoD in place units:** upper bathyal

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone; Description = Mudstone, minor sandstone/mudstone (QMAP database) – based on the distribution of sediments in the Rau-



kumara map area for the early Miocene described in Field and Uruski (1997), both shelf and bathyal sediments appear to be represented in the eMt map unit. The shelf slope break seems to run between the Hangaroa River section and the Waikura River section, out to the northeast to the east of the Waitangi Station section and between the Mangaorongo Stream and Waiau River sections. The north-east sections appear to be bathyal. Consequently, the map unit appears to encompass significant areas of both outer shelf and upper bathyal sediment. The map unit is defined here as upper bathyal but the reader is made aware that this fails to acknowledge possible shelf sediments represented by the map unit to the west of the map area. Includes two polygons that have a unique Map\_Unit; one = Ngatapa Mudstone, the other = Pukahika Mudstone.

- ?eMt

**Inferred age:** 22-16 Ma (Mazengarb and Speden, 2000)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone; Description = Mudstone and sandstone (QMAP database) – EoD is based on the main rock type combined with Fig. 3. However, an outer shelf environment may be appropriate based on the Field and Uruski (1997) description of the distribution of sediments which places basal Tolaga Group shelf sediments in the southwest of the Raukumara map area.

- eMt~

**Inferred age:** 22-16 Ma (Mazengarb and Speden, 2000)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone; Description = Mudstone, minor sandstone (QMAP database) – based on the main rock type an upper to lower bathyal EoD is possible.

- eMta

**Inferred age:** 19-18 Ma (Mazengarb and Speden, 2000)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone; Description = alternating sandstone/mudstone (QMAP database). “Alternating sandstone and mudstone units are locally distinguished (Mla)” (Mazengarb and Speden, 2000) – *alternating sandstone and mudstone beds can be interpreted as flysch deposits. This interpretation implies a mid-bathyal EoD. Includes two polygons that have a unique Map\_Unit; one = “Cocos Flysch”, the other = Rere Sandstone.*

- eMtb

**Inferred age:** 21 Ma (Mazengarb and Speden, 2000)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = breccia; Description = sedimentary breccia (QMAP database). “In the Tauwhareparae area units of Late Oligocene to Early Miocene (Waitakian-Otaian) tuffaceous sandstone-mudstone and breccia-conglomerate... are now recognised as part of the Tolaga Group (Mlb and Mlv)... These breccia-bearing units are considered to be synorogenic, deposited in “piggy-back” basins during and immediately following emplacement of the East Coast Allochthon. The wide range of lithologies present in some breccias indicates East Coast Allochthon units were being uplifted and eroded during the thrust sheet emplacement” (Mazengarb and Speden, 2000) – *this unit was deposited during and after the emplacement of the East Coast Allochthon so it is defined as upper bathyal.*

### ***Ihungia Conglomerate (eMtc)***

**Inferred age:** 20-19 Ma (Mazengarb and Speden, 2000)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = conglomerate; Sub\_Rocks = mudstone, sandstone; Description = Igneous conglomerate (QMAP database). “Igneous pebble conglomerate (Mlc; the Ihungia igneous conglomerate of McKay 1887) is common at or near the base of the Tolaga Group from Oweka Stream in the north (Y14/647875), Tarndale in the west (Y16/311121) and as far east as Puketiti Station... Conglomerate beds are channelized and range up to about 10 m thick. They

are commonly interbedded with dark grey, fine- to coarse-grained sandstone and intercalated with mudstone or alternating sandstone and mudstone facies” (Mazengarb and Speden, 2000) – *the map unit is interpreted to represent upper-submarine fan channel fill sediment deposited at upper bathyal depths (Fig. 3).*

### ***Moonlight and Kouetumarae limestones (eMtk)***

***Inferred age:*** 18-16 Ma (Field and Uruski, 1997)

***EoD:*** mid-shelf

***Basis for interpretation:*** Main\_Rock = limestone; Description = Shelly limestone (QMAP database). “In the upper Waipaoa valley the Moonlight Limestone consists of up to 150 m of moderately to well cemented, poorly bedded, locally flaggy, coarse- to very coarse-grained, bioclastic limestone interbedded with calcareous sandstone. Large oyster shells are common. The Kouetumarae Limestone is an equivalent... it consists of up to 20 m of poorly bedded, flaggy, bryozoan coquina limestone and shelly, bryozoan-rich sandstone. The limestones are **shallow marine** deposits, inferred to have accumulated at **shelf** depths...” (Mazengarb and Speden, 2000) – *EoD is based on the Mazengarb and Speden (2000) descriptions and interpretations of the limestones, combined with Fig. 3, implying a mid-shelf EoD for the map unit. This Moonlight Limestone is a different formation from the seep limestone occurrences described by Campbell et al. (2008) and Nyman et al. (2010).*

- **eMtl**

***Inferred age:*** 21 Ma (Mazengarb and Speden, 2000)

***EoD:*** mid-shelf

***Basis for interpretation:*** Main\_Rock = limestone; Description = Limestone (QMAP database). “At Huiarua, near the headwaters of the Mata River (Y16/420308), sandy and muddy limestone with basal breccia-conglomerate and intercalations of breccia (Mll) rest unconformably on Tikhore Formation” (Mazengarb and Speden, 2000) – *EoD is based on the lithologic description of the map unit and Fig. 3.*

### ***Whakai Formation (eMtm)***

***Inferred age:*** 21-18 Ma (Field and Uruski, 1997)

***EoD:*** lower bathyal

***Basis for interpretation:*** Main\_Rock = mudstone; Sub\_Rocks = tuff, conglomerate, breccia; Description = Mudstone, basal conglomerate and limestone, tuff (QMAP database). “In northernmost Raukumara Peninsula the Matakaoa Volcanics are overlain unconformably by the Whakai Formation (Chapman-Smith and Grant-Mackie 1971), the basal beds of which are limestone-cemented breccia with intercalated, flaggy, oyster-rich limestone (Fig. 23, Mlb). Most of the Whakai Formation consists of well bedded, **alternating sandstone and mudstone**, massive mudstone (Fig. 24, Mlm) and metre-bedded lensoidal bodies of igneous pebble conglomerate (Mlc) of Early Miocene (Otaian-Altonian) age” (Mazengarb and Speden, 2000). “At its base is a late Waitakian coarse breccia, conglomerate or bioclastic limestone where it rests on Matakaoa Volcanics. The remainder of the formation is mainly mudstone and **flysch... Deep-water** mudstone of the Whakai Formation ranges in age from Waitakian to Otaian. In a tributary of the Wharekahika River (Z14/c6), there is over 270 m of **mid- to lower bathyal** Whakai Formation mudstone of Otaian age” (Field and Uruski, 1997). “The biostratigraphy of a rapidly deposited, **deep bathyal**, lower Altonian (Early Miocene) sequence through Whakai Formation, East Cape, is presented... Benthic foraminiferal paleodepth proxies suggest that the site was on the **lower slope (>1000 m)** throughout, but the moderate abundance of planktonic taxa shows that it was not in fully oceanic water” (Morgans et al., 2002) – *the cited references indicate a mid- to lower bathyal depth of deposition for the Whakai Formation.*

- **eMts**

Partly allochthonous (Terrane = East Coast Allochthon), partly autochthonous.

***Inferred age:*** 18-17 Ma (Mazengarb and Speden, 2000)

***EoD allochthonous units:*** allochthonous

***EoD in place units:*** upper bathyal

***Basis for interpretation:*** Main\_Rock = sandstone; Sub\_Rocks = mudstone; Map\_Unit = Marine (shelf) sandstone; Description = muddy sandstone (QMAP database). “At Hangaroa River and

Mutuera Stream the basal sediments include a thin conglomerate, cross-bedded, shelly, pebbly sandstone (Joass 1987) and muddy fossiliferous sandstone of late Early Miocene (Altonian) age (Mls)" (Mazengarb and Speden, 2000). "Early Miocene Tolaga Group (Mls) consists of fossiliferous, blue-grey, calcareous sandstone and siltstone with sparse metre-bedded calcareous sandstone, and **alternating** centimetre- to decimetre-bedded sandstone and siltstone sequences" (Leonard et al., 2010) – *EoD is based on the description in Leonard et al. (2010) of metre-bedded sandstones and thinner bedded units, which implies a mass emplacement. Includes one polygon that has a unique Map\_Unit; Morunga Sandstone.*

- **eMtv**

**Inferred age:** 19-18 Ma (Mazengarb and Speden, 2000)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone; Description = Tuffaceous sandstone/mudstone (QMAP database). "In the Tauwhareparae area units of Late Oligocene to Early Miocene (Waitakian-Otaian) tuffaceous sandstone-mudstone and breccia-conglomerate... are now recognised as part of the Tolaga Group (Mlb and Mlv)" (Mazengarb and Speden, 2000) – *the alternating sandstone and mudstone beds are assumed here to be flysch deposits. Based on this assumption, and Fig. 3, the map unit is interpreted as mid-fan sediment gravity flow sediments deposited at mid-bathyal depths. As it was deposited during and after the emplacement of the East Coast Allochthon, upper bathyal may be an appropriate alternative.*

### **Whangara Sandstone (eMtw)**

**Inferred age:** 23-22 Ma (Field and Uruski, 1997)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Description = glauconitic sandstone / greensand (QMAP database). "It comprises up to 20 m of medium- to coarse-grained, highly glauconitic sandstone. Several small areas are mapped separately (Mlk)" (Mazengarb and Speden, 2000). "The Whangara greensands occur in parts of the Raukumara Peninsula, extending at least as far south as Waikura River (X18/c2; see map 19) and are considered to lie disconformably on Weber Formation. They comprise over 20 m of **bathyal or possibly mid-inner shelf** (a sample from the lowest 20 cm of the basal greensand gave an **outer shelf-upper bathyal** paleodepth, but this may have been contaminated by reworked bathyal ?Weber Formation), medium to coarse greensand alternating with siltstone..." (Field and Uruski, 1997). "The formation is glauconite rich and contains scattered fossil fragments, especially large benthic foraminifera and bryozoans (Ridd 1964). The lower mid part of the formation has at least five, graded, glauconite rich beds (thickness range 0.28-3.9 m), which are very coarse at their bases and fine to medium at the tops... The formation probably represents a **sand-filled bathyal channel**" (Neef and Bottrill, 1992). "The **shelfal** Whangara Sandstone is a highly glauconitic unit of earliest Miocene age (Waitakian) and, if the events controlling this glauconite accumulation were regional, there might be a time-correlative of this unit in the Raukumara Basin" (Stagpoole et al., 2008) – *based on the cited references an EoD of shelfal to upper bathyal is possible for the map unit. An upper bathyal paleodepth is chosen here after Neef and Bottrill (1992) and Field and Uruski (1997).*

### **Whangara Greensand (Ogws~)**

(QMAP database spelling: Weber Fm or basal Tolaga Gp)

**Inferred age:** 23-22 Ma (Field and Uruski, 1997)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Map\_Unit = Whangara Greensand; Description = Greensand (QMAP database) – *this polygon is labelled "Weber Fm or basal Tolaga Group" in the QMAP database, but is mapped as Whangara Greensand of the Tolaga Group (eMtw).*

### **Middle Miocene Tolaga Group**

"South of Te Puia they are mainly mudstone, locally with intercalations of metre-bedded sedimentary breccia and lenses of Bexhaven Limestone... Locally, however, the Middle Miocene beds are mainly **alternating**, centimetre- to decimetre-bedded, fine-grained sandstone and mudstone, with minor pebble conglomerate" (Mazengarb and Speden, 2000). "Clifdenian sediments of the Rauku-

mara Peninsula belong to the Tolaga Group... Pick (1962; ages reassessed) recorded at least 130 m of lower and mid-Clifdenian **upper bathyal** siltstone with sandstone beds at Whakatu Stream... Coarse deposits of the Tolaga Group are most common in the Altonian-Clifdenian record (Mazengarb et al., 1991) and it seems likely that this influx was caused partly by relative falls in sea level during this period, as found at Waiau River (Y16/c7). At this locality, the Clifdenian is 700-760 m thick and includes at least two **bathyal** lowstand channel-fill deposits... Lower Lillburnian strata are mainly mudstone while the upper Lillburnian is dominated by **flysch**... at Anauraiti Stream (Y16/c7), most of the 110 m of Waiau strata present is siltstone, with interbeds of sandstone near the top. The section is probably all **mid- to upper bathyal** lower Waiau...” (Field and Uruski, 1997).

- **mMt**

**Inferred age:** 15-12 Ma (Mazengarb and Speden, 2000)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone; Description = Mudstone, minor sandstone (QMAP database) – *EoD is based on the QMAP lithologic description, Fig. 3, and the Field and Uruski (1997) description of middle Miocene Tolaga Group rocks as predominantly bathyal deposits.*

- **?mMt, ?mMt~**

**Inferred age:** 15-12 Ma (Mazengarb and Speden, 2000)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone; Description = mudstone, minor sandstone (QMAP database) – *EoD is based on the QMAP lithologic description, Fig. 3, and the Field and Uruski (1997) description of middle Miocene Tolaga Group rocks as predominantly bathyal deposits.*

- **mMta**

**Inferred age:** 14-13 Ma (Mazengarb and Speden, 2000)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone; Description = Alternating sandstone/mudstone (QMAP database). “...**alternating** sandstone and mudstone have been mapped informally as Makaretu sandstone or Rerepe sandstone” (Mazengarb and Speden, 2000) – *the map unit’s alternating sandstone/mudstone deposits are sediment gravity flow deposits of a mid-fan at mid-bathyal depths (Fig. 3).*

### **Waiokaha Formation (mMth)**

(QMAP database spelling: Tolaga Gp, Waiokaha Fm)

**Inferred age:** 15 Ma (Mazengarb and Speden, 2000)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = sandstone, mudstone, conglomerate; Description = limestone, sandstone, mudstone, conglomerate (QMAP database) – *EoD is based on that of nearby rocks at the time.*

### **Tunanui Formation (mMtu, Mtu~)**

(QMAP database spelling: Tolaga Group, Tunanui Formation)

**Inferred age:** 15-14 Ma (Field and Uruski, 1997)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone; Description = **Alternating** sandstone/mudstone (QMAP database). “Locally, however, the Middle Miocene beds are mainly alternating, centimetre- to decimetre-bedded, fine-grained sandstone and mudstone, with minor pebble conglomerate... one such unit, the Tunanui Formation (Mlu), is up to 2000 m thick...” (Mazengarb and Speden, 2000) – *the map unit’s alternating sandstone/mudstone deposits are inferred to be sediment gravity flow deposits of a mid-fan at mid-bathyal depths (Fig. 3).*

## **Late Miocene Tolaga Group**

“Mudstone is the dominant lithology (Ml) with intercalations of well bedded alternating sandstone and mudstone (Mla; Fig. 25), and shelly muddy sandstone (Mlz). Late Miocene sandstone-dominated alternating sandstone and mudstone units present between Gisborne and Wairoa have been mapped as Makaretu sandstone” (Mazengarb and Speden, 2000).

- **IMt**

**Inferred age:** 11-6 Ma (Mazengarb and Speden, 2000)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone, tuff; Description = Mudstone, minor sandstone/mudstone, tuff (QMAP database). “The Miocene sedimentary succession, about 2,200 m thick, is dominated by calcareous mudstone interbedded with resedimented rhyolitic tuff beds, **turbiditic** sandstone and some massive debris-flow units up to 40 m thick” (Chanier et al., 1999) – *the interpretation of the minor sandstone (QMAP database) at Mahia peninsula as turbiditic (Chanier et al., 1999) implies a bathyal EoD for the map unit. The map unit is defined as upper bathyal here but could alternatively represent sedimentation at mid- to lower bathyal depths on parts of the continental slope affected by distal turbidites.*

- **?IMt**

**Inferred age:** 11-6 Ma (Mazengarb and Speden, 2000)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone; Description = mudstone, sandstone (QMAP database) – *the map unit is defined as upper bathyal here but could alternatively represent sedimentation at mid- to lower bathyal depths on parts of the continental slope affected by distal turbidites.*

- **IMt~**

**Inferred age:** 11-6 Ma (Mazengarb and Speden, 2000)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone; Description = Mudstone, minor sandstone, tuff (QMAP database) – *the map unit is defined as upper bathyal here but could alternatively represent sedimentation at mid- to lower bathyal depths on parts of the continental slope affected by distal turbidites.*

- **IMta, IMta~**

**Inferred age:** 10-8 Ma (Mazengarb and Speden, 2000)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone; Description = Sandstone dominated alternating sandstone/mudstone (QMAP database) – *the map unit's alternating sandstone/mudstone deposits are assumed to be sediment gravity flow deposits of a mid-fan at mid-bathyal depths (Fig. 3). Refer to “IMta” on the Hawke’s Bay map area for further information.*

## **Bexhaven Limestone (IMtl)**

(QMAP database spelling: Tolaga Group, Bexhaven Limestone)

**Inferred age:** 13 Ma (Field and Uruski, 1997)

**EoD:** lower bathyal

**Basis for interpretation:** Main\_Rock = limestone; Map\_Unit = Cold seep fauna limestone; Description = Fossiliferous limestone (QMAP database). “The Bexhaven Limestone is a micritic, sulphurous and fossiliferous limestone considered to have formed around cold water seeps on the sea floor, similar to the modern seeps known offshore” (Mazengarb and Speden, 2000). “The limestone units appear to be in situ **bathyal** biocommunities resembling bioherms and might be associated with sea-floor vents (see Marshall and Lewis 1996) and/or deep-sea condensed sections” (Field and Uruski, 1997). “We located three of the previously suspected seep sites (Lewis and Marshall, 1996) as well as six additional active seep sites at depths of **716–1166 m**” (Baco et al., 2010) – *EoD is based on the Mazengarb and Speden (2000) and Field and Uruski (1997) interpretations of the Bex-*

haven Limestone as having formed around cold seeps, combined with the observation by Baco et al. (2010) of active seep sites occurring at lower bathyal depths.

### **Patutahi Limestone**

(QMAP database spelling: Tolaga Group, Patutahi Limestone)

“Near Patutahi discontinuous outcrops of shelly limestone 10-20 m thick (Patutahi Limestone, Mlp; Beu 1995; Fig. 28) are present within mudstone and the basal contact may be partly or wholly unconformable” (Mazengarb and Speden, 2000). “It was deposited at ?mid-shelf depths and probably records a relative rise in sea level following a significant fall” (Field and Uruski, 1997).

- **IMtp**

**Inferred age:** 9 Ma (Field and Uruski, 1997)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = limestone; Description = shelly limestone (QMAP database) – this limestone is possibly a channelised, redeposited limestone.

- **?IMtp**

**Inferred age:** 9 Ma (Field and Uruski, 1997)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = limestone; Description = Sandy, shelly limestone (QMAP database).

### **Areoma Formation (IMtr)**

(QMAP database spelling: Tolaga Group, Areoma Formation)

**Inferred age:** 11-10 Ma (Field and Uruski, 1997)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone, tuff; mudstone, limestone; Description = fossiliferous sandstone, minor mudstone, tuff; fossiliferous sandstone, minor limestone (QMAP database). “Decimetre-to metre-bedded, fine-grained, fossiliferous sandstone which form a prominent tableland in Mangatu Forest (Areoma Sandstone, Mlr)...” (Mazengarb and Speden, 2000). “...In Y16, the Areoma Sandstone (Mazengarb et al. 1991; map 26 and enclosure 6 B-B’), a unit of Tongaporutuan sandstone with thin mudstone interbeds, lies at an unconformity on Waiau strata in the west but with a probably conformable basal contact to the east. The unit reaches 600 m thick at Moonlight Station and locally has a basal shelly conglomerate, channel fill units including rafts of sediment, and coquina limestone... The Areoma Sandstone is **upper bathyal to outer shelf near the base**, pebbly, and contains macrofossils. **Up-section, foraminifera indicate mid- to outer shelf depths...**” (Field and Uruski, 1997). “A regional up-sequence shallowing in facies near the base of the Late Miocene is associated with the widespread Areoma Sandstone. This unit is about 20 m thick at Anauraiti Stream where it unconformably overlies Middle Miocene bathyal siltstone. The sandstone is very fine, so reservoir quality could be compromised by diagenesis, but it is a regional unit that might have a correlative in the Raukumara Basin or at least suggest a likely influx of sand into the Raukumara Basin in the early Late Miocene” (Stagpoole et al., 2008) – based on the cited references the Areoma Formation was deposited at upper bathyal depths. The QMAP description of the map unit indicates that it is predominantly a fossiliferous sandstone, which in conjunction with Fig. 3 implies an innermost shelf EoD, but the fauna are probably in redeposited (mass emplaced) sandstone beds as part of a submarine fan or channel system.

• **IMtv, IMtv~**

**Inferred age:** 8-7 Ma (Mazengarb and Speden, 2000)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = tuff; Sub\_Rocks = mudstone; Description = tuffaceous sandstone/mudstone (QMAP database). “Some of the Late Miocene sequences include abundant volcanic tuff (Mlv) derived from rhyolitic eruptions in the Coromandel Peninsula area” (Mazengarb and Speden, 2000) – the alternating sandstone and mudstone beds are assumed here to be flysch deposits. Based on this assumption, and Fig. 3, the map unit is interpreted as a mid-fan sediment gravity flow deposited at mid-bathyal depths.

- IMtz, IMtz~

**Inferred age:** 8-7 Ma (Mazengarb and Speden, 2000)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Description = fossiliferous siltstone (muddy sandstone) (QMAP database) – *EoD is based on the QMAP lithologic description combined with Fig. 3.*

## Mangaheia Group

“The latest Miocene to Pliocene Mangaheia Group (Mazengarb et al. 1991a) consists of up to 2000 m of shelly sandstone, sandstone and mudstone” (Mazengarb and Speden, 2000). “...at Mangahona... The lower Tongaporutuan section is about 1100 m thick and is capped at an unconformity by **mid- to outer shelf**, probably lower Kapitean sandstone of the Mangaheia Group... Plio-Pleistocene successions commonly display more recognisable and higher frequency of facies cyclicity than Miocene rocks... The Opoitian appears to be a transgressive systems tract... Although foraminifera indicate that most of the formation was deposited at **outer shelf to bathyal depths**, diverse macrofossils near the top of the formation, similar to those at Oweka Stream, indicate **inner shelf** conditions... East of Waikaremoana (W18/c2), about 300 m of **?bathyal** Opoitian Mapiri Formation consists of alternating siltstone and sandstone, with common beds of redeposited pumice” (Field and Uruski, 1997).

### *Late Miocene to Early Pliocene Mangaheia Group (IMPm)*

(QMAP database spelling: Mangaheia Group?)

**Inferred age:** 6-5 Ma (Mazengarb and Speden, 2000)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = limestone, mudstone; Description = Silty sandstone with common tuff beds, sandy mudstone, minor shelly limestone (Waikura Limestone), local conglomerate (QMAP database). “In northern Raukumara Peninsula the East Coast Allochthon and Tolaga Group units are unconformably overlain by a **shallow marine** sequence of tuffaceous, fossiliferous sandstone, calcareous mudstone and minor limestone (Te Kahika Formation of Chapman-Smith & Grant-Mackie 1971). Near East Cape the rocks comprise an upwards-coarsening and **shallowing** sequence deposited at depths between **upper bathyal to shelf** (Ballance et al. 1984)” (Mazengarb and Speden, 2000). “At Oweka Stream... **shallow-marine** sandstone and about 4 m of interbedded sandstone and limestone (Waikura Limestone, Beu 1995)...” (Field and Uruski, 1997) – *on the Raukumara map area this unit is labelled as undifferentiated Late Miocene to Early Pliocene sediments, with a thin basal conglomerate of limestone, that is, the Waikura Limestone. This unit is assigned an average mid-shelf EoD.*

### *Tokomaru Sandstone (IMmk)*

(QMAP database spelling: Mangaheia Gp, Tokomaru Sandstone)

**Inferred age:** 7-6 Ma (Field and Uruski, 1997)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Description = sandstone, minor limestone, mudstone (QMAP database). “Between Te Puia and Tolaga Bay the Tolaga Group beds are unconformably overlain by bluff-forming shelly sandstone and muddy sandstone of the Tokomaru Sandstone (Mmk)...” (Mazengarb and Speden, 2000). “The formation is fine grained, but has at least one localised, basal conglomerate lens, some medium-grained calcarenites, and a tuff bed. From composite sections, the formation can be subdivided into a lower 100 m of homogeneous, thick-bedded, fine-grained sandstone, followed by at least 200 m of alternating, frequency graded, very fine sandstone and coarse siltstone... Foraminifera indicate **upper to mid bathyal** water depths, but transported inner shelf forms are also present... The conglomerates were possibly emplaced by high-density turbulent flows with subsequent tractional reworking. The thick-bedded sandstone and alternating sequence were deposited by many **turbidity currents**” (Blom, 1984). “...foraminifera indicate an **upper bathyal** paleobathymetry and recognised turbidity currents as a major depositional mechanism” (Field and Uruski, 1997) – *EoD is based on interpretations in Blom (1984) and Field and Uruski (1997). Mid-bathyal is an alternative depositional depth for the map unit.*

## **Early Pliocene Mangaheia Group**

- **ePmz, ePmz~**

“...Ramanui Formation (Pmz) consists mainly of alternating sandstone and mudstone, with lesser sandstone, mudstone, tuff and limestone (Mazengarb et al. 1991a; Field, Uruski et al. 1997)” (Mazengarb and Speden, 2000).

**Inferred age:** 5-4 Ma (Mazengarb and Speden, 2000)

**EoD breakdown:** 5 Ma: outer shelf  
4 Ma: mid-shelf

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone; Description = Siltstone, sandstone, tuff beds (QMAP database) – *EoD is based on the shelfal interpretation for the map unit, and that the Mangaheia Group shallows over time. Upper bathyal may be an appropriate initial environment.*

- **?ePmz**

**Inferred age:** 5-4 Ma (Mazengarb and Speden, 2000)

**EoD breakdown:** 5 Ma: outer shelf  
4 Ma: mid-shelf

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = tuff; Map\_Unit = **shelf** deposits; Description = Fossiliferous mudstone and tuffaceous sandstone (QMAP database) – *EoD is based on the shelfal interpretation for the map unit, and that the Mangaheia Group shallows over time. Upper bathyal may be an appropriate initial environment.*

- **ePms**

**Inferred age:** 5 Ma (Mazengarb and Speden, 2000)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = sandstone; Description = calcareous sandstone (QMAP database). “South of Gisborne Early Pliocene Mangaheia Group rocks are mainly sandstone, some of which are tuffaceous (Pms)...” (Mazengarb and Speden, 2000) – *EoD is based on the QMAP lithologic description combined with Fig. 3. The map unit could alternatively represent a mid-shelf depositional environment.*

- **Ormond Limestone (ePmm)**

(QMAP database spelling: Mangaheia Gp, Ormond Limestone)

**Inferred age:** 5 Ma (Field and Uruski, 1997)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = sandstone; Description = shelly sandy limestone (QMAP database). “...forms a basal or near-basal shellbed overlain by up to 1800 m of muddy sandstone, siltstone, flysch, and sparse pale grey tephra (Neef 1992b)” (Field and Uruski, 1997) – *EoD is based on the QMAP lithologic description combined with Fig. 3. The map unit could alternatively represent a mid-shelf depositional environment.*

- **Opoiti Limestone (ePmo)**

(QMAP database spelling: Mangaheia Gp)

**Inferred age:** 5 Ma (Field and Uruski, 1997)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = sandstone; Description = Sandy shelly limestone (QMAP database). “Several unconformity-based, discontinuous, shelly limestones have been differentiated (Opoiti Limestone, Pmo and Whakapunake Limestone, Pmw; Beu 1995)” (Mazengarb and Speden, 2000) – *EoD is based on the QMAP lithologic description combined with Fig. 3. The map unit could alternatively represent a mid-shelf depositional environment.*

- **Whakapunake Limestone (ePmw, ePmw~)**

**Inferred age:** 4 Ma (Field and Uruski, 1997)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = limestone; Description = Sandy limestone with coquina beds



/ sandy shelly limestone (QMAP database). “Several unconformity-based, discontinuous, shelly limestones have been differentiated (Opoiti Limestone, Pmo and Whakapunake Limestone, Pmw; Beu 1995)” (Mazengarb and Speden, 2000) – *EoD is based on the QMAP lithologic description combined with Fig. 3. The map unit could alternatively represent a mid-shelf depositional environment.*

### **Late Pliocene Mangaheia Group**

- **IPmz**

“South of Gisborne Early Pliocene Mangaheia Group rocks are mainly sandstone, some of which are tuffaceous (Pms), and mudstone (Pmz)” (Mazengarb and Speden, 2000).

**Inferred age:** 3-2 Ma (Mazengarb and Speden, 2000)

**EoD breakdown:** 3 Ma: mid-shelf  
2 Ma: innermost shelf

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = tuff; Description = Siltstone, tuffaceous sandstone, limestone (QMAP database) – *EoD is based on the shelfal interpretation for the map unit, and that the Mangaheia Group shallows over time.*

- **?IPmz**

**Inferred age:** 3-2 Ma (Mazengarb and Speden, 2000)

**EoD breakdown:** 3 Ma: mid-shelf  
2 Ma: innermost shelf

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone; Description = fossiliferous mudstone and tuffaceous sandstone (QMAP database) – *EoD is based on the shelfal interpretation for the map unit, and that the Mangaheia Group shallows over time.*

- **Tahaenui Limestone (IPmt)**

(QMAP database spelling: Mangaheia Group)

**Inferred age:** 3 Ma (Field and Uruski, 1997)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = limestone; Description = Sandy coquina limestone (QMAP database). “The unconformably overlying Late Pliocene shelly limestone (Tahaenui Limestone, Pmt; Beu 1995) is conformably and gradationally overlain by thick sandstone, mudstone and minor limestone” (Mazengarb and Speden, 2000) – *EoD is based on the QMAP lithologic description combined with Fig. 3. The map unit could alternatively represent a mid-shelf depositional environment.*

### **Quaternary – Sedimentary deposits**

- **All Q deposits** (except – see below)

**EoD:** onshore

**Basis for interpretation:** Based on the QMAP database which includes alluvial, beach, dune, estuarine, landslide, paleosol, sinter, and swamp sediments in the Quaternary deposits.

- **Q11b, Q9b, Q9m, Q7b, Q6b, Q5b, Q3b**

**EoD:** innermost shelf

**Basis for interpretation:** “Shallow marine... Elevated marine terraces...” (Mazengarb and Speden, 2000).

## TARANAKI AREA (Geological Map 7)

### Te Kuiti Group

“Rocks of the Te Kuiti Group (Ot) are exposed in the northeast corner of QMAP Taranaki and include in total up to 200 m of laterally discontinuous thin coal measures, bioclastic limestone, and calcareous and glauconitic sandstone (e.g. Fyfe 1945; Gregg et al. 1960)... The age of Te Kuiti Group rocks on QMAP Taranaki is probably restricted to the Late Oligocene (Sinclair 1987)” (Townsend et al., 2008).

#### *Okoko Subgroup (Otl)*

“The two-fold subdivision of the Te Kuiti Group is extended here to the central and northern regions. The lower five formations (Waikato Coal Measures, Mangakotuku, Glen Massey, Whaingaroa, and Aotea) are assigned to the Okoko Subgroup, and the three upper formations (Orahiri, Otorohanga, and Te Akatea) are assigned to the Castle Craig Subgroup” (Tripathi et al., 2008; Kamp et al., 2014a).

**Inferred age:** 34-27 Ma (Tripathi et al., 2008; Kamp et al., 2014a)

**EoD breakdown:**

34 Ma:	<u>onshore</u> (Waikato Coal Measures, Mangakotuku Formation)
33-32 Ma:	<u>outer shelf</u> (Mangakotuku Formation, Glen Massey Formation)
31-30 Ma:	<u>mid-shelf</u> (Glen Massey Formation, Whaingaroa Formation)
29 Ma:	<u>innermost shelf</u> (Whaingaroa Formation, Aotea Formation)
28-27 Ma:	<u>mid-shelf</u> (Aotea Formation)

**Basis for interpretation:** Main\_Rock = siltstone; Sub\_Rocks = sandstone, mudstone, limestone, coal; Description = Siltstone and sandstone with local limestone conglomerate and coal; calcareous in upper part (QMAP database) – *the EoD of the Okoko Subgroup is broken down into time intervals based on the EoD of the dominant or average formation at the time. Refer to “Okoko Subgroup (Otl)” on the Waikato map area for more information. The Okoko Subgroup has previously been referred to as the Lower Te Kuiti Subgroup (Tripathi et al., 2008).*

#### *Castle Craig Subgroup (Otu)*

**Inferred age:** 27-23 Ma (Tripathi et al., 2008; Kamp et al., 2014a)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = sandstone, conglomerate, coal; Description = Limestone, ranging from massive sandy to glauconitic and pebbly varieties through to pure flaggy bioclastic limestone, and thick (QMAP database). “The two-fold subdivision of the Te Kuiti Group is extended here to the central and northern regions. The lower five formations (Waikato Coal Measures, Mangakotuku, Glen Massey, Whaingaroa, and Aotea) are assigned to the Okoko Subgroup, and the three upper formations (Orahiri, Otorohanga, and Te Akatea) are assigned to the Castle Craig Subgroup” (Tripathi et al., 2008) – *the formations in this subgroup have an average EoD of mid-shelf. Refer to “Castle Craig Subgroup (Otu)” on the Waikato map area for more information. The Castle Craig Subgroup has previously been referred to as the Upper Te Kuiti Subgroup (Tripathi et al., 2008).*

### Mahoenui Group

“The Mahoenui megasequence accumulated mostly at **bathyal** depths; no regressive deposits are evident, having been eroded during subsequent uplift... The Mahoenui Group comprises massive mudstone (Taumatamaire Formation) and flysch (Taumarunui Formation) facies (Nelson and Hume 1977)” (Kamp et al., 2002). “The occurrence of turbidites and other mass flow deposits (flysch facies) in the Mahoenui Group are indicative of **submarine fan** deposition and hence a **slope or basin floor** environment” (Bear, 2006).

#### *Taumatamaire Formation (eMt)*

**Inferred age:** 22-21 Ma (Kamp and Vonk, 2006)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = limestone; Description = Bioturbat-

ed, massive to weakly bedded mudstone with rare interbedded limestone (QMAP database). “The Taumatamaire Formation (Met), resting unconformably on Te Kuiti Group, consists of massive to weakly bedded, blue-grey, calcareous mudstone to fine sandy mudstone, which is glauconitic at the base, and local limestone beds. The lack of coarse-grained sediments reflects initial sediment starvation as the basin deepened to **mid-bathyal** conditions...” (Townsend et al., 2008). “It accumulated in mainly **outer shelf to mid-bathyal** settings, the limestones deposited marginal to the Herangi High probably reflect periods of inner shelf deposition...” (Edbrooke, 2005) – *an average upper bathyal EoD is assigned to the map unit but outer shelf or mid-bathyal depositional depths are alternative options. Refer to “Taumatamaire Formation (eMt)” on the Waikato map area for further information.*

### **Taumarunui Formation (eMa)**

**Inferred age:** 21-20 Ma (Kamp and Vonk, 2006)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone; Description = Interbedded, massive or graded sandstone and mudstone (QMAP database). “The Taumarunui Formation (Mea) consists of well-bedded, redeposited sandstone, siltstone and mudstone (**flysch/turbidite**) facies that accumulated largely in the southern part of the depocentre around Taumarunui...” (Townsend et al., 2008) – *the map unit is interpreted as mid-fan deposit at mid-bathyal depths. Refer to “Taumarunui Formation (eMa)” on the Waikato map area for further information.*

### **Mokau Group**

#### **Maryville Coal Measures (eMm)**

**Inferred age:** 17 Ma (Kamp and Vonk, 2006)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone, coal, shale, conglomerate; Description = Grey-brown, muddy sandstone, mudstone, carbonaceous shale and thin coal seams (QMAP database). “Basal deposits of the Mokau Group (not exposed on QMAP Taranaki) are overlain by 120 m of conglomerate, sandstone, mudstone, carbonaceous mudstone and coal of the Maryville Coal Measures (Mum...)... The coal measures were deposited in a **deltaic coastal plain** in the late Early Miocene...” (Townsend et al., 2008) – *EoD is based on the interpretation of the formation in Townsend et al. (2008).*

#### **Tangarakau Formation (eMn)**

**Inferred age:** 16-15 Ma (Kamp and Vonk, 2006)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = siltstone, shale, shell beds; Description = Grey, massive to well bedded or laminated, fine muddy sandstone with thin siltstone beds and conglomerate; common shell beds (QMAP database). “The Tangarakau Formation was deposited in **shoreface to inner shelf** environments during the late Early Miocene to Middle Miocene” (Townsend et al., 2008) – *EoD is based on the interpretation of the formation in Townsend et al. (2008).*

### **Whangamomona Group**

#### **Mangarara and Otunui formations (mMo)**

**Inferred age:** 14-12 Ma (Kamp and Vonk, 2006)

**EoD:** outer shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone, conglomerate, limestone; Description = Massive argillaceous, fine- to medium-grained sandstone; mudstone and conglomerate; basal sandy limestone locally (Mangarara F.) (QMAP database). “The basal Whangamomona Group comprises a Middle Miocene sequence, which includes the Mangarara and Otunui formations (Mgo). The Mangarara Formation (Vonk 1999) forms the oldest part of this succession in the King Country Basin... The Otunui Formation is predominantly massive to weakly bedded sandy siltstone and silty sandstone, with intervals of blue-grey fissile mudstone containing thin glauconitic-

ic beds, and shelly granule to pebble conglomerate lenses... The Otunui Formation passes laterally westward into finer grained siltstone of the Manganui and Moki formations (not exposed at the surface) and gradually upward into the Mount Messenger Formation... To the east, Otunui Formation consists predominantly of fine sandstone containing lenses and beds of well-rounded greywacke pebble conglomerate..." (Townsend et al., 2008). "During the Middle Miocene (Upper Lillburnian), regional subsidence led to marked marine transgression across the Whangamomona block in the King Country with accumulation of an **inner neritic shellbed** (Mangarara Formation) followed by siliciclastic **shelf and upper bathyal** facies of the Otunui Formation" (Puga-Bernabéu et al., 2009) – a general outer shelf EoD is assigned to the map unit. Refer to "Otunui Formation (mMo)" in the Waikato map area for further information.

### **Mount Messenger Formation (Mgm)**

**Inferred age:** 11-9 Ma (King et al., 1993; Kamp and Vonk, 2006)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone siltstone; Description = Interbedded fine to very fine sandstone and mudstone or siltstone, with some channelized conglomerate horizons; massive mudstone (QMAP database). "In the west of QMAP Taranaki it consists of sheets of fine to medium sandstone interbedded with siltstone, with localised basal channel-filling conglomerates. Sandstone-dominated units include normally-graded **turbidites and debris flow deposits**, with several prominent convolute-bedded horizons reflecting slumping into deeper water of contemporary **continental slope deposits** (King et al. 1993). In the east, the base of the formation grades upward from the generally massive sandy siltstone – silty sandstone of the Otunui Formation into blue-grey mudstone and sandstone separated by units of fissile mudstone. The Mount Messenger Formation was deposited as aprons of sediment on the **lower continental slope** and, together with the Urenui, Kiore and Matemateaonga formations, formed a sediment wedge that prograded to the northwest..." (Townsend et al. 2008). "Lowermost sequences [of Mount Messenger Formation] are composed primarily of early lowstand system tract **basin floor fan** deposits, whereas uppermost cycles consist mainly of mid-lowstand **slope fan deposits**" (King and Thrasher, 1996). "[Lower sandstone unit:] ... is dominated by fine- to coarse grained, medium- to thick-bedded sandstone... The sandstone beds are massive or occasionally graded and contain water escape structures. Similar characteristics typify high density, non-turbulent (laminar) liquefied flow deposits, and also the upper beds (S3) of high density turbidity current deposits... [Middle siltstone/sandstone interbed unit:] In lower parts of the middle interbed unit, separate horizons contain upper and lower bathyal faunas in varying proportions. In all probability, background sedimentation was at **lower bathyal** depths, and admixing resulted from downslope re-working... some oscillation of bathymetry is possible... In upper parts of the middle interbed unit, the depocentre **shallowed to mid bathyal** water depths... [Upper sandstone unit:] **Uppermost mid-bathyal** water depths are inferred to the upper sandstone unit of the formation, though a marked upsequence decrease in paleobathymetry is not obvious" (King et al., 1993) – *the Mount Messenger Formation is dominantly a bathyal deposit, which shallowed over time from lower to upper bathyal. Mid-bathyal is inferred to be the dominant EoD; consequently this is the assigned EoD.*

### **Mount Messenger Formation (MgmK)**

**Inferred age:** 11-9 Ma (Kamp and Vonk, 2006)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone, siltstone; Description = Interbedded fine to very fine sandstone and mudstone or siltstone; massive mudstone (QMAP database) – refer to "Mount Messenger Formation (Mgm)" for reasoning for this interpretation. This formation occurs in the area north of Tahora and south of the Tangarakau Gorge.

### **Urenui Formation (Mgu)**

**Inferred age:** 9-8 Ma (King et al., 1993; Kamp and Vonk, 2006)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = siltstone; Sub\_Rocks = conglomerate sandstone; Description = Medium to light grey, weakly bedded, bioturbated siltstone and mudstone with incised, coarse channel-fill sequences (QMAP database). "The Urenui Formation (Mgu) of the Whangamomo-

na Group (Kamp et al. 2004) consists of massive to weakly bedded, heavily bioturbated siltstone and mudstone, with thin tuffaceous beds... Major channel systems 30 – 60 m thick, filled with debris-flow conglomerate, sandstone and/or mudstone (up to 2 km wide) punctuate the sequence... The Urenui Formation was deposited during the Late Miocene on a **continental slope**, facing and prograding northwest, and cut by slope-canyon complexes” (King et al., 1993; Townsend et al., 2008). “Large volumes of mainly fine-grained Urenui sediment were subsequently deposited on the **mid-upper slope**, at slightly slower sedimentation rates than the Mount Messenger Formation. Fine-grained sediments were preferentially deposited on the **slope**, whereas coarse-grained sediments were funnelled further into the **basin**, or deposited within isolated slope channel complexes” (King et al., 1993). “The predominantly fine-grained Urenui Formation represents background deposition on the prograding continental slope. This is corroborated by benthic foraminifera assemblages which indicate an up-sequence shallowing from **mid- to upper-bathyal** depths over the Urenui Formation stratigraphic interval exposed on the north Taranaki coast...” (King and Thrasher, 1996). “Extensive foraminiferal analysis of the overlying Urenui Formation (Faulconbridge 1994) indicates a paleodepth of 600-900 m (**upper bathyal**) at the basal contact of the Urenui Formation with the underlying Mount Messenger” (Manley and Lewis, 1998) – *the paleodepth range of the Urenui Formation is outer shelf to mid-bathyal (King and Thrasher, 1996). An average upper bathyal EoD is assigned to the map unit, and is supported by the upper bathyal interpretation of the Urenui Formation in Manley and Lewis (1998).*

### **Kiore Formation (Mgk)**

**Inferred age:** 9-6 Ma (King et al., 1993; Kamp and Vonk, 2006)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = siltstone, limestone, conglomerate; Description = Massive to finely laminated siltstone and sandstone with discontinuous sandstone, conglomerate and limestone channel fill sequence (QMAP database). “In the west, the Kiore Formation (Mgk...) is a massive to laminated siltstone, sandy siltstone and sandstone, up to 500 m thick... The Kiore Formation includes discontinuous channels that represent chutes and feeder channels, individual and nested channels, and troughs; the channels are filled with massive sandstone, siltstone, pebble to conglomerate and bioclastic limestone... In the east, organic-rich, micaceous and carbonaceous sandstone and shale with fossil bands were deposited near Retaruke on the fringes of the basin... The inferred environment of deposition in the west is **outer shelf to uppermost slope**, with mass-emplacment of channel fill units, and in the east **shallow marine, marginal marine, deltaic and coastal plain** environments” (Townsend et al., 2008) – *EoD is based on Fig. 3 and the similarities between the QMAP lithologic description and the lithologic descriptions of the western Kiore Formation, which is considered an outer shelf to uppermost slope deposit (Townsend et al., 2008).*

### **Matemateaonga Formation (Mga, Pga)**

**Inferred age:** 7-5 Ma (Kamp and Vonk, 2006)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone, limestone, conglomerate; Description = Repeated sequences of sandstone, siltstone, shellbeds and minor conglomerate (QMAP database). “The Matemateaonga Formation (Mga...) is characterised by repeated cycles of deposition (**cyclothems**), comprising predominantly muddy sandstone, with siltstone, mudstone, limestone or shellbeds, coal and locally conglomerate (particularly in areas of basement onlap...)... Shellbeds are usually laterally continuous, unlike those in the underlying Kiore Formation... The environment of deposition includes **shoreface to mid-shelf** (Hendy and Kamp, 2004) with a shoreline to the south and progradational front towards the north or northwest” (Townsend et al., 2008) – *the EoD is narrowed down to mid-shelf here.*

## **Rangitikei Supergroup**

“The base of the Rangitikei Supergroup represents a major regional subsidence event, referred to as the “Tangahoe pull-down”, and marks the initiation of the Wanganui Basin as a separate depocentre (Kamp et al. 2004). The Rangitikei Supergroup comprises mudstone in its lower part, with increasing amounts of sandstone and lithologically diverse cyclothems in its upper part. The contact

between the Matemateaonga Formation and the supergroup is an abrupt, but gradational (over 10–30 cm) transition from sandstone to mudstone, glauconitic in many sections. This transition represents a dramatic increase in paleodepth combined with stratigraphic condensation in the Early Pliocene (Hayton 1998; Kamp et al. 2004). In the west, older component units of the supergroup include Tangahoe Mudstone, and the Whenuakura, Paparangi, Okiwa and Nukumaru groups (Fleming 1953; see Fig. 28). In the east, equivalent stratigraphic units have traditionally been mapped slightly differently and include Tangahoe Mudstone, overlain by Utiku and Paparangi groups, and Mangarere, Tikapu, Makohine, Orangipongo, Mangaonoho and Vinegar Hill formations (Naish & Kamp 1995; Kamp et al. 2004)” (Townsend et al., 2008).

### **Tangahoe Mudstone (Pt)**

**Inferred age:** 4-3 Ma (Kamp and Vonk, 2006)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone, limestone; Description = Massive mudstone interbedded with well sorted, fine to medium, micaceous sandstone (QMAP database). “The lower part of the Rangitikei Supergroup in the map area comprises the Tangahoe Mudstone (Pt; Arnold 1957), a massive to weakly bedded, blue-grey mudstone containing packets of amalgamated, well-sorted, micaceous fine sandstone beds... In the east, the Tangahoe Mudstone consists of massive, blue-grey mudstone with calcareous concretions up to 2 m in diameter... The Tangahoe Mudstone accumulated during the Early Pliocene as muddy slope deposits in **upper to mid-bathyal** water depths, the packets of sandstone beds being parts of **submarine fan** deposits that probably accumulated during sea level low-stands” (Townsend et al., 2008). “...very rapid bathymetric deepening events in the Pliocene section of Wanganui Basin, the other occurring about 1.5 My earlier (~4.3 Ma) at the contact between the Matemateaonga and Tangahoe Formation, and involving at least 200-300 m of increase in water depth” (Kamp et al., 1998) – *an average upper bathyal EoD is assigned to the map unit here. Parts of the map unit may have been deposited at outer shelf or mid-bathyal depths.*

### **Whenuakura Group (Pw)**

**Inferred age:** 3 Ma (Kamp et al., 2004)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = siltstone, limestone, conglomerate; Description = Repeated sequences of pebbly to well sorted sandstone, poorly fossiliferous siltstone and coquina shell beds (QMAP database). “...the Whenuakura Group... comprises cyclical repetitions (cyclothems) of bioclastic limestone, pebbly sandstone, and bioturbated, micaceous fine sandstone and siltstone... that accumulated in **inner to mid-shelf** depositional environments...” (Naish et al., 2005; Townsend et al., 2008). “Environments of deposition vary from **shallow subtidal to estuarine** formations cropping out on the coast near Waitotara (Fleming, 1953), to **upper bathyal** depths at the base of the Whanganui River section (Collen, 1972)” (Murphy et al., 1994) – *the paleodepth range for the Whenuakura Group is onshore (estuarine) to upper bathyal (Murphy et al., 1994). An average mid-shelf EoD is assigned to the map unit. Innermost shelf is an alternative EoD based on the main rock type of sandstone and Fig. 3.*

### **Paparangi Group (Pp)**

**Inferred age:** 3 Ma (Kamp and McIntyre, 1998)

**EoD:** outer shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone, limestone; Description = Thin pebbly shell beds and massive, well sorted sandstone in the west, and massive silty mudstone in the east (QMAP database). “The Paparangi Group (Pp...) was deposited across the entire width of the Wanganui Basin during the middle Late Pliocene. Western parts of the group, unconformably overlying the Whenuakura Group, have basal thin pebbly, shellbeds containing **inter-tidal, estuarine and mid-shelf** fossils, and current-bedded pebbly sandstone... Above the shellbeds, Paparangi Group comprises a sandstone-dominated succession... This sandstone laps onto and overlies Paparangi Group mudstone facies towards the east... In the eastern Wanganui Basin, the Paparangi Group (Pp) comprises massive bioturbated, locally fossiliferous, blue-grey mudstone, which accu-

mulated in a **low energy, upper bathyal to outer shelf** environment” (Townsend et al., 2008). “... Mangaweka Mudstone (400 m thick) accumulated in an **outer shelf to upper slope** environment... A major shift in paleobathymetry from inner shelf to **outer shelf/upper slope** environments, a minimum of 100 m of deepening and possibly as much as 150 m, occurred at the base of the Mangaweka Mudstone... We attribute the increase in sedimentation rate and bathymetric deepening to a tectonic cause...” (Kamp et al., 1998) – *the paleodepth range for the Paparangi Group is onshore (estuarine) to upper bathyal* (Townsend et al., 2008). *Mangaweka Mudstone is the dominant lithology of the group* (Kamp et al., 1998).

## Lower Okiwa Group (Pal)

Includes Whauteihi, Whakaihūwaka, Tirotiro, and Parikino formations.

**Inferred age:** 3 Ma (Kamp and McIntyre, 1998)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone, limestone; Description = Bioclastic limestone, massive sandstone and siltstone, and minor conglomerate (QMAP database). “...generally consists of cyclothem with coarse, basal bioclastic limestone (coquina shellbeds) overlain by sparsely fossiliferous siltstone and sandstone units... Coquina beds are typically 1-3 m thick, weakly cemented, and have a sandy siltstone matrix... The coquina and sandstone members were typically deposited in **high-energy shoreface to inner-shelf conditions**. Siltstone units were deposited in **inner- to mid-shelf** environments and sandstone units represent shoaling up section to **inner-shelf, near-shore or shoreface** conditions” (Townsend et al., 2008). “Late Pliocene through to middle Pleistocene record is comprised of markedly cyclothem **mid- to inner-shelf** deposits” (Kamp and McIntyre, 1998). “The shellbed members at the base of the cycles accumulated during intervals of sediment starvation associated with stratigraphic condensation on the **shelf** during transgressions. Siltstone members accumulated in **mid-shelf** environments during sea-level highstands, while overlying sandstone members accumulated in **inner-shelf to shoreline** environments during falling sea-level conditions (Kamp & Naish in press)” (McIntyre and Kamp, 1998) – *the Lower Okiwa Group consists of cyclothem deposits* (Kamp and McIntyre, 1998; McIntyre and Kamp, 1998). *An innermost shelf depositional environment is an alternative interpretation.*

## Upper Okiwa Group (Pau)

Includes Hautawa Shellbed member and Whariki, Shaw and Wickham formations.

**Inferred age:** 3 Ma (Kamp and McIntyre, 1998)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone, limestone; Description = Bioclastic limestone, sandstone, massive siltstone and minor conglomerate (QMAP database). “The base of the Upper Okiwa Group is marked by the Hautawa Shellbed Member (Pkh...), a mollusc and brachiopod-rich, sandy siltstone-supported bioclastic limestone up to 3 m thick... Above the Hautawa Shellbed, the Upper Okiwa Group consists of sandstone, coquina limestone and siltstone cyclothem” (Townsend et al., 2008). “The variably erosional-conformable base of the Hautawa Shellbed and the broken molluscan fauna at its base are suggestive of localised **tidal current** channelling into the underlying silty sandstone... progressive **deepening** upwards within the shellbed to **middle shelf** depths... Overall upsection coarsening of this member [Shaw Formation] indicates progressively **shallower** depositional conditions, back into an **inner-shelf** setting... **nearshore** depositional conditions for the lower coquina, followed by upsection **deepening** into the lower of the siltstone members” (McIntyre and Kamp, 1998) – *the Upper Okiwa Group consists of cyclothem deposits* (Kamp and McIntyre, 1998; McIntyre and Kamp, 1998). *An innermost shelf depositional environment is an alternative interpretation.*

## Nukumarū Group (Pn)

**Inferred age:** 2 Ma (Naish and Kamp, 1995)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = sandstone, conglomerate; Description = Coquina limestone and sandstone ranging from pebbly to well sorted (QMAP database). “The

Nukumaru Group (Pn, Fleming 1953) comprises pebbly sandstone, coquina limestone with sandstone lenses, and well-sorted sandstone... Lateral changes in both thickness and facies are evident in the Nukumaru Group. The group is over 180 m thick at the coast, and thickens eastwards to c. 220 m near the Whanganui River and c. 300 m in the Turakina valley. The sandstone becomes siltier towards the east and coquina beds become fewer and thinner... The sandstone and coquina beds in the west accumulated in **shallow-water, current-scoured estuarine embayments and near-shore environments**, whereas the muddy sandstone and siltstone units towards the east accumulated in **mid- to outer shelf** settings" (Townsend et al., 2008) – *EoD is based on Fleming (1953) who describes the formations and members of this group as being very shallow, innermost shelf deposits. Onshore (estuarine) could be an alternative interpretation.*

## Utiku Group (Pu)

**Inferred age:** 3 Ma (Journeaux et al., 1996)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = siltstone; Description = Muddy, very fine sandstone (QMAP database). "The Utiku Group was deposited in a **mid-shelf** setting during the middle Pliocene (Waipipian), and represents the northward progradation of a shelfal succession from the southeastern margin of Wanganui Basin" (Townsend et al., 2008). "...accumulated predominantly in a **mid-shelf** environment... The Utiku Group accumulated in **inner to mid shelf** environments. Shoreface and foreshore deposits are not present, consistent with the facies descriptions..." (Kamp et al., 1998) – *EoD is based on the mid-shelf depositional environment interpretation in Kamp et al. (1998).*

## Mangarere Formation (Prm)

**Inferred age:** 3 Ma (Naish and Kamp, 1995)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone, limestone; Description = Weakly bedded, bioturbated sandstone and siltstone (QMAP database). "In the Rangitikei valley the Mangarere Formation is channelled into the Paparangi Group. Infilling the channel is moderately well-sorted, medium sandstone and silty sandstone... overlying the sandstone is weakly bedded, bioturbated, grey siltstone, which becomes sandier up-section, representing **shallowing from mid-shelf to inner shelf** conditions" (Townsend et al., 2008) – *the EoD is narrowed down to an average of mid-shelf. Refer to "Mangarere Formation (Prm)" on the Hawke's Bay map area for further information.*

## Tikapu & Makohine formations (Prt)

**Inferred age:** 2 Ma (Naish and Kamp, 1995)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone, limestone; Description = Sandy coquina limestone, poorly-fossiliferous, bioturbated massive siltstone and well sorted sandstone (QMAP database). "Sandstone members were deposited in **shoreface** environments, shellbeds accumulated during marine transgressions as water depth increased, and siltstone units represent **mid- to outer shelf** conditions" (Townsend et al., 2008) – *the paleodepth of these two formations of the Rangitikei Group changed due to eustatic sea level changes. The overall EoD of these two members is here defined as innermost shelf. Refer to "Tikapu & Makohine formations (Prt)" on the Hawke's Bay map area for further information.*

## Orangipongo, Mangaonoho and Vinegar Hill formations (Pro)

**Inferred age:** 2 Ma (Naish and Kamp, 1995)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone, limestone; Description = Sandy to silty coquina limestone, and poorly-fossiliferous, bioturbated siltstone and sandstone (QMAP database). "The Orangipongo, Mangaonoho and Vinegar Hill formations (Pio; Naish & Kamp 1995) are broadly contemporaneous with the Nukumaru Group in the western Wanganui Basin (Fleming 1953; Fig. 28) and are amalgamated into a single mapping unit. These formations, overall



about 440 m thick in the Rangitikei valley, comprise multiple sedimentary cycles each comprising shellbed, siltstone and sandstone members similar to those described above within the Makohine Formation (Naish & Kamp 1995)" (Townsend et al., 2008) – *these three formations of the Rangitikei Group appear to have been deposited in innermost to mid-shelf environments. The fluctuations from inner to mid-shelf are at too fine a scale to be discerned in this project, therefore the overall EoD of these three members is here defined as innermost shelf, but mid-shelf may also be appropriate. Refer to "Orangipongo, Mangaonoho and Vinegar Hill formations (Pro)" on the Hawke's Bay map area for further information.*

## Maxwell Group (Pm)

**Inferred age:** 1 Ma (Naish and Kamp, 1995)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone, peat, limestone, conglomerate; Description = Sandstone, mudstone, limestone shell beds, carbonaceous siltstone and lignite (QMAP database). "The Maxwell Group (Pm...), in contrast with the rocks below and above, consists of interbedded **terrestrial, non-marine and marginal marine rocks**... Non-marine parts of the group, up to 30 m thick, include quartzose sandstone, siltstone, carbonaceous claystone and lignite, with paleosols and tree stumps in growth position. Marginal marine parts of the group include up to 30 m of interbedded sandstone, laminated siltstone, mudstone, lenses of shelly conglomerate with rare moa bones, and thin carbonaceous, muddy to pumiceous siltstone..." (Townsend et al., 2008) – *the main rock type of mudstone is assumed to be a marginal marine deposit, perhaps estuarine, which is defined here as onshore. An innermost shelf EoD is an alternative interpretation. NB: on the 2 Ma interval we consider the adjacent/underlying innermost shelf Rangitikei Group to be the dominant deposit in this region, and as a consequence of the scale of detail in this project innermost shelf is the preferred environment displayed at 2 Ma.*

## Quaternary – Sedimentary deposits

- **All Q deposits** (except – see below)

**EoD:** onshore

**Basis for interpretation:** Based on the QMAP database which includes alluvial, beach, colluvial, dune, lahar, landslide, lignite, loess, peat, reclaimed land, rock fall, scree, swamp, and till sediments in the Quaternary deposits.

- **Kai-Iwi Group (eQk, uQb, Q17b), Okehu Group (eQo), Shakespeare Group (mQs, Q15b, Q13b, Q11b, Q9b), Pouakai Group (Q7b, Q5b)**

**EoD:** innermost shelf

**Basis for interpretation:** "...shallow-water coquina... uplifted **marine** terraces... Shellbeds were deposited in **estuarine, shallow water or near-tidal** environments, or formed during rapid marine transgression and sea level rise, followed by sediment starvation and formation of a hard-ground in deeper water. Sandstone beds generally formed under **shoreface or near-shore** conditions and siltstone beds formed in offshore environments during periods of high sea level... **marginal marine** deposits... **marine** terrace deposits..." (Townsend et al., 2008) – *onshore may be appropriate in some cases.*

## Tongariro Volcanic Centre

**Inferred age:** 1-0 Ma (references in Townsend et al., 2008)

"These volcanic rocks include lava and tephra (ash, ignimbrite, and other pyroclastic deposits), covering just over 2% of the mapped land area. Lava from Mt Ruapehu and related vents consists primarily of calc-alkaline, medium-K basic and acidic andesites, with common xenoliths originating from greywacke terranes (Graham & Hackett 1987)" (Townsend et al., 2008). Includes the following onshore intermediate eruptives: Hauhungatahi andesite (eQvh), Maungaku andesite (mQvm), Te Herenga Formation (mQvt), Wahianoa Formation (lQva), Mangawhero Formation (Q3vm, Q2vm), Whakapapa Formation (Q1vwi, Q1vwr), Ohakune lava (Q3vo), Pukeonake Andesite (lQvp).

## Taupo Volcanic Zone

**Inferred age:** < 0.5 Ma (references in Townsend et al., 2008)

“Remnants of three large middle to late Quaternary ignimbrite eruptions from the Taupo Volcanic Zone are preserved in the northeast of the map area” (Townsend et al., 2008). Includes the following onshore silicic eruptives: Whakamaru Group (Q9w), Oruanui Formation (Q3o), Taupo Pumice Formation (Q1ati). Refer to “Taupo Volcanic Zone” on the Rotorua map area for further information.

## Egmont Volcanic Centre

**Inferred age:** 1-0 Ma (references in Townsend et al., 2008)

“The Egmont Volcanic Centre comprises a chain of andesite volcanoes aligned in a northwest-southeast orientation. The oldest volcano is now reduced to volcanic plugs forming Paritutu and the Sugar Loaf Islands offshore from New Plymouth. Other volcanoes in the chain are progressively younger towards the southeast, with the youngest forming Mt Taranaki and Fanthams Peak (Arnold 1959; Neall 1979). The volcanic deposits are predominantly andesite, basaltic andesite and minor basalt (Stewart et al. 1996)” (Townsend et al., 2008). Includes the following onshore intermediate eruptives: Sugar Loaf Andesite (eQvsl), Kaitake andesite (mQvk), Pouakai andesite (mQvp), Pukeiti lava (Q2v).

### *Egmont Volcano and Fanthams Peak*

**Inferred age:** < 0.5 Ma (references in Townsend et al., 2008)

Includes the following onshore intermediate eruptives: Warwick lava (Q1vwk), Peters lava (Q1vpt), Staircase lava (Q1vst), Fanthams Peak lava (Q1vf), Skeet lava (Q1vsk), Summit lava (Q1vsu), German Hill lava (Q5vg), Undifferentiated Holocene andesite (Q1vl).

## Offshore Quaternary Volcanics (PMeQis)

**Inferred age:** 2 Ma (Strogen, 2011)

**EoD:** submarine intermediate eruptives

**Basis for interpretation:** Main\_Rock = basaltic andesite; Sub\_Rocks = submarine andesite to basaltic andesite; Description = submarine andesite and basaltic andesite volcanoes (after Edbrooke, 2005). “An andesitic volcanic arc was active in the northern Taranaki Basin and farther north during the Middle to Late Miocene (the Mohakatino Volcanic Arc). Offshore volcanism led to the accumulation of volcanoclastic sandstone and siltstone, and primary **andesitic lava** (the Mohakatino Formation; e.g. Nodder et al. 1990)” (Townsend et al., 2008). “The Mohakatino Volcanic Arc is a NNE-trending chain of **submarine andesite** stratovolcanoes and associated **intrusive** complexes in the northeast of Taranaki Basin, identified from seismic surveys and gravity and magnetic anomalies (King & Thrasher 1996)” (Edbrooke, 2005). “In the Pliocene, few submarine volcanoes were active” (Giba et al., 2010) – *the location of these centres is based on maps in Strogen (2011).*

## HAWKE'S BAY AREA (Geological Map 8)

### Tinui Group

#### *Whangai and Waipawa formations (Kiw, ?Kiw)*

(QMAP database spelling: Whangai Formation, Waipawa Form\*)

Includes Whangai Formation (Upper Calcareous, Porangahau and Te Uri Members) and Waipawa Formation.

"The microfossil assemblages indicate that it was deposited at **shelf to bathyal** depths... The Waipawa Formation (Fleming 1959; Moore 1989) conformably overlies the Whangai Formation. Because it is only 30 m thick at the type locality at Waipawa and its distribution in Hawke's Bay is poorly known, on this map it is included within the Whangai Formation..." (Lee et al., 2011). "The formation typically consists of 300-500 m of non-calcareous and calcareous shale and mudstone of Haumurian-Teurian age; rarely the formation may be up to 600 m thick (Moore 1988b)... Much of the Whangai Formation appears, from foraminiferal assemblages, to have accumulated at **bathyal** depths (...), although **outer shelf to upper bathyal** species have been found in the Upper Calcareous Member. This revises the interpretation given in Moore (1988b) of largely shelf depths for the Whangai. Planktics form generally less than 10% of Upper Calcareous Member foraminiferal assemblages" (Field and Uruski, 1997).

- **Upper Calcareous Member**

"...consists of poorly bedded, medium grey, hard, slightly to moderately calcareous (1-15%), micaceous mudstone, with laminae, bioturbation, sporadic calcareous concretions, pyrite nodules and beds of glauconitic sandstone. It is recognised throughout the region, but in some eastern areas it is partly replaced by the laterally equivalent Porangahau Member... **outer shelf to upper bathyal** species have been found in the Upper Calcareous Member" (Field and Uruski, 1997).

- **Porangahau Member**

"...is a well-bedded, light grey to white, hard, moderately calcareous mudstone, with common glauconitic sandstone beds" (Field and Uruski, 1997).

- **Te Uri Member**

"...interbedded glauconitic sandstone and slightly calcareous, glauconitic siltstone; it disconformably overlies Upper Calcareous Member in the Whangai Range, is entirely of Teurian age, and is probably partly a lateral equivalent of the Waipawa Formation... The Waipawa Formation is contemporaneous with, at least in part, the upper part of the **mid- to upper bathyal** Te Uri Member" (Field and Uruski, 1997).

- **Waipawa Formation**

"The presence in the Waipawa Formation of *Glomospira charoides* and, more especially, *Rzehakina epigona* (to which van Morkhoven et al., 1986 have accorded a bathyal to abyssal depth), is more consistent with a water depth corresponding to the **outer shelf to upper slope**" (Killops et al., 2000). "However, there has been little agreement on the depositional setting of the unit, with some arguing for a setting within a deep-water oxygen minimum zone (Leckie et al., 1995; Killops et al., 2000; Rogers et al., 2001; Hollis et al., 2005a) and others suggesting a more restricted, shallow marine setting (Moore, 1988; Schiøler et al., 2010)... Although these age models are relatively poorly constrained, there seems little reason to doubt that Waipawa organofacies deposition occurred as an isochronous event over a relatively short period of time (~700,000 years) in the late Middle to early Late Paleocene (59.4 to 58.7 Ma), spanning the Selandian–Thanetian Stage boundary" (Hollis et al., 2014).

**Inferred age:** > 65-57 Ma (Field and Uruski, 1997)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone; Description = siliceous mudstone, glauconitic sandstone, alternating sandstone and mudstone, minor chert lenses, chocolate shale (QMAP database) – *the EoD is defined here as upper bathyal, based on the QMAP description and lithology; however outer shelf or even mid-bathyal may be alternative environments, based*

on comments in the literature. The Upper Calcareous Member may be reworked downslope. On the geological map sheet ?Kiw is mapped as Kiw, so is here assumed to be part of Kiw.

## Mangatu Group

### **Wanstead Formation (Egw)**

**Inferred age:** 59-36 Ma (Field and Uruski, 1997)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = claystone; Sub\_Rocks = mudstone, sandstone, marl; Description = smectitic, soft to moderately hard claystone, greensand, sandstone and marl (QMAP database). "Deposition in **mid-bathyal to lower bathyal-abyssal** environments has been inferred for Wanstead Formation of eastern areas (Moore & Morgans 1987; Field, Uruski et al., 1997) but shallower environments were inferred for Wanstead Formation on the flanks of the Whangai Range (Lillie 1953)" (Lee et al., 2011). "The formation is known from all North Island East Coast basins where Paleogene aged strata are recorded... is mainly a poorly bedded, highly bioturbated, green-grey, calcareous mudstone with beds of glauconitic sandstone in places. In parts the formation is highly smectitic and can be siliceous or brecciated. Other lithofacies included in the formation are the Te Waka Greensand (Black 1980), breccia and conglomeratic units, poorly to well-bedded glauconitic sandstone and mudstone, flysch facies, and siliceous units... The Wanstead Formation is generally considered to represent the deepest depositional environment of the Late Cretaceous-Paleogene of the East Coast, with average paleodepths generally **mid-bathyal**, and **lower bathyal-abyssal** in parts" (Field and Uruski, 1997) – *the Wanstead Formation is defined here as mid-bathyal, based on the lithology and comments in Field and Uruski (1997). Lower bathyal-abyssal may be an alternative EoD, or even shelf in parts.*

### **Whangai, Waipawa, Wanstead and Weber formations (Kiw+Egw)**

(QMAP database spelling: Whangai, Waipawa and Wanstead F\*)

**Inferred age:** > 65-36 Ma (Field and Uruski, 1997)

**EoD breakdown:**

> 65-60 Ma:	<u>upper bathyal</u> (Whangai Formation)
59-57 Ma:	<u>mid-bathyal</u> (Waipawa Formation, Wanstead Formation)
56-36 Ma:	<u>mid-bathyal</u> (Wanstead Formation)

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = claystone sandstone; Description = siliceous mudstone, claystone and sandstone (QMAP database) – *based on the combined unit code, this unit appears to include Whangai, Waipawa and Wanstead Formations. The EoD range is based on that which has been determined in this report for the individual formations. Refer to "Whangai and Waipawa formations (Kiw, ?Kiw)" and "Wanstead Formation (Egw)" in the Hawke's Bay area for further interpretations and possible alternative environments.*

### **Weber Formation (Ogw)**

**Inferred age:** 35-22 Ma (Field and Uruski, 1997)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone; Description = Calcareous mudstone, limestone and alternating sandstone and mudstone (QMAP database). "Weber Formation was deposited in **mid-bathyal** water depths, in slightly shallower conditions than Wanstead Formation" (Lee et al., 2011). "The paleoecology of the Weber Formation is generally quite uniform, with high percentages of planktic foraminifera indicating oceanic conditions and generally **mid-bathyal** paleodepths. While there is evidence for shallower deposition, most of the shelf faunas are considered to have been **reworked downslope**. The Weber Formation was possibly deposited at slightly shallower depths than some of the preceding Wanstead Formation, suggesting a slight regional regression" (Field and Uruski, 1997) – *EoD is based on the Field and Uruski (1997) mid-bathyal interpretation. The main rock type of mudstone is consistent with deposition at mid-bathyal depths in an area isolated from submarine fans, although the alternating sandstone and mudstone mentioned in the QMAP description may represent sediment gravity flow deposits. The Weber Formation also occurs as a calc-turbidite facies.*

## **Wanstead and Weber formations (Egw+Ogw)**

**Inferred age:** 59-22 Ma (Field and Uruski, 1997)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = claystone and mudstone; Sub\_Rocks = sandstone, limestone marl; Description = smectitic greenish-grey or reddish mudstone, calcareous mudstone, sandy mudstone (QMAP database) – *based on the combined unit code, this unit appears to include Wanstead and Weber Formations. The EoD is based on that which has been determined in this report for the individual formations. Refer to “Wanstead Formation (Egw)” and “Weber Formation (Ogw)” for further interpretations and possible alternative environments.*

## **Whangamomona Group**

### **Otunui Formation (mMo)**

**Inferred age:** 14-12 Ma (Kamp and Vonk, 2006)

**EoD:** outer shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone, limestone; Description = Pebbly sandstone, fine-grained sandstone, sandy siltstone and limestone (QMAP database). “... Otunui Formation... comprises 100 -200 m of fine-grained sandstone, pebbly sandstone, sandy siltstone and limestone, unconformably overlying Oligocene to Early Miocene rocks... It was deposited at **shelf to upper bathyal** depths following subsidence and southeastward migration of the Taranaki Basin shoreline...” (Lee et al., 2011). “During the middle Miocene (late Lillburnian), regional subsidence led to marked marine transgression across the Whangamomona block in the King Country with accumulation of an **inner neritic shellbed** (Mangarara Formation) followed by siliciclastic **shelf and upper bathyal** facies of the Otunui Formation” (Puga-Bernabéu et al., 2009) – *a general outer shelf EoD is assigned to the map unit. Refer to “Otunui Formation (mMo)” in the Waikato map area for further information.*

### **Matemateaonga Formation**

“...consists of 800-1000 m of alternating limestone, sandstone, mudstone and minor conglomerate... The lower part of the formation is coarse grained with a basal conglomerate in places (Murrell 1998) but is mostly represented by mudstone, sandstone and shellbeds... The formation thins eastwards towards the range front, where it includes a greater proportion of sandstone and conglomerate. Pebbly limestone beds contain abundant barnacle and mollusc fragments. Sandstones are fine-to medium-grained, commonly with well-developed **cross-bedding**... The formation was deposited in **shoreline and shelf** settings as part of an extensive shelf-slope system...” (Lee et al., 2011). “The Matemateaonga Formation is characterised by the cyclical repetition of **coquina** shellbed, siltstone and sandstone lithologies... The Matemateaonga Formation succession accumulated in **shoreface to mid-shelf** environments” (Vonk et al., 2002).

- **Mga, Pga, MPg**

**Inferred age:** 7-5 Ma (Kamp and Vonk, 2006)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = sandstone; Description = Repeated sequences of limestone, sandstone, mudstone and minor conglomerate (QMAP database) – *the EoD is narrowed down to mid-shelf here.*

- **?Pga**

**Inferred age:** 5 Ma (Kamp and Vonk, 2006)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = sandstone; Description = Alternating limestone, sandstone, mudstone and conglomerate (QMAP database) – *the EoD is narrowed down to mid-shelf here.*

## Rangitikei Supergroup

“The base of the overlying Rangitikei Supergroup represents a regionally significant subsidence event (“Tangahoe pull-down”), which marks the inception of the Wanganui Basin as a discrete depocentre (Kamp et al. 2004). The lower parts of the supergroup consist mainly of mudstone with minor sandstone; middle and upper parts of the supergroup contain increasing amounts of limestone and sandstone. The constituent units typically become thinner and coarser grained towards the eastern edge of the basin, which was close to the modern range front” (Lee et al., 2011).

### Tangahoe Mudstone

“Tangahoe Mudstone (Pit...) disconformably overlies the Matemateaonga Formation... The formation, up to 500 m thick, consists of mudstone with **redeposited** sandstone beds. Large concretions are common in the upper part...Tangahoe Mudstone is pale to medium grey in colour, massive to weakly bedded, and coarsens upwards to sandy siltstone... Microfossil assemblages show that the Tangahoe Mudstone was deposited in a **middle to upper bathyal** environment...” (Lee et al., 2011). “...very rapid bathymetric deepening events in the Pliocene section of Wanganui Basin, the other occurring about 1.5 My earlier (~4.3 Ma) at the contact between the Matemateaonga and Tangahoe Formation, and involving at least 200-300 m of increase in water depth” (Kamp et al., 1998).

- Pt

**Inferred age:** 4-3 Ma (Kamp and Vonk, 2006)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone; Description = Mudstone with concretionary sandstone (QMAP database) – *an average upper bathyal EoD is assigned to the map unit here. Parts of the map unit may have been deposited at outer shelf or mid-bathyal depths.*

- ?Pt

**Inferred age:** 4-3 Ma (Kamp and Vonk, 2006)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone; Description = Massive mudstone with interbedded sandstone and large concretions (QMAP database) – *an average upper bathyal EoD is assigned to the map unit here. Parts of the map unit may have been deposited at outer shelf or mid-bathyal depths.*

## Utiku Group

“Utiku Group (Pu...) comprises 310 m of alternating, fine-grained sandstone and concretionary sandstone, and sandy mudstone. The formation becomes coarser grained and thinner towards the east... It was deposited at **inner to mid-shelf** water depths (Journeaux et al. 1996) as part of a shelf system that prograded out into the Wanganui Basin from the east” (Lee et al., 2011). “...accumulated predominantly in a **mid-shelf** environment... The four Utiku Group cyclothems (Cycles 1-4) are sand-dominated and display recurrent vertically stacked **mid-shelf to shoreline** facies successions, each sequence is bounded above and below by unconformities or correlative conformities (Fig. 3) (Journeaux et al., 1996) and comprise transgressive (TST), highstand (HST) and regressive (RST) systems tracts that can be readily interpreted using generic sequence stratigraphic models (e.g. Vail, 1987; Naish and Kamp, 1997a)... The Utiku Group accumulated in **inner to mid shelf** environments. Shoreface and foreshore deposits are not present, consistent with the facies descriptions...” (Kamp et al., 1998).

- Pu

**Inferred age:** 3 Ma (Journeaux et al., 1996)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone; Description = Sandstone, concretionary sandstone and sandy mudstone (QMAP database) – *an average EoD of mid-shelf is assigned to the unit here.*

- ?Pu

*Inferred age:* 3 Ma (Journeaux et al., 1996)

*EoD:* mid-shelf

*Basis for interpretation:* Main\_Rock = sandstone; Sub\_Rocks = mudstone; Description = Fine-grained sandstone, sandy mudstone, concretionary sandstone and limestone (QMAP database) – *an average EoD of mid-shelf is assigned to the unit here.*

### ***Omatane Limestone Member***

“A 10 to 20 m-thick conglomeratic limestone (Omatane Limestone Member, Puo...) at the top of the group forms prominent caps on hills near Utiku and Taoroa Junction... It was deposited at **inner to mid-shelf** water depths (Journeaux et al. 1996) as part of a shelf system that prograded out into the Wanganui Basin from the east” (Lee et al., 2011).

- Puo

*Inferred age:* 3 Ma (Lee et al., 2011)

*EoD:* innermost shelf

*Basis for interpretation:* Main\_Rock = limestone; Sub\_Rocks = sandstone; Description = Conglomeratic limestone and sandstone (QMAP database) – *EoD is based on the QMAP description. Mid-shelf may also be appropriate.*

- ?Puo

*Inferred age:* 3 Ma (Lee et al., 2011)

*EoD:* innermost shelf

*Basis for interpretation:* Main\_Rock = limestone; Sub\_Rocks = sandstone; Description = Conglomeratic limestone (QMAP database) – *EoD is based on the QMAP description. Mid-shelf may also be appropriate.*

### **Paparangi Group (Pp)**

*Inferred age:* 3 Ma (Kamp and McIntyre, 1998)

*EoD:* outer shelf

*Basis for interpretation:* Main\_Rock = mudstone; Sub\_Rocks = sandstone; Description = Massive mudstone, concretionary sandstone; limestone and conglomerate in the east (QMAP database). “Silty sandstone near the base fines upward into sparsely fossiliferous, massive mudstone with large spherical concretions... Microfossil assemblages from the Paparangi Group show that it accumulated in **outer shelf to upper bathyal** environments...” (Lee et al., 2011) – *an average outer shelf EoD is assigned here. Refer to “Paparangi Group (Pp)” in the Taranaki map area for further information.*

### **Mangarere Formation (Prm)**

*Inferred age:* 3 Ma (Naish and Kamp, 1995)

*EoD:* outer-shelf

*Basis for interpretation:* Main\_Rock = sandstone; Sub\_Rocks = siltstone, conglomerate; Description = Cross-bedded sandstone, siltstone and conglomerate (QMAP database). “The Mangarere Formation (Pim...) comprises sandstone and silty sandstone up to 200 m thick... Basal channel-fill conglomerate is succeeded by well-sorted, trough **cross-bedded** sandstone that grades upward into massive, concretionary siltstone and silty sandstone. Macrofauna and sedimentary structures indicate that the formation was deposited in **shelf to upper bathyal** environments...” (Lee et al., 2011). “The new formations are named: Mangarere, Tikapu, Makohine, Orangipongo, Mangaonoho, and Vinegar Hill. Each formation comprises one or more **cylothems** and includes a previously described and named distinctive basal horizon. Discrete sandstone, siltstone, and coquina within formations are assigned member status and correspond to systems tracts in sequence stratigraphic nomenclature... Sedimentary structures and fauna indicate deposition in **shoreface to innershelf** environments. **Mid-shelf** water depths are indicated at the base of Mrzm<sub>1</sub> by the in-situ occurrence of the mollusc *Lucinoma galathea*. Progressive **shallowing to inner shelf depths** is indicated by

upward coarsening and the successive appearance upwards within Mrzm<sub>1</sub> of *Nemocardium pulchellum*, *Chlamys gemmulata*, and *Atrina pectinata zelandica*" (Naish and Kamp, 1995) – *the Mangarere Formation's paleodepth range of innermost shelf to upper bathyal is narrowed down to an average mid-shelf EoD.*

### ***Tikapu & Makohine formations (Prt)***

***Inferred age:*** 2 Ma (Naish and Kamp, 1995)

***EoD:*** innermost shelf

***Basis for interpretation:*** Main\_Rock = siltstone; Sub\_Rocks = sandstone, limestone; Description = Alternating siltstone, sandstone and limestone (QMAP database). "The Tikapu Formation and the overlying Makohine Formation are collectively mapped as Pik... Both formations were deposited in **shoreface to shelf** environments..." (Lee et al., 2011). "The faunal content and sedimentary structures [of the Tikapu Formation] are consistent with an **inner shelf** environment of deposition... Faunal changes upsection within the shellbed indicate a progressive **increase in water depth from inner to mid-shelf** environments. The successive upsection occurrence, in siltstone member Tuzm<sub>1</sub>, of *Chlamys gemmulata*, *Amygdalum striatum*, *Nemocardium pulchellum*, and *Panopea zelandica* are interpreted as a **shallowing from mid-shelf to inner shelf** environments... The dominant molluscan fauna [of the Makohine Formation], *Gari lineolata*, *Scalpomactra scalpellum*, *Panopea zelandica*, *Fellaster zelandiae*, together with the occurrence of a variety of traction-emplaced sedimentary structures, indicate siliciclastic sandstone members were deposited in **transitional and shoreface** depositional environments. Coquina members accumulated due to stratigraphic condensation on the **inner to mid shelf** during marine transgression and are dominated by the molluscs *Chlamys*, *Tawera*, *Pleuromeris*, *Tiostrea*, *Gari*, *Nucula*, *Scalpomactra*, and Brachiopoda. Siltstone members are dominated by the **mid-shelf** molluscan taxa *N. pulchellum*, *A. striatum*, and *Neilo australis*" (Naish and Kamp, 1995) – *these two formations of the Rangitikei Group appear to have been deposited in innermost to mid-shelf environments, based on the faunal assemblages. The paleodepth changed due to eustatic sea level changes. The overall EoD of these two members is here defined as innermost shelf.*

### ***Orangipongo, Mangaonoho and Vinegar Hill formations (Pro)***

(QMAP database spelling: Orangipongo, Mangaonoho & Vineg\*)

***Inferred age:*** 2 Ma (Naish and Kamp, 1995)

***EoD:*** innermost shelf

***Basis for interpretation:*** Main\_Rock = limestone; Sub\_Rocks = sandstone, siltstone; Description = Alternating limestone, sandstone and siltstone (QMAP database). "Up to 440 m of alternating shellbeds, sandstone and siltstone, lithologically similar to the underlying Makohine Formation (in stratigraphic order from oldest to youngest: Orangipongo, Mangaonoho and Vinegar Hill formations; Poi) are mapped as a single unit..." (Lee et al., 2011). "Siliciclastic sandstone members [of the Orangipongo Formation] were deposited in transitional **inner shelf to shoreface** environments. Coquina members that accumulated during transgressions are ascribed a **shoreface to shelfal** depositional environment, whereas siltstone members accumulated during episodes of sea-level highstand aggradation, and show an upsection-shoaling from **mid to inner shelf** depositional environments... Siltstone members [of the Mangaonoho Formation] contain molluscan fauna indicative of **shelfal** deposition, whereas sandstone members are interpreted as having accumulated in transitional **inner shelf to shoreface** depositional environments... We report an open marine **shoreface to inner shelf** faunal assemblage for coquina members [of the Vinegar Hill Formation], the dominant molluscs being *Purpurocardia*, *Tiostrea chilensis lutaria*, *Notocorbula zelandica*, *Tawera subsulcata*, *Gari lineolata*, *Maorimactra ordinaria*, and *Bassina yatei*. Intense bioturbation and diagnostic open marine fauna are indicative of an **inner to mid-shelf** depositional environment for the siliciclastic siltstone. The occurrence of ripple-laminated and flaser-bedded structures in upper portions of sandstone members suggests **tidal** conditions during deposition" (Naish and Kamp, 1995) – *these three formations of the Rangitikei Group appear to have been deposited in innermost to mid-shelf environments. The fluctuations from inner to mid-shelf are at too fine a scale to be discerned in this project, therefore the overall EoD of these three members is here defined as innermost shelf, but mid-shelf may also be appropriate.*



## Maxwell Group (Pm)

**Inferred age:** 1 Ma (Naish and Kamp, 1995)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone, conglomerate, lignite; Description = Pumiceous and non-pumiceous sandstone, mudstone, conglomerate and lignite (QMAP database). "...include **marginal marine** pumiceous and non-pumiceous sandstone and mudstone, fossiliferous mudstone, and **non-marine** conglomerate and lignite" (Lee et al., 2011) – Lee et al. (2011) interprets the EoD of the Maxwell Group as marginal marine and non-marine. Marginal marine environments encompass both onshore and innermost shelf depositional environments as defined in this report (Fig. 3). The EoD of the map unit is defined as onshore here; however, innermost shelf is a possible alternative interpretation.

## Undifferentiated Rangitikei Supergroup (Pr)

(QMAP database spelling: Undifferentiated Rangitikei Sup\*)

**Inferred age:** 3 Ma (Lee et al., 2011)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone, conglomerate, limestone; Description = Sandstone, concretionary sandstone, mudstone, limestone, conglomerate (QMAP database). "The base of the overlying Rangitikei Supergroup represents a regionally significant subsidence event ("Tangahoe pull-down"), which marks the inception of the Wanganui Basin as a discrete depocentre" (Kamp et al. 2004). "The lower parts of the supergroup consist mainly of mudstone with minor sandstone; middle and upper parts of the supergroup contain increasing amounts of limestone and sandstone. The constituent units typically become thinner and coarser grained towards the eastern edge of the basin, which was close to the modern range front... About 600 m of Late Pliocene to Early Pleistocene (Waipipian to Nukumaruan) limestone, sandstone, mudstone and shelly conglomerate, unconformably overlying or faulted against Kaweka terrane and Esk Head belt along the Ruahine Range front, are mapped as undifferentiated Rangitikei Supergroup (Pi). Basal conglomerate, grit, concretionary beds and sandstone grade up into sandy mudstone and sandstone... **The coarse basal sediments were deposited in a rocky shoreline environment that deepened to shelf conditions**" (Lee et al., 2011) – based on the interpreted depositional environment of shoreline to shelf (Lee et al., 2011) and the main rock type of sandstone (QMAP database), in conjunction with Fig. 3, an innermost shelf EoD is assigned to the map unit. A mid-shelf depositional environment is an alternative interpretation.

## Tolaga Group

"Tolaga Group (mainly Early Miocene to Early Pliocene) unconformably overlies either Mangatu or Tinui groups, or Kaweka basement rocks. It crops out in the southeastern, and central to northeastern parts of the map area. The group is thickest in the northeast near Te Hoe, where it is at least 5000 m thick (Cutten 1994), and it is around 2000 m thick in the Makara and Akitio sub-basins (Lillie 1953; van der Lingen & Pettinga 1980). There are local variations in lithofacies and thicknesses, but the Tolaga Group is represented largely by massive mudstone and alternating sandstone and mudstone" (Lee et al., 2011).

### Early Miocene Tolaga Group

- eMt

**Inferred age:** 22-16 Ma (Lee et al., 2011)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone, conglomerate; Description = Calcareous mudstone, sandstone and conglomerate (QMAP database). "Early Miocene Tolaga Group rocks (Mls) in the Te Hoe area in northeastern Hawke's Bay comprise up to 750 m of basal conglomerate, sparsely fossiliferous, calcareous mudstone, and minor sandstone. Foraminifera indicate an Early Miocene age (Otaian-Altonian) and deposition in an **outer shelf to upper bathyal** environment (Cutten 1994)" (Lee et al., 2011) – the EoD is narrowed down here to upper bathyal. NB: three polygons in the south of the map area are assigned the attributes of eMt+mMt, because they are labelled as Early to Middle Miocene undifferentiated Tolaga Group on the Hawke's Bay map sheet.

- eMtl

**Inferred age:** 19-17 Ma (Lee et al., 2011)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = greensand; Description = Pebbly, fossiliferous limestone (QMAP database). “A pebbly limestone with basal greensand (Mlg) caps the hills south of Lake Hatuma where it unconformably overlies Mangatu Group (Weber Formation) and is up to 300 m thick” (Lee et al., 2011) – *the map unit is interpreted as an upper bathyal deposit based on Fig. 3 and descriptions given in Lee et al. (2011) and the QMAP database. The basal greensand may suggest sediment starvation due to rising relative sea-level. Outer shelf may be an appropriate alternative.*

### **Puhokio Formation (eMtp)**

**Inferred age:** 34-18 Ma (King et al., 1999)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone, breccia; Description = Glauconitic sandstone and mudstone with olistostrome deposits; tuffaceous towards the top (QMAP database). “In southeastern Hawke’s Bay near Waimarama, Puhokio Formation (Mlh) consists of about 40 m of olistostromal units intercalated with glauconitic sandstone and mudstone, overlain by 300 m of green-blue mudstone and alternating sandstone and mudstone (**flysch**) that is tuffaceous towards the top. Foraminifera indicate an Oligocene to Middle Miocene age (Pettinga 1980). The formation was deposited at **middle to outer shelf** depths in the proto-Makara sub-basin, adjacent to an actively growing high (Pettinga 1980, 1982, 1990)” (Lee et al., 2011). “The Puhokio Formation grades conformably from the underlying Weber Formation... The bulk of the succession exposed at the type locality has been emplaced by sediment-gravity flows... The Raratu and Weber Formations are thought to be **deep-water deposits (slope environment)**... based on micropaleontologic data a similar environment may be inferred for the Puhokio Formation beds” (Pettinga, 1980) – *EoD is based on the Pettinga (1980) middle to outer slope depth of deposition. The middle to outer slope EoD is refined to mid-bathyal based on the dominance of mudstone and flysch lithologies (Lee et al., 2011) which may indicate a mid-fan deposit. Olistostromal, conglomerate, and debris flow units may indicate deposition in channels.*

### **Early to Middle Miocene Tolaga Group**

- eMt+mMt

“Undifferentiated Early to Middle Miocene rocks (uMl) crop out to the east of Dannevirke in the cores of the Akitio and Omakere synclines and around the Whangai Range... North and west of the Whangai Range, undifferentiated Early to Middle Miocene rocks comprise 400 m of sandstone, concretionary limestone and glauconitic sandstone (Lillie 1953). To the east, the Akitio and Omakere synclines contain over 1000 m of massive, dark grey mudstone, sandy mudstone, ridge-forming sandstone (Mla) and minor fine grained sandstone, which becomes coarser grained and thicker to the north. Deposition was in **middle to lower bathyal environments** (Field, Uruski et al. 1997)” (Lee et al., 2011).

**Inferred age:** 21-16 Ma (Field and Uruski, 1997)

**EoD breakdown:** 21-19 Ma: upper bathyal (Coast Road Formation)

18-17 Ma: mid-bathyal (Coast Road Formation, Greenhollows Formation)

16 Ma: upper bathyal (Coast Road Formation)

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone, limestone; Description = Sandstone, massive mudstone, sandy mudstone with minor concretionary limestone (QMAP database) – *the EoD breakdown for the map unit is based on the depositional age and paleoenvironmental interpretation of the undifferentiated early Miocene Palliser Group (eMi) on the Wairarapa map area.*

### **Middle Miocene Tolaga Group**

- mMt, ?mMt

**Inferred age:** 15-12 Ma (Lee et al., 2011)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone, limestone; Description

= Alternating sandstone and mudstone, massive mudstone and minor limestone (QMAP database). "In the Te Hoe area of northwestern Hawke's Bay, more than 500 m of middle Miocene rocks (Ml) unconformably overlie Early Miocene sandstone and mudstone. Fossiliferous transgressive sandstone grades upward into **alternating** sandstone and mudstone, and massive mudstone. Foraminifera indicate a **deepening environment from shelf to middle bathyal conditions**... In southeastern Hawke's Bay, calcareous mudstone with interbedded fine-grained sandstone (Ml)... unconformably overlie early to Middle Miocene rocks preserved within the Omakere and Akitio synclines" (Lee et al., 2011) – *the alternating sandstone and mudstone described in the QMAP description are assumed to be flysch deposits which, combined with the main rock type of sandstone and Fig. 3, suggests that the map unit comprises sediment gravity flow deposits at mid-bathyal depths.*

### **Late Miocene Tolaga Group**

- IMt

**Inferred age:** 11-6 Ma (Lee et al., 2011)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone limestone; Description = Thick-bedded sandstone and mudstone, massive mudstone and minor limestone (QMAP database). "Late Miocene rocks (Ml) crop out widely in northwestern and central Hawke's Bay and in the southeastern part of the map area. The contact between Middle and Late Miocene units is commonly unconformable but is locally gradational and conformable, as at Dannevirke (Lillie 1953; Kingma 1971)... In central Hawke's Bay, east of Kuripapango, 170 m of fault-bounded massive, fossiliferous, sandy siltstone (Ml) was deposited in **shallow water to middle bathyal depths** (Bland 2006)... South of Cape Kidnappers in the Makara sub-basin, 2000 m of undifferentiated Late Miocene massive mudstone, massive sandstone, tuffaceous mudstone, **flysch** beds and concretionary sandstone (Ml) unconformably overlie Early to Middle Miocene Tolaga Group rocks... **Debris flow** deposits intercalated with the **flysch** are more common in the east and contain Cretaceous and Paleogene clasts up to several metres in diameters... In the Dannevirke area, west of the Oruawharo Fault Zone, a 100 m to 200 m-thick succession of Late Miocene basal pebbly mudstone, sandstone, sandy mudstone and limestone (Ml) unconformably overlies Waioeka petrofacies basement (Lillie 1953). Fossils indicate **inner to middle shelf** environments of deposition... Poorly bedded to massive mudstone and fine-grained sandstone (Ml), well exposed in coastal cliffs from Blackhead to Pourerere and along the shore platform at Paoanui Point, are apparently at least 500 m thick but there may be undetectable structural repetition. Foraminifera suggest a **bathyal** environment of deposition" (Lee et al., 2011) – *based on the Lee et al. (2011) depositional depth range and the main rock type of mudstone, the map unit is interpreted here to predominantly consist of fine grained sediment deposited at upper to mid-bathyal depths in an area isolated from submarine fans. Mid-bathyal is an alternative interpretation. NB: 11 polygons to the west of the Mohaka Fault are assigned outer shelf at 11 Ma, and upper bathyal from 10-6 Ma.*

- IMta

**Inferred age:** 10 Ma (Leonard et al., 2010)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone; Description = Thick-bedded, calcareous and non-calcareous sandstone and minor mudstone (QMAP database). "In north-eastern areas of the map, such as around Te Hoe, Te Haroto and Wairoa, Late Miocene rocks are mainly sandstone, passing upward into alternating sandstone and mudstone, and mudstone... Strike ridges in the northern part of the map area near Te Hoe consist of thick-bedded sandstone and minor mudstone (Mla)... The environments of deposition **fluctuated between nearshore and bathyal settings**... Calcareous and non-calcareous sandstone and fossiliferous concretionary sandstone beds (Mla) up to 10 m thick form prominent ridges, as in the Silver Range. The Makara sub-basin succession was deposited in a **shelf to bathyal** environment, in a trench-slope basin..." (Lee et al., 2011) – *the main rock type for the map unit may be sediment gravity flow deposits. Lee et al. (2011) interpret the map unit as consisting of shelf to bathyal sediment. Combined with the sediment gravity flow interpretation for the map unit and Fig. 3, the depositional depth range is narrowed down to mid-bathyal depths, with the map unit inferred here to be a mid-fan deposit.*

## ***Blowhard Formation (IMtb)***

***Inferred age:*** 7-6 Ma (Lee et al., 2011)

***EoD:*** innermost shelf

***Basis for interpretation:*** Main\_Rock = conglomerate; Sub\_Rocks = sandstone, limestone, siltstone; Description = Non- to marginal marine conglomerate and cross-bedded sandstone (QMAP database). “These Late Miocene rocks are unconformably overlain by 150 m of **non-marine to shallow marine shelf** conglomerate, cross-bedded sandstone, limestone and minor siltstone” (Lee et al., 2011) – *the EoD is narrowed to innermost shelf.*

## **Mangaheia Group**

“All Pliocene and some early Quaternary rocks on the map sheet east of the axial ranges are here included in the Mangaheia Group (mainly Late Miocene to Late Pliocene). The Late Pliocene stratigraphy, for the purposes of this map, is informally divided into ‘lower’ Late Pliocene (Pmz, Waipipian-Mangapanian) and ‘upper’ Late Pliocene (Pmm, Nukumaruan)” (Lee et al., 2011). “Rocks of the Mangaheia Group accumulated in a variety of **shelfal** depositional paleoenvironments. Limited incursions into **upper bathyal** water depths are recorded in some Lower Nukumaruan (Late Pliocene) rocks. **Non-marine** beds, although volumetrically uncommon, are geographically widespread in upper beds of the group” (Bland et al., 2007).

### ***Early Pliocene Mangaheia Group***

- **ePm**

“In the northeastern part of the map in the Wairoa sub-basin the remainder of the Early Pliocene sequence (Pmz) is muddy, very fine grained tuffaceous sandstone and siltstone... In western Hawke’s Bay at Kuripapango and Puketitiri, the Early Pliocene (Pmz) succession is up to 400 m thick and consists of fine-grained sandstone to sandy mudstone, pebbly limestone, conglomerate, and coarse-grained sandstone that unconformably overlie Kaweka terrane or Late Miocene Tolaga Group. Depositional environments **shallowed with time, from upper bathyal to nearshore and shallow shelf** settings... In the Cape Kidnappers area, at the northern end of what was the Ruataniwha Strait, Early Pliocene rocks (Pmz) over 500 m thick consist of calcareous, fossiliferous massive mudstone with less common, thin interbedded, fine-grained sandstone units that are concretionary in places” (Lee et al., 2011).

***Inferred age:*** 5-4 Ma (Lee et al., 2011; Bland and Kamp, 2014)

***EoD breakdown:*** 5 Ma: outer shelf  
4 Ma: mid-shelf

***Basis for interpretation:*** Main\_Rock = sandstone; Sub\_Rocks = mudstone, conglomerate, limestone; Description = Calcareous sandstone, mudstone, pebbly limestone and conglomerate (QMAP database) – *EoD is based on the shelf interpretation for the map unit, and that the Mangaheia Group shallows over time. Upper bathyal may be an appropriate initial environment. This is the same as ePmz on the Rotorua and Raukumara map areas. NB: 11 polygons in the south of this map area near Dannevirke have been assigned the EoD of Onoke Group (Pea) from Wairarapa.*

### ***Pakaututu Formation (ePmp, ?ePmp)***

***Inferred age:*** 5-4 Ma (Lee et al., 2011; Bland and Kamp, 2014)

***EoD:*** innermost shelf

***Basis for interpretation:*** Main\_Rock = limestone; Sub\_Rocks = conglomerate, sandstone; Description = Well cemented limestone, conglomerate and sandstone (QMAP database). “Pakaututu Formation forms the basal formation of Mangaheia Group west of Mohaka Fault in the Puketitiri and Pakaututu areas (Fig. 14D). Pakaututu Formation comprises a distinctive 8-15 m-thick highly fossiliferous limestone (Hukanui Limestone Member) that overlies either basement (west of Ruahine Fault) or thick (<50 m) greywacke conglomerate and concretionary sandstone (30 m thick). The conglomerate and sandstone facies are included in the Pakaututu Formation... Accumulation of Pakaututu Formation (including the Hukanui Limestone Member) in the Puketitiri area, occurred **adjacent to a rocky coastline**, probably in a large embayment” (Bland and Kamp, 2014). “*Tucetona* prefers clean water of **relatively high-energy**, and presently occupies environments such as **channels** in many Northland harbours. A similar depositional environment is envisaged for the

limestone and sandstone facies of the Pakaututu Formation. The presence of strong relief on the lower greywacke surface west of the Ruahine Fault indicates a rugged sea-bottom with sea stacks. The basal thick conglomerate facies adjacent to the Ruahine Fault probably accumulated as **alluvial fans**" (Bland et al., 2007). "The Pakaututu Formation probably represents the **nearshore** equivalent of the Titiokura Formation" (Bland et al., 2008) – *the EoD is defined as innermost shelf, however onshore may be an appropriate initial environment.*

### ***Kairakau Limestone (ePmk)***

***Inferred age:*** 5-4 Ma (Field and Uruski, 1997)

***EoD:*** innermost shelf

***Basis for interpretation:*** Main\_Rock = limestone; Sub\_Rocks = sandstone; Description = Yellow-grey, barnacle-rich, sandy limestone and cross-bedded sandstone (QMAP database). "Farther south, forming the Maraetotara plateau, Early Pliocene rocks comprise up to 80 m of hard, coarse grained, yellow-grey, **barnacle-rich**, sandy **coquina** limestone and **cross-bedded** calcareous sandstone that is mapped as Kairakau Limestone (Pmb...)" (Lee et al., 2011) – *EoD is based on the descriptions in Lee et al. (2011).*

### ***Lower Late Pliocene Mangaheia Group***

#### ***Titiokura Formation (Pmtt)***

***Inferred age:*** 4-3 Ma (Field and Uruski, 1997; Bland et al., 2004)

***EoD:*** mid-shelf

***Basis for interpretation:*** Main\_Rock = sandstone; Sub\_Rocks = limestone, siltstone, conglomerate; Description = Alternating sandstone, limestone, siltstone and conglomerate (QMAP database). "The formation is composed of alternating sandstone and limestone, with minor siltstone and conglomerate. Titiokura Formation is dominated by limestone in the south, where it is about 50 m thick (Bland, 2001), but it is laterally variable; near Willow Flat it comprises over 800 m of alternating sandstone and limestone (Graafhuis 2001; Bland et al. 2004). Limestone beds are typically **cross-bedded**, with abundant mollusc, bryozoans and barnacle fragments" (Lee et al., 2011) – *the formation is defined as shelfal based on the fossils present, and that energy must have been great enough for cross-beds to form.*

#### ***Te Waka Formation (IPma)***

***Inferred age:*** 3 Ma (Field and Uruski, 1997; Bland and Kamp, 2014)

***EoD:*** mid-shelf

***Basis for interpretation:*** Main\_Rock = limestone; Sub\_Rocks = sandstone, conglomerate; Description = Alternating limestone and sandstone with minor conglomerate (QMAP database). "Comprising over 100 m of **coquina** limestone, interbedded sandstone, and minor conglomerate..." (Lee et al., 2011). "The seaway was swept by strong tidal currents, as inferred from giant **cross-bedded** limestone facies in the Te Waka Formation near Puketitiri" (Bland et al., 2008). "...greyish to pinky brown grainstone, locally rudstone or floatstone, with abundant mollusc, barnacle, bryozoan, and foraminiferal bioclasts... The broken condition of the bioclastic material and abundance of trough cross-bedding indicates deposition by strong traction currents. In keeping with Beu's (1995) interpretation of Te Aute sediments, it is concluded that the rocks at Kuripapango were deposited as carbonate dunes or mounds, in **inner to mid-shelf** depths" (Browne, 2004). "The overall terrigenous-dominated and diverse skeletal composition of Titiokura and Te Waka Formations, the latter the western time-equivalent of Te Onepu Limestone, reflect the **proximity of rocky substrates** and of an eroding western source area that delivered siliciclastic sand and gravel to the carbonate-rich deposits" (Caron et al., 2004) – *EoD is based on the depositional depth range given in the cited literature, which is narrowed down to mid-shelf.*

#### ***IPml***

"In the northeastern part of the map area, up to 800 m of lower Late Pliocene (Pmz...) siltstone, sandstone and minor **shellbeds**... lower Late Pliocene fossiliferous mudstone and sandstone (Pmz)... The lower Late Pliocene sequence (Pmz) in the Dannevirke area comprises muddy sandstone and sandy mudstone, with calcareous concretions, and interbedded lenses of limestone" (Lee et al., 2011).

**Inferred age:** 3-2 Ma (Lee et al., 2011)

**EoD breakdown:** 3 Ma: mid-shelf  
2 Ma: innermost shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = siltstone, limestone shellbeds; Description = Sandstone, mudstone and minor shell lenses (QMAP database) – *the shelfal interpretation is based on the presence of shellbeds and that the Mangaheia Group shallows over time. NB: the polygons in the south of this map area near Dannevirke have been assigned the EoD of Onoke Group (Pea) from Wairarapa.*

### **Matahorua Formation (IPmj)**

**Inferred age:** 3 Ma (Lee et al., 2011; Bland and Kamp 2014)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone, conglomerate; Description = Alternating sandstone, mudstone and conglomerate (QMAP database). “The formation was deposited in fluctuating **mid-shelf to non-marine** environments; the conglomerate represents a fluvial braid plain that prograded into the basin during times of low sea level” (Lee et al., 2011). “Matahorua Formation includes up to four **cyclothems**, each with basal conglomerate overlain by siltstone and sandstone. These units correspond broadly to the four members defined in the Matahorua Formation (Deep Stream, Trelinnoe, and Papakiri members, Grassy Knoll)” (Bland and Kamp, 2014) – *the interpretation in Lee et al. (2011) implies an average innermost shelf EoD for the map unit. However, mid-shelf and onshore conditions also existed.*

### **Awapapa Limestone (IPmb)**

**Inferred age:** 3 Ma (Kamp et al., 1988; Field and Uruski, 1997)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = sandstone; Description = Yellow-grey, cross-bedded, barnacle-rich limestone (QMAP database). “It consists of up to 120 m of yellow-grey, **cross-bedded, barnacle-rich** limestone, of early Late Pliocene age...” (Lee et al., 2011). “The Pliocene limestones in eastern North Island... accumulated on the margins of a principal forearc basin as it was gradually and differentially uplifted through **inner shelf** depths to form land” (Kamp et al., 1988) – *based on the lithologic descriptions of the Awapapa Limestone and Fig. 3, the map unit may have depositional depths ranging from innermost shelf to mid-shelf.*

### **Rotoikiwa Limestone (IPmi)**

**Inferred age:** 3 Ma (Field and Uruski, 1997; Caron et al., 2004)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = limestone; Description = Soft, barnacle-rich, creamy-yellow limestone (QMAP database). “...soft, **barnacle-rich**, creamy-yellow limestone, which forms the western side of the Kaokaoroa Range...” (Lee et al., 2011). “Characteristics of such isolated platforms are that they are generally siliciclastic poor (best exemplified in the central Hawke’s Bay situation by the Rotoikiwa, Te Onepu, and Pakipaki Limestones; Fig. 2), and they lack the close interrelation with continent-derived sediments that typify continent-attached platforms” (Caron et al., 2004) – *this limestone was deposited on an isolated platform to the east of the Ruataniwha Strait, therefore a mid-shelf EoD is assigned to the map unit here.*

### **Whetukura Limestone (IPmr)**

**Inferred age:** 4-3 Ma (Field and Uruski, 1997)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = sandstone; Description = Coarse-grained, cross-bedded, yellow-grey limestone (QMAP database). “At the base of the succession is the coarse-grained, **cross-bedded**, yellow-grey Whetukura Limestone (Pmj...)..., which contains abundant bryozoans and bivalve fragments” (Lee et al., 2011) – *EoD is based on the fossils present and cross-bedding.*

### **Te Onepu Limestone (IPmt)**

**Inferred age:** 3 Ma (Field and Uruski, 1997; Caron et al., 2004)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = sandstone; Description = Yellow-grey, giant foreset-bedded, coarse-grained, barnacle-rich limestone (QMAP database). “Te Onepu Limestone (Pmu; Harmsen 1985; Beu 1995) is a yellow-grey, coarse-grained limestone with well-developed **cross-beds**...” (Lee et al., 2011) – *EoD is based on the presence of cross-beds. Refer to “Te Onepu Limestone (Pet)” on the Wairarapa map area for further information.*

## Upper Late Pliocene Mangaheia Group

### **Scinde Island Formation (IPmc)**

**Inferred age:** 2 Ma (Kamp et al., 1988; Field and Uruski, 1997)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = limestone; Description = Calcareous, cross-bedded sandstone and limestone (QMAP database). “Bluff and Hospital hills in Napier City are formed from calcareous, **cross-bedded** sandstone and limestone (Pmc; Scinde Island Formation...) which may, in part be laterally equivalent to the Matahorua, Mason Ridge and Sentry Box formations (Bland et al. 2007). The large scale cross-beds are well exposed at Bluff Hill and represent the strong influence of tidal currents at **shelf** depths...” (Lee et al., 2011). “Coevally, along the eastern side of the basin, Scinde Island Formation (Boyle, 1987), Mason Ridge Formation (Dyer, 2005), and Pakipaki Limestone (Beu, 1995) were deposited on and **around structural highs**, probably associated with the growing accretionary wedge” (Bland et al., 2008) – *the formation is interpreted as a shelfal deposit in Lee et al. (2011), which is narrowed to mid-shelf here.*

### **Sentry Box Formation (IPms, ?IPms)**

**Inferred age:** 2 Ma (Field and Uruski, 1997; Bland and Kamp, 2014)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = sandstone, siltstone; Description = Pebbly, barnacle rich limestone and sandstone (QMAP database). “...in the Ohara Depression, basal pebbly **barnacle-rich** limestone, sandstone and siltstone (Pms, Sentry Box Formation and Pmy, Mount Mary Limestone...)... These formations were deposited in a **high-energy environment on or near a rocky substrate**...” (Lee et al., 2011). “Deposition in a **shallow marine (<50 m depth)** setting is inferred based on the fossil content and sedimentary facies; the variety of sediments from gravel to siltstone suggest varied, very localised sedimentation histories” (Browne, 2004). “...**inner shelf** environment inferred for Sentry Box Formation” (Bland and Kamp, 2014) – *EoD is based on Browne (2004) and Bland and Kamp (2014).*

### **Mount Mary Limestone (IPmm)**

**Inferred age:** 2 Ma (Field and Uruski, 1997; Bland and Kamp, 2014)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = sandstone, siltstone; Description = Pebbly, barnacle-rich limestone, sandstone and siltstone (QMAP database). “...in the Ohara Depression, basal pebbly **barnacle-rich** limestone, sandstone and siltstone (Pms, Sentry Box Formation and Pmy, Mount Mary Limestone...)... These formations were deposited in a **high-energy environment on or near a rocky substrate**...” (Lee et al., 2011). “The Mount Mary Limestone is dominantly a pebbly, well cemented grainstone (based on the classification of Dunham 1962) and is composed of fragmental shells, bryozoans, and other calcareous or aragonitic hard parts” (Erdman and Kelsey, 1992). “Mount Mary Pebbly Limestone probably developed adjacent to a greywacke “island” (the proto- Wakarara Range) on the margins of a region of otherwise relatively deep-water (outer shelf to perhaps uppermost bathyal)... The presence of metre-scale relief on the lower contact on Mount Mary (U21/969681) indicates a **rocky coastline** environment in areas proximal to the Wakarara Range” (Bland et al., 2007) – *the EoD is based on the presence of shallow water fossils.*

### **Mason Ridge Formation (IPmn)**

**Inferred age:** 3 Ma (Caron et al. 2004; Lee et al., 2011)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = limestone, mudstone; Description

= Alternating sandstone, limestone and mudstone (QMAP database). “Mason Ridge Formation (Pmg...) is a 20 to 50 m-thick succession of alternating **shelf** sandstone, limestone and mudstone” (Lee et al., 2011). “The Mason Ridge Formation was deposited in a combination of **inner to middle shelf** environments” (Bland et al., 2007). “...a **cyclothem** succession of limestone and mudstone” (Bland and Kamp, 2014) – *the depth range of the Mason Ridge Formation is narrowed to innermost shelf, based on the main rock type (Fig. 3).*

### ***Pakipaki Limestone (IPmp)***

***Inferred age:*** 3 Ma (Field and Uruski, 1997; Caron et al. 2004)

***EoD:*** innermost shelf

***Basis for interpretation:*** Main\_Rock = limestone; Sub\_Rocks = sandstone; Description = Pale grey-white, coarse, barnacle-rich limestone with high angle cross-beds (QMAP database). “A fault-bounded block of soft, **cross-bedded**, cream-coloured, **barnacle-rich** limestone at Pakipaki...” (Lee et al., 2011). “...coarse barnacle-rich grainstone...” (Beu, 1995) – *EoD is based on the presence of barnacles as they are a near shore fauna.*

### ***Petane Formation (IPmx)***

***Inferred age:*** 2 Ma (Field and Uruski, 1997; Bland and Kamp, 2014)

***EoD:*** mid-shelf

***Basis for interpretation:*** Main\_Rock = limestone; Sub\_Rocks = sandstone, mudstone conglomerate; Description = Alternating sequences of limestone, sandstone, mudstone and conglomerate (QMAP database). “Repetitive alternating sequences (cyclothem) of limestone, sandstone, mudstone and conglomerate crop out in the Napier area between the Ngaruroro and Waikari rivers... The alternating conglomerate, limestone and sandstone facies are interpreted to represent deposition in fluctuating **non-marine to shelf** environments” (Lee et al., 2011). “...a unit that contains up to five **cyclothem**s... Although not preserved in the west, it is inferred that **fluvial** systems also existed during deposition of upper members of the Petane Formation based on the presence of common to abundant basement clasts in Tangoio and Waipatiki Limestone Members (Petane Formation)” (Bland and Kamp, 2014) – *based on the interpretations for the map unit in Lee et al. (2011) and Bland and Kamp (2014), the lithologic description of the map unit in the QMAP database, and Fig. 3, the map unit may have a depositional depth range of onshore to outer shelf.*

### ***Kaiwaka Formation (eQmk)***

***Inferred age:*** 2 Ma (Lee et al., 2011; Bland and Kamp, 2014)

***EoD:*** innermost shelf

***Basis for interpretation:*** Main\_Rock = sandstone; Sub\_Rocks = limestone conglomerate; Description = Coarse calcareous sandstone, limestone and conglomerate (QMAP database). “...conformably overlie the Petane Formation and reflect shallowing of water depths to **marginal marine** and **fluvial** conditions (Haywick et al. 1991; Bland et al. 2007)” (Lee et al., 2011) – *onshore may also be appropriate.*

#### **• IPmu**

“Undifferentiated upper Late Pliocene rocks (Pmm) in the Ohara Depression, west of Hastings, and north to the Wairoa area, consist mostly of locally fossiliferous mudstone, alternating sandstone and mudstone, tuffaceous mudstone and limestone. Macrofossils indicate an upper Late Pliocene (Nukumaruan) age and deposition at **shelf** depths...” (Lee et al., 2011).

***Inferred age:*** 3-2 Ma (Lee et al., 2011)

***EoD breakdown:*** 3 Ma: mid-shelf

2 Ma: innermost shelf

***Basis for interpretation:*** Main\_Rock = mudstone; Sub\_Rocks = sandstone; Description = Locally fossiliferous and tuffaceous massive mudstone, minor sandstone (QMAP database) – *EoD is based on the shelf interpretation for the map unit, and that the Mangaheia Group shallows over time.*

### ***Kereru Formation (IPme)***

***Inferred age:*** 2 Ma (Field and Uruski, 1997; Bland and Kamp, 2014)

***EoD:*** innermost shelf



**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = sandstone, siltstone; Description = Pebbly, barnacle-rich limestone and sandstone (QMAP database). "...is a pebbly **barnacle-rich** limestone up to 15 m thick that is similar to the Sentry Box and Mount Mary limestone but slightly younger" (Lee et al., 2011). "Uplift of the Wakarara Island was centred on the Big Hill-Ohara Depression section of the Mohaka Fault and the Wakarara Fault, and its emergence resulted in deposition of **shallow-marine** Kereru Formation around its margins..." (Bland et al., 2008) – *interpretations in Bland et al. (2008), as well as lithologic descriptions of the map unit, indicate an innermost shelf EoD for the Kereru Formation.*

### **Kumeroa Formation (IPmku)**

**Inferred age:** 2 Ma (Field and Uruski, 1997)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = limestone; Description = Alternating sequences of sandstone, limestone and mudstone (QMAP database). "...primarily comprise alternating sandstone and limestone beds..." (Lee et al., 2011). "The Lower Kumeroa Formation consists of sandy mudstone and detrital shelly limestone... The Upper Kumeroa Formation, consisting of sandy mudstones with bands of shelly detrital limestone..." (Boreham, 1963). "The Mangamaire Group was proposed by Neef (1974, 1984) for Nukumaruan rocks of the Eketahuna area, and was expanded by Beu (1995) to include Nukumaruan siliciclastics and limestone mapped near Dannevirke as Kumeroa Formation by Lillie (1953)... The stratigraphy consists of a cyclothem body of **shallow-water** mudstone, sandstone and limestone similar to Petane Group, with limestone beds formed as transgressive systems tract shellbeds resting on sequence boundaries" (Field and Uruski, 1997) – *the cyclothem nature of the Kumeroa Formation (Field and Uruski, 1997) and its variable lithologies suggest the formation was deposited in a range of environments, from innermost to outer shelf (Fig. 3). An average mid-shelf EoD is assigned to the map unit here.*

### **Tourere Formation (IPmo)**

**Inferred age:** 3-2 Ma (Lee et al., 2011)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone, limestone; Description = Alternating sandy mudstone, coarse-grained sandstone and barnacle-rich limestone (QMAP database). "It comprises at least 100 m of alternating sandy mudstone, coarse-grained sandstone and **barnacle-rich** limestone" (Lee et al., 2011) – *the EoD appears to be shelfal, and is narrowed down to mid-shelf based on the other units around it during deposition. Innermost shelf may also be appropriate.*

- **IPmy**

**Inferred age:** 3 Ma (Lee et al., 2011)

**EoD:** outer shelf

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = sandstone; Description = Ridge-forming sandstone or limestone horizons mapped from aerial photographs (QMAP database). "Undifferentiated, ridge-forming limestone or sandstone horizons (Pml) have been mapped in the Dannevirke area" (Lee et al., 2011) – *EoD is defined as outer shelf based on the proximity of the unit to the bathyal Tangahoe Mudstone. Mid-shelf may be an appropriate alternative. NB: two polygons to the east of Dannevirke have been assigned the EoD of Onoke Group (Pea) from Wairarapa.*

- **IPm**

"Undifferentiated Late Pliocene rocks (uPm) in the Manawatu Gorge area unconformably overlie greywacke basement; they are mostly coarse grained and represent **shallow water, inner shelf deposits**... Basal conglomerate is overlain by coarse-grained calcareous sandstone, siltstone, and pebbly limestone. In the Dannevirke area and south of the Wakarara Range, undifferentiated Late Pliocene rocks are represented by fossiliferous mudstone and sandy mudstone, indicating **deeper water** environments than those for rocks in the Manawatu Gorge area" (Lee et al., 2011).

**Inferred age:** 3-2 Ma (Lee et al., 2011)

**EoD breakdown:** 3 Ma: mid-shelf  
2 Ma: innermost shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = conglomerate, mudstone, limestone; Description = Shallow water conglomerate, sandstone, siltstone and limestone; deeper water mudstone and sandy mudstone (QMAP database) – *EoD is based on the shelf interpretation for the map unit, and that the Mangaheia Group shallows over time. NB: the polygons in the south of this map area near Dannevirke have been assigned the EoD of Onoke Group (Pea) from Wairarapa.*

## Quaternary – Sedimentary deposits

- All Q deposits (except – see below)

**EoD:** onshore

**Basis for interpretation:** Based on the QMAP database which includes alluvial, beach, colluvial, dune, estuarine, lacustrine, lahar, landslide, lignite, loess, reclaimed land, rock fall, scree, swamp, and till sediments in the Quaternary deposits.

- Kai-Iwi Group (eQk), Okehu Group (eQo), Shakespeare Group (mQs, Q11b, Q9b), Q5b, ?Q5b

**EoD:** innermost shelf

**Basis for interpretation:** “Deposition was in **subtidal to tidal beach** environments (Fleming 1953)... The group was deposited in **shallow water, estuarine to tidal flat** conditions... Middle Quaternary **marine terrace** deposits... late Quaternary **marine** deposits...” (Lee et al., 2011).

## Taupo Volcanic Zone

**Inferred age:** 1-0 Ma (references in Lee et al., 2011)

“Volcanic rocks high in silica (rhyolite, with minor amounts of dacite) are areally and volumetrically the most significant volcanic products, and pyroclastic flows erupted from the TVZ have deposited ignimbrites over large areas” (Lee et al., 2011). Includes the following onshore silicic eruptives: Undifferentiated Early Quaternary ignimbrite (eQi), Whakamaru Group (Q9wh), Raepahu Formation (eQr), Taupo Group (mQvtr), Echo Cliffs rhyolite (Q5te), Oruanui Formation (Q3o, ?Q3o), Taupo Pumice Formation (Q1ati). Refer to “Taupo Volcanic Zone” on the Rotorua map area for further information.

## Tongariro Volcanic Centre

**Inferred age:** < 0.5 Ma (references in Lee et al., 2011)

“Tongariro Volcanic Centre (TgVC) comprises four major, predominantly andesitic, volcanic massifs – Tongariro, Kakaramea, Pihanga and Ruapehu – along with several lesser cones and flows, including Mangaku, Maungakatote, Pukekaikiore, Pukeonake, Ngauruhoe and, west of the map area, Hauhungatahi and Ohakune (Cole 1978; Hackett & Houghton 1989; Townsend et al. 2008). Calc-alkaline, medium-K basic and acidic **andesites** predominate” (Lee et al., 2011). Includes the following onshore intermediate eruptives: Maungaku andesite (mQvm), Maungakatote andesite (mQvk), Kakaramea Formation (mQka), Pihanga Andesite (lQph), Undifferentiated Tongariro Group (Qta), Waimarino Basalt (lQw onshore mafic eruptives).

## Deposits of the Tongariro (composite) volcano

**Inferred age:** < 0.5 Ma (references in Lee et al., 2011)

“The volcanic deposits of Mount Tongariro comprise the remnants of six main periods of cone-building activity and can be broadly subdivided into older and younger eruptive phases (Stipp 1968; Topping 1973, 1974; Hobden et al. 1996, 2001; Nairn 1997; Hobden 1997)” (Lee et al., 2011). Includes the following onshore intermediate eruptives: Tama Formation (mQta), Mangahouhounui lavas (mQti), Tama Trig lavas (mQtg), Pukekaikiore Andesite (mQpk), Pahoka Formation (mQtk), Waihohonu Lavas (Q5tw), Summit Formation (Q5ts), Pukeonake Andesite (lQvp), Te Tatau Andesite (Q3tu), Blue Lake Andesite (Q2tb), North Crater Andesite (Q2th2, Q2th3, Q2th4, Q2ths, Q3th1), Makahikatoa Andesite (Q2pk), Tama Lakes Pyroclastics (Q1tl), Half Cone Pyroclastics (Q1tc), Te Mari Andesite (Q3tm1, Q2tm2, Q1tm3, Q1tm4), Red Crater Andesite (Q1td1, Q1td2), Red Crater Andesite (Q1td3 onshore mafic eruptives), Ngauruhoe Andesite (Q1tn).

### ***Deposits of the Ruapehu volcano***

***Inferred age:*** < 0.5 Ma (references in Lee et al., 2011)

“The Ruapehu Group (Hackett 1985) comprises the Mount Ruapehu andesitic lavas, pyroclastic flows, breccias and tuff, small intrusive bodies, and intercalated lahar deposits” (Lee et al., 2011). Includes the following onshore intermediate eruptives: Te Herenga Formation (mQvt), Wahianoa Formation (lQva), Mangawhero Formation (Q3vm, Q2vm), Whakapapa Formation (Q1vw, Q1vwi, Q1vwr).

## NELSON AREA (Geological Map 9)

### *Farewell Formation (Pkf)*

*Inferred age:* 65-56 Ma (King et al., 1999)

*EoD:* onshore

*Basis for interpretation:* Main\_Rock = sandstone; Sub\_Rocks = conglomerate; Description = Quartzofeldspathic sandstone and pebbly conglomerate (QMAP database). "...consists of **fluvial** quartzofeldspathic sandstone (Fig. 55) and pebbly conglomerate (Fig. 56) between Cape Farewell and Kahurangi Point, and is inferred to have formed on a **braided floodplain** or heavily laden meandering **river system**" (Rattenbury et al., 1998) – *the EoD is defined here as onshore based on the description of a fluvial quartzofeldspathic sandstone.*

### *Brunner Coal Measures (Eb)*

*Inferred age:* 38-28 Ma (Nathan et al., 1986)

*EoD:* onshore

*Basis for interpretation:* Main\_Rock = sandstone; Sub\_Rocks = shale, 'coal seams'; Description = Quartz sandstone and conglomerate carbonaceous shale and coal seams (QMAP database). "Eocene sedimentation commenced with the deposition of **non-marine** quartz sandstone, conglomerate, carbonaceous shale and coal seams of the Brunner Coal Measures" (Rattenbury et al., 1998). "**Fluviatile**, with meandering streams and peat swamps in the northwest and more active streams in the east" (Suggate, 1984). "Petrographic evidence suggest that most Brunner coals accumulated in **peat swamps**, dominated by reed and small herbaceous vegetation, and generally lacking trees" (Nathan et al., 1986) – *the unit is defined as onshore, after Suggate (1984). NB: the coal measures have differing minimum ages (e.g. 28 Ma in the north and 36 in the south) across this map (and regionally), which is an expression of the regional marine inundation.*

### *Kaiata Formation (Erk)*

"The [Brunner] coal measures are conformably (and in most places gradationally) overlain by **shallow-water marine** sediments. In the southwest these marine sediments are massive carbonaceous mudstone with minor muddy sandstone of the Kaiata Formation (Erk)..." (Rattenbury et al., 1998). "...**shallow-water** marine sediments, included in the Rapahoe Group (Nathan 1974). The most widespread unit, Kaiata Formation, consists of dark brown carbonaceous mudstone or muddy sandstone. Various sandstone units have been identified locally, mainly in the relatively stable areas at the margins or outside the main subsiding basins, but all are locally restricted..." (Nathan et al., 1986).

- **Kaiata Mudstone Member**

"Typical foraminiferal microfaunas are dominated by a small group of benthic arenaceous genera which can exist under bottom conditions not tolerated by normal marine assemblages, as well as a small number of planktonic species... These features suggest that the mudstone was formed under poorly oxygenated bottom conditions, but the presence of some planktonic foraminifera indicates that a connection with the open sea existed... The common situation of these mudstones at the base of a **transgressive marine** sequence is important as it implies both deposition in **shallow water** (probably in conditions of high organic productivity), and that the water circulation may have been poor, at least until sedimentary basins became large enough for an oceanic thermohaline circulation pattern to develop (Andrews 1977)" (Nathan et al., 1986).

*EoD:* initially innermost shelf, deepening to outer shelf or upper bathyal

*Basis for interpretation:* Planktonic foraminifera are not reported as abundant, indicating shelfal depths. Estuarine to shelfal conditions are likely. The Kaiata Formation in the Paparoa Trough is shallower than the Kaiata Mudstone Member of the Maruia Formation in the Murchison Basin, which accumulated in upper bathyal conditions.

- **Torea Breccia**

"Close to the axis of the [Paparoa] Trough the Kaiata Formation contains an interbedded sequence of coarse sandstone and granite-derived breccia and conglomerate in a sandy matrix (Torea Breccia Member; Laird & Hope 1968). It is interpreted as a **mass-flow** sequence originating from a near-by

rising source, and similar in origin to the Omotumotu Member..." (Nathan et al., 1986).

*EoD: upper bathyal*

*Basis for interpretation: EoD is the same as that of the Omotumotu Member which occurs further to the south of this map area, after Nathan et al. (1986) which says it is of similar origin. Mid-bathyal is a possible alternative EoD. Its occurrence is too brief to be included in the overall EoD of the Kaiata Formation.*

**Inferred age:** 38-32 Ma (Nathan et al., 1986)

**EoD breakdown:** 38-37 Ma: innermost shelf  
36 Ma: mid-shelf  
35-32 Ma: outer shelf

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone; Description = Massive mudstone and muddy sandstone (QMAP database) – *the EoD breakdown is based on the depositional age and paleoenvironmental interpretations of the members that occur in the Nelson map area. The formation is defined here as deepening over time, to match the deepening of the Kaiata Mudstone Member to the east in the Murchison Basin, except that the Murchison Basin is filled at bathyal depths during this interval.*

## **Maruia Formation (Em)**

Includes Brunner Coal Measures, Nuggety Member, and Kaiata Mudstone Member.

"Mudstone, commonly containing a high proportion of thick-bedded quartzofeldspathic sandstone, with minor conglomerate and thin coal seams, occurs in the Murchison area as Maruia Formation..." (Rattenbury et al., 1998). "...is composed of 50 to 500 m of coarse, quartzofeldspathic sandstone with minor conglomerate, carbonaceous mudstone and thin seams of bituminous coal. These rocks are overlain by up to 500 m of largely massive, dark brown, micaceous mudstone or siltstone with minor bands of feldspathic sandstone, becoming more calcareous towards the top. The Maruia Formation was deposited unconformably on basement rocks, initially in a **terrestrial** environment. The mudstone represents deposition in an **estuarine** to partly enclosed **inner shelf** environment with periodic incursion of **submarine fans** derived from a rising area of Separation Point Batholith granite, probably to the east (Suggate 1984)" (Rattenbury et al., 2006).

### ***Brunner Coal Measures***

"**Fluviatile**, with meandering streams and peat swamps in the northwest and more active streams in the east" (Suggate, 1984).

*EoD: onshore*

*Basis for interpretation: EoD is after Suggate (1984).*

### ***Nuggety Member***

"**Submarine fan...**" (Suggate, 1984). The occurrence of Nuggety Member as redeposited sandstone (turbidites and sandy debris flows) requires an upper to mid-bathyal EoD. *EoD: mid-bathyal*

*Basis for interpretation: The EoD is interpreted as a mid-bathyal submarine fan.*

### ***Kaiata Mudstone***

"The common situation of these mudstones at the base of a **transgressive marine** sequence is important as it implies both deposition in **shallow water** (probably in conditions of high organic productivity), and that the water circulation may have been poor..." (Nathan et al., 1986).

*EoD: initially shelf, deepening over time to upper to mid-bathyal*

*Basis for interpretation: The Kaiata Mudstone in the Murchison Basin represents a transgressive marine sequence that was initially approximately mid-shelf depth, and deepened over time to upper bathyal.*

**Inferred age:** 38-31 Ma (Nathan et al., 1986; Ghisetti and Beggs, 2007)

**EoD breakdown:** 38-36 Ma: onshore (Brunner Coal Measures)  
35 Ma: mid-shelf (Kaiata Mudstone)  
34-31 Ma: mid-bathyal (Kaiata Mudstone, Nuggety Member)

**Basis for interpretation:** Main\_Rock = conglomerate; Sub\_Rocks = sandstone, mudstone, siltstone, 'coal seams'; Description = Conglomerate quartzofeldspathic sandstone carbonaceous mudstone and siltstone thin coal beds (QMAP database) – *the EoD breakdown for the map unit is based on the depositional age and paleoenvironmental interpretations of the members that make up the unit. Kaiata Mudstone and Nuggety Member interfinger, so an average EoD of mid-bathyal is chosen to represent this interval. Refer to "Maruia Formation (Em)" on the Kaikoura map area for further information.*

## Jenkins Group (Ej)

Includes Marsden Coal Measures, Braemar Formation, Bishopdale Formation, Wakatu Formation, and Magazine Point Formation. Defined as lower and upper Jenkins Group in Rattenbury et al. (1998).

"Tectonic activity recommenced at about 38 Ma (late Middle Eocene), with regional extension leading to the formation of small, local basins, many of them fault-bounded, separated by areas of **low-lying land**... Continued **marine transgression** from late Eocene into the Oligocene led to the gradual drowning of the low-lying land, and by the end of the Oligocene virtually the whole map area was submerged..." (Rattenbury et al., 1998). "...basal coal measures overlain by a variety of marine sediments... The group was deposited immediately prior to and during a **marine transgression** that moved north over the South Island during the Lower Tertiary (Suggate 1950)" (Johnston, 1979).

### **Marsden Coal Measures**

"It consists of steeply southeast-dipping, very sheared, bedded sandstone with interbedded dark siltstone and mudstone, and scattered thin lenses of pebble conglomerate and seams of high volatile bituminous **coal**... In the early Tertiary the north of the South Island was reduced to a **low-lying terrain** on which coal measures, followed by marine sediments, accumulated (Suggate 1950). In Kaiatan or possibly Bortonian time Marsden Coal Measures were deposited in a basin centred near Nelson City. By Upper Kaiatan, marine deposition began in the basin, but to the east coal measures accumulated, possibly following down-faulting of the block east of the Flaxmore Fault" (Johnston, 1982a). "...Marsden (= Brunner) Coal Measures, inferred to be 500 m thick, consists of **non-marine** quartzose sandstone with interbedded dark grey mudstone, thin lenses of locally-derived conglomerate, and thin coal seams" (Nathan et al., 1986). "In the vicinity of Nelson City, steeply dipping and extensively faulted well-bedded sandstone, siltstone, conglomerate, and thin **coal seams** collectively form the lower part of the Jenkins Group..." (Rattenbury et al., 1998).

*EoD: onshore*

*Basis for interpretation: The initial depositional environment of Marsden Coal Measures during the Middle Eocene (Kaiatan or possibly Bortonian; Johnston, 1982a) was probably onshore. However, by the Late Eocene (Upper Kaiatan) parts of the Marsden Coal Measures may have a marine EoD: "By Upper Kaiatan, marine deposition began in the basin, but to the east coal measures accumulated..." (Rattenbury et al., 1998). Overall, however, Eocene Marsden Coal measures are probably mostly onshore deposits.*

### **Braemar Formation**

"...dominantly poorly bedded, dark-coloured, fine grained sediments... The remainder of the formation comprises dark grey to black, sheared and disjointed mudstone with scattered thin light grey sandstone beds, up to 25 mm thick, and concretions up to 1.7 m across... Thin fragile fragments of bivalves and, less commonly, gastropods, corals, and crustacea (crabs) occur throughout... as local depressions were invaded by the sea the dark coloured, fine-grained Braemar Formation was deposited on the coal measures" (Johnston, 1979).

*EoD: innermost shelf*

*Basis for interpretation: The deposition of the Braemar Formation occurred as the marine transgression began, therefore its EoD is defined as innermost shelf.*

### **Bishopdale Formation**

"...consists of conglomerate, locally stained red, with sandstone and dark grey siltstone beds near the top, particularly in the north... Some of the sandstone beds contain lenses, up to 10 mm thick, of **coal** and a sandstone outcrop behind the Nelson College dining room shows ill-defined cross

bedding... poorly cemented sandstone, with subangular pebbles and bands of poorly preserved macrofossils... deposition of conglomerate of the Bishopdale Formation indicates a still **shallow, perhaps deltaic**, environment” (Johnston, 1979).

*EoD: innermost shelf*

*Basis for interpretation: The EoD is interpreted as being innermost shelf at this time.*

### **Wakatu Formation**

“...grey to blue-grey siltstone with scattered sandstone beds, concretions and, locally at its base, impure limestone horizons (View Mount Limestone)... The View Mount Limestone is [...] composed of numerous echinoid spines and fragments of corals, barnacles and mollusca... In Whaingaroan time more **open sea** conditions prevailed and in the east the Wakatu Formation [...] was deposited on the Bishopdale Formation, or, as the sea transgressed eastwards, on the Marsden Coal Measures” (Johnston, 1979). “As the sea transgressed onto the coal measures from the south (Suggate 1950), massive sparsely fossiliferous blue-grey silt of the Wakatu Formation was deposited in the mapped area. Both molluscan and foraminiferal assemblages are of low diversity and suggest deposition in a **shallow, protected embayment...**” (Johnston, 1982b). “In Nelson city, the upper part of the Jenkins Group (Ej) contains Miocene graded sandstone-siltstone lenses, and massive blue-grey siltstone with minor conglomerate and breccia” (Rattenbury et al., 1998).

*EoD: (initially innermost shelf) outer shelf*

*Basis for interpretation: The lithologic description of the Wakatu Formation given in Johnston (1982b) suggests an outer shelf, or possibly mid-shelf EoD (Fig. 3). The formation is defined as outer shelf here, but would have initially been deposited in an innermost shelf setting. Upper bathyal may be appropriate for the upper part of the formation as the marine transgression continued leading to the Magazine Point Formation.*

### **Magazine Point Formation**

“Shallow water macrofossils, commonly crushed and broken, are scattered throughout and are locally abundant in lenses of fine breccia... The abundance of graded beds in the lower part of the formation indicates deposition by **turbidity currents**... Debris flows along the channels deposited the fossiliferous breccia...” (Johnston, 1979). “Magazine Point Formation faunas suggest deposition within the **uppermost bathyal to mid-bathyal** range (**200-800m**)... Argillaceous-rich packages (up to 35m thick) are primarily composed of very fine grained and highly argillaceous sandstone (c. 80-90%) with minor interbedded clean sandstone (c. 10-20%)... Within the argillaceous-rich packages, thin clean sandstone interbeds commonly display evidence of waning flow deposition, based on the presence of normal grading (from fine to very fine grain size) and Bouma cycle Tb-Tc beds... Clean sandstone beds are locally amalgamated (though rarely into intervals >2m thick), but are commonly interbedded with thin intervals of argillaceous sandstone... Conglomerate up to 1.5 m thick are locally interbedded with stacked sandstone... interpreted as the deposits of **submarine fan** systems” (Higgs et al., 2004).

*EoD: upper bathyal*

*Basis for interpretation: The EoD is based on the interpretation in Higgs et al. (2004) and our own observations. The shallow water fossils are assumed to have been redeposited into deeper water.*

**Inferred age:** 38-22 Ma (Johnston, 1979; King et al., 1999)

**EoD breakdown:**

38-37 Ma:	<u>onshore</u> (Marsden Coal Measures, Braemar Formation (37))
36-33 Ma:	<u>innermost shelf</u> (Braemar Formation (36), Bishopdale Formation (36-33), Wakatu Formation (34-33))
32-28 Ma:	<u>outer shelf</u> (Wakatu Formation)
27-22 Ma:	<u>upper bathyal</u> (Wakatu Formation, Magazine Point Formation)

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = siltstone, limestone, conglomerate, ‘coal seams’; Description = Marine sandstone, siltstone and limestone lenses of conglomerate and thin coal seams (QMAP database) – *the EoD breakdown for the map unit is based on the depositional age and paleoenvironmental interpretations of the formations and/or members that make up the unit. The EoD for 27-26 Ma is an average of the two formations that were being deposited during this time, so outer shelf or mid-bathyal may be more appropriate.*

## Nile Group (On)

**Inferred age:** 29-23 Ma (King et al., 1999)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = calcareous mudstone, 'calcareous siltstone', sandstone; Description = Crystalline to sandy limestone and calcareous mudstone and sandstone (QMAP database). "Nathan (1974b) included all the calcareous sediments in the Nile Group (On), and Nathan and others (1986) divided Nile Group lithologies into two major groupings: (a) Platform facies (usually <100 m thick), consisting of **shallow-water** bioclastic limestone and muddy micaceous limestone formed on a relatively stable **shelf**; and (b) Basinal facies (usually >100 m thick), predominantly muddy limestone, massive calcareous mudstone and interbedded calcareous sandstone and mudstone, formed in rapidly subsiding basins. The platform facies occurs as erosional remnants over much of Northwest Nelson, mainly as bluff-forming shelly, locally algal, limestone ... that includes the Takaka Limestone of Golden Bay. The basinal facies occur in the south (Figs 61 and 62) in the Murchison Basin and the Mokihinui catchment, where it is mapped as Matiri Formation (Om)" (Rattenbury et al., 1998) – *EoD is based on the main rock type for the map unit being limestone, which is likely the "shallow water bioclastic limestone" of the Nile Group's platform facies (Rattenbury et al., 1998). "Shallow water" is assumed here to be mid-shelf depths. The basinal facies of the Nile Group is distinguished from On and is mapped as Matiri Formation (Om).*

### Matiri Formation (Om)

Includes Scotty Mudstone Member, Doughboy Member and Trig M Member.

"(b) **Basinal facies** (usually >100 m thick), predominantly muddy limestone, massive calcareous mudstone and interbedded calcareous sandstone and mudstone, formed in rapidly subsiding basins... The basinal facies occurs in the south... in the Murchison Basin and the Mokihinui catchment, where it is mapped as Matiri Formation (Om)" (Rattenbury et al., 1998). "Continuing marine transgression through the Oligocene led to the gradual drowning of the low-lying land areas exposed at the end of the Eocene, so that by the beginning of the Late Oligocene (Duntroonian—early Waitakian Stages) virtually the entire West Coast Region was submerged... The Basinal Facies in the Murchison Basin consists of massive calcareous mudstone and calc-**flysch**, all included in the Matiri Formation... Detailed micropaleontological studies show that the Matiri Formation contains an assemblage of **deep-water** foraminifera" (Nathan et al., 1986).

#### • Scotty Mudstone Member

"At the base, rapid establishment of **fully marine** conditions is indicated by the ubiquitous colour change from Maruia Formation mudstone, increase in calcium carbonate content, and incoming of fully marine planktic foraminifera. Rapid increase of water depth from shelf to bathyal is recorded within the Whaingaroan..." (Suggate, 1984).

**EoD:** mid-bathyal

**Basis for interpretation:** *This member is defined as mid-bathyal after the Rattenbury et al. (2006) description of bathyal for the Matiri Formation, and the lithology of mudstone. Lower bathyal may also be appropriate.*

#### • Doughboy Member

"The coarse deposits result from short distance mass transport into an **outer shelf to bathyal** environment" (Suggate, 1984). "A wedge of **mass-flow** beds, mainly conglomerate, grit, and sandstone, containing identical granite clasts and a **redeposited** shallow-water fauna occur within the lower part of the Matiri Formation on the western margin of the Murchison Basin..." (Nathan et al., 1986).

**EoD:** upper bathyal

**Basis for interpretation:** *This member is defined as upper bathyal after the Rattenbury et al. (2006) description of bathyal and the identification of debris flows. Mid-bathyal may also be appropriate.*

#### • Trig M Member

"**Bathyal submarine fan** derived from erosion of shelly and algal inner shelf sediments" (Suggate, 1984).

**EoD:** mid-bathyal

**Basis for interpretation:** *This member is defined as mid-bathyal after the Rattenbury et al. (2006) de-*



*scription of bathyal, the occurrence of flysch and transportation of material down submarine canyons. Lower bathyal may also be appropriate.*

**Inferred age:** 30-24 Ma (Suggate, 1984, Ghisetti and Beggs, 2007)

**EoD breakdown:** 30-29 Ma: mid-bathyal (Scotty Mudstone Member)  
28-27 Ma: mid-bathyal (Scotty Mudstone Member, Doughboy Member)  
26-24 Ma: mid-bathyal (Scotty Mudstone Member [26-25], Trig M Member [24])

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = siltstone, limestone, sandstone grit; Description = Massive calcareous mudstone and siltstone sparsely fossiliferous (QMAP database) – EoD is based on the bathyal interpretation of the map unit in Rattenbury et al. (2006). Refer to “Matiri Formation (Om)” on the Kaikoura map area for further information.

## Lower Blue Bottom Group (Mb)

**Inferred age:** 21-17 Ma

**EoD:** outer shelf in west; upper bathyal in east

**Basis for interpretation:** Main\_Rock = siltstone; Sub\_Rocks = calcareous mudstone' sandstone; Description = Blue-grey calcareous siltstone and mudstone basal calcareous sandstone (QMAP database). “Apart from the Murchison Basin, the dominant lithology is light grey-brown calcareous mudstone or muddy sandstone, collectively mapped as Lower Blue Bottom Group...” (Rattenbury et al., 1998). “This subgroup [lower Blue Bottom Group]... is composed of Postal River Formation, Fenian Creek Sandstone, Scorpion Creek Sandstone, and Quoich Sandstone... Environment of deposition [undifferentiated Postal River Formation near Karamea River in the west]: Foraminifera indicate that the Sandstone Member was deposited in an **outer shelf** environment... Macrofossils from the Mudstone Member are rare and are consistent with **bathyal deposition**... Postal River Formation therefore represents a deepening sequence from **neritic** fossiliferous sandstone to mudstone in **deep water**, and finally **turbidite**... Environment of deposition [Fenian Creek Sandstone]: Foraminifera from samples... from the northern Oparara valley, and... Postal River, indicate **mid and outer neritic depths** of deposition... Environment of deposition [Scorpion Creek Sandstone]: The laminated sandstone, scours, and thanatocoenotic shells suggest that deposition was from much stronger currents (probably within the upper flow regime (Kulm et al. 1975)) than those which deposited the Fenian Creek Sandstone. The well rounded pebbles of concretion-like sediment indicate that Cenozoic strata were being eroded and the lignite fragments suggest that tree-covered **land was nearby**... Environment of deposition [Quoich Creek Sandstone]: ... indicate **mid-shelf** deposition. Finlay (in Wellman 1950a) considered that faunas of “the uppermost part of the section” are **brackish**... [Environment of deposition undifferentiated lower Blue Bottom Group:] Foraminifera... indicate deposition at **inner-mid-shelf** depths in clear water” (Neef, 1981) – *the EoD of the units that are currently located around the Karamea River in the west are defined as outer shelf, based on cited references, which generally indicate a neritic and shelfal depositional environment for the Lower Blue Bottom Group. The units in the east and north of the Nelson map area are defined as upper bathyal.*

## Mangles Formation (Mm)

Includes Tutaki Member, Crowe Member, Valley Creek sandstone, and Trig A Member.

“The lower part of the Mangles Formation, exposed within the Nelson QMAP area, consists of an alternating sandstone and mudstone **turbidite** sequence, which passes upwards into more massive, locally glauconitic, **shallow-water** sandstone” (Rattenbury et al., 1998). “An exceptional increase in the rate of subsidence initiated Mangles Formation deposition” (Suggate, 1984). “...the Mangles Formation, conformable or with only a minor disconformity over the Matiri Formation, accounts for 12, 000 ft and is subdivided into a lower portion with mainly thin-bedded, alternating sandstone, siltstone, and mudstone, and an upper portion that consists of massive sandstone and local massive siltstone beds; the siltstone in the lower, alternating beds are all calcareous but the formation as a whole is basically non-calcareous. On the western side of the basin the Lower Mangles is, however, represented by thick sandstone beds with only minor, thin shale-silt partings. In contrast with the dirty, dense, and greenish grey Upper Mangles, this sandstone is quartz-rich and light grey, somewhat micaceous but rather well sorted...” (Katz, 1968).

- **Tutaki Member**

“**Submarine fans** extending to **bathyal** depths, probably from both west and northeast” (Suggate, 1984).

*EoD: lower bathyal*

*Basis for interpretation: EoD is based on the stratigraphic position of the Tutaki Member in the lower part of the Mangles Formation.*

- **Crowe Member**

“**Submarine fan**” (Suggate, 1984).

*EoD: upper bathyal*

*Basis for interpretation: Graded beds and the presence of conglomerates in the graded beds are interpreted as upper fan sediments of upper bathyal depth (QMAP description). mid-bathyal may also be appropriate.*

- **Valley Creek Sandstone**

“The type section consists of about 1750 m of dark grey massive siltstone grading up to dark grey massive, muddy very fine sandstone... **Mid-outer shelf to bathyal**” (Suggate, 1984).

*EoD: initially upper to mid-bathyal, shallowing up section to mid-shelf*

*Basis for interpretation: To call this member a sandstone is a bit of a misnomer as the bulk of it is essentially a siltstone, inferred to be deposited at upper bathyal depths. The upper part of the member is a mid-shelf sandstone.*

- **Trig A Member**

“Fine to medium sandstone with scattered pebbles or pebble stringers... **Inner shelf**” (Suggate, 1984).

*EoD: innermost shelf*

*Basis for interpretation: Rattenbury et al. (2006) mention pebbly sandstone near the top of the Mangles Formation, which implies shallowing upwards through the formation.*

**Inferred age:** 23-17 Ma (Suggate, 1984; Ghisetti and Beggs, 2007)

**EoD breakdown:** 23-20 Ma: lower bathyal (Tutaki Member)

19-18 Ma: upper bathyal (Crowe Member, Valley Creek sandstone)

17 Ma: innermost shelf (Trig A Member)

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = siltstone mudstone; Description = Medium to fine grained quartz-mica sandstone locally glauconitic siltstone and massive sandstone beds (QMAP database) – *the EoD breakdown for the Mangles Formation is based on the depositional age and paleoenvironmental interpretations of the members that make up the formation. Refer to “Mangles Formation (Mm)” on the Kaikoura map area for further information.*

## Upper Blue Bottom Group (Pb)

**Inferred age:** 8-3 Ma (Rattenbury et al., 1998)

*EoD: mid-shelf*

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone limestone ‘coal seams’; Description = Massive brown calcareous mudstone minor sandstone limestone and coal seams (QMAP database). “Much of Northwest Nelson was emergent during the Late Miocene - Pliocene, and marine sediments (mapped as Upper Blue Bottom Group, Pb) are preserved only on the south-west side of the map area near Karamea and further south near the mouth of the Mohikinui River. At both places the lithology is similar, consisting of blue-grey muddy fine sandstone containing **shallow-water** fossils. There is a change at about the Miocene - Pliocene boundary to massive fine-grained sandstone, often weathered rusty brown in outcrop” (Rattenbury et al., 1998). “Environment of deposition [Upper Blue Bottom Group]: Foraminifera from Jordan Creek (L27/f3 and f4) indicate **inner and inner-mid shelf** depths respectively... Foraminifera from Upper Tongaporutuan strata commonly indicate *Haeuslerella* Biofacies (**60-300 m**) deposition... Thanatocoenotic macrofossils from a shellbed from the basal strata in Captain Creek (L27/f2)...which were derived from a **nearshore** environment. Presumably, like the Tongaporutuan shelly gravel beds, the gravel

and shells were transported to **deeper water** during storms. The overlying beds contain spatangoids and *Robulus calcar* (L26/f58), which indicate that deposition was at **c. 300 m**" (Neef, 1981) – *EoD is based on the QMAP and Rattenbury et al. (1998) lithologic description combined with Fig. 3, and interpretations in Neef (1981, which all indicate an innermost shelf to upper bathyal EoD for the group. The map unit is defined as mid-shelf primarily on the description of the group as "muddy fine sandstone containing shallow-water fossils" in Rattenbury et al. (1998) combined with Fig. 3. However, an innermost shelf or outer shelf EoD may be a more appropriate interpretation.*

## **Tadmor Group**

"**Non-marine** conglomerate and gravel of the Tadmor Group, resting unconformably on older rocks, are exposed further east" (Rattenbury et al., 1998). "**Terrestrial** deposits unconformably overlying Lower Tertiary and older rocks are mapped as Moutere Gravel and Glenhope Formation, and are included in the Tadmor Group" (Johnston, 1971).

### ***Glenhope Gravel (Ptg)***

**Inferred age:** 8-4 Ma (Mildenhall and Suggate, 1981)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = gravel; Sub\_Rocks = sand, silt, clay, lignite; Description = Terrestrial granitic-derived gravel sand and silt with carbonised wood. Lacustrine deposits with feldspathic clay and lignite (QMAP database). "...consists of locally derived conglomerate, sandstone, and **lignite seams** of latest Miocene-Pliocene age" (Rattenbury et al., 1998) – *EoD is based on Rattenbury et al. (1998) and Johnston (1971) interpretations.*

### ***Port Hills Gravel (Ptp)***

**Inferred age:** 7-5 Ma (King et al., 1999)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = gravel; Sub\_Rocks = sand, mud, clay, boulders; Description = Poorly to moderately well sorted clay bound gravel (QMAP database). "In Nelson City, the Port Hills Gravel (Ptp), up to 500 m thick, consists of granitic conglomerate grading upwards into conglomerate composed of clasts of volcanoclastic Permian/Triassic rocks largely derived from the east of the Waimea Fault..." (Rattenbury et al., 1998). "Port Hills Gravel Formation (PHG) is a Pliocene **terrestrial** deposit" (Westerson, 2007) – *EoD is based on interpretations in Rattenbury et al. (1998) and Westerson (2007).*

### ***Moutere Gravel (Ptm)***

**Inferred age:** 3-2 Ma (Mildenhall and Suggate, 1981)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = gravel; Sub\_Rocks = sand, mud, clay, boulders, peat; Description = Poorly to moderately well sorted clay bound gravel containing up to boulder sized clasts of quartzofeldspathic sandstone (QMAP database). "Rapid uplift of the Southern Alps in the Late Pliocene is reflected by a flood of Torlesse-derived gravel that extended west and northwest, and is inferred to have covered much of the present land area (Nathan and others 1986, their map 30). An extensive area of uniform yellow-brown, clay-bound gravel, with deeply weathered clasts almost entirely of Torlesse-derived sandstone and semi-schist (Moutere Gravel, Ptm), is preserved in the Moutere Depression" (Rattenbury et al., 1998) – *EoD is based on Rattenbury et al. (1998) and Johnston (1971) interpretations.*

## **Old Man Group (Po)**

**Inferred age:** 3-2 Ma (Rattenbury et al., 1998)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = gravel; Sub\_Rocks = sand, mud, clay, boulders; Description = Brown weathered greywacke, granite, schist conglomerate (QMAP database). "A similar weathered conglomerate, but also containing schist, granite and other igneous and sedimentary clasts, as well as a higher proportion of interbedded sandstone is exposed in the Karamea area where it is mapped

as Old Man Group (Po)” (Rattenbury et al., 1998) – *EoD is based on the main rock type. Refer to “Old Man Group” on the Greymouth map area for further information.*

### **Hillersden Gravel (Ph)**

(QMAP database spelling: Hillesden Gravel)

**Inferred age:** 3-1 Ma (Rattenbury et al., 1998)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = gravel; Sub\_Rocks = sand, mud, clay, boulders; Description = Clay bound gravel comprising greywacke and minor chert clasts (QMAP database). “The Late Pliocene Hillersden Gravel (Ph), composed of clay-bound Torlesse-derived quartzofeldspathic sandstone clasts, is preserved to the south of the Alpine Fault in the Wairau Valley” (Rattenbury et al., 1998) – *EoD is based on Begg and Johnston (2000) interpretation of the Hillersden Gravel as terrestrial.*

## **Quaternary – Sedimentary deposits**

- **All Q deposits** (except – see below)

**EoD:** onshore

**Basis for interpretation:** Based on the QMAP database which includes alluvial, beach, colluvial, dune, landslide, loess, reclaimed land, and swamp sediments in the Quaternary deposits.

- **uQb, Q5b**

**EoD:** innermost shelf

**Basis for interpretation:** “**Marine** and **beach** deposits consisting of gravel, sand and mud...” (Rattenbury et al., 1998).

## WELLINGTON AREA (Geological Map 10)

### Tora Group (Pt)

Includes Manurewa Formation, Awhea Formation, Mungaroo Limestone, Awheaiti Formation, Pukemuri Formation and Wanstead Formation.

“The Tora Group (Pt) (see Moore et al. 1986), as used here, is undifferentiated except for Mungaroo Limestone. The group consists of the following formations in stratigraphic succession: Manurewa Formation, Awhea Formation, Mungaroo Limestone, Awheaiti Formation, Pukemuri Formation and Wanstead (= Kandahar) Formation, only the first being of Cretaceous age” (Begg and Johnston, 2000).

#### **Manurewa Formation**

“Locally the base of the formation is a **glauconitic mudstone** up to 12 m thick, and the upper part comprises a thinly bedded sequence of hard, grey, calcareous and glauconitic fine-grained sandstone. Haumurian microfaunas date the lower part of the Manurewa Formation; the top may extend into the Paleocene. It was deposited in **mid to lower bathyal** depths and is possibly a more calcareous equivalent of the Porangahau Member of the upper Whangai Formation recognised to the northeast of the map area (Moore 1988; Field et al. 1997)” (Begg and Johnston, 2000). “At Manurewa Point and in Pukemuri Stream, the Manurewa Formation can be subdivided into two separate members (here designated the Lower and Upper Members) with distinct characteristics, separated by an erosion surface. The Lower Member is erosive into the underlying Whangai Formation, and is composed dominantly of calcareous or fine to very fine grained clastic deposits. The Upper Member, which rests on an erosion surface cut into the Lower Member, is dominated by glauconitic medium sandstone and **olistostromes**” (Laird et al., 2003).

*EoD: mid-bathyal*

*Basis for interpretation: It is inferred that both the Lower and Upper Members accumulated in mid- to lower bathyal environments. This is in contrast with the conclusions reached by Laird et al. (2003).*

#### **Awhea Formation**

“...consists of up to 270 m of alternating centimetre- to decimetre-bedded **glauconitic** fine sandstone and calcareous and micaceous mudstone” (Begg and Johnston, 2000).

*EoD: mid-bathyal*

*Basis for interpretation: This formation is inferred to be redeposited sandstone deposits forming submarine fans at mid-bathyal depths.*

#### **Mungaroo Limestone**

*EoD: mid-bathyal*

*Refer to “Mungaroo Limestone (Ptm)”.*

#### **Awheaiti Formation**

“...is about 40 m thick and consists of thinly bedded, glauconite-poor, locally calcareous, fine sandstone to dark micaceous siltstone” (Begg and Johnston, 2000).

*EoD: mid-bathyal*

*Basis for interpretation: Little environmental and temporal information could be found on this unit so it is given the same EoD and age as the Mungaroo Limestone.*

#### **Pukemuri Formation**

“...270 m-thick sequence of hard, poorly to very thinly bedded, blue-grey, calcareous and micaceous mudstone comprising the Pukemuri Siltstone. The siltstone are also red, brown or green, with glauconitic sandstone interbeds and sideritic concretions. They are of ?Mangaorapan to Heretaungan age and were deposited in an **outer shelf to upper bathyal** environment” (Begg and Johnston, 2000). “The paleodepth of the base of the Pukemuri Siltstone deepens from **outer shelf-upper bathyal** at Te Oro Stream to **mid-bathyal** at Awheaiti Stream. At Awheaiti Stream the paleodepths decreases up-formation to **outer shelf-upper bathyal**, a similar depth to the top of the formation at

Pukemuri Stream. Planktics are variable throughout the formation and, in general, the watermass is considered to have been **oceanic to marginal**, with some obviously **neritic** intervals” (Field and Uruski, 1997).

*EoD: upper bathyal*

*Basis for interpretation: the EoD is here narrowed down to upper bathyal. Outer shelf may be an alternative environment.*

### **Wanstead Formation**

“...(= Kandahar Formation of Waterhouse & Bradley 1957) outcrops extensively in Awheaiti Stream, and consists of massive blue-grey sandstone, blue mudstone and bentonite about 170 m thick” (Begg and Johnston, 2000). “The Wanstead Formation is generally considered to represent the deepest depositional environment of the Late Cretaceous-Paleogene of the East Coast, with average paleodepths generally **mid-bathyal**, and **lower bathyal-abyssal** in parts” (Field and Uruski, 1997).

*EoD: mid-bathyal*

*Basis for interpretation: the EoD is narrowed down here to mid-bathyal. Lower bathyal may be an alternative environment.*

**Inferred age:** 65-43 Ma (Field and Uruski, 1999; Boyes et al., 2011a)

**EoD breakdown:**

65 Ma:	<u>mid-bathyal</u> (Manurewa Formation)
64-61 Ma:	<u>mid-bathyal</u> (Awhea Formation)
60-58 Ma:	<u>mid-bathyal</u> (Mungaroo Limestone)
57-46 Ma:	<u>upper bathyal</u> (Pukemuri Formation)
45-43 Ma:	<u>mid-bathyal</u> (Wanstead Formation)

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = siltstone mudstone greensand; Description = Graded bedded to massive sandstone; siltstone; calcareous bentonitic mudstone; and greensand (QMAP database) – *the Tora Group has recognised formations within it that were deposited in a range of environments.*

### **Mungaroo Limestone (Ptm)**

**Inferred age:** 60-58 Ma (Boyes et al., 2011a)

*EoD: mid-bathyal*

**Basis for interpretation:** Main\_Rock = limestone; Map\_Unit = Mungaroo Limestone; Description = Lenses of well bedded muddy limestone (QMAP database). “In coastal Wairarapa, between Manurewa and Te Kaukau points, Late Cretaceous rocks (Manurewa Formation) are overlain, apparently conformably, by younger formations of the Tora Group totalling about 650 m in thickness. Only the Mungaroo Limestone, a prominent lithology, is differentiated on the map... Mungaroo Formation is up to 100 m thick and comprises a lower hard, poorly bedded, greenish-grey calcareous siltstone that is extensively burrowed, including feeding traces of *Zoophycos*, grading upward into a well bedded, hard, white, micritic limestone with minor mudstone and glauconitic sandstone interbeds. The extensive burrowing and microfossils (foraminifera and coccoliths) indicate deposition in **mid to lower bathyal** depths during the Teurian to Waipawan” (Begg and Johnston, 2000). “...is probably Teurian-Waipawan in age, but at some localities the limestone may be as young as Waipawan-Heretaungan. It is inferred to have been deposited at **mid- to lower bathyal** depths” (Field and Uruski, 1997) – *the EoD is here narrowed down to mid-bathyal. Lower bathyal may be an alternative environment.*

### **Otaihanga Outlier (Oo)**

Includes Otaihanga Quartzite and Muaupoko Greensand.

“The outlier at Otaihanga (Oo), a weakly indurated sedimentary sequence about 90 m thick, rests on weathered Rakaia terrane rocks (MacPherson 1949; D.W. Heron, pers. comm.). The basal 15 m is pebbly Otaihanga Quartzite, of probable late Middle-Late Eocene age (J.I. Raine, G.J. Wilson pers. comm.); it is overlain by the Muaupoko Greensand, a glauconitic sandstone with thin siltstone layers. Limonitic casts of brachiopods and bivalves in the lower part of the greensand, and more widely dispersed foraminifera, indicate an Early Oligocene (Whaingaroan) age for the formation” (Begg and Johnston, 2000).

**Inferred age:** 37-33 Ma (Macpherson, 1948; King et al., 1999)

**EoD breakdown:** 37-35 Ma: innermost shelf (Otaihanga Quartzite)  
34-33 Ma: outer shelf (Muaupoko Greensand)

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = sandstone siltstone; Description = Pebbly quartzite; glauconitic sandstone; and minor thin siltstone beds (QMAP database) – *no paleoenvironmental information could be found for the Otaihanga Outlier. Based on the rock type the Otaihanga Quartzite could be an innermost shelf deposit. The Muaupoko Greensand could be inner to outer shelf, so the EoD is defined as an initially innermost shelf deposit, deepening to outer shelf.*

### **Picton Conglomerate (Op)**

Includes Picton Conglomerate, Elevation Mudstone, and Shakespeare Bay Sandstone.

“The basal Picton Conglomerate contains subrounded to well rounded clasts, dominated by weakly metamorphosed Arapawa lithologic association sandstone, in a calcareous matrix. Unconformably on the conglomerate is the Elevation Mudstone, which in turn is overlain by, and partly interdigitates with, Shakespeare Bay Sandstone” (Begg and Johnston, 2000). “The Tertiary sequence is Oligocene in age and was deposited in **fluvial, lagoonal, marginal, and inner shelf shallow-marine** environments” (Nicol and Campbell, 1990).

#### • **Picton Conglomerate**

“Generally weathered, massive, green-brown, very well indurated, pebble congl., interbedded with sporadic sst lenses. Congl. clasts are entirely Pelorus group derived and fine rapidly up sequence from a basal boulder congl. Congl. matrix is calcareous with abundant foraminifers (UCF 1360) and **calcareous algae**. Sandstone diagenesis is extensive” (Nicol and Campbell, 1990).

*EoD: onshore*

*Basis for interpretation: the lithology of conglomerate, the EoD description in Nicol and Campbell (1990) of “fluvial, lagoonal”, and the presence of calcareous algae.*

#### • **Elevation Mudstone**

“The lower part of the mudstone contains lenses, up to several metres thick, of high-volatile bituminous coal” (Begg and Johnston (2000). “A massive, blue-grey, well indurated, mst composed of qtz rich silts and clays (up to 50%), interbedded with discontinuous restricted high volatile bituminous C rank coal beds up to several metres thick. Calcareous cement, secondary pyrite and gypsum are common, with sparse foraminifers (UCF 1359)” (Nicol and Campbell, 1990).

*EoD: onshore*

*Basis for interpretation: based on the presence of coal and the EoD description in Nicol and Campbell (1990) of “lagoonal, marginal [marine]” which is assumed to apply to the middle section of the Picton Conglomerate, i.e. the Elevation Mudstone.*

#### • **Shakespeare Bay Sandstone**

“...fossiliferous limestone, locally with abundant large *Flemingostrea* shells, occurs within the sandstone” (Begg and Johnston (2000). “Generally weathered, massive, yellow-brown, very well indurated, calcite-cemented medium sandstone, interbedded with occasional pebble-grit, conglomerate and limestone lenses. Quartz grains and Pelorus Group detritus predominate, with less common Tertiary mudstone intraclasts and schist fragments. Conglomerate clasts reach up to 10 cm in diameter. Extremely well indurated limestone lenses up to several metres thick contain gastropods, *Ostrea*, foraminifers (UCF 1361 and 1362), calcareous algae and echinoderm fragments, with common stylolites and calcite veins up to 10 cm wide” (Nicol and Campbell, 1990).

*EoD: innermost shelf*

*Basis for interpretation: based on the EoD description in Nicol and Campbell (1990) of “inner shelf shallow-marine”.*

**Inferred age:** 34-28 Ma (King et al., 1999)

**EoD breakdown:** 34-29 Ma: onshore (Picton Conglomerate, Elevation Mudstone)  
28 Ma: innermost shelf (Shakespeare Bay Sandstone)

**Basis for interpretation:** Main\_Rock = conglomerate; Sub\_Rocks = coal, siltstone, limestone; Description = Conglomerate; coal measures; siltstone and limestone (QMAP database) – *based on the*

range of depositional environments outlined in Nicol and Campbell (1990). NB: The Picton Conglomerate is not represented on the paleoenvironmental maps here due to difficulties in its palinspastic relocation.

## **Palliser and Soren Groups (Msp)**

Includes Putangirua Conglomerate, Sunnyside Conglomerate, Kupe's Sail beds, and basal Mangaoranga Formation.

"Miocene sediments overall represent a transgressive sequence that includes the Palliser and Soren groups in southern and northern Wairarapa respectively" (Begg and Johnston, 2000).

### ***Putangirua Conglomerate***

"...is of **alluvial origin**..." (Begg and Johnston, 2000). "At Putangirua Stream (S28/c6) there is about 200 m of Upper Waiauian or Lower Tongaporutuan Putangirua Conglomerate... of **alluvial fan** origin... Pebble imbrication suggests east-facing paleoslopes (map 25), but the conglomerates occur on the western flank of the Aorangi Range, suggesting that the range did not form until later..." (Field and Uruski, 1997).

*EoD: onshore*

*Basis for interpretation: EoD is based on the alluvial interpretation for the Putangirua Conglomerate given in Begg and Johnston (2000) and Field and Uruski (1997).*

### ***Sunnyside Conglomerate***

"...is interpreted as a **shallow marine** debris flow..." (Begg and Johnston, 2000).

*EoD: innermost shelf (innermost shelf to ?outer shelf)*

*Basis for interpretation: An innermost to mid-shelf, or possibly outer shelf, depositional environment is inferred from the shallow marine interpretation for the Sunnyside Conglomerate in Begg and Johnston (2000). The unit's debris flow origin and large grain size implies it is proximal to its source. An onshore or near shore source is assumed here. A mid-shelf (or ?outer shelf) EoD is an alternative interpretation.*

### ***Kupe's Sail beds***

"Kupe's Sail, calcareous sandstone with greywacke lag boulders rests on greywacke and is overlain by sandstone containing molluscs, brachiopods, barnacles and microfossils of Late Miocene (Tongaporutuan) age..." (Begg and Johnston, 2000).

*EoD: innermost shelf (onshore to innermost shelf)*

*Basis for interpretation: The conglomerate of the Kupe's Sail Beds is likely an onshore to innermost shelf deposit (Fig. 3) overlain by innermost shelf fossiliferous sandstone. An innermost shelf EoD is assigned to the Kupe's Sail Beds here but an onshore depositional environment is an alternative interpretation.*

### ***Basal Mangaoranga Formation***

"In northern Wairarapa, the basal Mangaoranga Formation (Neef 1984) of the Soren Group is an **alluvial** conglomerate" (Begg and Johnston, 2000). "The sedimentology of the lower part of the Mangaoranga Formation conglomerate in the Carrington area shows that deposition of the formation started in a **fluvial** environment. Fossil evidence indicates that the sandstone above the conglomerate was deposited in **shallow seas**..." (Wells, 1989).

*EoD: innermost shelf (onshore to mid-shelf)*

*Basis for interpretation: Paleoenvironments for the basal Mangaoranga Formation may have ranged from onshore to mid-shelf (Begg and Johnston, 2000; Wells, 1989; Fig. 3). An average innermost shelf EoD is assigned to the formation here.*

***Inferred age:*** 11-9 Ma (Field and Uruski, 1997)

***EoD breakdown:*** 11 Ma: onshore (Putangirua Conglomerate, Kupe's Sail beds)  
10-9 Ma: innermost shelf (basal Mangaoranga Formation, Sunnyside Conglomerate)

***Basis for interpretation:*** Main\_Rock = conglomerate; Sub\_Rocks = siltstone, sandstone, calcare-



ous sandstone; Description = Mod-poorly bedded; silty sandstone; and sandy siltstone; minor grit; mod-well bedded sandstone and calcareous sandstone (QMAP database) – *the EoD breakdown for the map unit is based on the depositional age and paleoenvironmental interpretations of the formations and/or members that make up the unit. 11 Ma consists of onshore Putangirua Conglomerate and onshore to innermost shelf Kupe's Sail Beds. The 11 Ma period is defined as onshore because it is a common environment shared by the Putangirua conglomerate and Kupe's Sail Beds.*

## **Palliser and Soren Groups (Msb)**

Includes Hurupi Formation, Bells Creek Mudstone, Clay Creek Limestone, and upper Mangaoranga Formation.

### ***Hurupi Formation***

“...Putangirua Conglomerate grades upward into Hurupi Formation, a massive, **fossiliferous, marine sandstone** with pebbly horizons” (Begg and Johnston, 2000). “Basal Upper Miocene (Tongaporutuan) strata known as the Hurupi Formation overlie older rocks with angular unconformity along an outcrop of about 120 kilometres in Wairarapa, East Wellington. Where microfaunas have been examined the lowest 50 to 100 metres of the formation contains **shallow-water** foraminifera whose age could be Middle or Upper Miocene, but higher beds contain *Bolivinita quadrilatera* the first appearance of which marks the base of the Tongaporutuan Stage throughout New Zealand” (Vella, 1968).

*EoD: innermost shelf*

*Basis for interpretation: The shallow water interpretation of the Hurupi Formation in Vella (1968) combined with its lithologic description in Begg and Johnston (2000) suggests an innermost shelf EoD for the formation (Fig. 3).*

### ***Bells Creek Mudstone***

“Bells Creek Mudstone may be in part a lateral equivalent of the upper Hurupi Formation... Members within Bells Creek Mudstone include the Ngatahuna and Halloween tuff beds, each approximately 3 m thick, and the channel-fill Ririwai Sandstone, up to 26 m thick. Microfossils indicate deposition at **upper to lower slope** depths (Crundwell 1997)...” (Begg and Johnston, 2000).

*EoD: mid-bathyal (upper to lower bathyal)*

*Basis for interpretation: The EoD range of upper to lower bathyal (assumed equivalent to upper to lower slope) given in Begg and Johnston (2000) is averaged to a mid-bathyal EoD here.*

### ***Clay Creek Limestone***

“...thin (< 10 m), poorly bedded conglomeratic Late Miocene (Kapitean) Clay Creek Limestone. The limestone contains abundant fossils and was deposited in a **very shallow sea** adjacent to an emergent high centred on the Aorangi Range. Miocene sediments southeast of the Aorangi Range consist largely of mudstone with minor sandstone, contain microfaunas of Tongaporutuan age and are correlated with Bells Creek Mudstone” (Begg and Johnston, 2000).

*EoD: innermost shelf (innermost to mid-shelf)*

*Basis for interpretation: EoD is based on the “very shallow sea” interpretation of the limestone in Begg and Johnston (2000). A mid-shelf EoD is an alternative interpretation.*

### ***Upper Mangaoranga Formation***

“West of Masterton the Late Miocene, 650 m thick upper Soren Group (upper Mangaoranga Formation) consists of **shallow marine** sandstone of Tongaporutuan age, grading upwards into massive mudstone of Kapitean age (Wells 1989b). Further north at Putara the sequence consists of 120 m of sandstone, c. 20 m of siltstone and c. 200 m of upper bathyal mudstone, all of Late Miocene (Tongaporutuan) age (Neef 1984; Wells 1985, 1987, 1989a, 1989b)” (Begg and Johnston, 2000). “Fossil evidence indicates that the sandstone above the conglomerate was deposited in **shallow seas** which deepened to **c. 300 m** by the end of the Miocene Epoch, when the mudstone member was deposited... Where the Mangaoranga Formation has been examined elsewhere in Wairarapa (Neef, 1984, Eketahuna; Wells, 1987, Mt Bruce) a similar trend of deposition in **progressively deepening** seas during the Late Miocene has been inferred. In the Carrington area the oldest marine sands are of Tongaporutuan age indicating that marine conditions were established over the area between 10 - 5 m.y. BP... Accumulation of c. 1000 m of marine sediment (Mangaoranga Formation) during

the Late Miocene in progressively deepening seas, which reached a depth of **c. 300 m** in Late Tongaporutuan to Kapitean times” (Wells, 1989).

*EoD: outer shelf (shelf to upper bathyal)*

*Basis for interpretation: Wells (1989) indicates progressive deepening of the depositional environment of the Mangaoranga Formation from onshore at the base of the formation to upper bathyal at its top. The upper Mangaoranga Formation may include the shelf to upper bathyal transition, and based on this premise, an average outer shelf EoD is assigned to the unit.*

**Inferred age:** 11-6 Ma (Field and Uruski, 1997)

**EoD breakdown:** 11-10 Ma: innermost shelf (restricted to south of Ruamahanga River: Hurupi Formation)  
9 Ma: outer shelf (Hurupi Formation, Bells Creek Mudstone, upper Mangaoranga Formation)  
8-7 Ma: upper bathyal (Bells Creek Mudstone, upper Mangaoranga Formation)  
6 Ma: innermost shelf (Clay Creek Limestone)

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = limestone; Description = Massive blue-grey calcareous mudstone with sparse fossils and discontinuous limestone lenses and sparse tuff beds (QMAP database) – the EoD breakdown for the map unit is based on the depositional age and paleoenvironmental interpretations of the formations and/or members that make up the unit. During the 11-10 Ma period deposition only occurs to the south of the Wairarapa Fault (as per Msp), as represented by the southern Hurupi Formation. The 9 Ma period consists of innermost shelf Hurupi Formation, mid-bathyal (average) Bells Creek Mudstone, and outer shelf (average) upper Mangaoranga Formation, giving a range of paleoenvironments from innermost shelf to mid-bathyal. An average outer shelf EoD is assigned to the map unit for the period. The 8-7 Ma period consists of mid-bathyal (average) Bells Creek Mudstone and outer shelf (average) upper Mangaoranga Formation, giving a range of paleoenvironments from outer shelf to mid-bathyal. An average upper bathyal EoD is assigned to the map unit for the period.

## **Onoke and Eketahuna Groups (Pea)**

Includes Makara Greensand, Mangaopari Mudstone, Haurangi Limestone, Dyerville Limestone, Hururua Limestone, Greycliffs Formation, Mangatarere Mudstone, Carrington Formation, Atea Sandstone, Eketahuna Mudstone, Saunders Siltstone, Marima Sandstone, and Makara outlier.

“Pliocene rocks (Pea) in the Wairarapa are dominated by fine-grained rocks of Onoke Group (Vella & Briggs 1971) in the south and Eketahuna Group (Neef 1974) in the north. In southern Wairarapa Onoke Group consists of Makara Greensand, Mangaopari Mudstone, Greycliffs Formation and Haurangi and Dyerville limestones... Mangaopari Mudstone, the dominant component of the Onoke Group. The Mangaopari Mudstone, up to 550 m thick, **coarsens upward**... The unconformably overlying Greycliffs Formation is about 100 m thick and is dominated by poorly bedded blue-grey sandy mudstone with widespread relatively **shallow marine** fossils (Vella & Briggs 1971). The lower Mangaopari Formation was deposited in an **upper slope to bathyal** environment in the centre of the Wairarapa Basin, but the upper part records a **shallowing of the sea to neritic depths**. Marine **regression** is also seen on the northern end of the Aorangi Range, where fossiliferous limestone interdigitate with the mudstone... Limestone deposition may have been controlled by eustatic changes in sea level (Vella & Collen Wairarapa geological map). In northern Wairarapa, basal Pliocene sediments of the Eketahuna Group belong to Atea Sandstone, which locally conformably overlies the Mangaoranga Formation and elsewhere rests directly on greywacke... Only the lower 335 m of the **mid-bathyal** Eketahuna Mudstone is preserved in the map area” (Begg and Johnston, 2000).

**Inferred age:** 6-2 Ma (Grant-Taylor and Hornibrook, 1964; Neef, 1984; Field and Uruski, 1997)

**EoD breakdown:** 6 Ma: upper bathyal (Makara Greensand)  
5 Ma: outer shelf (Mangaopari Mudstone, Atea Sandstone, Saunders Siltstone, Eketahuna Mudstone, Hururua Limestone, Makara outlier; innermost to mid-shelf in south: Haurangi Limestone)  
4 Ma: outer shelf (Mangaopari Mudstone, Dyerville Limestone, Saunders Siltstone, Hururua Limestone, Mangatarere Mudstone, Makara outlier)

3 Ma: mid-shelf (Mangaopari Mudstone, Marima Sandstone, Car-rington Formation)

2 Ma: mid-shelf (Greycliffs Formation)

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = mudstone, sandstone, coquina lime-stone; Description = Pebbly or muddy greensand; calcareous mudstone; well sorted sandstone; concretionary mudstone; shelly coquina limestone (QMAP database) – *the EoD breakdown for the map unit is based on the age and average EoD of the formations and/or members that make up the map unit. The unit of Pea could perhaps be divided into north vs. south (i.e. Eketahuna Group vs. Onoke Group, as detailed in Begg and Johnston (2000)), but such detail is beyond the scope of this project. This unit is the southern equivalent of the Mangaheia Group (see Hawke’s Bay map area). Refer to “Onoke Group (Pea)” on the Wairarapa map area for further information.*

## Onoke and Eketahuna Groups (Pep)

Includes Pukenui, Bull Creek, Ngaruru limestone, and Hautotara Formation.

**Inferred age:** 2 Ma (Field and Uruski, 1997)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = coquina, ‘calcareous sandstone’, silt-stone, ‘sandy mudstone’; Description = Poorly to well cemented shelly limestone; coquina and cal-careous sandstone; and siltstone and sandy mudstone with minor grit (QMAP database). “The up-permost Pliocene unit (Pep), extending northeast from the Aorangi Range, consists of widespread, **cyclothem**ic Pukenui Limestone, of Late Pliocene to earliest Pleistocene (Nukumaruan) age, and Hautotara Formation... The richly fossiliferous Pukenui Limestone is about 75 m thick and consists of six packets of alternating **coquina** limestone and loose shelly sand to muddy sandstone. These alternations have been attributed to low and high eustatic sea levels (Vella & Briggs 1971; Collen & Vella 1984)... The Early Pleistocene (late Nukumaruan) Hautotara Formation disconformably overlies Pukenui Limestone, is up to 40 m thick, and consists of thin, well sorted and well rounded conglomerate, muddy sandstone, cross-bedded sand and locally siltstone and peat horizons; **shal-low water marine** macrofossils are abundant. Although largely deposited in an **open sea** environ-ment, parts of the formation are of **beach, estuarine and locally freshwater** origin (Collen & Vella 1984; Gammon 1995)” (Begg and Johnston, 2002). “Onoke Group sequences record a fluctuation in depositional depth, interpreted as resulting from cyclothem sea level variation as well as tec-tonic influences (Vella 1963a). The coquina limestone that occur regularly through the sequence are of **shallow shelf** origin...” (Lee and Begg, 2002) – *the EoD for the map unit is based on the age and average EoD of the formations and/or members that make up the map unit. The formations are cyclothem, i.e. change rapidly from inner to outer shelf, but to display such detail is beyond the scope of this project.*

## Awatere Group

### **Upton Formation (Mau)**

**Inferred age:** 8-6 Ma (Roberts et al., 1994; Field and Uruski, 1997)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = conglomerate; Sub\_Rocks = sandstone, ‘sandy siltstone’; Description = Poorly sorted and poorly bedded channelized greywacke conglomerate with lens-es of sandstone and sandy siltstone (QMAP database). “Late Miocene rocks (Mau), equivalent to the upper Upton Formation, outcrop extensively in the Vernon Hills and consist of greywacke-de-rived, poorly sorted **marine** conglomerate... Awatere Group conglomerates are mass-flow deposits channelled into finer grained bathyal to inner shelf sediments (Browne 1995)” (Begg and Johnston, 2002) – *the Upton Formation as mapped on the Wellington map area is said to be equivalent to the upper Upton Formation. This is here assumed to be the Upton Sandstone (refer to “Upton Formation (Mau)” on the Kaikoura map area for further information). An average mid-shelf EoD is assigned to the map unit here.*

### **Starborough Formation (Pas)**

**Inferred age:** 6-3 Ma (Field and Uruski, 1997)

**EoD:** outer shelf

**Basis for interpretation:** Main\_Rock = siltstone; Sub\_Rocks = sandstone, 'sandy siltstone'; Description = poorly bedded sandstone and sandy siltstone in the Awatere Valley; and siltstone near White Bluffs (QMAP database). "South of White Bluffs, Late Miocene conglomerate is unconformably overlain by blue-grey **marine** siltstone (Pas), up to 100 m thick, of Early Pliocene (Opoitian) age" (Begg and Johnston, 2000) – *the map unit is defined as outer shelf here, although an upper bathyal EoD may still be appropriate. Refer to "Starborough Formation (Pas)" on the Kaikoura map area for further information.*

### **Wairau Conglomerate (Pw)**

**Inferred age:** 5-4 Ma (Begg and Johnston, 2000)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = conglomerate; Description = Poorly sorted and poorly bedded; channelized greywacke conglomerate (QMAP database). "The siltstone, included within the Starborough Formation, grades upward into a thick-bedded **marine** Wairau Conglomerate (Pw) that is similar to the Miocene part of the group" (Begg and Johnston, 2000) – *EoD is based on the Begg and Johnston (2000) interpretation of the unit as marine and its similarity to the Miocene part of the group, which is represented by the shelfal Upton Formation. It may also be marginally non-marine.*

### **Hillersden Gravel (Ph)**

**Inferred age:** 3-1 Ma (Begg and Johnston, 2000)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = conglomerate; Sub\_Rocks = sand, silt, clay; Description = Poorly sorted and poorly bedded clay-bound greywacke gravel; minor sand; silt and clay. "On the south side of the Wairau valley the **terrestrial** Hillersden Gravel (Ph), dominated by clasts of greywacke, underlies much of the Wither Hills and extends westward along the valley margin" (Begg and Johnston, 2000) – *EoD is based on Begg and Johnston (2000).*

## **Quaternary – Sedimentary deposits**

- All Q deposits (except – see below)

**EoD:** onshore

**Basis for interpretation:** Based on the QMAP database which includes alluvial, beach, colluvial, dune, estuarine, lacustrine, landslide, loess, peat, reclaimed land, and swamp sediments in the Quaternary deposits.

- mQb, Q9b, Q7b, Q5b

**EoD:** innermost shelf

**Basis for interpretation:** "Marginal marine sediments... Latest Interglacial **marginal marine** deposits..." (Begg and Johnston, 2000).

## WAIRARAPA AREA (Geological Map 11)

### Tinui Group

#### **Whangai Formation (Kiw)**

Includes Upper Calcareous Member and Te Uri Member.

“Microfossil studies indicate either **outer shelf to upper bathyal** (Killops et al. 2000) or **bathyal** depositional depths (e.g. Wilson & Morgans 1989)” (Lee and Begg, 2002). “The formation typically consists of 300-500 m of non-calcareous and calcareous shale and mudstone of Haumurian-Teurian age; rarely the formation may be up to 600 m thick (Moore 1988b)... Much of the Whangai Formation appears, from foraminiferal assemblages, to have accumulated at **bathyal** depths (...), although **outer shelf to upper bathyal** species have been found in the Upper Calcareous Member. This revises the interpretation given in Moore (1988b) of largely shelf depths for the Whangai. Planktics form generally less than 10% of Upper Calcareous Member foraminiferal assemblages” (Field and Uruski, 1997).

- **Upper Calcareous Member**

“...consists of poorly bedded, medium grey, hard, slightly to moderately calcareous (1-15%), micaceous mudstone, with laminae, bioturbation, sporadic calcareous concretions, pyrite nodules and beds of glauconitic sandstone. It is recognised throughout the region, but in some eastern areas it is partly replaced by the laterally equivalent Porangahau Member... **outer shelf to upper bathyal** species have been found in the Upper Calcareous Member” (Field and Uruski, 1997).

- **Te Uri Member**

“...interbedded glauconitic sandstone and slightly calcareous, glauconitic siltstone; it disconformably overlies Upper Calcareous Member in the Whangai Range, is entirely of Teurian age, and is probably partly a lateral equivalent of the Waipawa Formation... The Waipawa Formation is contemporaneous with, at least in part, the upper part of the **mid- to upper bathyal** Te Uri Member” (Field and Uruski, 1997).

**Inferred age:** > 65-57 Ma (Field and Uruski, 1997)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone; Description = rusty weathered mudstone with minor greensand and glauconitic sandstone (QMAP database) – *the EoD is defined here as upper bathyal, based on the QMAP description and lithology; however outer shelf or even mid-bathyal may be alternative environments, based on comments in the literature.*

### Mangatu Group

#### **Wanstead Formation (Egw)**

**Inferred age:** 59-36 Ma (Field and Uruski, 1997)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = claystone; Sub\_Rocks = mudstone, sandstone, marl; Description = smectitic, soft to moderately hard claystone, greensand, sandstone and marl (QMAP database). “...it contains abundant foraminifera of Paleocene to Late Eocene (Teurian to Runangan) age that suggest deposition at **mid to lower bathyal** depths...” (Lee and Begg, 2002). “The formation is known from all North Island East Coast basins where Paleogene aged strata are recorded... is mainly a poorly bedded, highly bioturbated, green-grey, calcareous mudstone with beds of glauconitic sandstone in places. In parts the formation is highly smectitic, and can be siliceous or brecciated. Other lithofacies included in the formation are the Te Waka Greensand (Black 1980), breccia and conglomeratic units, poorly to well-bedded glauconitic sandstone and mudstone, flysch facies, and siliceous units... The Wanstead Formation is generally considered to represent the deepest depositional environment of the Late Cretaceous-Paleogene of the East Coast, with average paleodepths generally **mid-bathyal**, and **lower bathyal-abyssal** in parts” (Field and Uruski, 1997) – *the EoD is defined here as mid-bathyal, based on the lithology and comments in Field and Uruski (1997). Lower bathyal-abyssal may be an alternative EoD.*

### **Weber Formation (Ogw)**

**Inferred age:** 35-22 Ma (Field and Uruski, 1997)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = marl, sandstone, limestone; Description = white weathered calcareous mudstone (QMAP database). "Foraminifera indicate deposition at **mid-upper bathyal** depths (Field, Uruski et al. 1997, Moore & Morgans 1987)" (Lee and Begg, 2002). "The paleoecology of the Weber Formation is generally quite uniform, with high percentages of planktic foraminifera indicating oceanic conditions and generally **mid-bathyal** paleodepths. While there is evidence for shallower deposition, most of the shelf faunas are considered to have been **reworked downslope**. The Weber Formation was possibly deposited at slightly shallower depths than some of the preceding Wanstead Formation, suggesting a slight regional regression" (Field and Uruski, 1997) – *EoD is based on the Field and Uruski (1997) interpretation of the Weber Formation being deposited generally at mid-bathyal depths, but an upper bathyal EoD may alternatively be appropriate in some areas (Lee and Begg, 2002). There is evidence that shelf deposits have been reworked downslope (Field and Uruski, 1997).*

### **Whangai, Wanstead and Weber formations (Kiw-Ogw)**

(QMAP database spelling: Whangai, Wanstead and Weber Form)

"A poorly exposed block south of the Porangahau River mouth comprises limestone, greensand, glauconitic mudstone, calcareous mudstone and dark mudstone. Lithologies are representative of Whangai, Waipawa, Wanstead and Weber formations... We are uncertain whether the block is a tectonic *mélange* or an olistostrome deposit, so it is mapped merely as a block of mixed Tinui and Mangatu group lithologies" (Lee and Begg, 2002).

**Inferred age:** > 65-22 Ma (Field and Uruski, 1997)

**EoD breakdown:** > 65-60 Ma: upper bathyal (Whangai Formation)

59-22 Ma: mid-bathyal (Wanstead Formation, Weber Formation)

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone, marl, mudstone; Description = undifferentiated Tinui and Mangatu groups (QMAP database) – *based on the combined unit code, this unit appears to include Whangai, Wanstead and Weber Formations. The EoD range is based on that which has been determined in this report for the individual formations. Refer to "Whangai Formation (Kiw)", "Wanstead Formation (Egw)" and "Weber Formation (Ogw)" for further interpretations and possible alternative environments.*

### **Whakataki Formation (Miw)**

**Inferred age:** 22-16 Ma (Field and Uruski, 1997)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone, limestone, conglomerate breccia; Description = well bedded alternating sandstone and mudstone with interbedded olistostrome deposits (QMAP database). "Sedimentology, trace fossils, shell fragments in the sandstone, and microfauna suggest deposition at **upper bathyal** depths (Crundwell 1997)" (Lee and Begg, 2002). "The most likely depositional setting for the unit studied on the East Coast is **deep water, marine, levee-overbank, near base of slope**... The Whakataki Formation is dominated by alternating sandstone and mudstone, locally with heterolithic conglomerate as well as thick-bedded channelised sandstone. In the study area, the dominant lithologies are alternating sandstone (beds <40 cm thick) and mudstone (up to 17 cm thick). Sandstone beds include parallel laminated (Bouma T<sub>b</sub> division), ripple and climbing-ripple laminated sandstone (Bouma T<sub>c</sub>), and convolute laminated sandstone (Bouma T<sub>d</sub>). Mudstone beds are typically sandy and are intensely bioturbated" (Field, 2005) – *the Whakataki Formation seems to have paleoenvironments ranging from upper bathyal (Lee and Begg, 2002) to lower bathyal (Field, 2005; based on the assumption that "base of slope" is equivalent to lower bathyal). Most of the unit comprises turbidites that accumulated in sub-marine fans. An average mid-bathyal EoD is assigned to the map unit here.*

### **Takiritini Formation**

"Takiritini Formation (Mit) consists of medium- to coarse-grained calcareous sandstone, algal limestone and fossiliferous mudstone... The typical lithologies of Takiritini Formation are thickly bedded to massive or poorly bedded, grey, medium- to coarse-grained, calcareous sandstone and

centimetre- to metre-bedded, cream-coloured algal limestone, with minor very fine-grained sandstone and fossiliferous mudstone” (Lee and Begg, 2002). “The Takiritini Formation consists of a thick **shallow marine** sandstone (indicated by the presence of echinoids) that grades from very fine-grained sandstone in the northeast to medium- to coarse-grained sandstone in the southwest. Algal limestone is found at the base of the formation and thickens to the south. A massive siltstone is interbedded with thick sandstone lenses to the north... The limestone was formed from the deposition of detrital material from the erosion of shallow water algal reefs or banks. Benthic and planktonic foraminifera as well as shallow water molluscan shell fragments are also present. Fine-grained sub-angular terrigenous material is found scattered throughout” (Wilkinson and Collen, 1994). “The primary target was the Takiritini Formation which, onshore, is up to 1000 metres thick and is a **shallow marine** sand unit with good porosity and permeability” (Uruski et al., 2004). “The Takiritini Formation is a succession of limestone and silty sandstone deposited in **relatively shallow water**, and is now exposed in the Tinui district in south-eastern North Island” (Nalin et al., 2008). “The mid-Altonian part of the [Whakataki] formation contains a sequence boundary that is overlain by the Takiritini Formation... This formation includes 1000 m of **channel-fill sandstone** with locally very high porosity, about 150 m of cemented algal limestone and up to 100 m of siltstone with lenses of calcareous sandstone...” (Field and Uruski, 1997).

- **Mit**

**Inferred age:** 18-16 Ma (Boyes et al., 2011a)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone, limestone; Description = thick sandstone, algal limestone and fossiliferous mudstone (QMAP database) – *EoD is based on the shallow water interpretations for the formation by Nalin et al. (2008), Wilkinson and Collen (1994), and Uruski et al. (2004), combined with the main rock type for the map unit being sandstone and Fig. 3. The lithology described in Wilkinson and Collen (1994) indicates that the formation is fine grained in the northeast of its extent, and coarser to the southwest. This implies that deposition of the southern part is in a higher energy, nearer shore environment. Where Mit and Mitl are mapped, Mit generally occurs to the south, so a shallower EoD of innermost shelf is assigned here.*

- **Mitl**

**Inferred age:** 18-16 Ma (Boyes et al., 2011a)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = algal limestone; Sub\_Rocks = sandstone, mudstone; Description = algal limestone (QMAP database) – *EoD is based on the shallow water interpretations for the formation by Nalin et al. (2008), Wilkinson and Collen (1994), and Uruski et al. (2004).*

## **Palliser Group**

“Miocene rocks, predominantly of outer shelf to bathyal depositional origin, are here included in a single lithostratigraphic unit – the Palliser Group (modified after Vella & Briggs 1971)” (Lee and Begg, 2002).

### ***Undifferentiated early Miocene, Palliser Group (eMi)***

Includes Coast Road and Greenhollows formations.

“Other Early Miocene rocks in Central Wairarapa are alternating sandstone and mudstone, sandstone, and minor debris flow conglomerate beds and were previously assigned to a number of formations... They are here mapped as undifferentiated Early Miocene Palliser Group (Mi)... Typical lithologies are alternating sandstone and mudstone, massive concretionary mudstone and massive very fine-grained sandstone. Sandstone beds have sharp bases, are graded and have Bouma sedimentary structures... Minor components of the unit are sandy, fossiliferous, calcareous conglomerate and greensand... Foraminifera and macrofauna suggest deposition at **shelf to mid-bathyal** depths (Neef 1992, 1995, 1997a; Reid 1998) and graded sandstone beds are interpreted as turbidites” (Lee and Begg, 2002).

## **Coast Road Formation**

“The formation is lightly indurated and comprises the Sandstone Member, which is overlain and underlain by the Upper Mudstone Member and the Lower Mudstone Members, respectively... Foraminifers from U25/f179 [Lower Mudstone] indicate **outer shelf – upper bathyal depths** of deposition, indicating a shallowing of the sea after deposition of the Whakataki Formation. Depths of deposition were **mid – outer shelf** for the Sandstone Member (U25/f170). The bryozoans, *Lithothamnium* algae, and foraminifers indicate a firm substrate and strong marine currents (Nelson et al. 1988) for the limestone beds. The upper mudstone was deposited in **deepening seas**” (Neef, 1997). “Foraminifera from f126 indicate **upper bathyal** (400-1000 m; Hayward 1986) depths of deposition, whereas those from f175 indicate **mid to upper bathyal deposition** (400-2000 m)” (Neef, 1995). “...at the Akitio River (U24/c13), there was an influx of sand in the upper Otaian, probably associated with paleobathymetric shallowing as the upper Otaian mudstone below the sandstone were deposited at outer shelf to upper bathyal depths, and those above the sandstone at mid- to outer shelf. The base of the 2 to 20 m thick sandstone is channelized, cutting down to Lower Waitakian in places. It is inferred to be a transgressive systems tract deposit resting on an erosional sequence boundary formed during a lowering of relative sea level in Upper Otaian time... On the west limb of the Cross Hill Syncline, the Otaian Coast Road Formation (1991a, 1995) is at least 430 m thick, including an **up-section shallowing to shelf** conditions in the Upper Otaian that might correlate with that seen at the Akitio River” (Field and Uruski, 1997).

**EoD breakdown:** 21-19 Ma: upper bathyal (outer shelf to upper bathyal: Lower Mudstone, Sandstone, and Upper Mudstone members)  
18-17 Ma: mid-bathyal (upper to mid-bathyal: Upper Mudstone Member)  
16 Ma: upper bathyal (Upper Mudstone Member)

*Basis for interpretation: the EoD is based on the depositional age and paleoenvironmental interpretations of the Lower Mudstone, Sandstone, and Upper Mudstone members that constitute the Coast Road Formation (Neef, 1995; Neef, 1997).*

## **Greenhollows Formation**

“Neef (1991a, 1992a, 1992c, 1997) identified the Greenhollows Formation (enclosure 6 I-I') of **sand-rich turbidites** on the east limb of the syncline and thought they represented the best potential hydrocarbon reservoir units in the Pongaroa area” (Field and Uruski, 1997). “The formation was deposited from a submarine ramp feeder system (term introduced by Heller & Dickinson 1985) (Neef 1992a) rather than from a submarine canyon system” (Neef, 1995). “Foraminifers from U25/f68 and U25/f171 indicate **mid to upper bathyal** deposition, whereas those from f172 are **upper bathyal**. Much of the formation was deposited from high concentration turbidity currents (Neef 1992a). Because flute and groove casts are rare, and neritic Altonian sandstone lies to the south, deposition was from north-flowing turbidity currents (Neef 1992a). Debris flow deposits of the Pongaroa district crop out near fault scarps, and this suggests a nearby submarine high, colonised by algae and barnacles, from which the two debris flow deposits were derived” (Neef, 1997).

*EoD: mid-bathyal*

*Basis for interpretation: Interpretations given in Neef (1997) for the Greenhollows Formation indicate a mid- to upper bathyal depth of deposition. This depth range is narrowed down to mid-bathyal based on recognition of the formation as sand rich turbidites, no mention in the descriptions of more proximal upper bathyal deposits (e.g. conglomerates and slumps), and Fig. 3.*

**Inferred age:** 21-16 Ma (Field and Uruski, 1997; Boyes et al., 2011a)

**EoD breakdown:** 21-19 Ma: upper bathyal (Coast Road Formation)  
18-17 Ma: mid-bathyal (Coast Road Formation, Greenhollows Formation)  
16 Ma: upper bathyal (Coast Road Formation)

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone, conglomerate; Description = alternating sandstone and mudstone, massive concretionary mudstone and fine sandstone (QMAP database) – *the EoD breakdown for the map unit is based on the depositional age and paleoenvironmental interpretations of the formations and/or members that make up the map unit.*



### ***Undifferentiated middle Miocene, Palliser Group (mMi)***

Includes Tattons Sandstone, Ngaumu Mudstone, Waimangu Sandstone, Karamu Sandstone, Bankview Mudstone, Settlement Road Formation, Tanawa Formation, Maunsell Formation, and Tutamoe Formation.

“Middle Miocene rocks are present in Central and Eastern Wairarapa and are mapped as undifferentiated Middle Miocene Palliser Group (Mi) deposits... The main rock type is blue-grey, calcareous, sandy mudstone and mudstone with sandstone interbeds. It is commonly fossiliferous and concretionary. Sandstone beds are dominantly fine- to medium-grained and graded, with sharp bases, sometimes with flute-casts” (Lee and Begg, 2002).

### ***Tattons Sandstone***

“In the Wainuioru area Tattons Sandstone, a locally developed, poorly bedded, fine- to medium-grained fossiliferous sandstone...” (Lee and Begg, 2002). “The Tattons Sandstone is a basal transgressive deposit resting on a sequence boundary... It is up to 300 m thick (Crundwell 1997) and consists mainly of bedded fine to medium sandstone fining up to sandy siltstone, locally with *Ostrea* near the base, disseminated carbonaceous material, scour structures and grading. It is mainly an **inner shelf** deposit, although foraminifera at the top of the unit record deepening to **mid- to outer shelf** depths over a thin interval which may mark a condensed section” (Field and Uruski, 1997).

*EoD: innermost shelf (innermost to outer shelf)*

*Basis for interpretation: Most of the unit is an inner shelf deposit, which deepens at the top.*

### ***Ngaumu Mudstone***

“Mudstone overlying the Tattons Sandstone was assigned to the Ngaumu Mudstone by Crundwell (1997)... It consists mainly of grey mudstone, but with cm-dm thick sandstone near the base, becoming less frequent up-section. The sandstone beds have rippled bases and sharp tops, with indistinct grading, laminae and cross-laminae and could be **tempestites**, which became less frequent as the water depths increased with time... Near Wainuioru, Crundwell (1997) recorded just over 800 m of Lillburnian Ngaumu Mudstone with **mid- to outer shelf** bathymetries (e.g. T26/c8)” (Field and Uruski, 1997).

*EoD: outer shelf (mid- to outer shelf)*

*Basis for interpretation: The mid- to outer shelf depositional depth range given in Field and Uruski is narrowed down to outer shelf based on the unit’s lithologic description, which indicates mudstone is the main lithology, and Fig. 3.*

### ***Waimangu Sandstone***

“A local unit of **flysch** within the Ngaumu Mudstone (e.g. T27/c13; map 23 and enclosure 6 J-J’) was named the Waimangu Sandstone by Crundwell (1997)...” (Field and Uruski, 1997).

*EoD: upper bathyal*

*Basis for interpretation: EoD is based on the interpretation of the Waimangu Sandstone as a flysch deposit and Fig. 3.*

### ***Karamu Sandstone***

“The Karamu Sandstone is a Waiauian **shallow-marine** transgressive sandstone, commonly 100-300 m... The sandstone fines up-section into the Bankview Mudstone, with the transition being marked by a deepening from **inner** to middle shelf... At least 100 m of Waiauian **shallow-marine** sands, probably Karamu Sandstone, occur at Ngarara Stream...” (Field and Uruski, 1997).

*EoD: innermost shelf*

*Basis for interpretation: Shallow marine is taken to be inner to mid-shelf depths.*

### ***Bankview Mudstone***

“The sandstone fines up-section into the Bankview Mudstone, with the transition being marked by a deepening from inner to **middle shelf**. The Bankview Mudstone includes indistinctly bedded graded sandstones that are probably tempestites and was deposited at **shelf and upper bathyal** depths” (Field and Uruski, 1997).

*EoD: outer shelf (mid-shelf to upper bathyal)*

*Basis for interpretation: The depositional depth range of the Bankview Mudstone is mid-shelf to upper bathyal (Field and Uruski, 1997). An average outer shelf EoD is assigned to the unit here.*

### **Settlement Road Formation**

“Foraminifers from the Lower Mudstone Member give **upper bathyal** depths of deposition (U25/f48, 837666), whereas those from the Sandstone Member indicate **inner to mid-shelf** deposition (U25/f176) and **mid-shelf** deposition (U25/f177)... The Upper Mudstone Member was deposited in deepening, **mid-upper bathyal** environments (U25/f178)” (Neef, 1997).

*EoD: outer shelf (inner/mid-shelf to upper/mid-bathyal)*

*Basis for interpretation: The Settlement Road Formation was deposited in environments ranging from inner/mid-shelf to upper/mid-bathyal. An average outer shelf EoD is assigned to the formation here.*

### **Tanawa Formation**

“The [Maunsell] formation grades to a thick sequence of graded beds (called the Tanawa Member by Johnston (1975)) to the northwest of the type section in the Tinui Valley” (Wilkinson and Collen, 1994). “Further south, near Tinui, **flysch** of the Tanawa Member of the Maunsell Formation is Lillburnian in its lower parts...” (Field and Uruski, 1997). “The formation was deposited in **bathyal** depths, except near the Owahanga Block where there are scattered, ?neritic rare macrofossils” (Neef, 1997).

*EoD: mid-bathyal*

*Basis for interpretation: EoD is based on the bathyal depth of deposition of the Tanawa Formation (Neef, 1997), its interpretation as a flysch deposit (Field and Uruski, 1997), and Fig. 3.*

### **Maunsell Formation**

“In the Tinui area (Central Wairarapa) equivalent rocks consist of c. 2800 m of massive, calcareous, concretionary, fossiliferous mudstone and alternating sandstone and mudstone of the Maunsell Formation (Johnston 1975, 1980). Minor lithologies include limestone and conglomerate. The formation rests conformably on the Early Miocene Takiritini Formation” (Lee and Begg, 2002). “The Maunsell Formation was first designated as a name for massive mudstone and siltstone with minor sandstone and pebbly shell limestone beds and concretions by Johnston (1975)... To the north-east the formation grades into thick sandstone of the Grassendale Member” (Wilkinson and Collen, 1994). “Johnston (1980) reported that the Waiau sandstone and siltstone forming the Grassendale Member of the Maunsell Formation is 700 m thick near Annedale. Plant remains and abundant molluscan shells indicate **shallow-marine** conditions adjacent to a tree-covered landmass, presumably to the south and west (map 24, T25)” (Field and Uruski, 1997).

*EoD: outer shelf (shallow marine to ?bathyal)*

*Basis for interpretation: The massive, calcareous, fossiliferous mudstone of the Maunsell Formation (Lee and Begg, 2002) could indicate outer/mid-shelf to bathyal depositional environments for the formation (Fig. 3) with the Grassendale Member representing deposition at generally shallower shelfal depths. An approximate average outer shelf EoD is assigned to the Maunsell Formation here. Note: the alternating sandstone and mudstone lithology included in the description for the Maunsell Formation in Lee and Begg (2002) probably refers to Tanawa Formation, which is dealt with separately.*

### **Tutamoe Formation**

“They consist largely of alternating sandstone and mudstone beds (with minor conglomerate) and are 530 m thick (Tutamoe Formation; Lillie 1953)” (Lee and Begg, 2002). “Characteristics of the axial profile of *G. miozea conoidea* in S44/f1160 are accentuated in a Waiau collection (N146/f438, Figs 53-58) from Tutamoe Formation, southern Hawke’s Bay (Lillie 1953, p. 47). Specimens are usually non-encrusted suggesting an epipelagic population. Lillie [no date given] interpreted the deposits as proximate to a reef and Finlay (1947) listed several larger foraminifera typical of warm **shallow shelf** environments. The rare encrusted individuals (Fig. 58) may indicate transport of the sediment to **deeper water**” (Scott, 1975). “Formations mapped in these districts that are of Southland age are the Ihungia and Tutamoe... the Tutamoe Formation is Lillburnian and Waiau (Waiau microfauas being most widely present in it, though a Lillburnian horizon is known to be present in the Muddy Creek section at least). In the Tutamoe Formation an alternate banding of thin sandstone and mudstone layers is commonly found” (Cotton, 1955).

EoD: mid-shelf

*Basis for interpretation: The lithologic description of the Tutamoe Formation given in Cotton (1955) (alternating thin sandstone and mudstone) combined with its shallow shelf interpretation (Scott, 1975) and Fig. 3 suggests that the unit is cyclothem in nature, with sandstone deposited at inner to mid-shelf depths and mudstone in mid- to outer shelf environments. An average mid-shelf EoD is assigned to the Tutamoe Formation here.*

**Inferred age:** 16-11 Ma (Cotton, 1955; Field and Uruski, 1997)

**EoD breakdown:** 16 Ma: mid-shelf (innermost to outer shelf; Tattons Sandstone, Settlement Road Formation)  
15-11 Ma: upper bathyal (outer shelf in south, mid-bathyal in north; Ngaumu and Bankview Mudstones, Waimangu and Karamu sandstones, Settlement Road, Tanawa, Maunsell, and Tutamoe formations)

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone, limestone, conglomerate; Description = sandy mudstone with mudstone and sandstone interbeds (QMAP database) – *the EoD breakdown for the map unit is based on the depositional age and paleoenvironmental interpretations of the formations and/or members that make up the map unit. The 16 Ma period consists of innermost shelf Tattons Sandstone and outer shelf (average) Settlement Road Formation. An average mid-shelf EoD is assigned to the period here. The upper bathyal EoD for the 15-11 Ma period is a generalised interpretation because the map unit shows greater environmental complexity during this period than is possible to display given the spatial EoD diversity. In general the southern part of the map unit has a shallower (outer shelf) EoD than northern parts of the map unit (mid-bathyal) for the 15-11 Ma period.*

### **Undifferentiated late Miocene, Palliser Group (IMi)**

Includes Bells Creek Mudstone, Ngarata Formation, Te Hoe Turbidite, Tiraumea Siltstone, Pakowhai Formation, Waihoki Formation, Hurupi Formation, and Mapiri Formation.

“They consist predominantly of massive mudstone with minor alternating sandstone and mudstone, and shelly conglomerate beds... A deepening depositional environment is also recorded from these rocks in the Tawhero area (Neef 1997) and elsewhere in the Wairarapa (Wells 1989b)” (Lee and Begg, 2002).

### **Bells Creek Mudstone**

“Macrofossils in the lower Bells Creek Mudstone in the Wainuioru area indicate deposition in an **uppermost bathyal** environment, and a **mid bathyal** environment in the upper part (Beu 1970)” (Lee and Begg, 2002).

**EoD breakdown:** 11-(c. 10) Ma: upper bathyal  
(c. 9)-7 Ma: mid-bathyal

*Basis for interpretation: EoD is based on the interpretation for the the Bells Creek Mudstone given in Lee and Begg (2002). The timing of the deepening from uppermost bathyal to mid-bathyal is arbitrarily placed at approximately the middle of the formation’s depositional period.*

### **Ngarata Formation**

“The tiny Lower Tongaporutuan coal deposits of the Spring Hill Anticline and the Pongaroa district indicate **nonmarine** deposition there. However, the coal of the Spring Hill Anticline overlies marine sandstone, indicating an interplay between marine and swamp environments. Pollen from the coal (T25/f773, 661561) indicates a fully terrestrial, freshwater swamp or riverside community (D.C. Mildenhall pers. comm. 1982). Abundant brachiopods in basal beds of the ng<sub>1</sub> Sandstone Member in Mangatiti Stream and near Breakdown Trig indicate deposition at a depth of **>18 m** and bottom temperature >7°C (Neall 1970). Deposition may have been on the **outer shelf**, like the Makara Greensand of the Aorangi Range area (Vella & Briggs 1971). The implication is that, after tilting, downwarping (or sea level rise) was very rapid... Occurrence of *Limopsis lawsi* in the ng<sub>3</sub> Siltstone Member suggests deposition there in **deeper neritic seas** (Vella 1962). Seas continued to deepen during the Tongaporutuan, and the ng<sub>4</sub> Mudstone Member was deposited at **mid-upper bathyal** (U25/f38, 728617; U25/f47, 749595) or **upper bathyal** (U25/f65, 719660) environments... The

ng, Rudite Member formed in a narrow rift adjacent to the Waihoki Fault (Neef 1993b). Foraminifers within the rudite indicate **mid-shelf** deposition (U25/f173, 771614)" (Neef, 1997).

**EoD breakdown:** 11 Ma: outer shelf (mid- to outer shelf)  
10-7 Ma: upper bathyal

*Basis for interpretation: It is inferred that the coal and swampy environments at the base of this member are close to the onshore Lower Tongaporutuan deposits of the Palliser Group on the Wellington map area (Msp), and because these polygons are adjacent on the map border they are assigned the attributes of Msp from Wellington. Following this, the Ngarata Formation then deepens to outer shelf, and mid- to upper bathyal.*

### **Te Hoe Turbidite**

"Foraminifers from T25/f34 and T25/f35 indicate **upper bathyal** deposition" (Neef, 1997).

*EoD: upper bathyal*

*Basis for interpretation: EoD is based on the upper bathyal interpretation in Neef (1997).*

### **Tiraumea Siltstone (?mudstone; Neef, 1997)**

"Foraminifers from T25/O4 and T25/O5 indicate **upper bathyal** deposition" (Neef, 1997).

*EoD: upper bathyal*

*Basis for interpretation: EoD is based on the upper bathyal interpretation in Neef (1997).*

### **Pakowhai Formation**

"Depths of deposition of the **lower part of the formation are mid-upper bathyal** (U25/f74, 769584). The basal 1-15 m thick sandstone was interpreted to be a seismoturbidite (Neef 1992a). Many features of the lower part of the formation (e.g., flute and groove casts and Bouma sequences) indicate southward deposition from high velocity, low density turbidity currents (Neef 1992a). Slumping beneath the formation at U25/ 779600, and onlap of the formation on the Takaritini Formation near Waihoki, suggests that the lower part of the formation filled a submarine canyon or depression. Flute and groove casts indicate that sediment transport was southwards from an active Waihoki Fault (Neef 1992a, fig. 17). Subsequently, turbidite deposition ceased abruptly and bathyal mud was deposited from suspension" (Neef, 1997).

*EoD: mid- to upper bathyal*

*Basis for interpretation: EoD is based on the description of the lower part of the formation as consisting of low density turbidity currents and its interpreted mid-upper bathyal depositional depth (Neef, 1997). The upper part of the formation consists of bathyal mud (Neef, 1997). Outer shelf to lower bathyal paleoenvironments are alternative depositional environments for the upper part of the formation (Fig. 3).*

### **Waihoki Formation**

"Most foraminifers from the formation indicate **upper bathyal** depths of deposition (i.e. 400-1000 m) (e.g., U25/D1, 708587), whereas one sample U25/f32, 712553, has an outer shelf to upper bathyal depth range. The turbidite flows were derived from east of an active Tinui Fault..." (Neef, 1997).

*EoD: upper bathyal*

*Basis for interpretation: EoD is based on the upper bathyal interpretation in Neef (1997).*

### **Hurupi Formation**

"Hurupi Formation, a massive, fossiliferous, **marine sandstone** with pebbly horizons..." (Begg and Johnston, 2000). "Where microfaunas have been examined the lowest 50 to 100 metres of the formation contains **shallow-water** foraminifera..." (Vella, 1968).

*EoD: innermost shelf*

*Basis for interpretation: The shallow water interpretation of the Hurupi Formation in Vella (1968) combined with its lithologic description in Begg and Johnston (2000) suggests an innermost shelf EoD for the formation (Fig. 3). Refer to "Hurupi Formation" on the Wellington map area for further information*

## **Mapiri Formation**

“...Lillie (1953) described the Mapiri Formation at Paeroa as 220 m of mudstone overlying 70 m of hard limestone which rests on basement” (Field and Uruski, 1997). “Mapiri rocks have approximately the same regional distribution as those of the Tutamoe – namely, to the east in the Pourerere Survey District, and to the west along a belt of country east of the Oruawharo-Waewaepa Fault-belt. In both these regions the formation consists chiefly of mudstone, usually containing fragments of white pumice, interstratified with occasional bands of white tuff” (Lillie, 1953).

*EoD: shelf deepening to bathyal*

*Basis for interpretation: EoD is based on the presence of basal limestone resting on basement, interpreted here to represent a transgressive shelf deposit (Fig. 3), which is in turn overlain by mudstone, interpreted here to be an outer shelf to bathyal deposit (Fig. 3).*

**Inferred age:** 11-6 Ma (Lillie, 1953; Field and Uruski, 1997; Neef, 1997)

**EoD breakdown:**

11 Ma:	<u>upper bathyal</u> (Bells Creek Mudstone, Waihoki Formation. Innermost shelf in far south: Ngarata, Hurupi and Mapiri formations)
10 Ma:	<u>upper bathyal</u> (Bells Creek Mudstone, Pakowhai Formation, Waihoki Formation. Innermost shelf in far south: Ngarata, Hurupi and Mapiri formations)
9 Ma:	<u>upper bathyal</u> (Bells Creek Mudstone, Te Hoe Turbidite, Tiraumea Siltstone, Pakowhai Formation, Waihoki Formation. Innermost shelf in far south: Ngarata, Hurupi and Mapiri formations)
8-7 Ma:	<u>upper bathyal</u> (Bells Creek Mudstone, Ngarata Formation, Te Hoe Turbidite, Tiraumea Siltstone, Pakowhai Formation, Waihoki Formation, and Mapiri Formations)
6 Ma:	<u>upper bathyal</u> (Te Hoe Turbidite, Tiraumea Siltstone, and Waihoki Formations)

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone, conglomerate, tuff; Description = dominantly massive mudstone with minor alternating beds of sandstone and mudstone (QMAP database) – *the EoD breakdown for the map unit is based on the depositional age and paleoenvironmental interpretations of the formations and/or members that make up the map unit. Although outer shelf and mid-bathyal environments may occur within the map unit, upper bathyal is the most dominant EoD throughout the 11-6 Ma period. Consequently, the map unit is assigned an upper bathyal EoD. NB: the southernmost IMi on this map area has been assigned the EoD of Msp and Msb from the Wellington map area (mapped as Palliser and Soren groups).*

## **Soren Subgroup (Ms)**

Includes Mangaoranga Formation, and Kaiparoro Limestone Member.

“Late Miocene rocks are present in Western, Central and Eastern Wairarapa. In Western Wairarapa, they unconformably overlie the much older basement rocks... and include **non-marine** and **shallow marine** beds. Neef (1974, 1984) named these rocks the Soren Group, and usefully distinguished the Western Wairarapa Miocene sequence from those of Central and Eastern Wairarapa, where Early and/or Middle Miocene sedimentary rocks commonly underlie those of the Late Miocene. Neef’s Soren Group is here relegated to the status of subgroup within the Palliser Group. The Soren Subgroup (Ms) (Neef’s Mangaoranga and Kaiparoro formations) is widely distributed in Western Wairarapa... The Soren Subgroup incorporates basal **alluvial** conglomerate, **shallow marine** sandstone and mudstone, and pebbly bioclastic limestone... Massive, concretionary sandstone and blue-grey mudstone of marine origin overlie the non-marine beds. The upper part of the group consists of concretionary, fossiliferous very fine-grained sandstone, minor conglomerate and the Kaiparoro Limestone Member... Microfossils from the mudstone in the upper section of the Soren Subgroup provide a Late Miocene age (Upper Tongaporutuan to Kapitean; Kennett 1966; Wells 1987, 1989b) and indicate deposition in an **upper bathyal to mid-shelf** environment” (Lee and Begg, 2002).

## ***Mangaoranga Formation***

“Fossil evidence indicates that the sandstone above the conglomerate was deposited in **shallow seas** which deepened to **c. 300 m** by the end of the Miocene Epoch, when the mudstone member was deposited... Where the Mangaoranga Formation has been examined elsewhere in Wairarapa (Neef, 1984, Eketahuna; Wells, 1987, Mt Bruce) a similar trend of deposition in progressively deepening seas during the Late Miocene has been inferred. In the Carrington area the oldest marine sands are of Tongaporutuan age indicating that marine conditions were established over the area between 10-5 m.y. BP” (Wells, 1989).

**EoD breakdown:** 9 Ma: mid-shelf  
8 Ma: outer shelf  
7 Ma: upper bathyal

*Basis for interpretation:* The interpretations of Wells (1989) for the base (fluvial and shallow sea) and top (c. 300 m, equivalent to upper bathyal (Fig. 3)) of the map unit are used here. The paleoenvironments through the middle portion of the map unit are inferred from the deepening upsequence trend noted in Wells (1989).

## ***Kaiparoro Limestone Member***

“...a bioclastic limestone... Late Miocene (Kapitean) in age (Beu 1995) and was deposited in an **inner shelf** environment” (Lee and Begg, 2002).

*EoD:* innermost shelf

*Basis for interpretation:* EoD is based on the interpretation for the Kaiparoro Limestone Member given in Lee and Begg (2002).

**Inferred age:** 9-6 Ma (Field and Uruski, 1997)

**EoD breakdown:** 9 Ma: mid-shelf (Mangaoranga Formation)  
8 Ma: outer shelf (Mangaoranga Formation)  
7 Ma: upper bathyal (Mangaoranga Formation)  
6 Ma: innermost shelf (Kaiparoro Limestone Member)

**Basis for interpretation:** Main\_Rock = conglomerate; Sub\_Rocks = sandstone, mudstone, limestone; Description = alluvial conglomerate with shallow marine sandstone, mudstone and bioclastic limestone (QMAP database) – the EoD breakdown for the map unit is based on the depositional age and paleoenvironmental interpretations of the formations and/or members that make up the map unit. The Kaiparoro Limestone Member (Msk) is only represented as lines on the geological map sheet and does not have a polygon in the database. Therefore the innermost shelf period of this map unit is only shown to occur on two polygons which are nearest to where the Msk lines are shown on the map sheet.

## ***Onoke Group (Pea)***

Includes Western Wairarapa: Atea Sandstone, Saunders Siltstone, Eketahuna Mudstone, Eketahuna Turbidite, Tawataia Sandstone, Newman Siltstone, Tane Sandstone, Marima Sandstone, Mangatoro Formation, Te Aute Formation, Kumeroa Formation, and Hautotara Formation. Eastern Wairarapa: Mangatoro Formation, Te Aute Formation, Kumeroa Formation, Rangiwahakaoma Formation, Makara Greensand, Mangaopari Mudstone, Greycliffs Formation, Atea Sandstone, Saunders Siltstone, Eketahuna Mudstone, Eketahuna Turbidite, Tawataia Sandstone, Newman Siltstone, Tane Sandstone, Makuri Sandstone, Lower Makuri Siltstone, Skye Farm Sandstone, Marima Sandstone, Kaitawa Formation, and Hautotara Formation. NB: there are 9 coquina limestones of the Onoke Group which are differentiated on this map area and have unique unit codes.

“The Pliocene rocks of the Wairarapa map area have previously been described under at least four group names... Laterally equivalent beds in the adjacent area to the north have been described under at least four other group names... Simplification and amalgamation has been necessary for this map; the latest Miocene and Pliocene rocks of the Wairarapa area are all described as Onoke Group... The predominant lithology in Western and Central Wairarapa is massive to poorly bedded, concretionary, calcareous, blue-grey mudstone, with minor alternating sandstone and mudstone... At least 11 individual limestones have been given formal status as formations or members... Onoke Group sequences record a **fluctuation in depositional depth**, interpreted as resulting from cyclothem sea level variation as well as tectonic influences (Vella 1963a). The coquina limestones that

occur regularly through the sequence are of **shallow shelf** origin (e.g. Kamp et al. 1988; Beu 1995), while mudstones above and below contain faunas (macrofossil and foraminifera) that indicate deposition in **outer shelf to upper bathyal** conditions. Overall however, there is an **upward-shallowing** trend in depositional environment through the Pliocene, culminating in the emergence of the area in the earliest Quaternary. At Wainuioru, late Early Pliocene mudstone were deposited in **upper bathyal** conditions, while those of Late Pliocene time were deposited in **inner to mid-shelf** environments... an overall marine **regression** through the Pliocene..." (Lee and Begg, 2002).

**Inferred age:** 6-2 Ma (Neef, 1984; Field and Uruski, 1997)

**EoD breakdown:**

6 Ma:	<u>upper bathyal</u> (Mangaopari Formation, Makara Greensand)
5 Ma:	<u>outer shelf</u> (Mangaopari Formation, Mangatoro Formation, Atea Sandstone, Saunders Siltstone, Eketahuna Mudstone, Eketahuna Turbidite, Tawataia Sandstone, Newman Siltstone)
4 Ma:	<u>outer shelf</u> (Mangaopari Formation, Mangatoro Formation, Saunders Siltstone, Eketahuna Turbidite, Tawataia Sandstone, Newman Siltstone, Tane Sandstone)
3 Ma:	<u>mid-shelf</u> (Mangaopari Formation, Te Aute Formation, Greycliffs Formation, Makuri Sandstone, Makuri Siltstone, Skye Farm Sandstone, Marima Sandstone)
2 Ma:	<u>mid-shelf</u> (Kumeroa Formation, Greycliffs Formation, Kaitawa Formation, Hautotara Mudstone)

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone, conglomerate, coquina, tephra; Description = massive, poorly bedded mudstone and minor alternating sandstone and mudstone (QMAP database) – *the EoD breakdown for the map unit is based on the age and average EoD of the formations and/or members that make up the map unit. This is the southern equivalent of the Mangaheia Group (see Hawke's Bay map area). Refer to "Onoke and Eketahuna Groups (Pea)" on the Wellington map area for further information.*

### **Hautotara Formation (Peah)**

**Inferred age:** 2 Ma (Field and Uruski, 1997)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = siltstone, conglomerate; Description = **marine and estuarine** deposits (QMAP database). "The top of the Onoke Group is marked by marine **transgression** with a change to a terrestrial (largely alluvial) depositional environment" (Lee and Begg, 2002). "The Late Pliocene - Early Pleistocene Hautotara Formation in southeastern Wairarapa, New Zealand, comprises cyclic **estuarine and shallow-marine** deposits" (Gammon, 1995). "Similarly, Lake Onoke and the adjacent beach face-bar complex provides a modern analogue for the Hautotara Formation" (Woolfe, 1993) – *based on the interpretations given in Gammon (1995) and the analogue in Woolfe (1993) the unit was deposited in environments ranging from on-shore to innermost shelf/mid-shelf.*

### **Kairakau Limestone (Pek)**

**Inferred age:** 5-4 Ma (Field and Uruski, 1997)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = coquina; Sub\_Rocks = limestone, sandstone; Description = barnacle grainstone (QMAP database). "At Cape Turnagain the Kairakau Limestone (Pek), an Early Pliocene (Opoitian) **cross-bedded coquina** limestone and calcareous sandstone, lies unconformably upon mudstone of similar age" (Lee and Begg, 2002). "The stratigraphy of Pliocene Te Aute Group of the East Coast Basin is described in detail by Beu et al. (1980), Harmsen (1985)... The strata consist of three limestone units separated by terrigenous mudstone and sandstone of variable thicknesses. The carbonate units in order of decreasing age are: Kairakau Limestone, Awapapa Limestone, and Te Onepu Limestone... Facies analysis suggests Te Aute Limestones were deposited in **shallow inshore to mid-shelf environments, largely at water depths of less than 50 m;** coeval fine-grained, highly bioturbated siltstone accumulated further offshore" (Harmsen, 1990) – *EoD is based on the Harmsen (1990) interpretation for the Te Aute Group, of which the Kairakau Limestone is a part, and the interpretation for the coquina limestone of the Onoke Group in Lee and Begg (2002).*

### **Rongomai Limestone (Per)**

Includes Mangamahoe, Whetukura, and Koroheke limestones.

**Inferred age:** 4-3 Ma (Field and Uruski, 1997)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = coquina; Sub\_Rocks = limestone, sandstone; Description = barnacle grainstone (QMAP database). “Rongomai Limestone (Per), a sandy barnacle-bivalve **coquina** limestone of early Late Pliocene (Waipipian) age, and its approximately coeval equivalents (Whetukura and Koroheke limestones, also mapped as Per; Beu 1995)...” (Lee and Begg, 2002) – *EoD is based on the shallow shelf interpretation for the coquina limestones of the Onoke Group in Lee and Begg (2002), of which the Rongomai, Mangamahoe, Whetukura, and Koroheke limestones are a part.*

### **Mangamahoe Limestone (Perm)**

**Inferred age:** 3 Ma (Field and Uruski, 1997)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = coquina; Sub\_Rocks = limestone, sandstone, siltstone; Description = massive coarse sandy coquina limestone (QMAP database) – *EoD is based on the shallow shelf interpretation for the coquina limestones of the Onoke Group in Lee and Begg (2002), of which the Mangamahoe Limestone is a part.*

### **Te Onepu Limestone (Pet)**

**Inferred age:** 3 Ma (Field and Uruski, 1997)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = coquina; Sub\_Rocks = sandstone, siltstone; Description = limestone (QMAP database). “...the typical lithology is a yellow-grey, cross-bedded, barnacle-rich **coquina**” (Lee and Begg, 2002). “On the eastern margin of the forearc basin, the Te Aute limestone accumulated as islands, banks, and bars in cool, **shallow seas** swept by strong tidal currents (Fig. 5) (Harmsen 1985, 1989; Kamp et al. 1988)...” (Ricketts et al., 2004). “The stratigraphy of Pliocene Te Aute Group of the East Coast Basin is described in detail by Beu et al. (1980) and Harmsen (1985)... The strata consist of three limestone units separated by terrigenous mudstone and sandstone of variable thicknesses. The carbonate units in order of decreasing age are: Kairakau Limestone, Awapapa Limestone, and Te Onepu Limestone... Facies analysis suggests Te Aute Limestones were deposited in **shallow inshore to mid-shelf environments, largely at water depths of less than 50 m**; coeval fine-grained, highly bioturbated siltstone accumulated further offshore” (Harmsen, 1990) – *EoD is based on the Harmsen (1990) interpretation for the Te Aute Group, of which the Te Onepu Limestone is a part of, and the interpretation for the coquina limestones of the Onoke Group in Lee and Begg (2002).*

### **Totaranui Limestone (Pept)**

Map unit includes Pukenui, Ngaruru, Waitahora, Otopo, Pori, and Castlepoint limestones.

**Inferred age:** 2 Ma (Field and Uruski, 1997)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = coquina; Sub\_Rocks = limestone; Description = limestone (QMAP database). “The many named late Late Pliocene (Nukumaruan) **coquina** limestones are here included within a single map unit (Totaranui Limestone, Pep, after the most prominent coquina limestone of the northwestern map area; Fig. 25). Others named, and here included within this unit, are Tourere, Kumeroa, Otopo, Pori, Ngaruru and Pukenui limestone. The map unit also includes the Castlepoint Formation...” (Lee and Begg, 2002) – *EoD is based on the shallow shelf interpretation for the coquina limestones of the Onoke Group in Lee and Begg (2002), of which the Totaranui Limestone and the other limestones included in this map unit are a part. Innermost shelf may be an alternative EoD.*

### **Ngaruru Limestone (Pepn)**

**Inferred age:** 2 Ma (Field and Uruski, 1997)

**EoD:** mid-shelf



**Basis for interpretation:** Main\_Rock = coquina; Sub\_Rocks = limestone; Description = limestone with aragonitic bivalves (QMAP database). “The coquina limestone that occur regularly through the sequence are of **shallow shelf** origin...” (Lee and Begg, 2002) – *EoD is based on the shallow shelf interpretation for the coquina limestones of the Onoke Group in Lee and Begg (2002).*

### **Waitahora Limestone (Pepw)**

**Inferred age:** 3 Ma (Field and Uruski, 1997)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = coquina; Sub\_Rocks = limestone; Description = limestone (QMAP database). “The coquina limestone that occur regularly through the sequence are of **shallow shelf** origin...” (Lee and Begg, 2002) – *EoD is based on the shallow shelf interpretation for the coquina limestones of the Onoke Group in Lee and Begg (2002).*

### **Castlepoint Limestone (Pepc)**

**Inferred age:** 2 Ma (Lee and Begg, 2002)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = coquina; Sub\_Rocks = sandstone; Description = shelly limestone and calcareous sandstone (QMAP database). “Castlepoint Formation (Johnston 1980), cropping out in a small, isolated area on the east Wairarapa coast at Castlepoint, is a muddy to pebbly limestone with *Zygochlamys delicatula* in some units and warm-water fossils in interbedded units, possibly representing up to three cycles of transgressive systems tracts and highstand systems tracts” (Field and Uruski, 1997). “Both differences – faunal and sedimentary – therefore suggest that this is possibly a New Zealand example of a succession deposited under the influence of coastal currents, as in the Omma Formation. However, the **deep-water** species present in small numbers in some lithologies and the chaotic **debris-flow** lithologies of the Castlepoint Formation suggest a more complex origin, such as **canyon-head debris flows** in response to cyclic sea-level changes on the adjacent shelf” (Beu and Kitamura, 1998) – *EoD is based on the “shallow shelf” interpretation of the map unit in Lee and Begg (2002) and the lithologic description in Field and Uruski (1997). An upper bathyal depth of deposition is an alternative EoD for the map unit (Beu and Kitamura, 1998).*

## **Quaternary – Sedimentary deposits**

- **All Q deposits** (except – see below)

**EoD:** onshore

**Basis for interpretation:** Based on the QMAP database which includes alluvial, beach, dune, estuarine, fluvial, lacustrine, landslide, and loess sediments in the Quaternary deposits.

- **mQb, Q5b**

**EoD:** innermost shelf

**Basis for interpretation:** “...**marginal marine** origin... wave-cut coastal terraces...” (Lee and Begg, 2002).

## GREYMOUTH AREA (Geological Map 12)

### ***Paparoa Coal Measures (Kpc)***

***Inferred age:*** > 65-56 Ma (King et al., 1999)

***EoD:*** onshore

***Basis for interpretation:*** Main\_Rock = sandstone; Sub\_Rocks = conglomerate, mudstone, 'coal seams'; Description = Fluvial sandstone; conglomerate and coal seams; locally with thick lacustrine mudstone (QMAP database). "...consist of a **non-marine** assemblage of **fluvial** conglomerate, sandstone, **lacustrine** mudstone, and lensoid coal seams... Detailed mapping within the Greymouth Coalfield (Gage 1952) showed that the Paparoa Coal Measures can be subdivided into seven units, now mapped as members (Nathan 1978a)... The Cretaceous-Tertiary boundary occurs within a coal seam in the upper part of the Rewanui Member (Raine 1994; Vajda and others 2001)" (Nathan et al., 2002). "Gage (1949a, 1952) presented a detailed reconstruction of the geological history of Paparoa Coal Measures within the Greymouth Coalfield. He recognised that sedimentation was controlled by continuing subsidence in the NNE-trending Paparoa Trough, alternately filled with **fluvial** sediments (predominantly alternating sandstone-mudstone floodplain sequences) derived from rising source areas to the east and northwest, and with **lacustrine** mud formed when subsidence exceeded sediment supply and a widespread lake or lakes covered the area" (Nathan et al., 1986) – *the unit is defined here as being onshore, involving fluvial and lacustrine sediments.*

### ***Pororari Group & Paparoa Coal Measures (eKpo+Kpc)***

***Inferred age:*** > 65-56 Ma (King et al., 1999)

***EoD:*** onshore

***Basis for interpretation:*** Main\_Rock = sandstone; Sub\_Rocks = breccia, 'coal measures'; Description = Fluvial conglomerate and sandstone (locally hematitic) with coal seams and locally thick lacustrine mudstone (QMAP database) – *this unit code is assumed to contain undifferentiated Pororari Group and Paparoa Coal Measures. The Pororari Group is entirely Cretaceous (Nathan et al., 2002) so its EoD is beyond the scope of this project. The upper Paparoa Coal Measures are younger than 65 Ma so the EoD for eKpo+Kpc is represented by the Paparoa Coal Measures in this project.*

### ***Brunner Coal Measures (Eb)***

***Inferred age:*** 38-36 Ma (Nathan et al., 1986; Ghisetti and Beggs, 2007)

***EoD:*** onshore

***Basis for interpretation:*** Main\_Rock = sandstone; Sub\_Rocks = coal seams'; Description = Quartz sandstone; conglomerate and carbonaceous shale with lensoid coal seams (QMAP database). "The oldest Eocene sedimentary rocks are Brunner Coal Measures (Eb), consisting of quartz sandstone, conglomerate, carbonaceous shale, and lensoid **coal seams** locally up to 10 m thick" (Nathan et al., 2002). "**Fluvial**, with meandering streams and peat swamps in the northwest and more active streams in the east" (Suggate, 1984). "Petrographic evidence suggest that most Brunner coals accumulated in **peat swamps**, dominated by reed and small herbaceous vegetation, and generally lacking trees. In a study of coal measure sedimentology and coal petrology, Newman & Newman (1982) concluded that the peat swamps in the Pike River coalfield were relatively alkaline and formed in a **marginal marine** environment" (Nathan et al., 1986) – *the unit is defined as onshore, after Suggate (1984).*

### ***Shallow marine sandstone (Ers)***

***Inferred age:*** 40-34 Ma (Nathan et al., 1986)

***EoD:*** innermost shelf

***Basis for interpretation:*** Main\_Rock = sandstone; Sub\_Rocks = sand; Description = Shallow marine sand and sandstone (QMAP database). "In some areas, the coal measures [i.e. Brunner] are overlain by **shallow marine** sandstone which has been given a variety of local names (e.g., Island Sandstone near Greymouth), but which are here generalised as a single unit (Ers)" (Nathan et al., 2002). "...a **nearshore marine** unit found only within the southern part of the Paparoa Trough... commonly containing abundant plant debris... makes up a substantial proportion of the marine Eocene sequence (generally over 50%)..." (Nathan et al., 1986). "**Shallow marine** sandstone" (Suggate,

2006). “The increase in bioturbation and finer grain size suggests an increase in depth of deposition during a continuing transgression in the lower part of the Rapahoe sequence through the Kaiatan to Runangan Stages” (Lever, 2001). “...the Island Sandstone is a **shallow marine**, probably **inner shelf**, deposit... The Island Sandstone is conformably overlain by Kaiata Formation” (Suggate and Waight, 1999) – *the EoD is defined here as innermost shelf based on the description in Nathan et al. (1986) of the Island Sandstone being nearshore marine and commonly containing plant debris.*

### ***Kaiata Formation (Erk)***

“The [Brunner] coal measures are conformably (and in most places gradationally) overlain by **shallow-water** sedimentary rocks. The most widespread unit is massive, dark brown carbonaceous mudstone of the Kaiata Formation (Erk), which locally contains interbedded **mass-flow** deposits near Greymouth and Westport (Nathan and others 1986)” (Nathan et al., 2002). “...**shallow-water** marine sediments, included in the Rapahoe Group (Nathan 1974). The most widespread unit, Kaiata Formation, consists of dark brown carbonaceous mudstone or muddy sandstone. Various sandstone units have been identified locally, mainly in the relatively stable areas at the margins or outside the main subsiding basins, but all are locally restricted...” (Nathan et al., 1986). “Marine mudstone and sandstone, mainly dark brown in colour; local areas of quartzose or arkosic sand... The Rapahoe Group consists of clastic marine sediments and in the Greymouth area includes the Island Sandstone, Kaiata Mudstone, Omotumotu Beds, and Port Elizabeth Beds of Morgan (1911) as well as formations of similar lithology and stratigraphic position elsewhere” (Nathan, 1974).

### ***Kaiata Mudstone Member***

“Typical foraminiferal microfaunas are dominated by a small group of benthic arenaceous genera which can exist under bottom conditions not tolerated by normal marine assemblages, as well as a small number of planktonic species... These features suggest that the mudstone was formed under poorly oxygenated bottom conditions, but the presence of some planktonic foraminifera indicates that a connection with the open sea existed... The common situation of these mudstones at the base of a **transgressive marine** sequence is important as it implies both deposition in **shallow water** (probably in conditions of high organic productivity), and that the water circulation may have been poor, at least until sedimentary basins became large enough for an oceanic thermohaline circulation pattern to develop (Andrews 1977)” (Nathan et al., 1986).

*EoD: initially innermost shelf, deepening to outer shelf or upper bathyal*

*Basis for interpretation: Planktonic foraminifera are not reported as abundant, indicating shelfal depths. The Kaiata Formation in the Paparoa Trough is shallower than the Kaiata Mudstone Member of the Maruia Formation in the Murchison Basin.*

#### **• Omotumotu Member**

“A thick lens of coarse redeposited sediments (Omotumotu Member) is interbedded within the Kaiata Formation on the eastern side of the Paparoa Trough” (Nathan et al., 1986). “**Submarine fan deposits**” (Suggate, 2006).

*EoD: upper bathyal*

*Basis for interpretation: EoD is based on the description of submarine fan deposits. Mid-bathyal is a possible alternative EoD.*

#### **• Elizabeth Member (Onp)**

*Inferred age:* 33-32 Ma (Nathan et al., 1986)

*EoD:* upper bathyal

*Basis for interpretation:* Main\_Rock = mudstone; Description = Grey-brown calcareous mudstone (QMAP database). “The **Basinal** facies occurs mainly around Greymouth, where calcareous mudstone of the Port Elizabeth Member (Onp) at the top of the Kaiata Formation...” (Nathan et al., 2002). “Marine calcareous mudstone” (Suggate, 2006). “For convenience, all mudstones between the Omotumotu Member and the Cobden Limestone are regarded as Port Elizabeth Member... Is lighter coloured and more calcareous than the underlying members, and is transitional to the overlying Cobden Limestone” (Suggate and Waight, 1999) – *EoD is after Nathan et al. (2002).*

*Inferred age:* 38-32 Ma (Nathan et al., 1986)

**EoD breakdown:** 38-37 Ma: innermost shelf  
36 Ma: mid-shelf  
35-32 Ma: outer shelf

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = conglomerate; Description = Brown carbonaceous mudstone; locally containing conglomeratic debris-flow beds (QMAP database) – *the EoD breakdown is based on the depositional age and paleoenvironmental interpretations of the members that occur in the Greymouth map area. It is defined here as deepening over time, to match the deepening of the Kaiata Mudstone Member to the east in the Murchison Basin, except that the Murchison Basin lay at bathyal depths during this interval.*

### **Maruia Formation (Em)**

Includes Brunner Coal Measures, Nuggety Member, and Kaiata Mudstone Member.

“Within the Murchison Basin, at the northeast edge of the map area, the Maruia Formation (Em) consists of carbonaceous mudstone containing a high proportion of thick-bedded quartzofeldspathic sandstone, with minor conglomerate and rare coal seams (Fyfe 1968; Roder & Suggate 1990)” (Nathan et al., 2002). “...is composed of 50 to 500 m of coarse, quartzofeldspathic sandstone with minor conglomerate, carbonaceous mudstone and thin seams of bituminous coal. These rocks are overlain by up to 500 m of largely massive, dark brown, micaceous mudstone or siltstone with minor bands of feldspathic sandstone, becoming more calcareous towards the top. The Maruia Formation was deposited unconformably on basement rocks, initially in a **terrestrial** environment. The mudstone represents deposition in an **estuarine** to partly enclosed **inner shelf** environment with periodic incursion of **submarine fans** derived from a rising area of Separation Point Batholith granite, probably to the east (Suggate 1984)” (Rattenbury et al., 2006).

#### • Brunner Coal Measures

“**Fluviatile**, with meandering streams and peat swamps in the northwest and more active streams in the east” (Suggate, 1984).

*EoD: onshore*

*Basis for interpretation: EoD is after Suggate (1984).*

#### • Nuggety Member

“**Submarine fan**...” (Suggate, 1984). The occurrence of Nuggety Member as redeposited sandstone (turbidites and sandy debris flows) requires an upper to mid-bathyal EoD.

*EoD: mid-bathyal*

*Basis for interpretation: The EoD is interpreted as a mid-bathyal submarine fan.*

### **Kaiata Mudstone**

“The common situation of these mudstones at the base of a **transgressive marine** sequence is important as it implies both deposition in **shallow water** (probably in conditions of high organic productivity), and that the water circulation may have been poor...” (Nathan et al., 1986).

*EoD: initially shelf, deepening over time to upper bathyal*

*Basis for interpretation: The Kaiata Mudstone in the Murchison Basin represents a transgressive marine sequence that was initially approximately mid-shelf depth, and deepened over time to upper bathyal (compilers).*

**Inferred age:** 38-31 Ma (Nathan et al., 1986; Ghisetti and Beggs, 2007)

**EoD breakdown:** 38-36 Ma: onshore (Brunner Coal Measures)  
35 Ma: mid-shelf (Kaiata Mudstone)  
34-31 Ma: mid-bathyal (Kaiata Mudstone, Nuggety Member)

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone, conglomerate; Description = Mudstone and quartzofeldspathic sandstone with minor conglomerate and thin coal seams (QMAP database) – *the EoD breakdown for the map unit is based on the depositional age and paleoenvironmental interpretations of the members that make up the unit. Kaiata Mudstone and Nuggety Member interfinger, so an average EoD of mid-bathyal is chosen to represent this interval. Refer to “Maruia Formation (Em)” on the Kaikoura map area for further information.*

## Eyre Group

### *Esk Formation (Eee)*

*Inferred age:* 34-28 Ma (Gage, 1970)

*EoD:* innermost shelf

*Basis for interpretation:* Main\_Rock = basalt; Sub\_Rocks = Thin basalt flows; Description = Thin basalt flows and glauconitic greensand (QMAP database). "On the southeast side of the Alpine Fault, vesicular, columnar basalt and adjacent glauconitic greensand in the Esk River near Grant Stream underlie late Tertiary sedimentary rocks. This section is similar to that in the Brechin Burn 15 km farther southwest (Newman & Bradshaw 1981). There the **basalt and greensand** are inferred to be Eocene (Field & Browne 1989), in the upper part of the Eyre Group (Ee)" (Nathan et al., 2002). "...glauconitic fine sandstone (locally **cross-bedded**) and sandy siltstone..." (Forsyth et al., 2008). "The formation accumulated under marine conditions and member E1 is probably a **high-energy shoreline** conglomerate reflecting the beginning of a marine transgression" (Newman and Bradshaw, 1981) – *the EoD is defined as innermost shelf after Newman and Bradshaw (1981). However, mid-shelf or submarine mafic eruptives may be alternative EoDs during this period. Refer to "Esk Formation (Oee)" on the Christchurch map area for further information.*

## Nile Group (On)

*Inferred age:* 29-22 Ma (King et al., 1999)

*EoD:* mid-shelf

*Basis for interpretation:* Main\_Rock = limestone; Description = Limestone; predominantly **shallow-water** bioclastic varieties (QMAP database). "Nathan (1974b) included all the calcareous sediments over much of the West Coast region in the Nile Group (On), which was divided into two major facies (Nathan and others 1986): (a) Platform facies (usually <100 m thick), consisting of **shallow-water** bioclastic limestone and muddy micaceous limestone formed on a relatively stable **shelf**; and (b) Basinal facies (usually >100 m thick), predominantly muddy limestone, massive calcareous mudstone and interbedded calcareous sandstone and mudstone, formed in rapidly subsiding **basins**. The **Platform** facies, which includes numerous units that have been distinguished in detailed mapping, is found as erosional remnants over much of the map area, mainly as bluff-forming limestone. On the coast south of Westport, limestone bluffs are one of the most striking features of the Paparoa National Park (Figs 27-29). The **Basinal** facies occurs mainly around Greymouth, where calcareous mudstone of the Port Elizabeth Member (Onp) at the top of the Kaiata Formation grades upwards into muddy micritic limestone of the Cobden Limestone (Onc)" (Nathan et al., 2002) – *EoD is based primarily on the QMAP description of the map unit as a predominantly shallow water bioclastic limestone. "Shallow water" is assumed here to be mid-shelf depths, but outer shelf depositional depths may also be appropriate in more marly areas. NB: some polygons in the north of this map area have a minimum age of 23 Ma as per the Nile Group on the Nelson map area.*

### *Cobden Limestone (Onc)*

*Inferred age:* 32-22 Ma (King et al., 1999)

*EoD:* mid-bathyal

*Basis for interpretation:* Main\_Rock = limestone; Description = Muddy micritic limestone (QMAP database). "The Oligocene Cobden Limestone is in places quite porous, being a sandy to gritty, foraminiferal and glauconitic limestone of sugary appearance" (Katz, 1968). "The Cobden Limestone is a planktonic foraminiferal and coccolithal limestone evidently deposited in **deep water**" (Evans, 1986) – *Nathan et al. (2002) includes the Cobden Limestone as part of the basinal facies of the Nile Group, and Evans (1986) refers to the limestone as a "deep water" deposit, which implies a bathyal depth of deposition.*

## Matiri Formation (Om)

Includes Scotty Mudstone Member, Doughboy Member, and Trig M Member.

"Within the Murchison Basin, at the northeastern corner of the map area, massive calcareous mudstone with interbedded calc-flysch is mapped as Matiri Formation (Om)" (Nathan et al., 2002). "Continuing marine transgression through the Oligocene led to the gradual drowning of the low-ly-

ing land areas exposed at the end of the Eocene, so that by the beginning of the Late Oligocene (Dunroonian—early Waitakian Stages) virtually the entire West Coast Region was submerged... The Basinal Facies in the Murchison Basin consists of massive calcareous mudstone and calc-**flysch**, all included in the Matiri Formation... Detailed micropaleontological studies show that the Matiri Formation contains an assemblage of **deep-water** foraminifera” (Nathan et al., 1986).

- **Scotty Mudstone Member**

“At the base, rapid establishment of **fully marine** conditions is indicated by the ubiquitous colour change from Maruia Formation mudstone, increase in calcium carbonate content, and incoming of fully marine planktic foraminifera. Rapid increase of water depth from shelf to bathyal is recorded within the Whaingaroan...” (Suggate, 1984).

*EoD: mid-bathyal*

*Basis for interpretation: This member is defined as mid-bathyal after the Rattenbury et al. (2006) description of bathyal for the Matiri Formation, and the lithology of mudstone. Lower bathyal may also be appropriate.*

- **Doughboy Member**

“The coarse deposits result from short distance mass transport into an **outer shelf to bathyal** environment” (Suggate, 1984). “A wedge of **mass-flow** beds, mainly conglomerate, grit, and sandstone, containing identical granite clasts and a **redeposited** shallow-water fauna occur within the lower part of the Matiri Formation on the western margin of the Murchison Basin...” (Nathan et al., 1986).

*EoD: upper bathyal*

*Basis for interpretation: This member is defined as upper bathyal after the Rattenbury et al. (2006) description of bathyal and the identification of debris flows. Mid-bathyal may also be appropriate.*

- **Trig M Member**

“**Bathyal submarine fan** derived from erosion of shelly and algal inner shelf sediments” (Suggate, 1984).

*EoD: mid-bathyal*

*Basis for interpretation: This member is defined as mid-bathyal after the Rattenbury et al. (2006) description of bathyal, the occurrence of flysch and transportation of material down submarine canyons. Lower bathyal may also be appropriate.*

**Inferred age:** 30-24 Ma (Nathan et al., 1986; Ghisetti and Beggs, 2007)

**EoD breakdown:** 30-29 Ma: mid-bathyal (Scotty Mudstone Member)  
28-27 Ma: mid-bathyal (Scotty Mudstone Member, Doughboy Member)  
26-24 Ma: mid-bathyal (Scotty Mudstone Member [26-25], Trig M Member [24])

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone; Description = Massive calcareous mudstone; with inter-bedded calcareous sandstone and mudstone (QMAP database) – *EoD is based on the bathyal interpretation of the map unit in Rattenbury et al. (2006). Refer to “Matiri Formation (Om)” on the Kaikoura map area for further information.*

## **Mangles Formation (Mm)**

Mislabelled as Matiri Formation in database.

“In Murchison Basin, in the northeast corner of the map area, calcareous mudstone of the Matiri Formation passes upwards into a **deep-water turbidite** sequence of interbedded quartz-mica sandstone and mudstone (Mangles Formation)” (Nathan et al., 2002). “An exceptional increase in the rate of subsidence initiated Mangles Formation deposition” (Suggate, 1984). “...the Mangles Formation, conformable or with only a minor disconformity over the Matiri Formation, accounts for 12, 000 ft and is subdivided into a lower portion with mainly thin-bedded, alternating sandstone, siltstone, and mudstone, and an upper portion which consists of massive sandstone and local massive siltstone beds; the siltstone in the lower, alternating beds are all calcareous but the formation as a whole is basically non-calcareous. On the western side of the basin the Lower Mangles is, however, represented by thick sandstone beds with only minor, thin shale-silt partings. In contrast with the dirty, dense, and greenish grey Upper Mangles, this sandstone is quartz-rich and light grey,

somewhat micaceous but rather well sorted..." (Katz, 1968). There may be little if any difference in *EoD* between Trig M Member and the lowermost *EoD* of Mangles Formation. *Note added by compilers:*

- **Tutaki Member**

"**Submarine fans** extending to **bathyal** depths, probably from both west and northeast" (Suggate, 1984).

*EoD: lower bathyal*

*Basis for interpretation: EoD is based on the stratigraphic position of the Tutaki Member in the lower part of the Mangles Formation.*

- **Crowe Member**

"**Submarine fan**" (Suggate, 1984).

*EoD: upper bathyal*

*Basis for interpretation: Graded beds and the presence of conglomerates in the graded beds are interpreted as upper fan sediments of upper bathyal depth (QMAP description). Mid-bathyal may also be appropriate.*

- **Valley Creek Sandstone**

"The type section consists of about 1750 m of dark grey massive siltstone grading up to dark grey massive, muddy very fine sandstone... **Mid-outer shelf to bathyal**" (Suggate, 1984).

*EoD: initially upper to mid-bathyal, shallowing up section to mid-shelf*

*Basis for interpretation: To call this member a sandstone is a bit of a misnomer as the bulk of it is essentially a siltstone, inferred to be deposited at upper bathyal depths. The upper part of the member is a mid-shelf sandstone.*

- **Trig A Member**

"Fine to medium sandstone with scattered pebbles or pebble stringers... **Inner shelf**" (Suggate, 1984).

*EoD: innermost shelf*

*Basis for interpretation: Rattenbury et al. (2006) mention pebbly sandstone near the top of the Mangles Formation, which implies shallowing upwards through the formation.*

**Inferred age:** 23-17 Ma (Nathan et al., 1986; Ghisetti and Beggs, 2007)

**EoD breakdown:** 23-20 Ma: lower bathyal (Tutaki Member)  
19-18 Ma: upper bathyal (Crowe Member, Valley Creek Sandstone)  
17 Ma: innermost shelf (Trig A Member)

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone; Description = Quartz-mica sandstone; locally glauconitic; and alternating sandstone and mudstone (QMAP database) – the *EoD* breakdown for the Mangles Formation is based on the depositional age and paleoenvironmental interpretations of the members that make up the formation. Refer to "Mangles Formation (Mm)" on the Kaikoura map area for further information.

## Rappahannock Group

"Farther south, at an equivalent stratigraphic level to the Longford Formation, the poorly dated **terrestrial** Rappahannock Group (Cutten 1979)..." (Rattenbury et al., 2006).

### **Lower Rappahannock Group (eMrl)**

Includes Frog Flat Formation.

**Inferred age:** 9-7 Ma (Lee, 2013)

*EoD: onshore*

**Basis for interpretation:** Main\_Rock = conglomerate; Sub\_Rocks = sandstone; Description = Muddy sandstone and conglomerate containing indurated volcanogenic sandstone clasts (QMAP database) – *EoD* is based on Rattenbury et al. (2006) interpretation. After Lee (2013) the Frog Flat Formation is considered to be equivalent to Rattenbury et al.'s (2006) Lower Rappahannock Group.

### ***Upper Rappahannock Group (mMru)***

Includes Spargo Formation, and Devil's Knob Formation.

***Inferred age:*** 7-4 Ma (Lee, 2013)

***EoD:*** onshore

***Basis for interpretation:*** Main\_Rock = conglomerate; Description = Conglomerate composed largely of schist clasts (QMAP database) – *EoD is based on Rattenbury et al. (2006) interpretation. After Lee (2013) the Spargo Formation and Devil's Knob Formation are considered to be equivalent to Rattenbury et al.'s (2006) Upper Rappahannock Group.*

### **Blue Bottom Group**

#### ***Welsh Formation (eMbw)***

***Inferred age:*** 21-16 Ma (King et al., 1999)

***EoD:*** outer shelf

***Basis for interpretation:*** Main\_Rock = mudstone; Description = Grey-brown calcareous mudstone (QMAP database). “West of the Paparoa Range, around Punakaiki, the uppermost unit of the Nile Group (Potikohua Limestone) is overlain sharply by brown calcareous sandy mudstone (Welsh Formation, Mbw), with 1-2 metres of glauconitic mudstone immediately above the contact” (Nathan et al., 2002). “...brown, calcareous, muddy sandstone with a thin (up to 0.3 m) discontinuous green-sand at the base; passes southwards into grey-brown, calcareous mudstone with limestone lenses up to 30 m thick” (Nathan, 1974) – *based on the cited literature the depth of deposition of the Welsh Formation could be mid- to outer shelf. The map unit is defined as outer shelf based on the main rock type of mudstone and Fig. 3.*

#### ***Rotokohu Coal Measures (eMbr)***

***Inferred age:*** 16-3 Ma (Nathan et al., 1986)

***EoD:*** onshore

***Basis for interpretation:*** Main\_Rock = conglomerate; Sub\_Rocks = sandstone; Description = Fluvial sandstone; conglomerate and lensoid coal seams (QMAP database). “With the increase in sand, there is a progressive shallowing into **estuarine and fluvial** facies, with local lensoid coal seams, mapped as Rotokohu Coal Measures...” (Nathan et al., 2002) – *EoD is based on the description of the unit as fluvial.*

#### ***Inangahua Formation (eMbi)***

Includes Hunt Member, Oweka Sandstone Member, De Filippi Mudstone Member, and Ram Creek Member.

“Further south, a thick sequence of grey-brown calcareous mudstone (Inangahua Formation, Mbi) occurs in the axis of the Grey valley trough...” (Nathan et al., 2002). “A phosphatized and glauconitized nodular shellbed and hardground occur at the top of the Whitecliffs Formation, separating it from the **deeper water** calcareous mudstone and sandstone of the overlying Blue Bottom Group (Inangahua Formation; Nathan, 1978a)... The formation is at least 300 m thick and **passes up into a regressive sequence that culminates in the non-marine** Rotokohu Formation...” (Carter et al., 1982). “The late Altonian to Waiauian Rotokohu Coal Measures formed as a fault controlled, rapidly subsiding fan-delta/delta sequence. The coal measures gradationally overlie **rapidly shallowing-upward Waitakian to late Altonian sediments of the marine Inangahua Formation**... The [Inangahua] formation was locally subdivided into four members within the northern Inangahua Valley... The basal Hunt Member... The Oweka Sandstone Member... De Filippi Mudstone Member... Ram Creek Member... The early Miocene stratigraphy of the Inangahua Valley (Chapter 2) indicates a **rapid shallowing** during the mid-Altonian from mid to outer shelf (De Filippi Mudstone), to shallow marine (Ram Creek Member), to marginal and non-marine (Rotokohu Coal Measures) by late Altonian time” (Johnston, 1987). “Open ocean calcareous mudstone” (Suggate, 2006).

- **Hunt Member**

“The basal Hunt Member is defined as Upper Waitakian to Lower Otaian, massive, brown, calcareous marine mudstone interbedded with thin beds of hard white foraminiferal or muddy limestone, and locally containing beds of white “arkosic” sandstone (Nathan 1974)” (Johnston, 1987).

***EoD:*** upper bathyal



*Basis for interpretation: Carter et al. (1982) interpret Inangahua Formation mudstone overlying the Whitecliffs Formation as flysch deposits. The Hunt Member is the basal unit of the Inangahua Formation therefore an upper bathyal environment has been inferred.*

- **Oweka Sandstone Member**

“The Oweka Sandstone Member is defined as mid-Otaian, light grey, slightly calcareous, marine, muddy medium sandstone with scattered concretionary bands (Nathan 1974)” (Johnston, 1987).

*EoD: mid-shelf*

*Basis for interpretation: EoD is based on the description of the member given in Johnston (1987), and that the Inangahua Formation is a regressive sequence.*

- **De Filippi Mudstone Member**

“...mid-Otaian to mid-Altonian, massive grey/brown, highly calcareous marine mudstone... Microfossil samples S31/f802 and f505 (Fletcher Creek), and S31/f805 (Hunt Creek) from the De Filippi Mudstone near the Ram Creek contact contain Lower? Altonian **mid to outer shelf** faunas, while a thin (34 m at Hunt Creek) Ram Creek Member is gradationally overlain by Upper Altonian Rotokohu Coal Measures” (Johnston, 1987).

*EoD: upper bathyal to outer shelf*

*Basis for interpretation: The mid- to outer shelf depositional depth range for the De Filippi Mudstone Member (Johnston, 1987) is refined to outer shelf here. Lower parts of this member contain redeposited sandstone that probably accumulated at upper bathyal depths; this is equivalent to the Tutaki Member and lower Valley Creek Sandstone of the Mangles Formation in the Murchison Basin.*

### **Ram Creek Member**

“...Lower to Upper Altonian, massive white, “arkosic sandstone”, interbedded with grey/brown, highly calcareous marine mudstone... Ram Creek provides a small but well exposed section showing the gradation from calcareous **shallow marine** sandstone and siltstone of the Ram Creek Member, into the Thomson Member of the Rotokohu Coal Measures” (Johnston, 1987).

*EoD: mid-shelf*

*Basis for interpretation: The Ram Creek Member’s lithologic description of sandstone interbedded with highly calcareous mudstone (Johnston, 1987) suggests fluctuating innermost shelf (sandstone) to outer shelf (mudstone) depositional environments (Fig. 3). An average mid-shelf EoD is in agreement with the member’s shallow marine interpretation (Johnston, 1987).*

**Inferred age:** 23-17 Ma (Johnston, 1987; King et al., 1999)

**EoD breakdown:** 23-21 Ma: upper bathyal (Hunt Member)  
20 Ma: outer shelf (Oweka Sandstone Member, De Filippi Mudstone Member)  
19 Ma: outer shelf (De Filippi Mudstone Member)  
18-17 Ma: mid-shelf (De Filippi Mudstone Member, Ram Creek Member)

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone; Description = Grey-brown calcareous mudstone; locally with sandstone interbeds (QMAP database) – *the EoD breakdown for the map unit is based on the depositional age and paleoenvironmental interpretations of the members that make up the Inangahua Formation. The 20 Ma period consists of mid-shelf Oweka Sandstone Member and outer shelf De Filippi Mudstone Member; an outer shelf EoD is assigned to the 20 Ma period here. The 18-17 Ma period consists of outer shelf De Filippi Mudstone Member and mid-shelf Ram Creek Member; a mid-shelf EoD is assigned to the period, in keeping with the “rapidly shallowing-upward” trend noted for the Inangahua Formation in Johnston (1987).*

### **Stillwater Mudstone (mMbs)**

**Inferred age:** 18-10 Ma (King et al., 1999)

*EoD: upper bathyal*

**Basis for interpretation:** Main\_Rock = calcareous mudstone; Description = Grey calcareous mudstone (QMAP database). “There is a gradational change into grey calcareous mudstone (Stillwater Mudstone, Mbs) near the base of the Middle Miocene” (Nathan et al., 2002). “**Upper, but not uppermost, bathyal** environment, probably in the range of 400-800 m” (Paleobiology database,

2012). "Open sea-bathyal calcareous mudstone" (Suggate, 2006) – *EoD is based on the upper bathyal interpretation for the Stillwater Mudstone given in the Paleobiology database.*

### **O'Keefe Formation (IMPbo)**

(QMAP database spelling: OKeefe Formation)

**Inferred age:** 12-3 Ma (King et al., 1999)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = sandstone; Description = Blue-grey; micaceous muddy sandstone (QMAP database). "West of the Paparoa Range there is a **shallow marine** sequence, predominantly blue-grey muddy sandstone, which is mapped as O'Keefe Formation (Mbo)" (Nathan et al., 2002) – *EoD is based on the shelf depositional setting interpretation of Nathan et al. (2002), the QMAP description (muddy sandstone), and Fig. 3.*

### **Eight Mile Formation (IMPbe)**

**Inferred age:** 7-6 Ma (King et al., 1999)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = sandstone; Description = Blue-grey; micaceous muddy fine sandstone (QMAP database). "In the Grey Valley and the lowland area to the south, the dominant lithologies are blue-grey muddy sandstone and yellow-brown fine-grained sandstone (Eight Mile Formation, Mbe)" (Nathan et al., 2002). "**Shallow marine** sandstone" (Suggate, 2006) – *EoD is based on QMAP and Nathan et al. (2002) descriptions and Fig. 3.*

### **Rotokohu Coal Measures (IMbf)**

**Inferred age:** 13-5 Ma (Nathan et al., 1986)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = conglomerate, 'coal seams'; Description = Local fluvial sandstone and coal seams (QMAP database). "A small area of **fluvial** sandstone with coal seams and conglomerate beds on the western side of the Grey Valley (Nathan 1978a) is mapped as Mbf" (Nathan et al., 2002) – *EoD is based on the QMAP description and interpretation.*

### **Upper Blue Bottom Group (Pbw)**

**Inferred age:** 3 Ma (Nathan et al., 2002)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone, conglomerate; Description = Fluvial sandstone; estuarine mudstone and minor conglomerate (QMAP database). "In the Inangahua Valley the Old Man Group rests on a thin unit of **fluvial** sandstone and **estuarine** mudstone, mapped as Pbw" (Nathan et al., 2002) – *EoD is based on the description in Nathan et al. (2002).*

## **Nile Group & Stillwater Mudstone (On+mMbs)**

Includes Nile Group and Stillwater Mudstone.

### **Nile Group**

"Nathan (1974b) included all the calcareous sediments over much of the West Coast region in the Nile Group (On), which was divided into two major facies (Nathan and others 1986): (a) Platform facies (usually <100 m thick), consisting of **shallow-water** bioclastic limestone and muddy micaceous limestone formed on a relatively stable **shelf**; and (b) Basinal facies (usually >100 m thick), predominantly muddy limestone, massive calcareous mudstone and interbedded calcareous sandstone and mudstone, formed in rapidly subsiding basins" (Nathan et al., 2002).

**EoD:** mid-shelf

**Basis for interpretation:** *EoD is based primarily on the QMAP description of the map unit as a predominantly shallow water bioclastic limestone. "Shallow water" is assumed here to be mid-shelf depths, but outer shelf depositional depths may also be appropriate in more marly areas.*

## **Stillwater Mudstone**

“**Upper, but not uppermost, bathyal** environment, probably in the range of 400-800 m” (Paleobiology database, 2012).

*EoD: upper bathyal*

*Basis for interpretation: EoD is based on the upper bathyal interpretation for the Stillwater Mudstone given in the Paleobiology database.*

**EoD breakdown:** 29-22 Ma: mid-shelf (Nile Group)  
18-10 Ma: upper bathyal (Stillwater Mudstone)

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = calcareous mudstone; Description = Limestone; predominantly **shallow-water** bioclastic varieties; and grey calcareous mudstone (QMAP database) – *the map unit appears to include undifferentiated Nile Group and Stillwater Mudstone, so the EoD is based on that of those units.*

## **Brechin Formation (IMPm)**

**Inferred age:** 16-3 Ma (Nathan et al., 2002; Forsyth et al., 2008)

*EoD: onshore*

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = conglomerate, ‘carbonaceous sandstone’, ‘coal seams’; Description = Muddy sandstone and carbonaceous sandstone with thin coal seams overlain by Torlesse-derived conglomerate and sandstone (QMAP database). “These blocks contain basal muddy sandstone, carbonaceous sandstone and thin coal seams, overlain by Torlesse-derived conglomerate and interbedded sandstone. The conglomerate correlates with the upper part of a similar section in the Brechin Burn, 15 km to the southwest (Newman and Bradshaw 1981) and is assigned to the Late Miocene to Pliocene Motunau Group (Pn)” (Nathan et al., 2002). “...the bulk of the Brechin Formation is the regressive B4, which marks the progradation of mainly **fluvial** conglomerate in response to major uplift of Torlesse basement” (Newman and Bradshaw, 1981) – *EoD is based on QMAP and Newman and Bradshaw (1981) descriptions.*

## **Old Man Group**

“Rapid uplift of the Southern Alps is reflected by a flood of **fluvial** gravel and sand that extended northwest from the Alpine Fault... The resulting conglomerate, containing predominantly clasts of greywacke and schist, is mapped as Old Man Group (Po)” (Nathan et al., 2002). “...a thick (>400 m) **terrestrial** sequence of predominantly conglomerate, with interbedded sandstone and carbonaceous mudstone” (Mortimer et al., 2001). “Mollusca at 1 locality and dinoflagellate cysts in sample S12/f582 (Mildenhall 1978) indicate that at least some of the basal part of the Old Man Group is **marine**” (Neef, 1981). “The earliest known drift in New Zealand is that of the Ross Glaciation, which is overlain by Pliocene Old Man Group conglomerates that may also be **glacigenic**” (Kiernan et al., 2001).

### • Pom

**Inferred age:** 4-2 Ma (Nathan et al., 2002)

*EoD: onshore*

**Basis for interpretation:** Main\_Rock = gravel; Description = Weathered gravel; with clasts predominantly of Torlesse sandstone or schist (QMAP database) – *EoD is based on the fluvial and terrestrial interpretations of the formation in Nathan et al. (2002) and Mortimer et al. (2001). Innermost shelf may also be appropriate (Neef, 1981).*

### • Pomc

**Inferred age:** 2 Ma (Nathan et al., 2002)

*EoD: onshore*

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = conglomerate ‘coal seams’; Description = Glauconitic and feldspathic sandstone; thin coal seams; and fluvial conglomerate containing largely Torlesse clasts (QMAP database) – *EoD is based on the fluvial and terrestrial interpretations of the formation in Nathan et al. (2002) and Mortimer et al. (2001).*

## Quaternary – Sedimentary deposits

- **All Q deposits** (except – see below)

*EoD:* onshore

*Basis for interpretation:* Based on the QMAP database which includes alluvial, beach, dredge tailings, dune, lacustrine, landslide, scree, swamp, and till sediments in the Quaternary deposits.

- **Q5b, Q7b, Q9b, uQb, eQb**

*EoD:* innermost shelf

*Basis for interpretation:* “Near the coast, the deposits of successive interglacial periods (including the postglacial) consist mainly of well sorted **beach** sand and **nearshore** gravel and sand” (Nathan et al., 2002).

## KAIKOURA AREA (Geological Map 13)

### Late Cretaceous to Eocene Eyre Group (IKEe)

Includes Claverley Sandstone and Loburn Mudstone.

“Undifferentiated Eyre Group (KEe) may also include Cretaceous sedimentary rock, where it is too thin to distinguish from the upper part of the group... At its northernmost extent, at Haumuri Bluffs, it is entirely Late Cretaceous, but towards the south of the Kaikoura map area it includes progressively younger rocks (as young as Eocene; see below). Rocks in the lower part of the Eyre Group were deposited in **alluvial, estuarine and shallow marine environments with progressive deepening to a restricted basin** (Browne & Field 1985; Field, Browne & others 1989)... In the south of the Kaikoura map area, deposition of the Eyre Group including Conway Formation and Loburn Mudstone (see above) continued through into the Paleocene. The upper part of the Eyre Group is commonly too thin to differentiate from lower parts and is mapped as undifferentiated (KEe; Fig. 28)” (Rattenbury et al., 2006).

#### Claverley Sandstone

“...constitutes up to 40 m of poorly bedded, yellow-grey glauconitic sandstone. Dinoflagellates indicate a mid-Haumurian age near the base and a late Haumurian-early Teurian age near the top (Warren 1995)” (Rattenbury et al., 2006). “...and Claverley Sandstone were deposited in open **marine** environments with considerable influx of terrestrial organic material” (Roncaglia et al., 1999).

*EoD: innermost shelf*

*Basis for interpretation: EoD is based on the lithology of sandstone. Mid- to outer shelf may be alternative environments.*

#### Loburn Mudstone

“...Conway Formation overlies [Broken River Formation], and in turn grades upwards into, the jarositic, sandy Loburn Mudstone” (Rattenbury et al., 2006). “This unit is a dark-coloured, soft, moderately bioturbated sandy mudstone that conformably overlies the Haumurian to Teurian, (Maastrichtian to Paleocene) Conway Siltstone (Browne and Field 1985). It is dated as Teurian (Paleocene; Danian) (Browne and Field 1985)... On balance, perhaps a **mid-shelf** interpretation best fits the available data” (Mannering and Hiller, 2008).

*EoD: mid-shelf*

*Basis for interpretation: EoD is based on Mannering and Hiller (2008).*

**Inferred age:** > 65-52 Ma (Boyes et al., 2012)

**EoD breakdown:** > 65-60 Ma: mid-shelf (Claverley Sandstone, Loburn Mudstone)

59-52 Ma: innermost shelf (Claverley Sandstone)

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone, siltstone, conglomerate; Description = Undifferentiated sandstone and siltstone, commonly glauconitic and slightly calcareous with conglomerate and pebbly sandstone (QMAP database) – *the lower Eyre Group contains recognised members that were deposited in a range of environments so the EoD is broken down accordingly.*

### Paleogene Eyre Group (PaEe)

Includes Loburn Mudstone, Waipara Greensand, Ashley Mudstone, Homebush Sandstone, and Karetu Sandstone.

Main\_Rock = sandstone; Sub\_Rocks = mudstone, siltstone; Description = Greenish, glauconitic sandstone, sandy mudstone, siltstone and quartzose sandstone (QMAP database). “Paleogene Eyre Group (PEe) includes the Paleocene to Early Eocene Waipara Greensand..., Early to Middle Eocene Ashley Mudstone..., Middle to Late Eocene Homebush Sandstone... The environment of deposition of upper Eyre Group rocks includes **shallow marine**, low energy **outer shelf (bathyal)**, and relatively high-energy **near-shore beach** settings” (Rattenbury et al., 2006).

### **Loburn Mudstone**

“This unit is a dark-coloured, soft, moderately bioturbated sandy mudstone that conformably overlies the Haumurian to Teurian, (Maastrichtian to Paleocene) Conway Siltstone (Browne and Field 1985). It is dated as Teurian (Paleocene; Danian) (Browne and Field 1985)... On balance, perhaps a **mid-shelf** interpretation best fits the available data” (Mannering and Hiller, 2008).

*EoD: mid-shelf*

*Basis for interpretation: EoD is based on Mannering and Hiller (2008).*

### **Waipara Greensand**

“...Waipara Greensand, consisting of fine- to medium-grained, glauconitic sandstone that becomes increasingly muddy up section (Browne & Field 1985)” (Rattenbury et al., 2006). “The Waipara Greensand has been interpreted as having been deposited in a **shallow marine** setting under conditions of very slow sedimentation (Browne and Field 1985)... On balance, perhaps a **mid-shelf** interpretation best fits the available data” (Mannering and Hiller, 2008).

*EoD: mid-shelf*

*Basis for interpretation: EoD is based on Mannering and Hiller (2008). Refer to “Conway Fmn/Waipara Greensand” on the Christchurch map area for further information.*

### **Ashley Formation (Eea)**

*Inferred age:* 54-39 Ma (Boyes et al., 2012)

*EoD: lower bathyal*

*Basis for interpretation:* Main\_Rock = mudstone; Description = Greenish-grey, sandy glauconitic mudstone; grades laterally north and west into shallow to mid-water sandstone (QMAP database). “The overlying Early to Middle Eocene Ashley Mudstone consists of glauconitic, calcareous sandy mudstone, siltstone and sandstone. In general the Ashley Formation rests disconformably on Waipara Greensand (commonly with a burrowed, phosphatised contact) but, locally, around the lower Hurunui River-Culverden area, it is unconformable on Pahau terrane (Fig. 28)” (Rattenbury et al., 2006). “Paleobathymetric indicators within the benthic foraminiferal assemblages, including *Anomalinooides semicibratus*, *A. capitatus*, *Nuttallides carinotruempii*, and *Pleurostomella* spp., indicate a **lower bathyal** depositional depth (van Morkhoven et al., 1986). Because terrestrial palynomorphs compose >30% of the palynomorph assemblage (Fig. 1A), a steep west to east shelf-slope profile is inferred for the northern Canterbury basin” (Hollis et al., 2009) – *the EoD is inferred to be of lower bathyal depth in the North Canterbury region, based on the available literature, but shallower depths (up to outer shelf) may be appropriate in other regions.*

### **Homebush Sandstone**

“In the far south of the Kaikoura map area, the Middle to Late Eocene Homebush Sandstone overlies Ashley Mudstone. It is a massive, glauconitic, unfossiliferous, well-sorted, quartzose sandstone, that may have become remobilised or intruded into underlying and overlying units since deposition (Browne & Field 1985)” (Rattenbury et al., 2006). “...**shallow marine** quartzose sandstone...” (Field and Browne, 1989).

*EoD: innermost shelf*

*Basis for interpretation: The sandstone is described as shallow marine, so mid- or outer shelf are possible alternative EoDs.*

### **Karetu Sandstone**

“...a slightly calcareous, quartz-rich unit that becomes finer up-sequence, locally overlies the Homebush in southern North Canterbury. Both the Homebush and Karetu sandstones probably grade eastwards into the Ashley Mudstone” (Field and Browne, 1989).

*EoD: innermost shelf*

*Basis for interpretation: The sandstone must be shallower than the bathyal Ashley Mudstone (closer to the paleoshoreline), so it is here assumed to be an innermost shelf deposit, although mid-shelf could be an alternative EoD.*

## Paleogene Eyre Group East of Kaiwara Fault/Scargill

**Inferred age:** > 65-39 Ma (Boyes et al., 2012)

**EoD breakdown:** > 65-54 Ma: mid shelf (Waipara Greensand, Loburn Mudstone)  
53-39 Ma: lower bathyal (Ashley Mudstone)

**Basis for interpretation:** *The eastern Paleogene Eyre Group contains recognised members that were deposited in a range of environments so the EoD is broken down accordingly. Refer to “Paleogene Eyre Group (PEe)” on the Christchurch map area for further interpretations of these units.*

## Paleogene Eyre Group West of Kaiwara Fault/Scargill

**Inferred age:** > 65-35 Ma (Boyes et al., 2012)

**EoD breakdown:** > 65-54 Ma: mid shelf (Waipara Greensand, Loburn Mudstone)  
53-35 Ma: innermost shelf (Homebush Sandstone, Karetu Sandstone)

**Basis for interpretation:** *The western Paleogene Eyre Group contains recognised members that were deposited in a range of environments so the EoD is broken down accordingly. Where units are contemporaneous an average EoD is assigned. Refer to “Paleogene Eyre Group (PEe)” on the Christchurch map area for further interpretations of these units.*

## Eyre Group (IKEe\_)

**EoD:** Refer to Paleogene Eyre Group (PaEe): “Paleogene Eyre Group East of Kaiwara Fault/Scargill”

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone, siltstone, conglomerate; Description = Undifferentiated sandstone and siltstone, commonly glauconitic and slightly calcareous with conglomerate and pebbly sandstone (QMAP database) – *this unit is mapped as E (undifferentiated Eocene sediments) on the Rattenbury et al. (2006) map sheet, so is here considered to include Eocene sediments of the Eyre Group.*

## Muzzle Group (IKPz)

Includes Mead Hill Formation, Waipawa Formation, and Amuri Limestone.

“The Muzzle Group (Reay 1993) consists of mainly strongly indurated micritic limestone and calcareous mudstone, chert, and minor greensand and volcanic rocks. The group contains two formations, the Mead Hill Formation and the Amuri Limestone, and in areas where both formations are thin the Muzzle Group is undifferentiated (KPz) on the map” (Rattenbury et al., 2006). “Muzzle Group has previously been divided into two formations (Reay, 1993; Strong et al., 1995): Upper Cretaceous–upper Paleocene Mead Hill Formation and upper Paleocene–upper middle Eocene Amuri Limestone. Following recent work (Killops et al., 2000; Hollis et al., 2000), we emend this division below by placing the lowest portion of the Amuri Limestone at Mead Stream into a third formation, the upper Paleocene Waipawa Formation (Fig. 5). Waipawa Formation has not been identified in sections to the south where the contact between Mead Hill Formation and Amuri Limestone is an unconformity (Reay, 1993) or has not been confidently located (Hancock et al., 2003)” (Hollis et al., 2005a). “...Cretaceous-middle Eocene, **outer shelf-bathyal** Muzzle Group” (Hollis et al., 2005b). “Paleocene-Eocene strata exposed along Mead Stream consist of well-bedded units of chert, siliceous limestone with chert nodules, siliceous mudstone, limestone and marl, which form three formations within the Muzzle Group (Reay 1993)” (Hollis, 2006).

**Inferred age:** > 65-39 Ma (Field and Uruski, 1997)

**EoD breakdown:** > 65-61 Ma: outer shelf (Mead Hill Formation)  
60-56 Ma: upper bathyal (Amuri Limestone)  
55-41 Ma: mid-bathyal (Amuri Limestone)  
40-39 Ma: lower bathyal (Amuri Limestone)

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = calcareous mudstone, chert; Description = Undifferentiated indurated micritic limestone, calcareous mudstone and chert (QMAP database) – *this undifferentiated unit includes Mead Hill Formation, Waipawa Formation and Amuri Limestone. The Waipawa Formation is noted in Hollis et al. 2005a and 2014 as not always being present between the Mead Hill Formation and Amuri Limestone in the Kaikoura area. In the East Coast Basin it occurs at the top of the Whangai Formation (refer to Hawke’s Bay map area). It is represented here as an outermost shelf to upper bathyal deposit (Hollis et al. 2005a) at the base of the Amuri*

Limestone. Refer to “Mead Hill Formation (IKzm)” and “Amuri Formation (PaEza, Eza)” for more information and interpretations of their EoDs.

### **Mead Hill Formation (IKzm)**

**Inferred age:** > 65-59 Ma (Field and Uruski, 1997)

**EoD:** outer shelf

**Basis for interpretation:** Main\_Rock = chert; Sub\_Rocks = limestone dolomite; Description = Strongly indurated, greenish-grey, micritic limestone, calcareous mudstone and black siliceous chert (QMAP database). “In the northern Clarence valley and in coastal eastern Marlborough, the formation contains the Cretaceous-Paleogene boundary, which is particularly well exposed in Mead Stream (Fig. 38) and is marked by major changes in microfossil assemblages” (Rattenbury et al., 2006). “...deposition of lower Mead Hill Formation in depths that rapidly reached at least **outer shelf** and were probably **bathyal**” (Field and Uruski, 1997). “Paleoenvironmental analysis suggests a marked shallowing from an upper slope (Haumurian) to an **outer shelf** (Teurian) facies at Woodside Creek, but a deepening trend from inner shelf (Haumurian) to **mid shelf** (Teurian) conditions at Kaikoura... Foraminifera from thinner sequences south of Branch Stream, indicate water depths equivalent to modern inner to mid shelf conditions (e.g. P31/f14, O31/f181, O30/f56) during the late Haumurian. The relative abundance of pelagic foraminifera suggests that water depths gradually increased northeastwards from outer shelf (P31/f43), to upper slope (P29/f34), into mid to upper bathyal environments (P29/f219)” (Morris, 1987) – *the unit is defined here as outer shelf based on Morris’ (1987) definition of Mead Hill Formation in the Teurian in the vicinity of Woodside Creek, which is where the unit code of IKzm is mapped. However, mid-shelf to upper bathyal may be alternative environments within the Paleogene.*

### **Amuri Formation (PaEza, Eza)**

Includes “Black Siltstone”, Lower Limestone, Teredo Member, Lower Marl, Grasseed Volcanics, Middle/Upper Limestone, Woodside Formation, Fells Greensand, and Upper Marl.

“The Amuri Limestone (Pza, Eza) is widely preserved in the eastern part of the Kaikoura map area (Figs 39, 40). In the north it is included within the Muzzle Group (Reay 1993; Field, Uruski & others 1997), but south of Kaikoura it has not previously been assigned to any group (e.g. Browne & Field 1985; Field, Browne & others 1989). The southern occurrences of the Amuri Limestone are now included within the Eyre Group on the Kaikoura map following stratigraphic rationalisation (e.g. Forsyth 2001). The formation consists predominantly of white, hard, siliceous, micritic limestone or interbedded limestone and marl (Fig. 40), composed of coccolith and foraminifera tests and clay... From Kaikoura southwards, the Amuri Limestone youngs progressively: at Haumuri Bluffs, the age range is Early to Late Eocene; at Hurunui River it is entirely Late Eocene; at Napenape it is Late Eocene to Early Oligocene; and at Waipara River, on the southern edge of the Kaikoura map area, the formation is entirely Oligocene (Field, Browne & others 1989)... The bulk of the Amuri Limestone was deposited under pelagic to hemipelagic conditions (Strong & others 1995; Hollis & others 2005a)... Microfossils indicate an **upper to lower bathyal** setting (Field, Uruski & others 1997)” (Rattenbury et al., 2006). “The following informal units, based on Reay (1993), are recognised within Amuri Limestone at Mead Stream: Black Siltstone, Lower Limestone, Lower Marl, Upper Limestone, Upper Marl... The most significant benthics for paleoenvironmental interpretation are *Nuttallides carinotruempyi* in the Dannevirke Series and *N. truempyi* and *Uvigerina wanzea* in the Arnold Series. All indicate water depths of **500 m** or more (van Morkhoven et al. 1986; Hayward 1986). *Tritaxilina zealandica*, recorded in the upper half of the Upper Marl, suggests a minimum depth of **1300 m** for deposition of this unit” (Strong et al., 1995).

#### • “Black Siltstone”

“The late Teurian thin black siltstone capping Mead Hill Formation... is inferred to be the lateral equivalent of the Teredo Formation to the south... There is no evidence for major depth change, suggesting deposition under **bathyal** conditions” (Strong et al., 1995). “Mead Hill Formation is overlain by a pair of thin, dark grey siliceous mudstone units separated by 4.8 m of siliceous limestone (Figs. 7 and 8). The lower mudstone was referred to as the “black siltstone” by Strong et al. (1995). Both mudstone units (2.4 and 0.3 m thick and called Mudstones A and B, respectively) have a distinctive organic geochemical signature... This chemistry characterizes Waipawa Formation, an upper Paleocene organic-rich, siliciclastic unit first described in the East Coast Basin of the North



Island, but since identified in several basins on both islands of New Zealand (Killops et al., 2000)" (Hollis et al., 2005a).

*EoD: upper bathyal*

*Basis for interpretation: Comments in the cited references and that it could be a southern equivalent of the Waipawa Formation, found in the Hawke's Bay and Wairarapa map areas.*

- **Lower Limestone**

"The sparse foraminiferal evidence indicates an **outer shelf to bathyal** environment (Appendix I). The existence of a paleoslope cannot be determined on the limited evidence, but lack of slumping may indicate that only very gentle paleoslopes, if any, existed. Water depths, especially those to the south of the depocentre, appear to have been considerably greater than those during Mead Hill Formation deposition" (Morris, 1987).

*EoD: upper bathyal*

*Basis for interpretation: Comments in the cited references and that it was deposited in a deeper environment than the Mead Hill Formation (1Km), which is defined in this report as outer shelf.*

- **Teredo Member**

"The term Teredo Limestone (Member) as used by Reay (1993) is here referred to as Teredo Member as it is primarily sandstone rather than limestone. Reay (1993) recognised two informal lithofacies: a basal massive, cream to grey, slightly calcareous sandstone and an upper, green, glauconitic, highly calcareous sandstone. The Teredo Member thickens southwestward from a few centimetres in the northeast to 24 m at Seymour Stream (figure 3.4). A **shallow-marine, inner shelf** environment was inferred by Strong (Reay 1993)..." (Field and Uruski, 1997). "Paleoenvironmental interpretations of the foraminiferal component indicate that the setting was oceanic and probably **bathyal**" (Morris, 1987).

*EoD: upper bathyal*

*Basis for interpretation: The innermost shelf interpretation cited in Field and Uruski (1997) seems to be inconsistent with the other rocks in this formation and the interpretation in Morris (1987). An upper bathyal environment is preferred here.*

- **Lower Marl**

"Foraminiferal assemblages suggest water depths equivalent to modern **bathyal** conditions. The presence of *Propeamussium*, which is typically found at **outer shelf to bathyal** depths (J. Crampton, NZGS, pers. comm. 1986), reinforces this view. The genus is also indicative of a **very low energy environment**. The Lower Marl is interpreted to represent a pelagic facies deposited during a regressive-transgressive cycle" (Morris, 1987).

*EoD: mid-bathyal*

*Basis for interpretation: The EoD is narrowed down to mid-bathyal.*

- **Grasseed Volcanics**

"The member comprises both **intrusive** and **extrusive** igneous rocks, including dikes, flows, sills, **pillow lavas** (Fig. 41) and agglomerate of peridotite, gabbro, dolerite and **basalt**" (Rattenbury et al., 2006).

*EoD: submarine mafic eruptives*

*Basis for interpretation: The unit is defined here as occurring in a submarine environment, as it contains pillow lavas and is intercalated within the upper members of the Amuri Limestone. This therefore gives it an upper to mid-bathyal depth.*

- **Middle/Upper Limestone**

"Apart from foraminifera, the Middle Limestone is virtually devoid of useful paleoenvironmental indicators. The overwhelming predominance of planktonic foraminifera indicates oceanic conditions equivalent to modern **bathyal** depths. This interpretation is consistent with those of the enclosing Formations" (Morris, 1987).

*EoD: mid-bathyal*

*Basis for interpretation: The EoD is narrowed down to mid-bathyal, based on the enclosing formations.*

- **Woodside Formation**

“...is largely coeval with lower marl... Fossil evidence indicates that the Woodside Formation accumulated at **bathyal** depths” (Field and Uruski, 1997). “The conformable contact with underlying bathyal marls and the presence of dominantly planktonic foraminifera may support a deep marine environment. This environment is consistent with a **turbiditic** origin for the sandstones” (Morris, 1987).

*EoD: mid-bathyal*

*Basis for interpretation: The EoD is narrowed down to mid-bathyal, because the Lower Marl has been defined as such. Upper bathyal may also be appropriate.*

- **Fells Greensand**

“In the southern Clarence valley, at Oaro, and along Kekerengu River, are fine to medium grained, glauconitic quartz sandstone of the Fells Greensand” (Field and Uruski, 1997). “From textural considerations (Chapter 6.3), and internal sedimentary structures, the Fells Greensand is interpreted as having been deposited from sediment **gravity flows**. Detrital quartz and glauconite accumulated closer to shore and were transported into the pelagic environment during high energy events” (Morris, 1987).

*EoD: mid-bathyal*

*Basis for interpretation: Based on the deposit being a result of gravity flows. Lower bathyal may be an appropriate alternative.*

- **Upper Marl**

“On the basis of analysis of the foraminiferal population, deposition took place in an oceanic environment. Water depths were probably comparable with those in modern **outer shelf to bathyal** settings (Appendix I)” (Morris, 1987). “*Tritaxilina zealandica*, recorded in the upper half of the Upper Marl, suggests a minimum depth of **1300 m** for deposition of this unit” (Strong et al., 1995).

*EoD: lower bathyal*

*Basis for interpretation: EoD is after Strong et al. (1995).*

- **PaEza (Pza on map sheet)**

*Inferred age:* 60-39 Ma (Strong et al., 1995; Field and Uruski, 1997; Rattenbury et al., 2006; Boyes et al., 2011a)

*EoD breakdown:*

60-56 Ma:	<u>upper bathyal</u> (“Black Siltstone”, Lower Limestone, Teredo Member)
55-41 Ma:	<u>mid-bathyal</u> (Lower Limestone, Lower Marl, Grasseed Volcanics, Upper Limestone, Woodside Formation, Fells Greensand Member, Upper Marl)
40-39 Ma:	<u>lower bathyal</u> (Upper Marl)

*Basis for interpretation:* Main\_Rock = limestone; Description = Pale, creamy, hard, siliceous, micritic limestone locally interbedded with siltstone, marl, sandstone, chert or greensand; local (QMAP database). *This unit code appears to encompass Amuri Limestone of Paleocene to Eocene age. NB: three polygons located south of Gore Bay are assigned the EoD of Oligocene Amuri Limestone (Oea) from Christchurch.*

- **Eza**

*Inferred age:* 55-39 Ma (Strong et al., 1995; Field and Uruski, 1997; Rattenbury et al., 2006; Boyes et al., 2011a)

*EoD breakdown:*

55-41 Ma:	<u>mid-bathyal</u> (Lower Limestone, Lower Marl, Grasseed Volcanics, Upper Limestone, Woodside Formation, Fells Greensand Member, Upper Marl)
40-39 Ma:	<u>lower bathyal</u> (Upper Marl)

*Basis for interpretation:* Main\_Rock = limestone; Sub\_Rocks = marl, chert, sandstone; Description = Pale, creamy, hard, siliceous, micritic limestone locally interbedded with siltstone, marl, sandstone, chert or greensand; local (QMAP database). *This unit code appears to encompass Amuri Limestone of Eocene age.*

## ***Grasseed Volcanics (Ezg, Ezg\_)***

***Inferred age:*** 53-43 Ma (Rattenbury et al., 2006)

***EoD:*** intrusive/submarine mafic eruptives

***Basis for interpretation:*** Main\_Rock = **basalt**; Sub\_Rocks = peridotite gabbro dolerite; Description = Intrusive and extrusive igneous rocks, including dikes, flows, sills, pillow lavas and agglomerate of peridotite, gabbro, dolerite (QMAP database). “The member comprises both **intrusive** and **extrusive** igneous rocks, including dikes, flows, sills, **pillow lavas** (Fig. 41) and agglomerate of peridotite, gabbro, dolerite and **basalt**. Gabbro sills up to several tens of metres thick locally intrude the limestone. The dikes intrude the Seymour Group and the Mead Hill and Amuri formations, becoming extrusive in the upper parts of the Amuri Limestone” (Rattenbury et al., 2006). “Eruption occurred at **bathyal** depths, as indicated by paleoenvironmental interpretation of enclosing sediments” (Field and Uruski, 1997) – *the unit is defined here as occurring in a submarine environment, as it contains pillow lavas and is intercalated within the upper members of the Amuri Limestone. This therefore gives it an upper bathyal depth. Intrusive or extrusive may also be appropriate settings for certain time intervals.*

## **Cookson Volcanics Group (Olnc)**

(QMAP database spelling: Cookson volcanics)

***Inferred age:*** 31-26 Ma (Timm et al., 2010)

***EoD:*** submarine mafic eruptives

***Basis for interpretation:*** Main\_Rock = **basalt**; Sub\_Rocks = tuff; Description = plugs, flows, pillows, dikes and sills of basalt; breccia, volcanoclastic sandstone and interbedded tuff (QMAP database). “Associated foraminifera indicate that the volcanics are Upper Whaingaroan, and that they accumulated at **bathyal** depths” (Field and Uruski, 1997). “The preserved deposits are **marine**, generally bedded and include horizons of shelly limestone with thick shelled bivalves, other molluscs, and echinoid debris. An eroded surface suggestive of marine planation separates the volcanic rocks from overlying and overlapping Spy Glass Formation, Waima Siltstone or Mt Brown Formation” (Campbell et al., 2005). “Coote (1987) inferred a **shallow marine** setting for Cookson Volcanics in the Waiiau area 45km to the NE...” (Mould, 1992) – *EoD is based on the map unit’s main rock type of basalt (QMAP database) and the interpreted shallow marine to bathyal depth of the rocks that surround it.*

## **Motunau Group**

### ***Undifferentiated Oligocene***

The unit codes Olnc\_, Olni\_, Olnw\_ and Olza\_ are mapped as O: undifferentiated Oligocene sedimentary and minor volcanic rocks (Rattenbury et al. 2006 geological map sheet). Oligocene rocks on this map area are members of the lower Motunau Group (Oln). Refer to “Undifferentiated lower Motunau Group” for EoD and interpretations of these units.

The unit codes Eza\_, EzaOlnw, Olni, Olnt, Olnw and OlncOlni are mapped as Oln: undifferentiated lower Motunau Group (Rattenbury et al. 2006 geological map sheet). Refer to “Undifferentiated lower Motunau Group” for EoD and interpretations of these units.

### ***Undifferentiated lower Motunau Group (Olnc\_, Olni\_, Olnw\_, Olza\_, Eza\_, EzaOlnw, Olni, Olnt, Olnw, OlncOlni, lKe)***

Includes Omihi Formation, Weka Pass Stone, Tekoa Limestone, Flaxdown Limestone, Whales Back Limestone, Spy Glass Formation, Isolated Hill Limestone, and Hanmer Marble.

“Widespread, undifferentiated Late Oligocene basal greensand, limestone and calcareous mudstone (**Oln**) are included within the lower Motunau Group. The limestone commonly forms prominent bluffs and distinctive landforms with local stratigraphic names including Omihi and Spy Glass formations, Tekoa, Flaxdown, Isolated Hill, Weka Pass and Whales Back limestones, and Hanmer Marble (Fig. 44a,b). Collectively, however, these undifferentiated rocks are **shallow to deep-water** sedimentary facies variants of a semi-continuous blanket of Late Oligocene carbonate deposition that only locally exceeded 50 m in thickness” (Rattenbury et al., 2006). “The western depocentre

comprises calcareous lithofacies of Waitakian age, that were deposited in **shelf** (see Reay 1993) to **bathyal** depths (H.E.G. Morgans pers. comm., 1992). It comprises two distinct lithologies; a lower calcareous sandstone (Weka Pass Stone), and overlying interbedded wackestone and calcareous mudstone (Whales Back Limestone, new; Fig. 2)... The eastern depocentre comprises the Spy Glass Formation (Browne & Field 1985, Fig. 13)...” (Browne, 1995).

### ***Omihi Formation***

“The Duntroonian in North Canterbury is represented by the five members of the Omihi Formation – the Berrydale and Gorries Creek Greensands, Weka Pass Stone, Isolated Hill Limestone and Hanmer Marble” (Field and Browne, 1989).

### ***Berrydale Greensand***

“A grey-green, glauconitic, calcareous sandstone into which the Weka Pass Stone grades laterally in the south-west of the region. A **shallow-water** facies-equivalent of the Weka Pass Stone” (Andrews, 1963) – *EoD = c. mid- to outer shelf*.

### ***Gorries Creek Greensand***

“A glauconitic, calcareous sandstone facies-equivalent of the Weka Pass Stone in the east and north-east of the region” (Andrews, 1963) – *EoD = outer shelf*.

### ***Weka Pass Stone***

“A hard, cream-coloured, slightly glauconitic limestone. It occupies the central part of North Canterbury, and is a **comparatively deep-water** deposit” (Andrews, 1963) – *EoD = outer shelf*.

### ***Isolated Hill Limestone***

“Oliver (1915) records that *Patella k. Kermadecensis* lives on rocks from just above low water mark down to 2-3 m...” (Fleming, 1973) – *EoD = innermost shelf*.

### ***Hanmer Marble***

“A barnacle- and bryozoan rich limestone. This is a common association in Cenozoic **shallow shelf**, temperate to cold-water depositional settings” (Scholle and Ulmer-Scholle, 2003) – *EoD = mid-shelf*.

*EoD:*

27-25 Ma:	<i>outer shelf (innermost shelf to outer shelf; Berrydale Greensand, Gorries Creek Greensand, Weka Pass Stone, Isolated Hill Limestone, Hanmer Marble)</i>
24-23 Ma:	<i>innermost shelf to outer shelf (Berrydale Greensand, Gorries Creek Greensand, Isolated Hill Limestone, Hanmer Marble)</i>

*Basis for interpretation: EoD is based on the depositional age and paleoenvironmental interpretations of the members which make up the Omihi Formation. The depositional depth range for the 27-25 Ma period ranges from innermost shelf to outer shelf. Outer shelf Weka Pass Stone, Berrydale Greensand, and Gorries Creek Greensand are assumed to be the dominant lithologies for the time period and consequently an outer shelf EoD is assigned to the 27-25 Ma interval.*

### ***Weka Pass Stone***

“It occupies the central part of North Canterbury, and is a **comparatively deep-water** deposit... The Weka Pass Stone is typically a thoroughly cemented, cream to light grey, massive, sandy limestone with fine disseminated glauconite. The member is usually thickly bedded (except at Laverock, Fig. 8, col. 17), with some borings throughout, mainly near the base” (Andrews, 1963).

*EoD: outer shelf*

*Basis for interpretation: EoD is based on the lithologic descriptions, and Fig. 3. Mid-shelf may be an alternative environment.*

### ***Tekoa Limestone***

“At Pahau River and Cascade Stream the Tekoa Tuffs consist of coarse, black agglomerates (with a tuffaceous matrix) which occasionally show pillow structures. They are interbedded with lenses of

hard, **shelly**, semi-crystalline limestone up to 60 ft thick" (Andrews, 1963). "Coote (1987) inferred a **shallow marine** setting for Cookson Volcanics in the Waiiau area 45 km to the NE and a similar environment is inferred for the [Tekoa Formation]" (Mould, 1992).

*EoD: mid-shelf*

*Basis for interpretation: The shallow marine interpretation for the Tekoa Limestone (Mould, 1992) implies an innermost to mid-shelf EoD for the unit.*

### **Flaxdown Limestone**

"A cream-coloured, shelly limestone which overlies the Tekoa Tuffs in the Mandamus-Pahau district only. It is a facies-equivalent of the upper part of the Weka Pass Stone, into which it grades laterally... According to Mason (1949, p. 419) the Flaxdown Limestone is composed "almost entirely of comminuted shells of brachiopods and molluscs, which have been cemented by calcite to form a hard and resistant rock..." This limestone is similar in lithology to that forming the limestone lenses of the Tekoa Tuffs in Cascade Stream..." (Andrews, 1963). "The Flaxdown Limestone Member is probably a **shelf** limestone, which developed on the flanks of a submerged volcanic complex" (Mould, 1992).

*EoD: mid-shelf*

*Basis for interpretation: EoD is based on the shelf interpretation for the Flaxdown Limestone given in Mould (1992) combined with the unit's lithologic description (Andrews, 1963) and Fig. 3.*

### **Whales Back Limestone**

"...the Whales Back Limestone (Browne 1995), an interbedded glauconitic wackestone and mudstone" (Field and Uruski, 1997).

*EoD: upper bathyal*

*Basis for interpretation: EoD is based on the lithologic description of the Whales Back Limestone given in Field and Uruski (1997), combined with Fig. 3.*

### **Spy Glass Formation**

"...cream, centimetre- to decimetre-bedded (stylobedded) wackestone (Fig. 6)... Fish teeth, echinoderm spines and molluscan shell debris have also been found. Clastic material includes well-rounded to angular quartz, biotite (up to 0.3 mm diameter), and greenish yellow, well-rounded glauconite (up to 0.5 mm diameter). Interbedded with the wackestone are millimetre- and decimetre-bedded, very fine- to medium-grained, well-sorted glauconitic sandstone with comminuted carbonaceous debris" (Browne, 1995). "...is a wackestone deposited in an eastern depocentre at **bathyal** depths (Browne 1995)" (Field and Uruski, 1997). "The microfauna indicates that the Spy Glass Formation was deposited in **mid-bathyal** depths..." (Warren, 1995).

*EoD: mid-bathyal*

*Basis for interpretation: EoD is based on the interpretation in Warren (1995).*

### **Isolated Hill Limestone**

"A large fossil limpet from the Isolated Hill Limestone (Oligocene) of Mason River, Marlborough, is described as *Patella (Scutellastra) Kermadecensis aurorae* n. subsp., a subspecies of the living Kermadec giant limpet... Oliver (1915) records that *Patella k. Kermadecensis* lives on rocks from just above low water mark down to 2-3 m... The difficulty of distinguishing the Oligocene from the living specimens emphasizes the conservative nature of limpets, despite their exposure to a more hazardous and changeable environment, in the **wave zone**..." (Fleming, 1973).

*EoD: innermost shelf*

*Basis for interpretation: EoD is based on the limpet fossil found in the limestone.*

### **Hanmer Marble**

"A barnacle- and bryozoan rich limestone. This is a common association in Cenozoic **shallow shelf**, temperate to cold-water depositional settings" (Scholle and Ulmer-Scholle, 2003).

*EoD: mid-shelf*

*Basis for interpretation: EoD is based on the shallow shelf interpretation and lithologic description for the member given in Scholle and Ulmer-Scholle (2003), and Fig. 3.*

**Inferred age:** 27-22 Ma (Andrews, 1963; Field and Browne, 1989; Mould, 1992; Field and Uruski, 1997; Rattenbury et al., 2006)

**EoD breakdown:** 27-26 Ma: outer shelf (Omihī Formation, Berrydale Greensand, Gorries Creek Greensand, Weka Pass Stone, Tekoa Limestone, Flax-down Limestone, Isolated Hill Limestone, Hanmer Marble)  
25 Ma: upper bathyal (mid-bathyal in east; Omihī Formation, Berrydale Greensand, Gorries Creek Greensand, Weka Pass Stone, Whales Back Limestone, Spy Glass Formation, Isolated Hill Limestone, Hanmer Marble)  
24-22 Ma: upper bathyal (mid-bathyal in east; Omihī Formation, Berrydale Greensand, Gorries Creek Greensand, Whales Back Limestone, Spy Glass Formation, Isolated Hill Limestone, Hanmer Marble)

**Basis for interpretation:** *The EoD breakdown for Onl is based on the depositional age and paleo-environmental interpretations of the formations/members that make up the map unit. Units with an outer shelf depositional environment are the most common elements within the 27-26 Ma period. The environment deepens from 25 Ma with the deposition of upper bathyal Whales Back Limestone and mid-bathyal Spy Glass Formation. When assessing the EoD for the 25-22 Ma period less emphasis has been placed on the depositional environments of the Berrydale and Gorries Creek greensands and Hanmer Marble because these units have generalised ages associated with them and the extent of their presence within the 25-22 Ma interval is uncertain.*

### **PaEzaOnw**

**EoD breakdown:** 34-32 Ma: outer shelf (Amuri Limestone)  
27-26 Ma: outer shelf (Lower Motunau Group)  
25-22 Ma: upper bathyal (Lower Motunau Group)

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = siltstone; Description = undifferentiated limestone, calcareous siltstone; (QMAP database) – based on the combined unit code, this unit appears to include Amuri Limestone and lower Motunau Group. The EoD range is based on that which has been determined in this report for the individual formations. Refer to “Amuri Limestone (Oea)” on the Christchurch map area and “undifferentiated lower Motunau Group” on the Kaikoura map area for further interpretations.

### **Miocene Motunau Group (Mn, Mnk\_, Mnb\_)**

“The Motunau Group occurs widely through the eastern Kaikoura map area and in most cases unconformably overlies older rocks (Carter & Landis 1972; Findlay 1980; Field 1985). Many of the formations within the group are too thin to be shown on the Kaikoura map, and these are mapped as undifferentiated (Mn)” (Rattenbury et al., 2006). “Overall, the Waipara-Waikari region, North Canterbury experienced a shallowing from **outer shelf to mid shelf** environment during the Otaian stage reflected in the Waikari Formation deposits, and **mid to inner shelf** depositional environment during the Altonian stage, reflected in the Mount Brown Formation deposits” (Hobbs, 2010).

**Inferred age:** 23-9 Ma (Boyes et al., 2012)

**EoD breakdown:** 23-21 Ma: outer shelf (Waikari Formation)  
20 Ma: mid-shelf (Waikari Formation)  
19-9 Ma: mid-shelf (Mount Brown Formation)

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = siltstone; Description = Undifferentiated sandstone and siltstone, includes Mt Brown and Waikari formations (QMAP database) – the EoD breakdown for the map unit is based on the depositional age and paleoenvironmental interpretations of the formations/members that make up the map unit. Mnb\_ and Mnk\_ are shown on the geological map sheet as Mn: undifferentiated Miocene Motunau Group. Refer to “Waikari Formation (Mnk)” and “Mount Brown Formation (Mnb)” for further information and interpretations of these units.

### **Waima Formation (Mnw)**

**Inferred age:** 23-15 Ma (Boyes et al., 2012)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = siltstone; Sub\_Rocks = mudstone, siltstone, conglomerate; Description = massive to poorly-bedded, bluish-grey calcareous silty mudstone; in the north includes lenses of poorly-sorted pebble to boulder (QMAP database). "It comprises more than 360 m of generally massive to poorly bedded, greenish to bluish-grey calcareous silty mudstone (Fig. 45a)" (Rattenbury et al., 2006). "The bulk of the early Neogene succession in southern Marlborough comprises pale blue-grey, calcareous, micaceous, fine- to medium-grained sandy bioturbated siltstone of the Waima Formation... Centimetre to decimetre thick, well-sorted, fine to medium-grained sandstone are intercalated within the siltstone forming flysch packages several 10's of metres thick... Foraminifera indicate **outer shelf to bathyal** settings throughout the formation (Reay 1993), **in water depths as great as 1500 m**... The Waima Formation forms the background sediment into which the Great Marlborough Conglomerate (GMC) was deposited. The GMC comprises channelised cohesive debris flow deposits that crop out in many parts of southern Marlborough" (Browne, 1995) – *the bathyal interpretation combined with thin turbidite beds and channels indicate an upper bathyal EoD. However, flysch packages indicate that mid-bathyal is also possible.*

### **Waikari Formation (Mnk)**

Includes Pahau Siltstone, Scargill Siltstone, Gowan Hill Sandstone, Tommys Creek Concretionary Sandstone, and Glenesk Sandstone.

"The formation includes basal calcareous glauconitic siltstone; massive blue-grey siltstone; and bedded, yellow-brown sandstone" (Rattenbury et al., 2006). "Good microfaunas, however, show an extreme age range of Waitakian to Awamoan for the formation. Most of the formation is Otaian, but in some sections the top is as young as Awamoan, as for example at Weka Creek... It is thought necessary to recognise five members within the formation (Figs. 4 and 5)" (Andrews, 1963). "Overall, the Waipara-Waikari region, North Canterbury experienced a **shallowing from outer shelf to mid shelf** environment during the Otaian stage reflected in the Waikari Formation deposits, and mid to inner shelf depositional environment during the Altonian stage, reflected in the Mount Brown Formation deposits" (Hobbs, 2010).

#### • **Pahau Siltstone**

"The basal member of the formation, it is uniformly present throughout the region except in the north-east at Waikari River (Fig. 10, col. 27), where the Glenesk Sandstone overlies the Gorries Creek Greensand... This thin basal unit ranges from a calcareous, glauconitic, silty sandstone in the west to a calcareous, glauconitic siltstone in the central and eastern areas... The Pahau Siltstone is coarsest in the west" (Andrews, 1963). "Overall based on sedimentology, tracefossils, macrofossils and foraminiferal components the Pahau Siltstone was deposited in a **mid to outer shelf** environment" (Hobbs, 2010).

*EoD: outer shelf (mid-shelf in the west, onshore (estuarine) in the far south-west)*

*Basis for interpretation: Deposition at shallower depths to the west is implied by the coarser lithologies in that area, with onshore (estuarine) and innermost shelf deposition in the south west (Andrews, 1963).*

#### • **Scargill Siltstone**

"A thick, massive, light blue-grey calcareous siltstone that is widely distributed... It conformably overlies the Pahau Siltstone... The Scargill Siltstone is everywhere a light blue-grey, very calcareous, foraminiferal siltstone, containing a very small amount of fine glauconite and mica" (Andrews, 1963). "The Scargill Siltstone was deposited in a **mid-shelf** depositional environment based on foraminifera identified in Sample Associations, DCA, planktic: benthic percentages, macrofossil and tracefossil evidence" (Hobbs, 2010).

*EoD: mid-shelf*

*Basis for interpretation: EoD is based on the mid-shelf interpretation in Hobbs (2010).*

#### • **Gowan Hill Sandstone**

"This member consists of interbedded yellow-brown sandstone and light blue-grey siltstone. It occurs over a broad zone extending roughly east and west from the Motunau River to the Middle Waipara River. It overlies the lower part of the Scargill Siltstone Member and grades laterally north and south into the middle and upper parts of the Scargill Siltstone" (Andrews, 1963). "Samples tak-

en from the Gowan Hill Sandstone consisted of foraminifera indicating a **mid-shelf** environment...” (Hobbs, 2010).

**EoD:** mid-shelf

*Basis for interpretation: EoD is based on the mid-shelf interpretation in Hobbs (2010).*

- **Tommys Creek Concretionary Sandstone**

“This member consists of medium blue-grey, calcareous siltstone and fine sand commonly cemented to form concretionary bands, and is confined to a small area in the west of the region. It is the uppermost member in that part of the region, and grades laterally south and east into the upper part of the Gowan Hill Sandstone. To the north it grades laterally into the Scargill Siltstone” (Andrews, 1963).

*EoD:* outer shelf

*Basis for interpretation: EoD is based on the lithologic description in Andrews (1963) and Fig. 3.*

- **Glenesk Sandstone**

“This member consists of blue-grey to brown-grey fine sandstone weathering brown, occasionally cemented, with rare bands of light blue-grey siltstone. It is confined to the north-east part of the region and is the upper member of the formation in that district. It grades laterally into the Gowan Hill Sandstone to the south and into the Scargill Siltstone to the west” (Andrews, 1963).

*EoD:* mid-shelf

*Basis for interpretation: EoD is based on the lithologic description in Andrews (1963) and Fig. 3.*

**Inferred age:** 23-19 Ma (Andrews, 1963; Boyes et al., 2012)

**EoD breakdown:**

23-22 Ma:	<u>outer shelf</u> (mid-shelf in the west, onshore in the far southwest; Pahau Siltstone)
21 Ma:	<u>outer shelf</u> (Pahau Siltstone, Scargill Siltstone, Gowan Hill Sandstone, Glenesk Sandstone)
20-19 Ma:	<u>mid-shelf</u> (Pahau Siltstone, Scargill Siltstone, Gowan Hill Sandstone, Tommys Creek Concretionary Sandstone, Glenesk Sandstone)

**Basis for interpretation:** Main\_Rock = siltstone; Sub\_Rocks = sandstone; Description = calcareous, glauconitic siltstone, massive, blue-grey siltstone, and bedded, yellow-brown sandstone (QMAP database) – *the EoD breakdown for the map unit is based on the depositional age and paleoenvironmental interpretations of the members that make up the Waikari Formation. The transition from outer shelf to mid-shelf deposition between 21 and 20 Ma is based on a shallowing trend through the Waikari Formation described in Hobbs (2010).*

### **Mount Brown Formation (Mnb)**

**Inferred age:** 19-9 Ma (Boyes et al., 2012)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = siltstone, conglomerate, limestone; Description = Siltstone, sandstone and bioclastic limestone with interbedded debris flow conglomerate (QMAP database). “...consists of siltstone, sandstone and bioclastic limestone with interbedded debris flow conglomerate that conformably overlies the finer grained Waikari Formation. It is locally up to 830 m thick and was deposited in **mid- to outer shelf** environments in a rapidly subsiding basin (Browne & Field 1985)” (Rattenbury et al., 2006). “In summary, sedimentary structures, bryozoans, bivalves, brachiopods, trace fossils and foraminifera determine a **mid to inner shelf** depositional environment for the Mount Brown Formation... Overall, the Waipara-Waikari region, North Canterbury experienced a shallowing from outer shelf to mid shelf environment during the Otaian stage reflected in the Waikari Formation deposits, and **mid to inner shelf** depositional environment during the Altonian stage, reflected in the Mount Brown Formation deposits” (Hobbs, 2010) – *the depositional depth range of the Mount Brown Formation ranges from innermost to outer shelf. An average mid-shelf EoD is assigned here.*

### **Greta Formation (Png)**

Includes Ferniehurst siltstone, Bourne pebbly mudstone, Hawkswood deltaic, Brookdale coquina, Rutherford



littoral, Leader siltstone, and Albyn conglomerate lithofacies.

“The conformably overlying Middle Miocene to Early Pleistocene Greta Formation (Png; Fig. 45c) is dominated by fine-grained siltstone (Browne & Field 1985; Warren 1995). Other facies are only locally developed and include poorly bedded marine, deltaic and fluvial mudstone, limestone and debris flow conglomerate, and a small proportion of sandstone” (Rattenbury et al., 2006). “...**marine** Greta Formation...” (Litchfield et al., 2003). “The Greta Formation consists of a wide variety of **marine and terrestrial** facies, all but one (the Brookdale lithofacies, predominantly of **shallow-water** coquina limestone) being dominated by strongly bimodal clastic sediments (mudstone and conglomerate), with only a small proportion of sand-grade sediment... Stratigraphic and structural relationships within the Greta Formation are difficult to establish... Although some of the mudstone units contain quite rich foraminiferal or molluscan faunas giving a well-defined age, most do not... The Greta Formation rocks have therefore been grouped into map units based on the lithology of an area of outcrop, i.e. into informal lithofacies units...” (Warren, 1995).

- **Ferniehurst siltstone lithofacies**

“Ferniehurst siltstone lithofacies is interpreted as the background sediment that accumulated, largely by pelagic deposition on the **mid to outer shelf**, and locally in **bathyal** sites, before the onset of, or positionally isolated from, coarser sediments resulting from the effects of rapid uplift and/or canyon formation... Most of the sedimentological evidence suggests deposition of the Ferniehurst lithofacies in **inner or mid shelf** environments...” (Warren, 1995).

*EoD: outer shelf*

*Basis for interpretation: The depositional depth range of the Ferniehurst Siltstone ranges from innermost shelf to bathyal. An average outer shelf EoD is assigned to the unit here.*

- **Bourne pebbly mudstone lithofacies**

“A very rich mid-Nukumaruan **upper bathyal** fauna near Oaro (f8843, 491526, Beu 1979) is also within a Bourne canyon-fill mudstone sequence containing reworked pebbles and blocks... The sedimentological evidence, and geometry of the basal contacts, suggest that the unit was deposited primarily as a succession of debris flows within the relatively steep walls of a submarine canyon (or system of branching canyons)...” (Warren, 1995).

*EoD: upper bathyal*

*Basis for interpretation: EoD is based on the interpretations in Warren (1995).*

- **Hawkswood deltaic lithofacies**

“Lewis and Ekdale interpreted the Hawkswood sequence as a set of fan delta distributary lobes deposited, mostly below sea-level, in **channels incised into a narrow coastal shelf and slope** that led to the nearby Conway Trough, and receiving a flood of coarse detritus from the rapidly rising Hawkswood Range immediately to the west” (Warren, 1995).

*EoD: shelf to bathyal*

*Basis for interpretation: EoD is based on the interpretations in Warren (1995).*

- **Brookdale coquina lithofacies**

“...pale yellow, highly fossiliferous, sandy algal limestone and cemented quartz-rich sandstone... Sedimentological and fossil evidence suggests deposition in **shallow water close to wave-base**” (Warren, 1995).

*EoD: innermost to mid-shelf*

*Basis for interpretation: EoD is based on the lithologic description and shallow water interpretation in Warren (1995).*

- **Rutherford littoral lithofacies**

“A distinctive sequence, at least 30 m thick, including **marine** coarse soft sandstone with an unusual fauna dominated by **rocky-shore** gastropods and bivalves... No good contacts with surrounding rocks are known, but it appears to represent the infilling of a channel that had been eroded, perhaps not long before, into partly consolidated **nearshore** sediments” (Warren, 1995).

*EoD: innermost shelf*

*Basis for interpretation: A coarse sandstone lithology and shallow water fauna (Warren, 1995) sug-*

gests the unit was deposited in an innermost shelf environment (Fig. 3).

- **Leader siltstone lithofacies**

"A distinctive blue-grey siltstone... It includes some richly fossiliferous bands in otherwise uniform massive siltstone with a scattering of **marine** macrofossils... deposition of the Leader siltstone during the Castlecliffian in a **shallow, near-shore environment**... The Leader siltstone reflects a phase of local basin deepening and marine transgression within a longer period dominated by the deposition of fluvial or very shallow marine conglomerates in a shallow, near-shore environment..." (Warren, 1995).

*EoD: mid-shelf*

*Basis for interpretation: The shallow near-shore interpretation for the unit (Warren, 1995) suggests an innermost to mid-shelf depositional environment. The generally (relatively) fine grain size of the unit tends to support the deeper end of the depositional depth range (Fig. 3). Consequently, a mid-shelf EoD is assigned to the unit here.*

- **Albyn conglomerate lithofacies**

"The Albyn conglomerate lithofacies is **non-marine, and locally estuarine**. The siltstone is probably of **loessial** origin..." (Warren, 1995).

*EoD: onshore*

*Basis for interpretation: EoD is based on the interpretation in Warren (1995).*

**Inferred age:** 17-1 Ma (Warren, 1995; Boyes et al., 2012)

**EoD breakdown:**

17-5 Ma:	<u>outer shelf</u> (Ferniehurst siltstone lithofacies)
4 Ma:	<u>outer shelf</u> (Ferniehurst siltstone and Bourne pebbly mudstone lithofacies)
3 Ma:	<u>outer shelf</u> (Ferniehurst siltstone, Bourne pebbly mudstone, Hawkswood deltaic, and Brookdale coquina lithofacies)
2 Ma:	<u>outer shelf</u> (Ferniehurst siltstone, Bourne pebbly mudstone lithofacies)
1 Ma:	<u>innermost shelf</u> (Ferniehurst siltstone, Rutherford littoral, Leader siltstone, Albyn conglomerate lithofacies)

**Basis for interpretation:** Main\_Rock = siltstone; Sub\_Rocks = sandstone mudstone conglomerate; Description = Fine-grained siltstone; poorly bedded marine, deltaic and terrestrial mudstone, sandstone and conglomerate (QMAP database) – *the EoD breakdown for the map unit is based on the depositional age and paleoenvironmental interpretations of the lithofacies that make up the Greta Formation. The Ferniehurst siltstone lithofacies is considered to represent background sediment of the Greta Formation (Warren, 1995). This suggests that the Bourne pebbly mudstone, Hawkswood deltaic, and Brookdale coquina lithofacies are more localised lithologies deposited within or on the fringes of the Ferniehurst siltstone lithofacies. Consequently a greater emphasis has been placed on the Ferniehurst siltstone lithofacies for the 17-2 Ma period. Although deposition of the Ferniehurst siltstone lithofacies apparently continued into the 1 Ma period, increased deposition of shallower innermost to mid-shelf sediment and onshore conglomerates indicate shallowing.*

## **Awatere Group**

### **Medway Formation (Mam)**

Includes Medway Conglomerate and Medway Siltstone.

"The formation is interpreted as a syntectonic, **inner to mid-shelf** deposit (Melhuish, 1988), formed near an actively rising Pahau terrane hinterland at sedimentation rates of up to 870 m/Ma (Browne, 1995)" (Rattenbury et al., 2006).

- **Medway Conglomerate**

"**Near shore deposit. Fluvial** at some localities, **marine** at others... This member is interpreted as being a coastal deposit, shallow marine at the type locality, but fluvial in some places, as at Upton Brook..." (Roberts and Wilson, 1992). "The conglomerates consist of **inner shelf**, matrix and clast-supported gravels and thin interbedded sandstone forming units up to 390 m thick. They are

overlain by trough cross-bedded sandstone up to 400 m thick (Maxwell 1990). Paleocurrents indicate paleoflows toward the northeast and northwest (Browne 1995), probably in a depositional setting close to an actively rising, greywacke dominated hinterland and deepening toward the north and northeast" (Field and Uruski, 1997).

*EoD: innermost shelf*

*Basis for interpretation: EoD is based on the inner shelf interpretation in Field and Uruski (1997).*

- **Medway Siltstone**

"Pebbly sandstone at base, mudstone with conglomeratic lenses at top. Siltstone is dominant... At the type locality (NZMS 260 P29 and Q29 823325 - 828359) c. 500 m of poorly sorted, calcareous, sandy siltstone, with sandy horizons, is overlain by c. 200 m of interbedded siltstone and sandstone, with pebbly horizons becoming more common in the upper c. 50 m. This unit was deposited in an **inner to mid-shelf** environment" (Roberts and Wilson, 1992). "The majority (up to 1000 m) of the Medway Formation consists of **bathyal**, fine sandy mudstone with interbedded sandstone" (Field and Uruski 1997).

*EoD: outer shelf*

*Basis for interpretation: The depositional depth range of the unit ranges from innermost shelf to bathyal. An average outer shelf EoD is assigned to the unit here.*

*Inferred age: 11-8 Ma (Field and Uruski, 1997)*

*EoD breakdown: 11-10 Ma: innermost shelf (Medway Conglomerate)*

*9-8 Ma: outer shelf (Medway Siltstone)*

*Basis for interpretation: Main\_Rock = sandstone; Sub\_Rocks = conglomerate, siltstone; Description = conglomerate grading upwards into sandstone with conglomerate lenses and mudstone and siltstone (QMAP database) – the EoD breakdown for the map unit is based on the depositional age and paleoenvironmental interpretations of the members that make up the map unit.*

## ***Upton Formation (Mau)***

Includes Upton Conglomerate, Upton Mudstone, and Upton Sandstone.

"It consists of basal sandstone or conglomerate that grades upward into siltstone-dominated rocks, with scattered macrofossils and shellbeds. The lower part of the Upton Formation was deposited near actively rising ranges, while the finer grained parts were deposited in a bathyal setting (Browne 1995). The upper part of the formation coarsens upwards into sandstone in the northwest" (Rattenbury et al., 2006). "Kennett (1966) observed that despite overall differences in facies between Upton Brook [shallow water succession] and Blind River [deeper water succession], significant and apparently synchronous changes in depth of deposition are apparent at both sections. There was a particularly marked shallowing of the sea between the uppermost Tongaporutuan and Lower Kapitean; at Upton Brook lithology coarsens from mudstone to sandstone with associated change in biofacies. At Blind River, the main evidence for shallowing comes from interpretation of biofacies (Fig. 3) as well as the presence of several coarser-grained horizons... The decrease in grain size of sediments across the Awatere district (west to east), from conglomerate to mudstone above the Upton Conglomerate, probably reflects continued submergence. Sediment supply was from a nearby emergent landmass to the west and southwest" (Roberts and Wilson, 1992).

- **Upton Conglomerate**

"**Marine** conglomerate, thick in west and thin in east" (Roberts and Wilson, 1992). "The lower part of the Upton Formation was deposited **near actively rising ranges**, while the finer grained parts were deposited in a bathyal setting (Browne 1995)" (Rattenbury et al., 2006). "...90 m of well stratified, cross-bedded pebbly sandstone, interpreted as a high energy **shoreface** sand (Brown 1995)" (Field and Uruski 1997).

*EoD: mid-shelf (innermost shelf to upper bathyal)*

*Basis for interpretation: The Upton Conglomerate was deposited in a wide range of environments, from the shoreface, to inner shelf to bathyal channel fill. From the description in Roberts and Wilson (1992), it seems likely that the shallow water Upton Conglomerate occurred in the west and southwest, with deeper water conglomerate in the east. An average mid-shelf EoD is assigned to the unit here.*

- **Upton Mudstone**

“The Upton Mudstone member overlies the Upton Conglomerate and is c. 750 m thick... It is a massive medium to well sorted, calcareous silty mudstone and was deposited in a **mid-shelf** environment. There is a 60 m thick sequence of turbidite beds (Fig. 5) in the massive mudstone... This turbidite sequence is recognised only in successions that were deposited at **relatively shallow water** depths and does not have correlatives in deeper water successions (e.g. Blind River)... Biofacies and lithofacies shallow significantly at Tt-Tk boundary, near the top of the Upton Mudstone” (Roberts and Wilson, 1992).

*EoD: mid-shelf*

*Basis for interpretation: EoD is based on the mid-shelf interpretation in Roberts and Wilson (1992).*

- **Upton Sandstone**

“Coarsening upwards sequence. In shallow water successions (Upton Brook), thick sandstone units were deposited at **inner shelf** depths. Silty mudstone dominates deeper water successions with occasional sandstone beds representing distal turbidite correlatives of inner shelf sandstones... The Upton Sandstone crops out as a thick and distinct unit at Upton Brook [shallow water succession] and adjacent localities, but can be recognised only as a much thinner **outer shelf** turbidite correlative at Blind River [deeper water succession]” (Roberts and Wilson, 1992).

*EoD: mid-shelf (innermost to outer shelf)*

*Basis for interpretation: Interpretations for the Upton Sandstone given in Roberts and Wilson (1992) suggest the unit has a depositional depth range of innermost to outer shelf. An average mid-shelf EoD is assigned to the map unit here.*

**Inferred age:** 8-6 Ma (Roberts et al., 1994; Field and Uruski, 1997)

**EoD:** mid-shelf (shallower in west, outer shelf to upper bathyal in east)

**Basis for interpretation:** Main\_Rock = siltstone; Sub\_Rocks = conglomerate, ‘sandy siltstone’; Description = Poorly sorted and poorly bedded channelized greywacke conglomerate with lenses of sandstone and sandy siltstone (QMAP database) – *the EoD for the map unit is based on the depositional age and paleoenvironmental interpretations of the formations and/or members that make up the map unit. It appears that shallower facies tend to occur to the west and deeper water lithologies occur in eastern parts of the map unit.*

### **Starborough Formation (Pas)**

**Inferred age:** 6-3 Ma (Field and Uruski, 1997)

**EoD:** outer shelf

**Basis for interpretation:** Main\_Rock = siltstone; Sub\_Rocks = sandstone, ‘sandy siltstone’; Description = poorly bedded sandstone and sandy siltstone in the Awatere Valley; and siltstone near White Bluffs (QMAP database). “The overlying latest Miocene to Late Pliocene Starborough Formation is generally poorly exposed and consists of poorly bedded brownish-grey fossiliferous sandstone and sandy siltstone” (Rattenbury et al., 2006). “The benthic species suggest **outer shelf or upper bathyal** depths (the bathymetry implied by Kennett’s biofacies is poorly defined), but proximity to land is inferred from the low frequency and small size of planktic species” (Scott, 1980). “The decrease in grain size of sediments across the Awatere district (west to east), from conglomerate to mudstone above the Upton Conglomerate, probably reflects continued submergence” (Roberts and Wilson, 1992) – *the map unit is defined as outer shelf here, although an upper bathyal EoD may still be appropriate.*

### **Whanganui Siltstone (Plu)**

**Inferred age:** 5-3 Ma (Rattenbury et al., 2006)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = siltstone; Description = blue-grey calcareous siltstone and sandstone with Torlesse-derived debris-flow conglomerate (QMAP database). “Undifferentiated Early Pliocene blue-grey calcareous siltstone and sandstone, with Pahau-derived **debris-flow conglomerate...**” (Rattenbury et al., 2006) – *the calcareous sandstone and siltstone are assumed to be flysch, debris flow conglomerate is assumed to be channel infill, and the siltstone is assumed to be hemipelagic sediment. These assumptions are interpreted with reference to Fig. 3.*

### ***Kowai Formation (Plk)***

"It consists of up to 650 m of Pahau-derived **fluvial** and **shallow marine** conglomerate..." (Rattenbury et al., 2006). "Conformably over the top of the Mt Brown beds **shallow marine** sands and sandy gravels of the Kowai Formation are exposed for about another kilometre downstream before passing below the fill of late Pleistocene gravels. Elsewhere, the Kowai Formation extends through the Pliocene into the early Pleistocene, becoming progressively more **estuarine and fluvial** with an increasing proportion of well rounded, weathered Torlesse-derived clasts" (Campbell et al., 2005). "This timing coincides with the change from deposition of marine Greta Formation to **terrestrial**, Torlesse Terrane derived, Kowai Formation, which is inferred to signal the onset of regional tectonic uplift" (Litchfield et al., 2003). "The Kowai Formation, a correlative of the Maori Bottom Formation, occurs between the Waitaki Valley and North Canterbury, and west to the Mackenzie Basin where it was known as Glentanner Formation. Kowai Formation consists of Torlesse-derived **fluvial** sheet conglomerates that interfinger in the east with sandstone, mudstone, lignite and **shellbeds**" (Field and Browne, 1989).

**Inferred age:** 7-2 Ma (Boyes et al., 2012)

**EoD breakdown:** 7-5 Ma: innermost shelf  
4-2 Ma: onshore

**Basis for interpretation:** Main\_Rock = conglomerate; Sub\_Rocks = sandstone, mudstone; Description = Torlesse-derived **fluvial** conglomerates interbedded with **shallow marine** sandstone and mudstone (QMAP database) – *EoD is based on the comments in the literature which suggest that the Kowai Formation was initially deposited in a shallow marine (i.e. innermost shelf) environment which became progressively more estuarine and fluvial. It is unlikely that there was an instantaneous transition from marine to non-marine, but probably fluctuated between marine and non-marine deposition for some time. The time when non-marine becomes dominant over marine is assumed to have taken place between 5 and 4 Ma.*

### ***Brunner Coal Measures (Eb)***

**Inferred age:** 38-35 Ma (Nathan et al., 1986; Ghisetti and Beggs, 2007)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = shale, 'coal seams'; Description = Quartz sandstone and conglomerate carbonaceous shale and coal seams (QMAP database). "**Fluviatile**, with meandering streams and peat swamps in the northwest and more active streams in the east" (Suggate, 1984). "Coal measures deposited in the basinal sequences are predominantly **fluvial** sand (locally including conglomerate), with only a minor component of carbonaceous mudstone and coal... Petrographic evidence suggest that most Brunner coals accumulated in **peat swamps**, dominated by reed and small herbaceous vegetation, and generally lacking trees" (Nathan et al., 1986) – *the unit is defined as onshore, after Suggate (1984).*

### ***Maruia Formation (Em)***

Includes Brunner Coal Measures, Nuggety Member, and Kaiata Mudstone Member.

"...is composed of 50 to 500 m of coarse, quartzofeldspathic sandstone with minor conglomerate, carbonaceous mudstone and thin seams of bituminous coal. These rocks are overlain by up to 500 m of largely massive, dark brown, micaceous mudstone or siltstone with minor bands of feldspathic sandstone, becoming more calcareous towards the top. The Maruia Formation was deposited unconformably on basement rocks, initially in a **terrestrial** environment. The mudstone represents deposition in an **estuarine** to partly enclosed **inner shelf** environment with periodic incursion of **submarine fans** derived from a rising area of Separation Point Batholith granite, probably to the east (Suggate 1984)" (Rattenbury et al., 2006). "...**submarine fan** sediments of the upper Maruia Formation and the Matiri Formation (Suggate 1984; Nathan et al., 1986), were deposited in a deep and rapidly subsiding basin and are characteristic of the Murchison Basin in the Oligocene" (Turnbull et al., 1993).

- **Brunner Coal Measures**

"**Fluviatile**, with meandering streams and peat swamps in the northwest and more active streams in the east" (Suggate, 1984).

EoD: onshore

Basis for interpretation: EoD is after Suggate (1984).

- **Nuggety Member**

“...similar sandstone [to Brunner Coal Measures] but commonly bioturbated and containing interbedded **marine** carbonaceous mudstone, both in thin-bedded graded sandstone-mudstone sequences and as thick beds of massive mudstone (Fig. 3.15). Such a large and apparently localised influx of sand is presumed to represent a fan, at first subaerial and later submarine, derived by uplift of granitic rocks immediately east or northeast of the Murchison Basin (Suggate 1984)... The coarse, sandy **submarine fan** deposits are mapped as the Nuggety Member of the Maruia Formation” (Nathan et al., 1986). “**Submarine fan**...” (Suggate, 1984). The occurrence of Nuggety Member as redeposited sandstone (turbidites and sandy debris flows) requires an upper to mid-bathyal EoD.

EoD: mid-bathyal

Basis for interpretation: The EoD is interpreted as a mid-bathyal submarine fan.

- **Kaiata Mudstone**

“Typical foraminiferal microfaunas are dominated by a small group of benthic arenaceous genera which can exist under bottom conditions not tolerated by normal marine assemblages, as well as a small number of planktonic species... These features suggest that the mudstone was formed under poorly oxygenated bottom conditions, but the presence of some planktonic foraminifera indicates that a connection with the open sea existed... The common situation of these mudstones at the base of a **transgressive marine** sequence is important as it implies both deposition in **shallow water** (probably in conditions of high organic productivity), and that the water circulation may have been poor, at least until sedimentary basins became large enough for an oceanic thermohaline circulation pattern to develop (Andrews 1977)” (Nathan et al., 1986).

EoD: initially shelf, deepening over time to upper bathyal

Basis for interpretation: The Kaiata Mudstone in the Murchison Basin represents a transgressive marine sequence that was initially approximately mid-shelf depth, and deepened over time to upper bathyal.

**Inferred age:** 38-31 Ma (Nathan et al., 1986; Ghisetti and Beggs, 2007)

**EoD breakdown:** 38-36 Ma: onshore (Brunner Coal Measures)

35 Ma: mid-shelf (Kaiata Mudstone)

34-31 Ma: mid-bathyal (Kaiata Mudstone, Nuggety Member)

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone, conglomerate; Description = Quartzofeldspathic sandstone overlain by carbonaceous mudstone and siltstone with minor conglomerate and thin coal seams (QMAP database) – the EoD breakdown for the map unit is based on the depositional age and paleoenvironmental interpretations of the members that make up the unit. Kaiata Mudstone and Nuggety Member interfinger, so an average EoD of mid-bathyal is chosen to represent this interval.

## **Matiri Formation (Om)**

Includes Scotty Mudstone Member, Doughboy Member, and Trig M Member.

“...comprises calcareous mudstone with bioclastic and crystalline limestone, and is channelled by sandstone and conglomerate. It locally rests unconformably on basement and elsewhere is conformable on Maruia Formation. The Matiri Formation is up to 1200 m thick and was deposited in an open sea environment that reached **bathyal** depths” (Rattenbury et al., 2006). “However, **submarine fan** sediments of the upper Maruia Formation and the Matiri Formation (Suggate 1984; Nathan and others 1986), were deposited in a **deep** and rapidly subsiding basin and are characteristic of the Murchison Basin in the Oligocene” (Turnbull et al., 1993). “Continuing marine transgression through the Oligocene led to the gradual drowning of the low-lying land areas exposed at the end of the Eocene, so that by the beginning of the Late Oligocene (Duntroonian—Lower Waitakian Stages) virtually the entire West Coast Region was submerged... The Basinal Facies in the Murchison Basin consists of massive calcareous mudstone and calc-**flysch**, all included in the Matiri Formation... Detailed micropaleontological studies show that the Matiri Formation contains an assemblage of **deep-water** foraminifera” (Nathan et al., 1986).

- **Scotty Mudstone Member**

“At the base, rapid establishment of **fully marine** conditions is indicated by the ubiquitous colour change from Maruia Formation mudstone, increase in calcium carbonate content, and incoming of fully marine planktic foraminifera. Rapid increase of water depth from shelf to **bathyal** is recorded within the Whaingaroan...” (Suggate, 1984). “The dominant lithology [of the Matiri Formation] is blue-grey to grey-brown calcareous mudstone or muddy limestone (Scotty Mudstone Member; Suggate 1984)” (Nathan et al., 1986).

*EoD: mid-bathyal*

*Basis for interpretation: This member is defined as mid-bathyal after the Rattenbury et al. (2006) description of bathyal for the Matiri Formation, and the lithology of mudstone. Lower bathyal may also be appropriate.*

- **Doughboy Member**

“The coarse deposits result from short distance mass transport into an **outer shelf to bathyal** environment. The member is presumably channelled into Scotty Mudstone, with finer further travelled material interfingering with the mudstone” (Suggate, 1984). “A wedge of **mass-flow** beds, mainly conglomerate, grit, and sandstone, containing identical granite clasts and a **redeposited** shallow-water fauna occur within the lower part of the Matiri Formation on the western margin of the Murchison Basin (Doughboy Member of Suggate 1984), suggesting that the coarser terrigenous material was derived from the adjacent basin margins, presumably by **debris flows** down submarine valleys into **deeper water**” (Nathan et al., 1986).

*EoD: upper bathyal*

*Basis for interpretation: This member is defined as upper bathyal after the Rattenbury et al. (2006) description of bathyal and the identification of debris flows. Mid-bathyal may also be appropriate.*

- **Trig M Member**

“**Bathyal submarine fan** derived from erosion of shelly and algal inner shelf sediments” (Suggate, 1984). “Scattered graded beds of **redeposited** bioclastic limestone occur locally in the upper part of the Matiri Formation, and increase in abundance upward until the formation locally changes into a calc-**flysch** sequence with a sand:mud ratio of 1:1 (Member C of Crooks & Carter 1976; Trig M Member of Suggate 1984)... The calc-flysch sequence is interpreted as a **submarine fan** assemblage, with shallow-water bioclastic material transported into deeper water down submarine canyons” (Nathan et al., 1986).

*EoD: mid-bathyal*

*Basis for interpretation: This member is defined as mid-bathyal after the Rattenbury et al. (2006) description of bathyal, the occurrence of flysch and transportation of material down submarine canyons. Lower bathyal may also be appropriate.*

**Inferred age:** 30-24 Ma (Nathan et al., 1986; Ghisetti and Beggs, 2007)

**EoD breakdown:** 30-29 Ma: mid-bathyal (Scotty Mudstone Member)  
28-27 Ma: mid-bathyal (Scotty Mudstone Member, Doughboy Member)  
26-24 Ma: mid-bathyal (Scotty Mudstone Member [26-25], Trig M Member [24])

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = siltstone, limestone, sandstone, grit; Description = Massive calcareous mudstone and siltstone sparsely fossiliferous (QMAP database) – *EoD is based on the bathyal interpretation of the map unit in Rattenbury et al. (2006).*

## **Mangles Formation (Mm)**

Includes Tutaki Member, Crowe Member, Valley Creek sandstone, and Trig A Member.

“...consists of graded quartz-mica sandstone and mudstone beds, and is up to 1600 m thick. The lower Mangles Formation was deposited from **deep-water turbidity currents** when the Murchison Basin rapidly deepened, but as subsidence slowed, the basin filled with **shallow marine** sediments in which sandstone became dominant (Suggate 1984). The upper part of the Mangles Formation is dominated by thick-bedded sandstone with dark mudstone and siltstone and, towards its top, pebbly sandstone and thick conglomerate beds containing schist clasts, Separation Point granite, and sedimentary rock from the Caples and Matai terranes” (Rattenbury et al., 2006). “An

exceptional increase in the rate of subsidence initiated Mangles Formation deposition” (Suggate, 1984). “...the Mangles Formation, conformable or with only a minor disconformity over the Matiri Formation, accounts for 12,000 ft and is subdivided into a lower portion with mainly **thin-bedded, alternating** sandstone, siltstone, and mudstone, and an upper portion which consists of **massive sandstone** and local massive siltstone beds; the siltstones in the lower, alternating beds are all calcareous but the formation as a whole is basically non-calcareous. On the western side of the basin the Lower Mangles is, however, represented by thick sandstone beds with only minor, thin shale-silt partings. In contrast with the dirty, dense, and greenish grey Upper Mangles, this sandstone is quartz-rich and light grey, somewhat micaceous but rather well sorted...” (Katz, 1968).

- **Tutaki Member (Mmt)**

Defined as Mangles Formation (Mm) on the Rattenbury et al. (2006) geological map sheet.

**Inferred age:** 23-20 Ma (Nathan et al., 1986; Ghisetti and Beggs, 2007)

**EoD:** lower bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = calcareous mudstone; Description = Graded sandstone and calcareous mudstone with thick sandstone dominant in west (QMAP database). “The conformably overlying Mangles Formation, of Early Miocene age, consists of graded quartz-mica sandstone and mudstone beds, and is up to 1600 m thick. The lower Mangles Formation was deposited from **deep-water turbidity currents** when the Murchison Basin rapidly deepened...” (Rattenbury et al., 2006). “**Submarine fans** extending to **bathyal** depths, probably from both west and northeast” (Suggate, 1984) – *EoD is based on the stratigraphic position of the Tutaki Member in the lower part of the Mangles Formation combined with a deep-water turbidity current interpretation of the lower Mangles Formation given in Rattenbury et al. (2006). Mid-bathyal may also be appropriate.*

- **Crowe Member (Mmc)**

Defined as Mangles Formation (Mm) on the Rattenbury et al. (2006) geological map sheet.

**Inferred age:** 19 Ma (Nathan et al., 1986; Ghisetti and Beggs, 2007)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = conglomerate; Sub\_Rocks = sandstone, mudstone; Description = Conglomerate, sandstone and mudstone in graded beds (QMAP database). “**Submarine fan**” (Suggate, 1984) – *graded beds and the presence of conglomerate in the graded beds are interpreted as upper fan sediments of upper bathyal depth. Mid-bathyal may also be appropriate.*

- **Valley Creek Sandstone**

“The type section consists of about 1750 m of dark grey massive siltstone grading up to dark grey massive, muddy very fine sandstone... **Mid-outer shelf to bathyal**” (Suggate, 1984).

**EoD:** *initially upper to mid-bathyal, shallowing up section to mid-shelf*

**Basis for interpretation:** *To call this member a sandstone is a bit of a misnomer as the bulk of it is essentially a siltstone, inferred to be deposited at upper bathyal depths. The upper part of the member is a mid-shelf sandstone.*

- **Trig A Member (Mma)**

Defined as Mangles Formation (Mm) on the Rattenbury et al. (2006) geological map sheet.

**Inferred age:** 17 Ma (Nathan et al., 1986; Ghisetti and Beggs, 2007)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = sandstone; Description = Muddy fine-medium grained sandstone with pebble layers (QMAP database). “Fine to medium sandstone with scattered pebbles or pebble stringers... **Inner shelf**” (Suggate, 1984) – *Rattenbury et al. (2006) mention pebbly sandstone near the top of the Mangles Formation, which implies shallowing upwards through the formation.*

**Inferred age:** 23-17 Ma (Nathan et al., 1986; Ghisetti and Beggs, 2007)

**EoD breakdown:** 23-20 Ma: lower bathyal (Tutaki Member)  
19-18 Ma: upper bathyal (Crowe Member, Valley Creek sandstone)  
17 Ma: innermost shelf (Trig A Member)

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = siltstone mudstone; Description =



Quartz-mica sandstone and mudstone graded beds, locally sandstone dominated, with thick conglomerate, grading up into sandstone (QMAP database) – *the EoD breakdown for the Mangles Formation is based on the depositional age and paleoenvironmental interpretations of the members that make up the formation.*

### **Longford Formation (MI)**

**Inferred age:** 17-9 Ma (Nathan et al., 1986; Ghisetti and Beggs, 2007)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = conglomerate; Sub\_Rocks = sandstone ,mudstone 'coal seams'; Description = **Fluvial** conglomerate with sandstone, mudstone and coal seams (QMAP database). "The formation accumulated in an **estuarine** environment in the south with extensive deposition farther north by meandering rivers in an **alluvial** plain setting" (Rattenbury et al., 2006) – *EoD is based on QMAP and Rattenbury et al. (2006) descriptions.*

### **Rappahannock Group**

"Farther south, at an equivalent stratigraphic level to the Longford Formation, the poorly dated **terrestrial** Rappahannock Group (Cutten 1979)..." (Rattenbury et al., 2006).

#### **Lower Rappahannock Group (eMrl)**

Includes Frog Flat Formation.

**Inferred age:** 9-7 Ma (Lee, 2013)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = conglomerate; Sub\_Rocks = sandstone; Description = Muddy sandstone and conglomerate containing indurated volcanogenic sandstone clasts (QMAP database) – *EoD is based on Rattenbury et al. (2006) interpretation. After Lee (2013) the Frog Flat Formation is considered to be equivalent to Rattenbury et al.'s (2006) Lower Rappahannock Group.*

#### **Upper Rappahannock Group (mMru)**

Includes Spargo Formation, and Devil's Knob Formation.

**Inferred age:** 7-4 Ma (Lee, 2013)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = conglomerate; Description = Conglomerate composed largely of schist clasts (QMAP database) – *EoD is based on Rattenbury et al. (2006) interpretation. After Lee (2013) the Spargo Formation and Devil's Knob Formation are considered to be equivalent to Rattenbury et al.'s (2006) Upper Rappahannock Group.*

### **Tadmor Group**

"**Non-marine** conglomerate and gravel of the Tadmor Group, resting unconformably on older rocks..." (Rattenbury et al., 1998). "**Terrestrial** deposits unconformably overlying Lower Tertiary and older rocks are mapped as Moutere Gravel and Glenhope Formation, and are included in the Tadmor Group" (Johnston, 1971).

#### **Glenhope Gravel (Ptg)**

**Inferred age:** 8-4 Ma (Mildenhall and Suggate, 1981)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = gravel; Sub\_Rocks = sand, silt, clay, lignite; Description = Terrestrial granitic-derived gravel sand and silt with carbonised wood. Laucustrine deposits with feldspathic clay and lignite (QMAP database) – *EoD is based on Rattenbury et al. (1998) and Johnston (1971) interpretations. Refer to "Glenhope Gravel (Ptg)" on the Nelson map area for further information.*

#### **Moutere Gravel (Ptm)**

**Inferred age:** 3-2 Ma (Mildenhall and Suggate, 1989)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = gravel; Sub\_Rocks = sand, mud, clay, boulders peat; Description = Poorly to moderately well sorted clay bound gravel containing up to boulder sized clasts of greywacke (QMAP database) – *EoD is based on Rattenbury et al. (1998) and Johnston (1971) interpretations. Refer to “Moutere Gravel (Ptm)” on the Nelson map area for further information.*

## **Quaternary – Sedimentary deposits**

- **All Q deposits** (except – see below)

**EoD:** onshore

**Basis for interpretation:** Based on the QMAP database which includes alluvial, beach, colluvial, dune, lacustrine, landslide, loess, scree, swamp, and till sediments in the Quaternary deposits.

- **uQb, Q9b, Q7b, Q5b, Q4b**

**EoD:** innermost shelf

**Basis for interpretation:** “Marine sand and gravel deposits...” (Rattenbury et al., 2006).

## HAAST AREA (Geological Map 14)

### Undifferentiated Late Cretaceous (IK)

**Inferred age:** > 65-61 Ma (King et al., 1999)

**EoD:** submarine mafic eruptives

**Basis for interpretation:** Main\_Rock = sandstone (QMAP database). “Late Cretaceous sedimentary and volcanic rocks (lKu) include the Tauperikaka Coal Measures, Whakapohai Sandstone and **Arnott Basalt**, and occur between the Paringa and Waita rivers (Nathan 1977). These stratigraphic units are generally thin or laterally discontinuous and have not been differentiated apart from coastal occurrences of the Arnott Basalt south of the Whakapohai River” (Rattenbury et al., 2010) – *the Tauperikaka Coal Measures and Whakapohai Sandstone are older than 65 Ma, so the EoD of IK is taken to be that of the Arnott Basalt (refer to “Arnott Basalt (lKa)”*).

### Arnott Basalt (lKa)

**Inferred age:** > 65-61 Ma (King et al., 1999)

**EoD:** submarine mafic eruptives

**Basis for interpretation:** Main\_Rock = **basalt**; Sub\_Rocks = tuff (QMAP database). “The unit includes agglomerate, breccia, tuff and lava flows (Fig. 29), and has a mildly alkaline, within-plate **basalt** composition (Sewell and Nathan 1987)” (Rattenbury et al., 2010). “...consisting of tuff, volcanic breccia, and flows of aphyric, mildly alkaline **basalt**... Mutch & McKellar (1964) originally named this unit Arnott Volcanics, but as it is wholly composed of **basalt** the name Arnott Basalt is preferred... Although no clear pillow structures were seen, the presence of **marine fossils** within fragmental lithologies of the Arnott Basalt indicates that it was **erupted, at least in part, beneath the sea**. No sources have so far been identified although geophysical evidence suggests that there may be several vents offshore (see later section)... Although the Arnott Basalt is not dated precisely, the maximum time available for the complete volcanic episode is 15-20 m.y., and the actual time was probably much less” (Nathan, 1977) – *EoD is based on Nathan (1977) where it is defined as a basalt. The presence of marine fossils indicates a submarine eruption. Onshore mafic eruptives may also be appropriate.*

### Undifferentiated Paleogene (PO)

Includes Tokakoriri Formation, Abbey Formation, and Otitia Basalt.

“Paleocene to Oligocene sedimentary rocks occur between the Makawhio and Waita rivers and are mapped as undifferentiated Paleogene (PO). They include the Tokakoriri Formation, Abbey Formation and Otitia Basalt...” (Rattenbury et al., 2010). “The younger Tokakoriri Formation (Dt-w) consists of calcareous mudstone and sandstone, and is conformably overlain by the Abbey Formation (Dw-Lwh)... Basaltic volcanism was continuous from Paleocene to Late Eocene time near the mouth of the Paringa River, and Otitia Basalt (?Dw-Ar) consists of tuff, volcanic breccia, and flows of alkali basalt (with minor hawaiite and trachyandesite) interbedded with the Abbey Formation” (Nathan, 1977).

### Tokakoriri Formation

**Inferred age:** 60-56 Ma (King et al., 1999)

**EoD:** initially innermost shelf, deepening over time to upper bathyal

**Basis for interpretation:** “The Tokakoriri Formation overlies Arnott Basalt and is composed of well-bedded calcareous mudstone and muddy sandstone. The formation contains interbedded volcanoclastic deposits, including lapilli tuff and volcanic conglomerate. It is a **marine** unit that records **progressive deepening**, and microfossils indicate a Paleocene to earliest Eocene age” (Rattenbury et al., 2010). “Overall, the Tokakoriri Formation records a transition from active volcanism and sedimentation in a **nearshore** environment to the deposition, in the overlying Abbey Limestone, of foraminiferal siltstone at **bathyal** depths” (Phillips et al., 2005) – *EoD is based on Phillips et al. (2005), who interpret the formation as being wholly marine, initially in a nearshore environment, deepening over time to a bathyal (perhaps upper bathyal) environment.*

## **Abbey Formation**

**Inferred age:** 55-34 Ma (King et al., 1999)

**EoD:** upper bathyal

**Basis for interpretation:** “Cream to brown, muddy limestone and calcareous mudstone of the Abbey Formation gradationally overlies Tokakoriri Formation near Abbey Rocks (Nathan 1977). Pillowed basalt forms Browne Island and may be Otitia Basalt (Sutherland 1995a)” (Rattenbury et al., 2010). “At the type locality the Abbey Formation can be divided into three members, which are informally named upper Abbey Mudstone, middle Abbey Limestone, and lower Abbey Limestone... The lower Abbey Limestone (Dm-h) indicates a period of quiet carbonate sedimentation when little clastic material was being transported. The predominance of pelagic foraminifera indicates **relatively deep-water** sedimentation. The thicker, muddy middle Abbey Limestone (?Dp) overlain by the upper Abbey Mudstone (Ab-r) represents a gradually increasing terrigenous mud component, possibly due to uplift and erosion in the source area” (Nathan, 1977). “The foraminiferal assemblage includes abundant planktonic species, indicating deposition in relatively deep water, equivalent to **outer shelf or slope** depths” (Nathan et al., 1986) – *EoD is defined as upper bathyal, however outer shelf may also be appropriate.*

## **Otitia Basalt**

**Inferred age:** 41-36 Ma (King et al., 1999)

**EoD:** submarine mafic eruptives

**Basis for interpretation:** “**Submarine volcanism** started locally in Upper Dannevirke time (see later section), but only became widespread in the Kaiatan when volcanic rocks were incorporated in the sedimentary sequence, mainly by the **slumping** of unstable pyroclastic material into deep water... In thin section most specimens resemble **alkali basalts**, but several are lighter coloured and are classified as **hawaiite** and **trachyandesite**” (Nathan, 1977) – *the Otitia Basalt is contemporaneous with the upper Abbey Formation. It is a submarine mafic deposit with some redeposition also occurring at upper bathyal depth. Parts of the deposit are also described as trachyandesite, indicating an intermediate composition is also possible.*

**Inferred age:** 60-34 Ma (King et al., 1999)

**EoD breakdown:**

60 Ma:	<u>innermost shelf</u> (Tokakoriri Formation)
59-58 Ma:	<u>mid-shelf</u> (Tokakoriri Formation)
57 Ma:	<u>outer shelf</u> (Tokakoriri Formation)
56-34 Ma:	<u>upper bathyal</u> (Tokakoriri Formation, Abbey Formation, Otitia Basalt)

**Basis for interpretation:** Main\_Rock = sandstone (QMAP database) – *Rattenbury et al. (2010) mentions three formations as occurring in this area, therefore the overall EoD of PO is based on those formations. The Otitia Basalt is included as upper bathyal in the deposition of the Abbey Formation, instead of being labelled separately as an igneous deposit.*

## **Awarua Limestone (Oa)**

**Inferred age:** 25-24 Ma (King et al., 1999)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = limestone (QMAP database). “...**shallow marine** Oligocene bioclastic Awarua Limestone (Oa) rests directly on pre-Cretaceous rocks” (Rattenbury et al., 2010). “Slow subsidence led to widespread deposition of **shallow-water** bryozoan limestone in the south, and deeper-water foraminiferal ooze in the north” (Nathan, 1978) – *the EoD is based on the predominantly shallow water interpretations of Rattenbury et al. (2010), Sutherland et al. (1996) and Nathan (1978). As this map area contains the northern Awarua Limestone, a deeper environment may be more appropriate. Refer to “Awarua Limestone (Oa)” on the Wakatipu map area for further interpretations.*

## **Tititira Formation (mMt)**

“Thick, graded beds of conglomerate and pebbly sandstone, grey feldspathic sandstone and calcareous mudstone form the Tititira Formation... Microfossils and sedimentological features in the Tititira Formation indicate rapid deepening and sedimentation in a **submarine fan** environment”

(Rattenbury et al., 2010). "...a **deep-water** sequence passing upwards from hemipelagic mudstone through **distal and proximal turbidites** (Kaipo Member) into a **mass-flow conglomerate-sandstone complex** (Long Reef Member)... Microfossil samples collected from calcareous mudstone throughout the Tititira Formation contain very similar **deep-water foraminiferal** assemblages indicating a Lillburnian to Waiauan age... Largely on the basis of sedimentary structures, Wellman (1955, p. 24) recognised that "the bulk of the formation consists of **redeposited sediments** that were **transported into deep water** by submarine landslides and turbidity currents"... In summary, the Tititira Formation is interpreted as a **deep-water** submarine fan sequence, grading upwards from pelagic mudstone through distal and proximal turbidites (**outer to middle fan**) to coarser-grained **inner fan** and channel deposits composed of a mixture of inertia-flow and turbidity current deposits. Current direction measurements indicate transport from NE to SW, approximately along the line of the present coastline" (Nathan, 1978).

**Inferred age:** 14-9 Ma (Sutherland et al., 1996)

**EoD breakdown:** 14-11 Ma: lower bathyal (Kaipo Member)

10-9 Ma: upper bathyal (Long Reef Member)

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = conglomerate (QMAP database) – the lower part of the formation, represented by the Kaipo Member, is interpreted as being deposited in mid- to lower bathyal depths, after the description of distal to proximal turbidites, and is here narrowed down to lower bathyal. The upper part of the formation, represented by the Long Reef Member, is interpreted as being an upper bathyal deposit. The age of the members is approximated from Figure 2 in Nathan (1978). The Tititira Formation is the outcrop equivalent of foreland basin (foredeep) deposits mapped offshore by Sircombe and Kamp (1998).

### **Halfway Formation (Ph)**

**Inferred age:** 5-4 Ma (Rattenbury et al., 2010)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = conglomerate (QMAP database). "The outcrops include conglomerate with well rounded clasts, laminated silty sand, and mudstone. Molluscs, gastropods, microflora and foraminifera indicate an Early Pliocene age" (Rattenbury et al., 2010). "Sediment entering the sea from the Cascade River moved down the steep continental slope and (based on faunal evidence) was deposited locally in **c. 200-1000 m water depth** as Halfway Formation. **Slumping** after or during deposition may have been caused by seismic shaking, dewatering, or gravitational instability owing to over steepening" (Sutherland et al., 1995) – Sutherland et al. (1995) indicates upper bathyal to mid-bathyal depositional depths for the formation (Fig. 3).

## **Quaternary – Sedimentary deposits**

- **All Q deposits** (except – see below)

**EoD:** onshore

**Basis for interpretation:** Based on the QMAP database which includes alluvial, dune, landslide, scree, swamp, and till sediments in the Quaternary deposits.

- **Qbt, uQb, Q1b**

**EoD:** innermost shelf

**Basis for interpretation:** "...**shallow marine** siltstone... the sediments are interpreted to have accumulated **near shore**, partly in a fiord setting... **marine** sand and gravel deposits... Late Holocene **marine** sand, gravel and silt" (Rattenbury et al., 2010).

## AORAKI AREA (Geological Map 15)

### ***Karangarua Basalt (Pb)***

***Inferred age:*** > 65-61 Ma (King et al., 1999)

***EoD:*** onshore mafic eruptives

***Basis for interpretation:*** Main\_Rock = **basalt**; Description = Interbedded basalt flows and breccia; possibly Haumurian-Teurian Arnott Basalt; or Kaiatan-Runangan Otitia Basalt (QMAP database). “Near the Karangarua River, basalt with minor breccia (Pab) unconformably overlies Greenland Group and is tentatively correlated with Paleocene basalt exposed near the Makawhio River, west of the Aoraki map area (Nathan 1978; Sewell & Nathan 1987; Mortimer et al. 1984)” (Cox and Barrell, 2007) – *the EoD is defined after the main rock type of basalt. The unit appears to be an onshore deposit as there is no mention of submarine products; however it could be submarine if it is a correlative of the Arnott Basalt in the Haast map area.*

### ***Rapahoe Group (Er)***

***Inferred age:*** 38-32 Ma (Nathan et al., 1986)

***EoD breakdown:*** 38-37 Ma: innermost shelf

36 Ma: mid-shelf

35-32 Ma: outer shelf

***Basis for interpretation:*** Main\_Rock = siltstone; Sub\_Rocks = sandstone, conglomerate; Description = Moderately hard brown-grey calcareous siltstone underlain by calcareous granite/Greenland Group conglomerate (QMAP database). “Middle to Late Eocene calcareous conglomerate and brown-grey, moderately hard, calcareous siltstone within a fault-bounded outlier in the Mikonui catchment are correlated with Rapahoe Group (Er)” (Cox and Barrell, 2007). “...**shallow-water** marine sediments, included in the Rapahoe Group (Nathan 1974)” (Nathan et al., 1986) – *the EoD for the Rapahoe Group on the Aoraki map area is defined as the same as that of the Kaiata Formation on the Greymouth map area because it is described as being the most widespread and dominant unit of the Rapahoe Group (Nathan et al., 1986). Refer to “Kaiata Formation (Erk)” on the Greymouth map area for more detail of the individual members.*

### ***Blue Bottom Group***

#### ***Lower Blue Bottom Group (Mb)***

***Inferred age:*** 21-17 Ma

***EoD:*** upper bathyal

***Basis for interpretation:*** Main\_Rock = sandstone; Sub\_Rocks = mudstone, limestone; Description = Hard calcareous sandstone and sandy mudstone; conglomeratic (greywacke/granite) limestone at base; sandy limestone at top (QMAP database). “...Early Miocene hard calcareous sandy mudstone and sandstone, and 50 m of probably Middle Miocene limestone...” (Cox and Barrell, 2007). “Apart from the Murchison Basin, the dominant lithology is light grey-brown calcareous mudstone or muddy sandstone, collectively mapped as Lower Blue Bottom Group...” (Rattenbury et al., 1998) – *this Miocene Blue Bottom Group has been defined here as upper bathyal. Outer shelf may be an alternative interpretation.*

#### ***Upper Blue Bottom Group (Plb)***

***Inferred age:*** 6-4 Ma (Cox and Barrell, 2007)

***EoD:*** innermost shelf

***Basis for interpretation:*** Main\_Rock = sandstone; Description = Light grey medium to fine sandstone; weak (QMAP database). “...a thin layer of weak, light grey, medium- to fine-grained, Pliocene sandstone” (Cox and Barrell, 2007) – *EoD is based on the main rock type being sandstone and Fig. 3.*

#### ***Tititira Formation (Mb\_t)***

(QMAP database spelling: Blue Bottom Gp Tititira Formation)

“Vertically dipping Middle Miocene blue-grey calcareous mudstone...” (Cox and Barrell, 2007). “...a **deep-water** sequence passing upwards from hemipelagic mudstone through **distal and proxi-**

**mal turbidites** (Kaipo Member) into a **mass-flow conglomerate-sandstone complex** (Long Reef Member)...” (Nathan, 1978).

**Inferred age:** 14-9 Ma (Sutherland et al., 1996)

**EoD breakdown:** 14-11 Ma: lower bathyal (Kaipo Member)  
10-9 Ma: upper bathyal (Long Reef Member)

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = siltstone; Description = Grey calcareous mudstone (QMAP database) – *the lower part of the formation, represented by the Kaipo Member, is interpreted as being deposited in mid- to lower bathyal depths. The upper part of the formation, represented by the Long Reef Member, is interpreted as being an upper bathyal deposit. Refer to “Tititira Formation (mMt)” on the Haast map area for further information.*

## Eyre Group

“The Eyre Group sedimentary succession began with quartzose fluvial sediments, followed by quartzose marine sandstone, mudstone, greensand, calcareous mudstone and limestone” (Cox and Barrell, 2007).

### **Broken River Formation (lKe\_b, Pe\_b)**

(QMAP database spelling: Eyre Gp Broken River Formation)

“In the Canterbury foothills, the lowermost Eyre Group consists of largely **non-marine** Broken River Formation (lKb, Peb) quartz sandstone, carbonaceous mudstone and claystone, locally with minor conglomerate and lensoidal coal seams (Fig. 22A). **Marginal marine** cross-bedded quartz sandstone, with some disseminated glauconite and pebble horizons, occurs in the upper part of the formation near Mt Somers... Broken River Formation accumulated in valleys, river plains, swamps and estuaries as the sea transgressed westwards. Coal seams, where present, are generally less than 5 m thick and occur near the base of the formation” (Cox and Barrell, 2007). “Fine-grained **fluvio-deltaic** quartzose coal measures...” (Field and Browne, 1989).

**Inferred age:** > 65-46 Ma (Boyes et al., 2012)

**EoD breakdown:** > 65-56 Ma: onshore (Pe\_b = 58-56 Ma only)  
55-46 Ma: innermost shelf (lKe\_b = 55-47 Ma only)

**Basis for interpretation:** Main\_Rock = claystone; Sub\_Rocks = lignite, sandstone; Description = Carbonaceous and quartzose claystone mudstone and sandstone; local coal seams (QMAP database) – *the EoD is initially defined as onshore because it is described as being a non-marine, fluvial deposit containing coal measures. In the upper part it has a marginal marine influence as the sea transgresses westwards; this boundary is nominated as the beginning of the Waipawan. The Broken River Formation is younger in the south than in the north (i.e. on Christchurch), where the minimum age is older than 65 Ma. It is only younger than 65 m.y. on the Waitaki (Eeb) and Aoraki map areas (Boyes et al., 2012).*

### **Tengawai Coal Measures (Ee\_t)**

(QMAP database spelling: Eyre Gp Tengawai Coal Measures)

**Inferred age:** 37-35 Ma (Cox and Barrell, 2007)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = claystone; Sub\_Rocks = lignite, sandstone, conglomerate, clay; Description = Carbonaceous claystone; fossiliferous siltstone; calcareous cemented conglomeratic sandstone (QMAP database). “In inland Canterbury, marine Eyre Group generally rests directly on basement, apart from limited occurrences of Late Eocene or Early Oligocene **non-marine** carbonaceous claystone and sandstone with localised lignite and conglomerate (Tengawai Coal Measures; Eet). These **non-marine** deposits overlie leached Rakaia terrane rocks at upper Tengawai valley, Mowbray valley and northwest of Lake Heron...” (Cox and Barrell, 2007). “...Runangan **terrestrial** sediments...” (Field and Browne, 1989) – *the EoD is defined as onshore because these coal measure have been described as non-marine and terrestrial deposits.*

### **Undifferentiated Paleocene to Middle Eocene Eyre Group**

“The Broken River Formation is overlain by **marginal marine to shallow marine** sedimentary rocks (undifferentiated Paleocene to Middle Eocene Eyre Group; PEe) comprising pale glauconitic

quartz sandstone (Charteris Bay Sandstone) towards the northeast and quartz-pebbly, concretionary, shelly sandstone (Kauru Formation) to the southwest” (Cox and Barrell, 2007).

- **Charteris Bay Sandstone (PEec)**

**Inferred age:** > 65-42 Ma (Boyes et al., 2012)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = greensand; Description = Pale yellow-grey to green-grey quartz sandstone; medium to dark green-grey glauconitic quartz sands mainly near top (QMAP database). “The quartzose, slightly glauconitic Charteris Bay Sandstone, for example, was deposited in **shallow, high energy marine environments – very shallow marine, almost tidal** in the west around Broken River...” (Field and Browne, 1989) – *the EoD is defined as innermost shelf, after Field and Browne (1989), however a deeper EoD may be appropriate.*

- **Kauru Formation (PEe)**

**Inferred age:** 47-43 Ma (Boyes et al., 2012)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = greensand; Description = Pale yellow-grey to green-grey quartz sandstone; medium to dark green-grey glauconitic quartz sands mainly near top (QMAP database). “This unit marks the transition between the terrestrial Haumurian-Waipawan Papakaio and Broken River Formations and the marine Bortonian Tapui Glauconitic Sandstone and Waihao Greensand” (Field and Browne, 1989) – *this formation is defined as innermost shelf, because it is said to mark the transition between terrestrial and marine sediments. Refer to “Eyre Group (Ee)” on the Waitaki map area for further information.*

### ***Middle Eocene to Early Oligocene Eyre Group (Ee)***

Includes Homebush Sandstone, Burnside Mudstone, Waratah Sandstone, and Amuri Limestone.

“An unconformity or disconformity generally occurs at the base of the overlying Middle Eocene to Early Oligocene Eyre Group (Ee) **marine** sedimentary rocks... Deposition took place in environments that ranged from **shoreface to outer shelf** depths (Field & Browne et al. 1989; King et al. 1999)” (Cox and Barrell, 2007).

- **Homebush Sandstone (Ee\_h)**

(QMAP database spelling: Eyre Gp Homebush Sandstone)

**Inferred age:** 55-39 Ma (Boyes et al., 2012)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone; Description = Green to yellow glauconitic quartz sandstone; minor silt beds and quartz pebble and grit horizons (QMAP database). “...poorly-dated yellowish grey, non-calcareous, locally gritty, quartzose sandstone of **nearshore** facies...” (Field and Browne, 1989). “...a massive **estuarine deltaic** deposit...” (Carlson et al., 1980) – *EoD is based on the interpretation of the formation in Field and Browne (1989). Interpretations from Carlson et al. (1980) and Mould (1992) indicate an onshore paleoenvironment is also likely. Refer to “Homebush Sandstone (Ee)” on the Christchurch map area for further information.*

- **Burnside Mudstone (Ee\_b)**

(QMAP database spelling: Eyre Gp Burnside Mudstone)

**Inferred age:** 38-35 Ma (Cox and Barrell, 2007)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone; Description = Light-coloured fine-grained calcareous glauconitic mudstone (QMAP database). “Siltstone and mudstone are sufficiently extensive to map separately (Eem) in the Kakahu area” (Cox and Barrell, 2007). “... calcareous **?mid shelf** Burnside Mudstone” (Field and Browne, 1989). “Blue-grey calcareous siltstone and mudstone, sometimes glauconitic, with **open marine** invertebrate faunas. Sometimes rich also in biopelagic siliceous microfossils” (Carter, 1988) – *the EoD is (tentatively) defined as mid-shelf after Field and Browne (1989).*



- **Waratah Sandstone (Ee\_w)**

(QMAP database spelling: Eyre Gp Waratah Sandstone)

**Inferred age:** 36-35 Ma (Boyes et al., 2012)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone; Description = Greenish-grey silty very fine glauconitic quartz sandstone (QMAP database). "The base of the Ashley Mudstone, particularly in the west, is sandy (Waratah Sandstone Member) though the top is typically calcareous mudstone that ranges into the Lower Whaingaroan" (Field and Browne, 1989). "... is probably a more **near-shore** facies of the Ashley Mudstone. Foraminifera indicate **inner shelf depths**" (Boyes et al., 2012) – *the EoD is defined as innermost shelf, after comments in Boyes et al. (2012). However mid-shelf may also be appropriate.*

- **Amuri Limestone**

**EoD:** outer shelf

"Although originally defined as a stand-alone formation (Field & Browne et al. 1989), on this map Amuri Limestone is included within the uppermost part of the Eyre Group. Amuri Limestone is characteristically a pale, fine-grained, muddy limestone or very calcareous mudstone, which is generally less than 10 m thick but reaches 80 m in the upper Hinds River and Castle Hill Basin (Gage 1970; Field & Browne 1986; Oliver & Keene 1990). This limestone is absent in several locations, probably due to erosion before the overlying beds were deposited" (Cox and Barrell, 2007). "Much of Canterbury was submerged in the Oligocene, when micrite (Amuri Limestone) [...] was deposited... The Amuri generally has an **outer neritic to bathyal** microfauna and this, coupled with its fine texture, suggests an **outer shelf or slope** paleoenvironment" (Field and Browne, 1989) – *EoD is based on comments in Field and Browne (1989). Amuri Limestone is younger and shallower here than in the north in the Kaikoura map area.*

**Inferred age:** 55-33 Ma (Boyes et al., 2012)

**EoD breakdown:** 55-39 Ma: innermost shelf (Homebush Sandstone)

38-35 Ma: mid-shelf (Burnside Mudstone, Waratah Sandstone)

34-33 Ma: outer shelf (Amuri Limestone)

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = limestone, siltstone, greensand; Description = Micaceous quartz sandstone/mudstone; pebbly shelly concretionary beds; glauconitic sandstone/mudstone; marl and impure limestone (QMAP database) – *the Eocene Eyre Group in the Aoraki map area contains several formations and members, some of which are differentiated in the GIS database and are described in the above paragraphs. The EoD therefore of Ee is based on the differentiated members and the Amuri Limestone.*

### **Acheron Gabbro (PMIOmi)**

**Inferred age:** 26-25 Ma (Timm et al., 2010)

**EoD:** mafic intrusives

**Basis for interpretation:** Main\_Rock = basalt. "The **intrusives** are transitional subalkaline **gabbros** with minor, more evolved differentiates. These rocks are a product of the strongly alkaline to transitional intraplate volcanism which produced the mid-Late Oligocene Cookson Volcanics of North Canterbury (Gregg, 1965; Coote, 1987), the associated tuffs within the Thomas Formation (Gage, 1970; McLennan, 1981), the Brothers Basalt of the Mt. Somers area (Browne and Field, 1985) as well as the intrusives found within the Tertiary sediments at Avoca (McLennan, 1981)... Therefore the rocks are best termed gabbros" (Eady, 1995) – *this polygon was created from original QMAP polygons based on samples grouped as Oxford Volcanics and dated in Timm et al. (2010). The samples are simply described as basalts.*

### **Kekenodon Group**

"The Late Oligocene to earliest Miocene Kekenodon Group (eMk) generally consists of green-grey, calcareous, glauconitic, quartz sandstone (Kokoamu Greensand), overlain by coarse-grained, sandy limestone (Otekaike Limestone)... In inland Canterbury east of Lake Heron, Kekenodon Group is represented by 65 m of Late Oligocene calcareous quartz sandstone (Field & Browne, 1986).

Kekenodon Group sedimentary rocks accumulated slowly in sediment-starved, **shallow marine** platform environments. Sedimentary structures suggest strong current activity at times (Field & Brown et al. 1989), while crustal flexure or sea level changes resulted in local unconformities” (Cox and Barrell, 2007).

### ***Kekenodon Group (eMk)***

(QMAP database spelling: Kekenodon Gp Otekaike/Kokoamu)

**Inferred age:** 30-23 Ma (Boyes et al., 2012)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = greensand, basalt tuff, sandstone; Description = Calcareous greensand and cemented bioclastic limestone; locally with interbedded basalt flows or tuff. Sandstone in west (QMAP database). “An **outer shelf** fauna in the lower part of the Kokoamu Greensand is replaced in the upper Kokoamu Greensand by a relatively shallow **mid-shelf** fauna which persists into the Otekaike Limestone. In the upper Waitakian part of the Otekaike Limestone an **inner-shelf** environment is indicated” (Ayress, 1993). “The Otekaike Limestone is also a massive fossiliferous marine rock, more resistant than the Kokoamu... Foraminiferal faunas indicate quiet **mid-shelf** depths in a sheltered setting; upper parts of the unit become more muddy and eventually grade into calcareous deep water mudstone of the Mount Harris Formation. The Otekaike is widespread, and can be traced northwards scores of km into Canterbury and beyond” (Fordyce and Maxwell, 2003). “Kokoamu Greensand (bedded and macrofossil-rich in places) and Otekaike Limestone mark shallower settings, probably of **mid-shelf** depths below storm wave base” (Fordyce, 2009) – *the EoD is an average of the two formations based on Ayress (1993) and Fordyce and Maxwell (2003) who interpret the Kokoamu Greensand and Otekaike Limestone sequence as outer shelf at the base, mid-shelf through the middle, and inner-shelf at its top.*

### ***Brothers Volcanics (eMk\_b)***

(QMAP database spelling: Kekenodon Gp Brothers Volcanics)

**Inferred age:** 27 Ma (Field and Browne, 1989)

**EoD:** submarine mafic eruptives

**Basis for interpretation:** Main\_Rock = **basalt**; Sub\_Rocks = limestone greensand; Description = Basaltic tuff and palagonitic basalt flows **interbedded with limestone**; locally **pillow texture**; commonly weathered (QMAP database). “Glassy basaltic flows, pillow lavas and tuffs (Brothers Basalt; eMb), up to 30 m thick, are interbedded with Otekaike Limestone and Kokoamu Greensand in the Mt Somers area (Oliver & Keene 1989)” (Cox and Barrell, 2007). “...**tholeiitic** olivine basalt and volcanoclastics...” (Field and Browne, 1989) – *submarine setting is based on Cox and Barrell (2007) because it is described as being interbedded with the Otekaike Limestone and Kokoamu Greensand.*

### ***Thomas Formation (eMk\_t)***

(QMAP database spelling: Kekenodon Gp Thomas Formation)

**Inferred age:** 25-23 Ma (Field and Browne, 1989)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = tuff, basalt, conglomerate, breccia; Description = Cream indurated limestone; basaltic tuff; associated flow units and volcanogenic breccia (QMAP database). “In Castle Hill Basin, Kekenodon Group consists of 125 m of interbedded limestone, basaltic tuff and scoriaceous breccia” (Cox and Barrell, 2007). “The Thomas Formation limestone is a typical New Zealand cool water biosparite deposited on the **inner shelf** as a result of storms and debris flows, with the upper cross-bedded limestone lithofacies being reworked by currents in shallow water... The interbedded tuffs are a result of basaltic marine volcanism on the **inner to mid shelf**” (Congdon, 2003) – *on the Aoraki map area the formation is dominantly a limestone that formed on the innermost shelf. Mid-shelf may be an appropriate alternative. To the west on the Christchurch map area the Thomas Formation is only mapped at Avoca, which is described by Gage (1970) as being a volcanic deposit in a location unfavourable for limestone deposition (refer to “Thomas Formation (Ot)”).*

## Eyre Group + Kekenodon Group (Ee-eMk)

**Inferred age:** 55-33, 30-23 Ma (Boyes et al., 2012)

**EoD breakdown:** 55-39 Ma: innermost shelf (Homebush Sandstone)  
38-35 Ma: mid-shelf (Burnside Mudstone, Waratah Sandstone)  
34-33 Ma: outer shelf (Amuri Limestone)  
30-23 Ma: mid-shelf (Kekenodon Group)

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = lignite, mudstone, limestone, green-sand; Description = Poorly exposed; deformed Tertiary sediments near Maori Lakes; South Ashburton catchment (QMAP database) – based on the unit code this unit appears to include Eocene Eyre Group (Ee) and Kekenodon Group (eMk) sediments. The EoD is therefore based on the members within those groups.

## Motunau Group (eMn)

**Inferred age:** 22-16 Ma (Boyes et al., 2012)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = siltstone, mudstone; Description = Blue-grey to yellow-grey quartz sandstone and siltstone; commonly calcareous with tabular concretions (QMAP database). “Early Miocene quartzose sandstone and minor siltstone (Motunau Group; Mn) overlies Kekenodon Group rocks... Motunau Group comprises several distinctive facies to which a range of local formation names have been applied. Greenish grey, calcareous, muddy fine sandstone, commonly with scattered macrofossils and concretions (Tokama Siltstone) is a common lithology in South Canterbury... Well-bedded muddy fine sandstone (Southburn Sand), blue-grey weathering to yellow-brown and containing prominent tabular concretions, is also widespread. North of the Rangitata River, yellow-grey, well-sorted, locally cross-bedded, fossiliferous fine sandstone (Curiosity Shop Sandstone) is a predominant rock type” (Cox and Barrell, 2007). “At Tengawai River the start of the Otaian times was marked by an influx from the west of cross-bedded sand (Southburn Sand). This **shallow shelf** sand unit prograded eastwards, extending to eastern onshore Canterbury by Altonian times... Between the prograding sand wedge and the Endeavour High, silty fine sandstone and siltstone (Tokama Siltstone) accumulated until the Altonian, when it was blanketed with Southburn Sand... [in mid Canterbury] the Oligocene, where preserved, is overlain unconformably by Altonian **coastal sand** (Curiosity Shop Sandstone and ?Altonian-Waiau-an Chalk Quarry Sandstone) and phosphatic greensand” (Field and Browne, 1989) – overall the Motunau Group appears to be an innermost shelf deposit in this region, although mid-shelf may be appropriate in some cases. NB: the six southernmost polygons of eMn on this map area are assigned a mid-shelf EoD to match that of Mo (Otakou Group, southern equivalent of Motunau Group) on the Waitaki map area.

## White Rock Coal Measures (Mn\_w)

(QMAP database spelling: Motunau Gp White Rock CM)

**Inferred age:** 16-6 Ma (Boyes et al., 2012)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = claystone; Sub\_Rocks = sandstone, lignite, conglomerate shell beds; Description = Quartzose claystone and sandstone; commonly carbonaceous; local lignite; minor siltstone conglomerate or shell beds (QMAP database). “In the Opihi catchment, Motunau Group marine sandstone is commonly succeeded by **shallow marine to non-marine** weak claystone, siltstone and sandstone of the Early Miocene White Rock Coal Measures” (Cox and Barrell, 2007). “To the south-west the sequence becomes dominantly **non-marine** (White Rock Coal Measures of Gair 1959) in the Fairlie-Geraldine-Timaru area” (Carlson et al., 1980) – EoD is based on the interpretations in Cox and Barrell (2007) and Carlson et al. (1980). The map unit could alternatively have an innermost shelf EoD.

## Kekenodon Gp + Motunau Gp (eMk-eMn)

**Inferred age:** 30-16 Ma (Boyes et al., 2012)

**EoD breakdown:** 30-23 Ma: mid-shelf (Kekenodon Group)  
22-16 Ma: innermost shelf (Motunau Group)

**Basis for interpretation:** Main\_Rock = sandstone; Description = Poorly exposed quartz sandstone at Haast Stream; South Ashburton catchment (QMAP database). *Based on the unit code this unit appears to include Kekenodon Group (eMk) and Motunau Group (eMn) sediments. The EoD is therefore based on that of the respective groups.*

### **Kowai Formation (PL\_k; PL\_kc; PL\_kg)**

Includes local names: Cannington Gravel (PL\_kc), and Glentanner Beds (PL\_kg).

**Inferred age:** 5-1 Ma (Boyes et al., 2012)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = gravel; Sub\_Rocks = sand, silt, clay; Description = **Fluvatile** gravel with clay silt and sand beds; mainly greywacke-derived; commonly brown-weathered; occasionally blue-grey (QMAP database). “Brown-weathered greywacke conglomerate with interbedded sandstone, mudstone and minor lignite (Kowai Formation; Pk)... Local names have been applied in coastal South Canterbury (Cannington Gravel) and the Mackenzie Basin (Glentanner Beds)” (Cox and Barrell, 2007). “Field & Browne (1986) synonymised Cannington Gravels with the Kowai Formation, which they interpreted as a **non-marine/shallow marine** unit with a wide distribution in Canterbury” (Feldmann et al., 2008) – *EoD is based on the comments in the literature which suggest that the Kowai Formation was initially deposited in a shallow marine (i.e. innermost shelf) environment which became progressively more estuarine and fluvial. It is unlikely that there was an instantaneous transition from marine to non-marine, but for this project, it is assumed to have taken place between 5 and 4 Ma. On the paleogeography maps these gravels are included in the onshore area as the marine part of them was probably only a brief inundation, the detail of which is beyond the scope of this project.*

### **Timaru Basalt (IPlt)**

**Inferred age:** 3 Ma (Hoernle et al., 2006)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = **basalt**; Sub\_Rocks = tuff; Description = Olivine and hypersthene basalt flows (QMAP database). “It includes a number of flows of coarse-grained olivine, hypersthene and olivine-hypersthene **basalt**, locally underlain by tuff” (Cox and Barrell, 2007) – *refer to “Timaru Basalt (IPlt, IPlt~)” on the Waitaki map area for further information.*

### **Geraldine Basalt (IPlg)**

**Inferred age:** 3 Ma (Cox and Barrell, 2007)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = **basalt**; Sub\_Rocks = tuff; Description = Olivine and hypersthene basalt flows (QMAP database). “Geraldine Basalt, up to 15 m thick and dipping gently east, overlies Kowai Formation at Geraldine Downs” (Cox and Barrell, 2007) – *EoD is based on there being no mention of submarine products, and because the basalt overlies Kowai Fm (Cox and Barrell, 2007) which seems to be predominantly onshore, so the basalt is assumed to be subaerial as well.*

## **Quaternary – Sedimentary deposits**

- **All Q deposits** (except – see below)

**EoD:** onshore

**Basis for interpretation:** Based on the QMAP database which includes alluvial, beach, colluvial, lacustrine, landslide, loess, man-made fill, scree, swamp, and till sediments in the Quaternary deposits.

- **mQb\_sc, mQb\_pc, mQb\_ch**

**EoD:** innermost shelf

**Basis for interpretation:** “...isolated remnants of raised **marine** terraces” (Cox and Barrell, 2007).

## CHRISTCHURCH AREA (Geological Map 16)

### Eyre Group

"...**marine** sedimentary rocks of the Eyre Group at the Canterbury range front are of Paleocene and Eocene age. Dark grey, concretionary, silty sandstone (at the base), greensand, and pale grey, glauconitic quartzose sandstone are mapped as Pe. Above these lies pale grey, burrowed quartzose sandstone with minor greensand at the top near Oxford (Ee). Along the central and northern parts of the range front, these rocks and their lateral correlatives, including significant mudstone, are combined on the map as PEe" (Forsyth et al., 2008). "...the map area became inundated by the sea in the early part of the Tertiary Period (about 65 Myr ago). Over the succeeding 50 million years, a thin sequence of siliceous and volcanic-derived sedimentary rocks of the Eyre Group and the Burnt Hill Group was slowly deposited on a **shallow marine shelf**. The presence of unconformities within the sequence suggests that the sea floor may have been periodically uplifted to become dry land. Some of these rocks are now exposed between Governors Bay and Charteris Bay" (Sewell et al., 1992).

### Paleocene Eyre Group (Pe)

Includes Charteris Bay Sandstone, and Waipara Greensand.

#### **Conway Fmn/Charteris Bay Sst**

**Inferred age:** > 65-57 Ma (Boyes et al., 2012)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = siltstone, greensand; Description = Jarositic silty sst (Conway Fmn) overlain by glauconitic quartzose sandstone (Charteris Bay Sst). Marine (QMAP database). "The quartzose, slightly glauconitic Charteris Bay Sandstone, for example, was deposited in **shallow**, high energy marine environments – very **shallow marine, almost tidal** in the west around Broken River, and also at Resolution-1" (Field and Browne, 1989) – *this unit code appears to include Conway Formation and Charteris Bay Sandstone. Conway Formation is older than 65 m.y. in this map area therefore the EoD of the Charteris Bay Sandstone is adopted here.*

#### **Conway Fmn/Waipara Greensand**

**Inferred age:** 65-51 Ma (Boyes et al., 2012)

**EoD:** mid shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = siltstone, greensand; Description = Jarositic concretionary silty sandstone (Conway Fmn) overlain by greensand (Waipara Greensand). Marine. (QMAP database). "The top of the Waipara Greensand marks the Teurian – Waipawan local stage boundary, which is correlated internationally with the Paleocene – Eocene boundary (Cooper 2004)... The Waipara Greensand has been interpreted as having been deposited in a **shallow marine** setting under conditions of very slow sedimentation (Browne and Field 1985). An analysis of the glauconite content suggested to Bassett and Kapoutsos (2005) that the sedimentation rates were extremely low with glauconite formation taking place in nearshore marine, or possibly estuarine, environments... Of interest are the palaeogeographic reconstructions by King (2000) that place the Waipara River area of North Canterbury in a shallow to **mid-shelf** position during the Late Cretaceous and Paleocene... On balance, perhaps a **mid-shelf** interpretation best fits the available data" (Mannering and Hiller, 2008) – *this unit code appears to include Conway Formation and Waipara Greensand. Conway Formation is older than 65 m.y. in this map area therefore the EoD of the Waipara Greensand is adopted here.*

#### **Conway/Waipara/Charteris Bay**

**Inferred age:** > 65-51 Ma (Boyes et al., 2012)

**EoD breakdown:** > 65-57 Ma: innermost shelf (Charteris Bay Sandstone)  
56-51 Ma: mid-shelf (Waipara Greensand)

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = siltstone greensand; Description = Jarositic silty sst (Conway) overlain by interfingering greensand (Waipara) and glauconitic quartz sst (Charteris Bay). Marine (QMAP database) – *this unit code appears to include Conway Formation,*

Waipara Greensand and Charteris Bay Sandstone. Conway Formation is older than 65 m.y. in this map area so it is ignored here. The EoDs of the Charter Bay Sandstone and Waipara Greensand are adopted here.

## Paleogene Eyre Group (PEe)

### Charteris Bay Sandstone (PEe)

*EoD*: innermost shelf

- 2 polygons in the inland basins

*Inferred age*: > 65-42 Ma (Boyes et al., 2012)

*Basis for interpretation*: Main\_Rock = sandstone; Sub\_Rocks = greensand, mudstone; Description = Marine, pale green, glauconitic quartzose sandstone grading upward to dark greensand (QMAP database). "In the inland Canterbury basins... **marine** rocks including fine, glauconitic, quartzose sandstone that grades upwards into dark greensand (PEe)" (Forsyth et al., 2008) – *the EoD is defined as innermost shelf, after Field and Browne (1989), however a deeper EoD may be appropriate. Refer to "Charteris Bay Sandstone (PEec)" on the Aoraki map area for further information.*

- 3 polygons in Charteris Bay

*Inferred age*: > 65-57 Ma (Boyes et al., 2012)

*Basis for interpretation*: Main\_Rock = sandstone; Sub\_Rocks = mudstone; Description = Massive, light grey/yellow-brown, medium to fine, quartzose (qtz-cemented) sandstone; locally glauconitic with thin beds of mudstone (QMAP database). "The rest of the Eyre Group, exposed in a few places nearby, consists of quartzose sandstone that is locally glauconitic with thin beds of mudstone, tuffaceous sandstone and gritty sandstone" (Forsyth et al., 2008).

### Loburn Mudstone

"This unit is a dark-coloured, soft, moderately bioturbated sandy mudstone that conformably overlies the Haumurian to Teurian, (Maastrichtian to Paleocene) Conway Siltstone (Browne and Field 1985). It is dated as Teurian (Paleocene; Danian) (Browne and Field 1985)... On balance, perhaps a **mid-shelf** interpretation best fits the available data" (Mannering and Hiller, 2008).

*EoD*: mid-shelf

*Basis for interpretation*: *EoD is after Mannering and Hiller (2008).*

### Waipara Greensand

"The Waipara Greensand has been interpreted as having been deposited in a **shallow marine** setting under conditions of very slow sedimentation (Browne and Field 1985)... On balance, perhaps a **mid-shelf** interpretation best fits the available data" (Mannering and Hiller, 2008).

*EoD*: mid-shelf

*Basis for interpretation*: *Refer to "Conway Fmn/Waipara Greensand" for further information.*

### Ashley Mudstone

"Paleobathymetric indicators within the benthic foraminiferal assemblages, including *Anomalinoidea semicribratus*, *A. capitatus*, *Nuttallides carinotruempii*, and *Pleurostomella* spp., indicate a **lower bathyal** depositional depth (van Morkhoven et al., 1986). Because terrestrial palynomorphs compose >30% of the palynomorph assemblage (Fig. 1A), a steep west to east shelf-slope profile is inferred for the northern Canterbury basin" (Hollis et al., 2009).

*EoD*: lower bathyal

*Basis for interpretation*: *The Ashley mudstone is inferred to be of lower bathyal depth in this region, based on the available literature, but shallower depths (up to outer shelf) may be appropriate in other regions.*

### Homebush Sandstone (Ee)

*Inferred age*: 53-35 Ma (Boyes et al., 2012)

*EoD*: innermost shelf

*Basis for interpretation*: Main\_Rock = sandstone; Sub\_Rocks = greensand; Description = Pale grey,

soft, fine-med quartzose sandstone (Homebush Sandstone); minor greensand at top (Feary Greensand) (QMAP database). "...a poorly-dated yellowish grey, non-calcareous, locally gritty, quartzose sandstone of **nearshore** facies... The Homebush Sandstone is the main Middle (to ?Late) Eocene unit of mid Canterbury and reflects the **shallow marine** conditions that prevailed around the western end of the Chatham Rise at that time" (Field and Browne, 1989). "The depositional environment for the formation is regarded as **nearshore to beach** (Van der Lingen, 1984)" (Mould, 1992). "...a massive **estuarine deltaic** deposit..." (Carlson et al., 1980) – *based on the description in the QMAP text and the map sheet, this unit code appears to include undifferentiated Eocene Eyre Group. However the Strat\_Unit is Homebush Sandstone, so the EoD of this formation is adopted here. Interpretations from Carlson et al. (1980) and Mould (1992) indicate an onshore paleoenvironment as an alternative/minor EoD for the Homebush Sandstone.*

### **Karetu Sandstone**

"...a slightly calcareous, quartz-rich unit that becomes finer up-sequence, locally overlies the Homebush in southern North Canterbury. Both the Homebush Sandstone and Karetu Sandstone probably grade eastwards into the Ashley Mudstone" (Field and Browne, 1989).

*EoD: innermost shelf*

*Basis for interpretation: The sandstone must be shallower than the bathyal Ashley Mudstone, so it is here assumed to be an innermost shelf deposit, although mid-shelf could be an alternative EoD.*

### **Paleogene Eyre Group East of Kaiwara Fault/Scargill**

**Inferred age:** > 65-39 Ma (Boyes et al., 2012)

**EoD breakdown:** > 65-54 Ma: mid shelf (Waipara Greensand, Loburn Mudstone)  
53-39 Ma: lower bathyal (Ashley Mudstone)

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = greensand sandstone; Description = Calcareous, bentonitic, sandy mst (Ashley Mst) in upper part; greensand (Waipara GS) and micaceous mst (Loburn Mst) in lower part (QMAP database) – *the EoD of this Strat\_Unit is based on the comprising units. Where units may be contemporaneous, an average EoD is given. These polygons are located east of the Kaiwara Fault and Scargill. Refer to "Paleogene Eyre Group (PaEe)" on the Kaikoura map area for further interpretations of these units.*

### **Paleogene Eyre Group West of Kaiwara Fault/Scargill**

**Inferred age:** > 65-35 Ma (Boyes et al., 2012)

**EoD breakdown:** > 65-54 Ma: mid shelf (Waipara Greensand, Loburn Mudstone)  
53-35 Ma: innermost shelf (Homebush Sandstone, Karetu Sandstone)

**Basis for interpretation:** Main\_Rock = greensand OR mudstone OR sandstone; Sub\_Rocks = mudstone, sandstone OR greensand, sandstone OR greensand, mudstone; Description = Glauconitic quartz sandstone (Hbush/Karetu) and calcareous, bentonitic, sandy mustone (Ash) in upper part; greensand (Waip) and mica mudstone (Loburn) in lower (QMAP database) – *the EoD is based on the units which make up the upper western Eyre Group. Where units are contemporaneous an average EoD is assigned. These polygons are located west of the Kaiwara Fault and Scargill. Refer to "Paleogene Eyre Group (PaEe)" on the Kaikoura map area for further interpretations of these units.*

### **Broken R/Conway/Waipara/Loburn (IKPe)**

Includes Claverley Sandstone and Loburn Mudstone.

**Inferred age:** > 65-52 Ma (Boyes et al., 2012)

**EoD breakdown:** > 65-60 Ma: mid-shelf (Claverley Sandstone, Loburn Mudstone)  
59-52 Ma: innermost shelf (Claverley Sandstone)

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = siltstone, mudstone, greensand; Description = Non-marine coal measures at base, overlain by marine siltstone, mudstone, and greensand; grouped for cartographic reasons (QMAP database) – *this unit code is mapped as undifferentiated Late Cretaceous and Paleocene Eyre Group. All but one of the polygons are labelled as Conway Formation which in this map area is older than 65 Ma. The EoD for this single polygon is assigned the same as that of the adjacent IKEe Eyre Group from Kaikoura. It is labelled as IKc+PEe on the map sheet. Refer to "Late Cretaceous to Eocene Eyre Group (IKEe)" on the Kaikoura map area for further interpretation of these units.*

## ***View Hill Volcanics (Eev)***

- **Basalt**

***Inferred age:*** 58-48 Ma (Boyes et al., 2012)

***EoD:*** submarine mafic eruptives

***Basis for interpretation:*** Main\_Rock = basalt; Sub\_Rocks = tuff breccia, sandstone, mudstone, limestone; Description = Interbedded basalt lava flows, pillow lavas, marine tuff, mudstone, sandstone, limestone, rare volcanogenic breccia (QMAP database). “This formation consists of **shallow marine sedimentary** as well as volcanic rocks, and includes interbedded **basaltic flows, pillow lava, tuff**, mudstone, sandstone, limestone and rare volcanic breccia. It also includes a dolerite intrusion near Coalgate” (Forsyth et al., 2008). “Speight (1927) first described the alkaline basalts and limburgites of the Oxford area as flows, sills, and notably pillow lavas. Gregg (1964) defined them as View Hill Basalt Formation with its type locality at Whites Creek where pillow lavas are overlain by Mangaorapan tuffaceous mudstone” (Carlson et al., 1980) – *the EoD is defined because the main rock type is basalt, the mention of pillow lavas, and that it is interbedded with shallow marine sediments. Innermost to mid-shelf may be an alternative environment.*

- **Dolerite**

***Inferred age:*** 58-48 Ma (Boyes et al., 2012)

***EoD:*** mafic intrusives

***Basis for interpretation:*** Main\_Rock = **dolerite**; Sub\_Rocks = basalt, sandstone; Description = Mainly consisting of a large dolerite sill (Speight 1928) and many dikes; quartzose sandstone xenoliths (QMAP database). “**Olivine dolerite** dikes are found in the Coalgate area (Carlson & Rodgers 1975) with no associated flows or pillow lavas” (Carlson et al., 1980) – *this polygon near Coalgate is a mafic dolerite intrusion.*

## ***Amuri Limestone (Oea)***

***Inferred age:*** 34-32 Ma (Boyes et al., 2012)

***EoD:*** outer shelf

***Basis for interpretation:*** Main\_Rock = limestone; Sub\_Rocks = micrite; Description = Pale grey, hard, bioturbated, fine grained, slightly glauconitic, micritic limestone. Stylolitic fractures common. (QMAP database). “The uppermost unit of the Eyre Group in the Canterbury foothills is Amuri Limestone (Oea). It is a distinctive and typically hard, pale grey, thinly bedded, fine-grained limestone. Oxford Chalk is a local and less cemented facies (van der Lingen et al. 1978; Andrews et al. 1987)... Although Amuri Limestone is of Paleocene to Eocene age further north (Rattenbury et al. 2006), in the Christchurch map area it is Early Oligocene in age (Whaingaroan; Andrews et al. 1987; Field, Browne et al. 1989)” (Forsyth et al., 2008). “Much of Canterbury was submerged in the Oligocene, when micrite (Amuri Limestone) [...] was deposited... In northern Canterbury, north of the Waiau River, the Amuri is moderately siliceous near the base (e.g., 032/c8), at Oxford it is chalky (L35/c3; “Oxford Chalk”) and in much of southern Canterbury it is marly. In North Canterbury the Amuri limestone was locally referred to as Amberley Limestone and in South Canterbury as Holme Station Limestone... The Amuri generally has an outer neritic to bathyal microfauna and this, coupled with its fine texture, suggests an **outer shelf or slope** paleoenvironment” (Field and Browne, 1989) – *the Amuri Limestone is younger here than on the Kaikoura map area, where it is a Paleocene to Eocene bathyal deposit. Upper bathyal may be an alternative environment in the Christchurch map area.*

## ***Esk Formation (Oee)***

“...glauconitic fine sandstone (locally cross-bedded) and sandy siltstone unconformably overlies older Eyre Group or Torlesse rocks (Newman & Bradshaw 1981; McLennan & Bradshaw 1984). The unconformity is marked by a basal conglomerate in places” (Forsyth et al., 2008). “...**marginal marine conglomerate, pillow lava and pillow breccias** occur (Members E1 and E2 of the Esk Formation of Newman & Bradshaw 1981) and, although poorly dated, are inferred here to be Early to Middle Eocene...” (Field and Browne, 1989). “The formation accumulated under marine conditions and member E1 is probably a **high-energy shoreline** conglomerate reflecting the beginning of a marine transgression. **Basic volcanic** rocks of member E2 are probably **shallow marine to subaerial**. The 40 m remnant relief on the volcanics was sufficient to have a marked effect on the



sedimentation of E3, which suggests that depth was still modest at that time... Members E3 and E4 are similar to Whaingaroan glauconitic sands in the lower Puffers and lower Coleridge Formations" (Newman and Bradshaw, 1981).

- **Esk Formation**

Main\_Rock = sandstone; Sub\_Rocks = siltstone; Description = Glauconitic, trough cross-bedded very fine sandstone and massive very fine sandy siltstone (thin greensand at top) (QMAP database).

- **Esk Formation (member E1,E3, E4)**

Main\_Rock = sandstone; Sub\_Rocks = siltstone; Description = Glauconitic, trough cross-bedded very fine sandstone and massive very fine sandy zst, shellbeds adjacent to Oev, thin congl at base (NE) (QMAP database).

- **Esk Formation (member E3, E4)**

Main\_Rock = sandstone; Sub\_Rocks = siltstone; Description = Glauconitic, trough cross-bedded very fine sandstone with concretionary beds, and massive very fine sandy siltstone (QMAP database).

**Inferred age:** 34-28 Ma (Gage, 1970)

**EoD:** innermost shelf

**Basis for interpretation:** **E1:** "comprises conglomerate of subrounded Torlesse sandstone pebbles and cobbles (max. 30 cm) in a matrix of well-indurated sandy glauconitic biosparite." **E3:** "This member is predominantly trough cross-bedded, moderately sorted, very fine sandstone: glauconitic quartzarenite, with concretionary bands... Overall the sedimentology, thickness, and faunal characters of member E3 strongly suggest the progressive burial of volcanic mounds in a **shallow marine** setting." **E4:** "This unit is mainly a yellow brown, massive, friable, bioturbated, glauconitic, poorly sorted, very fine sandy siltstone" (Newman and Bradshaw, 1981) – *the lower 3 (dominantly) sedimentary members of the Esk Formation (there is a total of 7 members as defined by Newman and Bradshaw (1981), E2 is a dominantly volcanic member – see below) that are mentioned in the QMAP database are here inferred to have been deposited in an innermost shelf environment. However, mid-shelf may be an alternative EoD during this period.*

- **Esk Formation (Puffer Fmn P1-P3)**

**Inferred age:** 34-28 Ma (Gage, 1970)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = conglomerate, greensand; Description = Pale green, cross bedded, glauconitic fine sandstone with concretionary beds; unconformable base marked locally by conglomerate (QMAP database). "...the most significant member of Puffer Formation is the basal unit, P1... The fossils in the sandy matrix of member P1 suggest that the basal conglomerate was deposited under **marine** conditions, and the sediment textures indicate debris flow or other mass-flow modes of emplacement, perhaps associated with storms. Occasional pebbles of coal measures and pale calcareous mudstone (which resemble the calcareous rocks of the coeval Coleridge Formation) in the overlying crossbedded member (P2) indicate later, minor pulses of uplift and additional intrabasinal cannibalism" (McLennan and Bradshaw, 1984). "...although volcanic material was not seen in the Puffer Formation, it is present in the otherwise very similar contemporary Esk Formation..." (Gage, 1970) – *the Puffer Formation is considered to be a lateral equivalent of the Esk Formation so is here assigned the same EoD and age.*

- **Esk Formation (member E2) (Oev)**

**Inferred age:** 34-28 Ma (Gage, 1970)

**EoD:** submarine mafic eruptives; and mafic intrusives

**Basis for interpretation:** Main\_Rock = basalt; Sub\_Rocks = tuff breccia; Description = Basalt pillow lava; pillow breccia; tuff (QMAP database). "In the Brechin Burn, Esk Formation is associated with **basaltic pillow breccia, tuff and a stock (Oev)**" (Forsyth et al., 2008). "Member E2 forms the base of the continuous succession. It comprises pillow lava, pillow breccia, tuff, and related intrusive bodies of basalt with well-marked columnar jointing" (Newman and Bradshaw, 1981). "Tuff, pillow breccia and columnar basalts also occur at the Brechin Burn (Member E2 of Newman & Bradshaw

1981) and are correlated, on the basis of stratigraphic position, with the View Hill Volcanics” (Field and Browne, 1989) – *there are two polygons of this unit code; one of them is described as pillow lava, breccia and tuff and is here considered to be a submarine mafic eruption. The other polygon is described as an intrusive stock, so is here considered to be a mafic intrusive.*

### **Thomas Formation (Ot)**

**Inferred age:** 25-23 Ma (Field and Browne, 1989)

**EoD:** submarine mafic eruptives

**Basis for interpretation:** Main\_Rock = tuff; Sub\_Rocks = basalt volcanic sandstone; Description = Carbonate-cemented basaltic bedded and agglomeratic tuff; associated feeder dikes, minor volcanoclastic sandstone (QMAP database). “At Avoca, the Thomas Formation (Ot) consists of carbonate-cemented basaltic tuff intruded by dikes and sills of similar composition (McLennan 1981). Just west of the map area in Castle Hill basin, Thomas Formation is predominantly limestone” (Forsyth et al., 2008). “At Avoca, where the formation is represented only by thick **tuffs intruded by basaltic sills and dikes**, it is thought most likely that proximity to **submarine** eruptive centres was unfavourable for limestone deposition” (Gage, 1970). “The interbedded tuffs are a result of **basaltic marine volcanism** on the **inner to mid shelf**” (Congdon, 2003) – *the only mapped occurrence of this formation on the Christchurch map area is at Avoca. This area is described by Gage (1970) as being unfavourable for limestone deposition, so is considered here to be submarine mafic eruptives (with minor mafic intrusives), that formed at innermost to mid-shelf depth. To the west on the Aoraki map area Thomas Formation is a sedimentary innermost shelf deposit (eMk\_t).*

### **Mounseys Creek plug (Ov)**

**Inferred age:** 30 Ma (McLennan and Weaver, 1984)

**EoD:** mafic intrusives

**Basis for interpretation:** Main\_Rock = olivine **nephelinite**; Description = Olivine nephelinite plug at Mounseys Creek (QMAP database). “A small **plug** of olivine nephelinite (Ov) occurs beside a fault at Mounseys Creek, on the range front north of the Eyre River near View Hill” (Forsyth et al., 2008). “Petrographically, the Mounseys Creek rock is a glassy olivine-nephelinite or limburgite” (McLennan and Weaver, 1984) – *nephelinite is a basic igneous rock, here implied to be an intrusion after comments in McLennan and Weaver (1984).*

## **Motunau Group**

### **Undifferentiated lower Motunau Group (Onl)**

(QMAP database spelling: Omihi Fmn (Weka Pass Stone mb))

Includes Omihi Formation, Weka Pass Stone, Tekoa Limestone, Flaxdown Limestone, Whales Back Limestone, Spy Glass Formation, Isolated Hill Limestone, and Hanmer Marble.

“Motunau Group marks a period of mainly **shallow marine** sedimentation that culminated in marine regression... Much of the Motunau Group is undifferentiated on the map, but some formations are shown where exposure and map scale allow... Along the Canterbury range front the basal unit of Motunau Group is Omihi Formation (Onl), which consists of hard, glauconitic sandy limestone in the Waipara area (“Weka Pass Stone”; Fig. 31) and calcareous greensand further southwest” (Forsyth et al., 2008). “It occupies the central part of North Canterbury, and is a **comparatively deep-water** deposit... The Weka Pass Stone is typically a thoroughly cemented, cream to light grey, massive, sandy limestone with fine disseminated glauconite” (Andrews, 1963). “Two distinct, coarser-grained lithologies were deposited at **shelf to bathyal** depths in the western depocentre... It is not known if the two lithofacies [Weka Pass Stone and Whales Back Limestone] are separated by a fault or represent simply a shelf-slope transect” (Field and Uruski, 1997).

**Inferred age:** 27-22 Ma (Andrews, 1963; Field and Browne, 1989; Mould, 1992; Field and Uruski, 1997; Rattenbury et al., 2006)

**EoD breakdown:** 27-26 Ma: outer shelf (Omihi Formation, Berrydale Greensand, Gorries Creek Greensand, Weka Pass Stone, Tekoa Limestone, Flaxdown Limestone, Isolated Hill Limestone, Hanmer Marble)  
25 Ma: upper bathyal (mid-bathyal in east; Omihi Formation, Berrydale Greensand, Gorries Creek Greensand, Weka Pass Stone,

Whales Back Limestone, Spy Glass Formation, Isolated Hill Limestone, Hanmer Marble)  
24-22 Ma: upper bathyal (mid-bathyal in east; Omihi Formation, Berrydale Greensand, Gorries Creek Greensand, Whales Back Limestone, Spy Glass Formation, Isolated Hill Limestone, Hanmer Marble)

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = sandstone; Description = Hard, glauconitic, sandy limestone. Mainly comprises Weka Pass Stone member (QMAP database). *The EoD breakdown for Onl is based on the depositional age and paleoenvironmental interpretations of the formations/members that make up the map unit. Units with an outer shelf depositional environment are the most common elements within the 27-26 Ma period. The environment deepens from 25 Ma with the deposition of upper bathyal Whales Back Limestone and mid-bathyal Spy Glass Formation. Refer to “Undifferentiated lower Motunau Group” on the Kaikoura map area for more information.*

### **Mount Brown/Tokama/Waikari Formations (Mn)**

(QMAP database spelling: Mt Brown/Tokoma/Waikari Fmns)

“Undifferentiated Motunau Group (Mn) includes blue-grey, calcareous, sandy siltstone; brown, calcareous sandstone (locally with limestone or minor fossiliferous greywacke-clast conglomerate); and grey calcareous, glauconitic, sandy siltstone” (Forsyth et al., 2008). “Overall, the Waipara-Waikari region, North Canterbury experienced a shallowing from **outer shelf to mid shelf** environment during the Otaian Stage reflected in the Waikari Formation deposits, and **mid to inner shelf** depositional environment during the Altonian Stage, reflected in the Mount Brown Formation deposits” (Hobbs, 2010).

#### • **Tokama Siltstone (Mn)**

(QMAP database spelling: Tokoma Siltstone)

*EoD: mid-shelf*

**Basis for interpretation:** Main\_Rock = siltstone; Sub\_Rocks = sandstone, conglomerate, shell beds; Description = Blue-grey calcareous, sandy siltstone with two fossiliferous pebble conglomerate bands (Double Corner Shell Beds) (QMAP database). “...**middle neritic**, calcareous, fine sandy siltstone” (Field and Browne, 1989) – *middle neritic is taken to be equivalent to a mid-shelf EoD.*

**Inferred age:** 23-9 Ma (Boyes et al., 2012)

**EoD breakdown:** 23-21 Ma: outer shelf (Waikari Formation)

20 Ma: mid-shelf (Waikari Formation)

19-9 Ma: mid-shelf (Mount Brown Formation, Tokama Siltstone)

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = siltstone, limestone; Description = Blue-grey calcareous, sandy siltstone; brown, calcareous sandstone, locally with limestone beds; grey calcareous glauconitic sandy siltstone.

Main\_Rock = sandstone; Sub\_Rocks = siltstone, limestone; Description = Blue-grey calcareous, sandy siltstone; brown, calcareous sandstone, with 20 m thick limestone bed; grey calcareous glauconitic sandy siltstone.

Main\_Rock = sandstone; Sub\_Rocks = siltstone, limestone, conglomerate, shell beds; Description = Blue-grey calcareous, sandy siltstone with conglomerate beds in southwest; brown, calcareous sandstone, locally with limestone beds; calcareous glauconitic sandy siltstone.

Main\_Rock = sandstone; Sub\_Rocks = siltstone, limestone, conglomerate, shell beds; Description = Blue-grey calcareous, sandy siltstone; brown, calcareous sandstone with 40 m thick limestone (west) & conglomerate beds; calcareous glauconitic sandy siltstone (QMAP database) – *the EoD breakdown for the map unit is based on the depositional age and paleoenvironmental interpretations of the members that make up the map unit. Refer to “Waikari Formation (Mnk)” and “Mount Brown Formation (Mnb)” on the Kaikoura map area for further information and interpretations of these units.*

## ***Brechin (Enys) Formation (Mne)***

"In the inland basins, Brechin Formation (Mne) mainly comprises **fluvial** conglomerate with greywacke clasts, with some gabbro-clast conglomerate, **marine** sandstone and minor carbonaceous mudstone near the base..." (Forsyth et al., 2008). "...the bulk of the Brechin Formation is the regressive B4 which marks the progradation of mainly **fluvial** conglomerate in response to major uplift of Torlesse basement... Brechin member B2 lithologies resemble the lower Enys Formation (Gage 1970) at Castle Hill, while the greywacke conglomerate in the upper Enys Formation corresponds broadly to member B4" (Newman and Bradshaw, 1981). "In the western part of central Canterbury, at Broken River, over 600 m of **estuarine** siltstone, lignite, and sandstone pass up-sequence into thick greywacke-derived boulder to pebble conglomerate (Brechin Formation), probably reflecting active faulting" (Field and Browne, 1989).

### • **Brechin Formation**

Main\_Rock = conglomerate; Sub\_Rocks = sandstone, siltstone, mudstone, limestone, tuff; OR sandstone, siltstone, mudstone; Description = **Fluvial** greywacke-clast conglomerate with local basal units of reworked tuff and limestone, gabbro-clast conglomerate, **marine** sandstone and mudstone; OR **Fluvial** greywacke-clast conglomerate and minor sandstone with local basal units of gabbro-clast conglomerate, **marine** sandstone and mudstone (QMAP database).

Main\_Rock = sandstone; Description = Sandstone with shell beds and concretions, disturbed by numerous faults; OR Light brown sandstone with calcified bands, greywacke conglomerate at base (Gage 1956); OR Green-grey, friable, fine quartz-rich sand with <5% glauconite (QMAP database).

### • **Enys Formation**

Main\_Rock = siltstone; Sub\_Rocks = sandstone, mudstone, conglomerate, coal; Description = Pale green siltstone and carbonaceous mudstone. Minor pebbly sandstone at top. Coal, basalt-clast conglomerate, shellbeds at base (QMAP database). "A thick succession of sediments marking a **transition from shallow marine to estuarine and possibly lacustrine and fluvial** conditions... In the eastern part of the area a seam of coal occurs in Slovens Creek immediately above a basalt conglomerate made up largely of basalt pebbles. **Marine** fossils are limited to the lowest 10 ft or so of the succeeding grey silts and sands which grade up into greenish grey **non-marine** clays and sands" (Gage, 1970).

**Inferred age:** 16-5 Ma (Forsyth et al., 2008)

**EoD:** onshore (conglomerates); innermost shelf (sandstones and siltstones)

**Basis for interpretation:** *EoD for the polygons labelled "Brechin (Enys) Formation" is based on the interpretation in Newman and Bradshaw (1981) and the QMAP lithologic descriptions. Each polygon has a unique description in the database. Onshore Brechin Formation is also mapped on the Grey-mouth map area (IMPm).*

## ***View Hill Volc and Brechin Fmn (Mne)***

(QMAP database spelling: View Hill Volc and Brechin Fmn)

**Inferred age:** 58-48, 16-5 Ma (Forsyth et al., 2008; Boyes et al., 2012)

**EoD breakdown:** 58-48 Ma: submarine mafic eruptives (View Hill Volcanics)  
16-5 Ma: innermost shelf (Brechin Formation)

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = conglomerate, limestone, tuff, coal; Description = Fault-bounded sliver of yellow sands, conglomerate, coal (Brechin Fmn) and Eocene tuff and limestone (View Hill Volc) (QMAP database) – *on the geological map sheet this polygon has the unit code Mne+Eev which implies that it is undifferentiated Brechin Formation and View Hill Volcanics. Refer to "View Hill Volcanics (Eev)" and "Brechin (Enys) Formation (Mne)" for further information.*

## ***Greta Formation (Pln)***

Includes Ferniehurst siltstone, Bourne pebbly mudstone, Hawkswood deltaic, Brookdale coquina, Rutherford littoral, Leader siltstone, and Albyn conglomerate lithofacies.

"...consists of blue-grey, fine sandy siltstone, mudstone and minor debris-flow conglomerate, and is

the lateral equivalent of the more widespread Kowai Formation further west and south” (Forsyth et al., 2008). “The Greta Formation consists of a wide variety of **marine and terrestrial** facies, all but one (the Brookdale lithofacies, predominantly of **shallow-water** coquina limestone) being dominated by strongly bimodal clastic sediments (mudstone and conglomerate), with only a small proportion of sand-grade sediment” (Warren, 1995).

**Inferred age:** 17-1 Ma (Warren, 1995; Boyes et al., 2012)

**EoD breakdown:**

17-5 Ma:	<u>outer shelf</u> (Ferniehurst siltstone lithofacies)
4 Ma:	<u>outer shelf</u> (Ferniehurst siltstone and Bourne pebbly mudstone lithofacies)
3 Ma:	<u>outer shelf</u> (Ferniehurst siltstone, Bourne pebbly mudstone, Hawkswood deltaic, and Brookdale coquina lithofacies)
2 Ma:	<u>outer shelf</u> (Ferniehurst siltstone, Bourne pebbly mudstone lithofacies)
1 Ma:	<u>innermost shelf</u> (Ferniehurst siltstone, Rutherford littoral, Leader siltstone, Albyn conglomerate lithofacies)

**Basis for interpretation:** Main\_Rock = siltstone; Sub\_Rocks = mudstone, conglomerate; Description = Blue-grey fine sandy siltstone; mudstone; and minor debris-flow conglomerate (QMAP database) – *the EoD breakdown for the map unit is based on the depositional age and paleoenvironmental interpretations of the lithofacies that make up the Greta Formation. The Ferniehurst siltstone lithofacies is considered to represent background sediment of the Greta Formation (Warren, 1995), consequently a greater emphasis has been placed on the Ferniehurst siltstone lithofacies for the 17-2 Ma period. Refer to “Greta Formation (Png)” on the Kaikoura map area for further information and description of the lithofacies in this formation.*

### **Kowai Formation (Plk)**

“Brown, weathered, greywacke-clast conglomerate with interbedded sandstone, siltstone, mudstone and carbonaceous layers more common near the base (Kowai Formation, Plk) occurs widely in central and northern Canterbury. The entire formation was penetrated in the J.D. George-1 well, where it is 650 m thick, and similar thicknesses occur in other drillholes and sections (Andrews et al. 1987). In many places the lower part is **marine** with scattered shellbeds” (Forsyth et al., 2008). “Conformably over the top of the Mt Brown beds **shallow marine** sands and sandy gravels of the Kowai Formation are exposed for about another kilometre downstream before passing below the fill of late Pleistocene gravels. Elsewhere, the Kowai Formation extends through the Pliocene into the Early Pleistocene, becoming progressively more **estuarine and fluvial** with an increasing proportion of well rounded, weathered Torlesse-derived clasts” (Campbell et al., 2005). “This timing coincides with the change from deposition of marine Greta Formation to **terrestrial**, Torlesse Terrane derived, Kowai Formation, which is inferred to signal the onset of regional tectonic uplift” (Litchfield et al., 2003). “The Kowai Formation, a correlative of the Maori Bottom Formation, occurs between the Waitaki Valley and North Canterbury, and west to the Mackenzie Basin where it was known as Glentanner Formation. Kowai Formation consists of Torlesse-derived **fluvial** sheet conglomerates that interfinger in the east with sandstone, mudstone, lignite and **shellbeds**” (Field and Browne, 1989).

**Inferred age:** 7-2 Ma (Boyes et al., 2012)

**EoD breakdown:**

7-5 Ma:	<u>innermost shelf</u>
4-2 Ma:	<u>onshore</u>

**Basis for interpretation:** Main\_Rock = conglomerate; Sub\_Rocks = sandstone, siltstone, mudstone, shell beds; Description = Brown-weathered greywacke-clast conglomerate with beds of sandstone, siltstone, mudstone, carbonaceous layers and shellbeds more common towards base (QMAP database) – *EoD is based on the comments in the literature which suggest that the Kowai Formation was initially deposited in a shallow marine (i.e. innermost shelf) environment which became progressively more estuarine and fluvial. It is unlikely that there was an instantaneous transition from marine to non-marine, but probably fluctuated between marine and non-marine deposition for some time. The time when non-marine becomes dominant over marine is assumed to have taken place between 5 and 4 Ma.*

## Burnt Hill Group

“Burnt Hill Group occurs in the Oxford and Harper Hills areas, and on Banks Peninsula. It overlies Eyre Group, and is laterally equivalent to part of Motunau Group (Andrews et al. 1987). Burnt Hill Group is Miocene in age and consists of basaltic flows and volcanoclastic rocks, interbedded with sedimentary rocks” (Forsyth et al., 2008).

### ***Burnt Hill Group undifferentiated (Muu)***

(QMAP database spelling: Burnt Hill Gp undifferentiated)

**Inferred age:** 19-12 Ma (Forsyth et al., 2008)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = tuff breccia, claystone, basalt; Description = Basalt breccia and tuff sandstone (Wairiri); feldspathic sandstone (Chalk Quarry); clay (Chalk Hill); tuff (Sandpit); basalt breccia and flows (Bluff) (QMAP database). “The remainder of the group – basalt breccia, flows and tuff, feldspathic sandstone and minor smectitic claystone – is shown as undifferentiated (Muu)” (Forsyth et al., 2008). “Conditions at the time of deposition of the oldest sediments of Burnt Hill Group were **marine** at Burnt Hill, but probably **fluvial to estuarine** at Harper Hills. **Shallow marine** conditions prevailed in the Oligocene and middle Miocene at Burnt Hill with deposition of Thongcaster Formation and the basal shell bed of Chalk Quarry Sandstone” (Carlson et al. 1980) – *the QMAP database identifies the Wairiri, Chalk Quarry, Chalk Hill, and Sandpit units, as well as basalt, breccias and flows, as contributing to the Burnt Hill Group. These units represent fluctuations between marine and onshore deposition (Carlson et al., 1980). EoD is defined as innermost shelf here because many of the units seem to be shallow marine and shoreface deposits, although an onshore EoD may also be appropriate.*

### ***Harper Hills Basalt (Muv)***

**Inferred age:** 12-11 Ma (Timm et al., 2010)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = **basalt**; Sub\_Rocks = sometimes clay; Description = Dark grey fine grained porphyritic and vesicular tholeiitic basalt lava flows. Up to three flows, oldest is 15 m thick; Porphyritic and vesicular tholeiitic basalt lava flows. Up to three flows, oldest is 15 m thick. Overlain by Coalgate Bentonite (QMAP database). “...the Harper Hills Basalt consists of up to three **subaerially** erupted quartz-**tholeiite** flows...” (Field and Browne, 1989) – *EoD is based on Field and Browne (1989) and the QMAP lithologic description which does not mention pillow basalts or a phreatomagmatic eruption style.*

### ***Bradley Sandstone (Mub)***

**Inferred age:** 18-12 Ma (Boyes et al., 2012)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = sandstone; Description = White, medium quartzose sandstone; also coarse to small pebble sandstone. Includes Eocene tuffaceous sandstone and gritty sandstone in northwest (QMAP database). “On Banks Peninsula, Bradley Sandstone (Mub) consists of white quartzose sandstone, slightly carbonaceous or pebbly in places (Sewell et al. 1988). It is exposed only at Charteris Bay” (Forsyth et al., 2008). “Erosion, probably associated with faulting, at Banks Peninsula left significant topographic relief and locally exposed Torlesse basement, though the area was **transgressed** in part (Bradley Sandstone) in the late Early Miocene...” (Field and Browne, 1989) – *the Field and Browne (1989) interpretation of the Bradley Sandstone as a transgressive sandstone, and the QMAP lithologic description of medium to coarse to small pebble sandstone (indicating a proximal environment; Fig. 3) favours an innermost shelf EoD for the map unit.*

## Igneous rocks of Banks Peninsula

“Banks Peninsula forms the largest accumulation of Cenozoic volcanic rocks in the South Island. It consists of Late Miocene rocks erupted from two large overlapping volcanoes (Lyttelton and Akaroa) with many minor vents. Four volcanic groups are mapped, following Sewell (1988): Lyttelton (11–9.7 Ma), Mt Herbert (9.7–8.0 Ma), Akaroa (9.0–8.0 Ma), and Diamond Harbour (7.0–5.8 Ma). Most comprise basalts, andesites or trachytes, with many varieties identified on the basis

of their geochemical composition (Fig. 33). The un-grouped Allandale Rhyolite and Governors Bay Andesite preceded the main Lyttelton volcano, although they may represent an early phase of Lyttelton volcanism (Barley et al. 1988). Mt Herbert Group represents the transition from Lyttelton to Akaroa volcanism, and Diamond Harbour Group comprises the youngest volcanic rocks on Banks Peninsula” (Forsyth et al., 2008).

### **Allandale Rhyolite (Mvra)**

**Inferred age:** 11 Ma (Field and Browne, 1989)

**EoD:** onshore silicic eruptives

**Basis for interpretation:** Main\_Rock = **rhyolite**; Sub\_Rocks = dacite obsidian breccia; Description = Flow-banded porphyritic rhyolite and dacite lava flows and domes; local rhyolite breccias around dome bases; rare tuffs and obsidian (QMAP database). “Volcanic activity [of Banks Peninsula] commenced with the eruption of andesite and **rhyolite** (Governors Bay Andesite and **Allandale Rhyolite**)...” (Field and Browne, 1989) – *the EoD is based on Field and Browne (1989).*

### **Governors Bay Andesite (Mvgb)**

**Inferred age:** 11 Ma (Field and Browne, 1989)

**EoD:** onshore intermediate eruptives

**Basis for interpretation:** Main\_Rock = **andesite**; Description = Flow-banded plagioclase-pyroxene-olivine porphyritic andesitic lava flows (QMAP database). “Governors Bay Andesite (Mvg) is genetically related to and conformably overlies Allandale Rhyolite (Sewell et al. 1988)” (Forsyth et al., 2008) – *the EoD is based on the QMAP description.*

### **Lyttelton Volcanic Group (Mvl)**

**Inferred age:** 11-10 Ma (Sewell, 1988)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = **hawaiite**; Sub\_Rocks = basalt, trachyte tuff, pyroclastic epiclastic; Description = **Basaltic** (hawaiite) to trachytic lava flows interbedded with tuff and breccia (including lahars), many dikes and minor lava domes (QMAP database). “**Hawaiian-type** eruptions produced thick extensive hawaiite lava flows. Small, localised scoria cones within the main succession indicate that, from time to time, Hawaiian-type effusion was interrupted by short **Strombolian** outbursts... The absence of hyaloclastite breccias and pillow lavas indicates that Lyttelton Volcano was constructed entirely **subaerially**” (Sewell, 1988) – *EoD is based on Sewell (1988) and the QMAP description which indicate subaerial, extrusive mafic eruption products.*

### **Mt Herbert Volcanic Group (Mvh)**

**Inferred age:** 10-8 Ma (Sewell, 1988)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = **hawaiite**; Sub\_Rocks = basalt, tuff, breccia, conglomerate, sandstone, siltstone, mudstone; Description = **Basaltic** lava flows & plugs; minor interbedded volcanoclastic breccia, conglomerate, sst, siltstone, carbonaceous mst, & tuff (QMAP database). “...comprises a volcanic complex of mildly alkalic **basalt** plugs, lava flows, and intercalated clastic deposits intermediate in age between Lyttelton and Akaroa Volcanoes” (Sewell, 1988) – *EoD is based on Sewell (1988) and the QMAP description which indicate subaerial, extrusive mafic eruption products.*

### **Akaroa Volcanic Group**

“...mainly comprises **basaltic to trachytic lava flows** with some intercalated tuff and pyroclastic breccia, forming the eastern part of Banks Peninsula, and centred on Akaroa Harbour (Sewell & Weaver 1990)... Numerous dikes are exposed on the shoreline of Akaroa Harbour (Smith 1972), only some of which can be shown on the map” (Forsyth et al., 2008). “The Akaroa Volcanics in central Banks Peninsula comprise a mildly alkaline association of basalt to mugearite lava flows and high-level basaltic to trachytic intrusive rocks” (Sewell, 1985). “The deposits located around the central harbour of Akaroa represent the emergent and early **subaerial** phases of volcanic activity at Akaroa Volcano” (Trent, 2012).

### ***Akaroa Volcanic Group (Mva)***

***Inferred age:*** 9-8 Ma (Sewell, 1988)

***EoD:*** onshore mafic eruptives

***Basis for interpretation:*** Main\_Rock = **hawaiite**; Sub\_Rocks = basalt, breccia, tuff, agglomerate, trachyte; Description = **Basaltic** to trachytic lava flows (**mainly hawaiite** composition) intercalated with tuff, pyroclastic breccia, and agglomerate (QMAP database) – *EoD is based on the Main\_Rock type of hawaiite and the cited literature which says that these products were erupted subaerially.*

### ***Akaroa Volcanic Group (Mva)***

***Inferred age:*** 9-8 Ma (Sewell, 1988)

***EoD:*** onshore silicic eruptives

***Basis for interpretation:*** Main\_Rock = trachyte; Sub\_Rocks = syenite basalt; Description = Massive, coarse to fine grained, trachyte to microsyenite dome (QMAP database). “Several formations have been identified, including a trachyte dome on the western side of Akaroa Harbour” (Forsyth et al., 2008). “The Tikao Trachyte Formation (at) (Sewell 1992) is a **trachytic exogenous** dome located on the western side of Akaroa Harbour, between Tikao Bay and Petit Carenage Bay (Fig 3.4 see appendix)” (Trent, 2012) – *EoD is after whole-rock major element analysis by Trent for which the Tikao Trachyte was identified as a high silica trachyte.*

### ***Lushington Breccia (Mva)***

***Inferred age:*** 9-8 Ma (Sewell, 1988)

***EoD:*** onshore silicic eruptives

***Basis for interpretation:*** Main\_Rock = tuff; Sub\_Rocks = breccia trachyte; Description = Polyolithic trachytic breccia to lapilli tuff (QMAP database). “The deposits consist of weakly bedded, blue grey, poorly to moderately sorted, clast supported, angular to sub-rounded, polyolithic, trachyte tuff breccia to trachyte tuff” (Trent, 2012) – *Trent (2012) carried out whole-rock major element analysis on the Lushington Breccia and determined that its composition is trachytic, trachydacitic, dacitic and rhyolitic, which means in the classification used in this report it is an onshore silicic eruptive.*

### ***Onawe Syenite/Duvauchelle Gabbro (Mvas)***

***Inferred age:*** 9 Ma (Stipp and McDougal, 1968)

***EoD:*** silicic intrusives

***Basis for interpretation:*** Main\_Rock = **syenite**; Sub\_Rocks = gabbro, hawaiite, breccia, tuff, trachyte; Description = Syenite and minor gabbro; hawaiite lava flows and trachytic breccia (QMAP database). “Onawe peninsula, at the head of the harbour, is near the centre of a radial dike swarm and hosts **syenite** and minor **gabbro intrusions** (Mva) (Sewell & Weaver 1990)” (Forsyth et al., 2008) – *this unit includes both intrusive syenite (silicic) and gabbro (mafic), however in the QMAP description it says that the gabbro intrusions are minor, so the dominant rock type is syenite.*

### ***Diamond Harbour Volcanic Group (Mvd)***

***Inferred age:*** 7-6 Ma (Sewell, 1988)

***EoD:*** onshore mafic eruptives

***Basis for interpretation:*** Main\_Rock = **basalt**; Sub\_Rocks = hawaiite, basanite, breccia, conglomerate, sandstone, mudstone; Description = Basaltic (basanite, basalt, hawaiite) lava flows, dikes, vent plugs, sills; minor interbeds of breccia, conglomerate, sandstone, carbonaceous mudstone (QMAP database). “It consists of Stoddart **Basalt** and Kaioruru **Hawaiite**... The Stoddart Basalt is the dominant formation of the Diamond Harbour Volcanic Group. It consists of basanite and olivine basalt lava flows cropping out on the flanks of Lyttelton Volcano, and olivine hawaiite flows and sediments cropping out within its crater... The absence of hyaloclastite breccias and pillow lavas indicates that Lyttelton Volcano was constructed entirely **subaerially**” (Sewell, 1988) – *EoD is based on the Sewell (1988) subaerial interpretation for eruptives from the Lyttelton Volcano.*



## Quaternary – Sedimentary deposits

- **All Q deposits** (except – see below)

*EoD: onshore*

**Basis for interpretation:** Based on the QMAP database which includes alluvial, beach, dune, estuarine, lacustrine, landslide, loess, man-made fill, rock fall, scree, swamp, and till sediments in the Quaternary deposits.

- **mQb, Q5b**

*EoD: innermost shelf*

**Basis for interpretation:** “Uplifted **coastal deposits** formed during previous interglacials... The sediments include **beach or shallow marine** gravels or sands (Fig. 49), shellbeds, estuarine sand and mud, alluvial fan gravel, sand and silt, dune sand and loess (Jobberns 1926, 1928; Suggate 1965; Carr 1970)” (Forsyth et al., 2008) – *onshore may be appropriate in some cases.*

## FIORDLAND AREA (Geological Map 17)

### Annick Group

“...largely **non-marine**, Eocene Annick Group... In northern Fiordland, undifferentiated Annick Group (Ea) conglomerate, sandstone, carbonaceous mudstone and rare coal are locally infaulted along the Hollyford Fault System” (Turnbull et al., 2010).

#### **Sandfly Formation (Easc)**

(QMAP database spelling: Sandfly Fmn; Annick Gp)

**Inferred age:** 41-39 Ma (King et al., 1999)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = conglomerate; Sub\_Rocks = sandstone, breccia; Description = conglomerate and breccia with minor sandstone (QMAP database). “A thinner sequence, recording rapid changes from bouldery scree to alluvial channel then **flood plain** and **shallow marine** environments, is preserved on islands in Middle Fiord” (Turnbull et al., 2010) – *this conglomerate located in Middle Fiord is an innermost shelf deposit. Refer to “Sandfly Formation (Easc)” on the Wakatipu map area for further interpretations.*

#### **Earl Mountains Sandstone (Eaa)**

**Inferred age:** 39-35 Ma (King et al., 1999)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = conglomerate, mudstone, coal; Description = sandstone with minor conglomerate; fines upward with mudstone and rare coal at top (QMAP database). “The basin-wide, Late Eocene Earl Mountains Sandstone (Eaa; Turnbull 1985, 1986a) conformably overlies Sandfly Formation or rests on basement. It is dominated by crossbedded (Fig. 47B) and channel-filling sandstone, and includes subordinate carbonaceous mudstone and rare coal seams. Channels filled by coarse conglomerate (Eaa) are also mapped... Earl Mountains Sandstone reflects regional subsidence and formation of an extensive **fluvial** system extending from north of Fiordland, southward across the Te Anau Basin (Turnbull et al. 1993; Zink 2000)” (Turnbull et al., 2010) – *the unit is defined as onshore because it is described as fluvial and lagoonal. Refer to “Earl Mountains Sandstone (Eaa)” on the Wakatipu map area for further interpretations.*

### Waiau Group

#### **Hope Arm Formation**

“...is a correlative of the Earl Mountains Sandstone [...] although slightly younger. Basal conglomerate is well exposed around the Manapouri shoreline, unconformably overlying Hunter Intrusives. Clasts are mostly granite derived from the west, with some boulders up to 5 m in diameter; gabbroic clasts predominate north of the lake. The conglomerate is overlain by sandstone and minor carbonaceous mudstone (Owh). Thin coal seams with *in situ* tree stumps occur in the Iris Burn. Hope Arm Formation accumulated in **proximal alluvial fan** and **fluvial** environments, in a paleo-valley in the northwest part of the Monowai Sub-basin” (Turnbull et al., 2010). “...an atypical western shelf facies... Clarke (1978) interpreted the formation as an **alluvial fan** complex. Rare *Ophiomorpha* burrows in sandstone suggest the fans were building into a **shallow marine** environment... a sandy **shelf** to the northwest [...] represented by units such as Hope Arm Formation (Clarke 1978) and the Point Burn Formation. This shelf area was only **very shallow marine** or even **subaerial** in the Middle Oligocene” (Turnbull et al., 1993).

- **E0lwhc**

**Inferred age:** 28-27 Ma (King et al., 1999)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = conglomerate; Sub\_Rocks = breccia; Description = sandstone with subordinate conglomerate and carbonaceous mudstone (QMAP database) – *the basal conglomerate is defined as an onshore deposit.*

- **E0lwh**

**Inferred age:** 28-27 Ma (King et al., 1999)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = conglomerate; Description = sandstone with subordinate conglomerate and carbonaceous mudstone (QMAP database) – *EoD is based on the Turnbull et al. (2010) interpretation, but the mention of the fans building into a shallow marine environment in Turnbull et al. (1993) indicates an innermost shelf EoD may be appropriate.*

## **Waioe Formation**

(QMAP database spelling: Waioe Fmn; Waiau Gp)

- **OIMiww**

Main\_Rock = mudstone; Sub\_Rocks = sandstone; Description = Massive to bedded mudstone; subordinate sandstone; rare limestone (QMAP database).

- **OIMiwws**

Main\_Rock = sandstone; Sub\_Rocks = mudstone; Description = Graded to massive sandstone lenses within background mudstone (QMAP database).

“Waiau Group rocks represent two depositional settings: a shallow marine shelf over eastern Fiordland, on the western flank of the basin; and submarine fans and fan deltas infilling the main basin. A background, **deep-water** facies of massive, calcareous mudstone, the Waioe Formation (Oww), occurs throughout. It overlies and interfingers with submarine fan sandstone deposits” (Turnbull et al., 2010). “Facies range from very proximal rock-fall and debris flow deposits, including clasts several metres in size, through thick sand-dominated **fluvial** and **submarine fan** successions, to **hemipelagic** mudstone (Waioe Formation of Fig. 3)” (Zink and Norris, 2004). “...in the Waiau Basin is the Waioe Formation, which Turnbull et al. (1989) suggested is generally **deep marine** and merges eastward into the shallower Winton Hill Formation” (Cahill, 1995) – *the occurrence of Waioe Formation has been aligned with descriptions in the Wakatipu, Fiordland and Murihiku QMAP bulletins, Turnbull et al. (1993), and the chronostratigraphic panels in King et al. (1999). Waioe Formation on the Fiordland map area occurs in Waiau Basin, Monowai Sub-basin (of Te Anau), and Waitutu Sub-basin (of Solander).*

- **Waiau Basin**

“During the Oligocene, the Waiau Basin with its constituent sub-basins was a complex, tectonically active area, where a wide variety of sediments accumulated from several source areas... In earliest Oligocene time the area came under **marine** influence, but there were no major lithologic changes, and the Waioe Formation mudstone gradually succeeded the Orauea Formation... The Waioe Formation mudstone in the Waiau Basin is a blue-grey, slightly calcareous to non-calcareous, slightly carbonaceous pelite (D45/c29, c100; Arafin 1982), of Early Oligocene to Pliocene age. The Oligocene part lacks sedimentary structures and coarse clastic sediment, and was deposited in quiet water conditions. Microfauna indicate a **steadily deepening** environment, from **inner to outer shelf or upper slope** conditions, sheltered from full open-ocean influence... The lithostratigraphy of the Early and Middle Miocene Waiau Group in the Waiau and Te Anau basins resembles that of the Oligocene. Deposition of the basin-wide Waioe Formation mudstone continued through the Miocene” (Turnbull et al., 1993).

**Inferred age:** 34-12 Ma (Turnbull et al., 1993)

**EoD breakdown:**

34-33 Ma:	<u>innermost shelf</u>
32 Ma:	<u>mid-shelf</u>
31 Ma:	<u>outer shelf</u>
30-29 Ma:	<u>upper bathyal</u>
28-26 Ma:	<u>mid-bathyal</u>
25-12 Ma:	<u>lower bathyal</u>

- **Monowai Sub-basin**

“The sequence [Point Burn, Tunnel Burn, and Hope Arm formations] is truncated by a Late Oligocene unconformity, and is overlain by Early Miocene Waioe Formation mudstone... The plank-

tic-dominated microfauna from the Waicoe and Borland formations indicates a **bathyal** environment of deposition of those formations... **subsided rapidly** in earliest Miocene times in response to the accelerating compressional tectonic regime... In the Early Miocene, the onshore western shelf area **abruptly subsided** and the basin-wide Waicoe Formation mudstone facies, already established in Oligocene time in the Waiau Basin, extended westwards over eastern Fiordland” (Turnbull et al., 1993).

**Inferred age:** 21-12 Ma (Turnbull et al., 1993; 2010)

**EoD breakdown:** 21-12 Ma: lower bathyal

- **Waitutu Sub-basin**

“Waicoe Formation mudstone in the Waitutu Sub-basin is Early to Late Miocene in age and is interpreted as a **deep marine basin** deposit” (Turnbull et al., 2010). “The onshore part of this sub-basin probably resembled the Monowai depocentre of the western Waiau Basin in the Late Oligocene... [in the Early to Middle Miocene] was buried by **deep marine** Waicoe Formation mudstone and a **turbidite** sequence... A continuous succession at least 3000 m thick, from Waitakian (earliest Miocene) to Kapitean (Late Miocene) in age, is exposed between Hump Ridge and the Hauroko Fault. It is predominantly Waicoe Formation mudstone... Microfauna in this sequence indicate **bathyal** conditions until the Late Miocene... Subsidence and sedimentation continued during the Miocene... The Early Miocene Waitutu Sub-basin, both onshore and offshore, was dominated by mudstone in a **deep marine** setting... The central part of the onshore Waitutu Sub-basin was still bathyal in the Middle Miocene...” (Turnbull et al., 1993).

**Inferred age:** 29-12 Ma (Turnbull et al., 1993; 2010)

**EoD breakdown:** 29 Ma: upper bathyal

28-26 Ma: mid-bathyal

25-12 Ma: lower bathyal

### ***Point Burn Formation (10lw)***

(QMAP database spelling: Point Burn Fmn; Waiau Gp)

**Inferred age:** 27-26 Ma (King et al., 1999)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = conglomerate mudstone coal; Description = quartzose sandstone with minor conglomerate; carbonaceous mudstone and rare coal (QMAP database). “Waiau Group rocks represent two depositional settings: a **shallow marine shelf** over eastern Fiordland, on the western flank of the basin... The eastern Fiordland shelf sequence rests unconformably on basement rocks. The oldest rocks are thin and discontinuous breccia, conglomerate and sandstone of the Point Burn Formation...” (Turnbull et al., 2010). “The Point Burn Formation is of **marginal** and **shallow marine origin**, as indicated by trace-fossils, cyclic sediments and the presence of calcareous algae *Lithophyllum*, *Lithothamnium* and *Lithoporella*...” (Carter et al., 1982). “The formation is inferred to represent **transition from fluvial conditions to a very shallow marine shelf or near-shore** environment. The poorly sorted carbonaceous sequence may be a paleosol or fossil talus” (Turnbull and Uruski, 1995) – *EoD is based on the interpretations in Turnbull et al. (2010) and Carter et al. (1982).*

### ***Tunnel Burn Formation (10lwt)***

(QMAP database spelling: Tunnel Burn Fmn; Waiau Gp)

**Inferred age:** 26-22 Ma (King et al., 1999)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = sandstone mudstone, or sandstone breccia; Description = massive to crossbedded sandy bioclastic limestone (QMAP database). “This unit comprises a massive to cross-bedded, bioclastic limestone blanket... Tunnel Burn limestone rests on basement over paleo-highs such as Mt Luxmore (Lee et al. 1983)” (Turnbull et al., 2010). “The depositional environment of the limestone was a continuation of the **shallow marine shelf**, as indicated by the traction-dominated sedimentary structures and macrofauna. At Mount Luxmore, the limestone rests directly on basement with a rocky shoreline macrofauna indicating **inter-**

**tidal to sub-tidal** water depths...” (Turnbull et al., 1993). “The overlying bioclastic limestone and associated quartzo-feldspathic sandstone of Tunnel Burn Formation are generally massive. The commonest sedimentary structure is large-scale cross-stratification (Fig 4a) which, together with rubbly shell-beds, is consistent with an **inshore marine or “shelf”** origin” (Carter et al., 1982). “On the west side of the Waiau Graben, another Late Oligocene **rocky shoreline** formed at Mt Luxmore on the Fiordland margin (Lee et al. 1983)” (Lee et al., 2014) – *EoD is based on the cited references. Mudstone sub-rock types may indicate mid-shelf depositional depths.*

### **Stuart Formation (Ow)**

(QMAP database spelling: Point Burn; Stuart fmns; Waiau G)

**Inferred age:** 36-35 Ma (King et al., 1999)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = conglomerate, mudstone, coal; Description = Sandstone and minor conglomerate; rare shellbeds and mudstone (QMAP database). “Northwest of Lake Te Anau, the Stuart Formation (Ows) rests conformably on Annick Group, and consists of massive, **marine** mudstone (Fig. 49A), and cross-bedded and graded sandstone. The mudstone is carbonaceous and locally hydrocarbon-bearing (Turnbull et al. 1993; Zink 2000)” (Turnbull et al., 2010). “At the north end of Lake Te Anau, **lagoonal marine** mudstone, cross-bedded sandstone, and graded sandstone sequences of the Stuart Formation...” (Turnbull, 2000) – *this formation is defined as innermost shelf based on “lagoonal marine”, however onshore may be an appropriate alternative. NB: only one polygon is defined as Stuart Formation. The other, to the north of Middle Fiord, is defined after Stuart, Spear Peak, and Point Burn formations (refer to “Stuart, Spear Peak, and Point Burn formations (Ow)” on the Wakatipu map area).*

### **Kaherekoau Formation**

(QMAP database spelling: Kaherekoau Fmn)

“The formation is interpreted as a large **submarine fan** complex (Turnbull et al. 1989)... The upper Kaherekoau Formation locally includes sandy, graded, bioclastic limestone (Owa) (Fig. 46), possibly an eastern, **redeposited** equivalent of the Tunnel Burn Formation...” (Turnbull et al., 2010). “Undated, **non-marine to shallow marine** sediments of the Kaherekoau Formation... The coarse conglomerate of the Kaherekoau Formation, however, represent the latest phase of this basin margin sedimentation... Northeast of Lake Monowai the conglomerate is red-weathered, contains angular clasts and is probably **alluvial**... Further south, conglomerate contains scattered **marine** microfossils, suggesting that the sub-basin deepened to the south” (Turnbull et al., 1993). “Upper sandstone and graded sequences of the Kaherekoau Formation represent gradual expansion of the fan aprons beyond the Hauroko Fault slope (and the down-slope basement highs). The upper fan areas may have extended west over the Hauroko Fault. The limestone facies may represent small fan lobes derived from areas of shelf limestone between feeder channels west of the fault scarp” (Turnbull and Uruski, 1995).

- **Olwk**

**Inferred age:** 34-27 Ma (King et al., 1999)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone; Description = massive to graded sandstone with mudstone interbeds; and rare conglomerate (QMAP database) – *this formation is an alluvial to shallow shelf deposit, so is assigned an average innermost shelf EoD here.*

- **Olwkc**

**Inferred age:** 34-27 Ma (King et al., 1999)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = conglomerate; Sub\_Rocks = breccia, sandstone; Description = massive to bedded coarse conglomerate and breccia with subordinate sandstone (QMAP database) – *this formation is an alluvial to shallow shelf deposit, so is assigned an average innermost shelf EoD here.*

- **Olwkl**

**Inferred age:** 34-27 Ma (King et al., 1999)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = sandstone, breccia; Description = sandy limestone; calcareous sandstone; and breccia-bearing crystalline limestone (QMAP database) – *this formation is an alluvial to shallow shelf deposit, so is assigned an average innermost shelf EoD here.*

### ***Borland Formation (Miwb)***

(QMAP database spelling: Borland Fmn; Waiau Gp)

**Inferred age:** 18-16 Ma (King et al., 1999)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone; Description = graded sandstone and mudstone (QMAP database). “...is another **submarine fan** sequence consisting of northerly- and westerly-derived, graded sandstone and mudstone...” (Turnbull et al., 2010). “The general origin of the Borland Formation is by **turbidite emplacement**... The surrounding stratigraphy suggests strongly that the environment was a small **flysch** basin, in which the Borland facies represent an axial fill...” (Carter and Norris, 2005) – *EoD is based on Turnbull et al. (2010) and Carter and Norris (2005). A lower bathyal EoD may be an appropriate interpretation.*

### ***Monowai Formation (mMiwM)***

(QMAP database spelling: Monowai Fmn; Waiau Gp)

**Inferred age:** 16-15 Ma (King et al., 1999)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = conglomerate; Sub\_Rocks = sandstone; Description = conglomerate and pebbly mudstone with graded sandstone and mudstone (QMAP database). “...conglomerate and pebbly mudstone, sandy conglomerate, and interbedded sandstone and mudstone of the Monowai Formation (Mwm). Monowai Formation is largely derived from Caples terrane rocks lying northeast of the Te Anau Basin, and is interpreted as a shallow marine delta-top and delta-slope deposit, with significant **redeposition by submarine slumping** (Carter and Norris 1977b)” (Turnbull et al., 2010). “The faunal and sedimentary evidence described above is perhaps open to two alternative interpretations; either the Monowai Formation accumulated as a **deep-marine fan**, or on a **shallow-marine delta and delta slope**...” (Carter and Norris, 1977). “...records shallowing conditions... Carter & Norris (1977b) interpreted the Monowai Formation as a delta front to delta top deposit, with slide sheets and mass-flow conglomerate at the base and a tidally influenced, shallow marine facies at the top. Redeposited macrofaunas in the formation include shallow marine bivalves and gastropods, usually abraded. The microfauna is relatively poor in benthic forms, and the upper part of the unit lacks microfauna altogether” (Turnbull et al., 1993) – *based on the summary of Carter and Norris 1977 in Turnbull et al. (1993), the Monowai Formation is defined here as shallow marine sediments redeposited at bathyal depths. Upper bathyal may be an appropriate alternative.*

### ***Dunraigen Formation (Miwd)***

(QMAP database spelling: Dunraigen Fmn; Waiau Gp)

**Inferred age:** 14-12 Ma (King et al., 1999)

**EoD:** lower bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone, conglomerate; Description = laminated sandstone and mudstone with rare conglomerate (QMAP database). “...another **submarine fan** sequence...” (Turnbull et al., 2010) – *the EoD is defined as lower bathyal here based primarily on Carter and Norris (1977, 2005). Refer to “Dunraigen Formation (mMiwd)” on the Murihiku map area for further information.*

### ***Prospect Formation (MiPlp)***

(QMAP database spelling: Prospect Fmn)

**Inferred age:** 11-3 Ma (King et al., 1999)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = conglomerate; Sub\_Rocks = sandstone, mudstone, sandstone, lignite; Description = cross-bedded conglomerate and sandstone with rare carbonaceous mudstone and lignite, and massive to crossbedded greywacke conglomerate; sandstone interbeds; mudstone units to 50 m thick (QMAP database). “Within the Fiordland map area, the formation erosively overlies Duncraigen Formation with low-amplitude channels cutting laminated siltstone. The channels are filled by cross-bedded sandstone, in turn erosively overlain by massive to thick-bedded, sandy conglomerate... with rare lignite” (Turnbull et al., 2010) – *EoD is based on Manville (1996). Refer to “Prospect Formation (MPp)” on the Wakatipu map area for further information.*

## **Waiau Group** *continued*

### **Sand Hill Point Formation (Es)**

(QMAP database spelling: Sand Hill Point Fmn)

**Inferred age:** 38-35 Ma (Turnbull and Uruski, 1995)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = conglomerate; Sub\_Rocks = breccia sandstone; Description = red weathering conglomerate and breccia with minor sandstone (QMAP database). “This unit is interpreted as a locally derived **scree to proximal fluvial** deposit” (Turnbull et al., 2010). “The formation is interpreted to be a **subaerial talus fan** eroded from a nearby fault scarp. It is adjacent to the **fluvial** environment represented by the basal Hump Ridge Formation” (Turnbull et al., 1993) – *the EoD is defined as onshore because the formation is described as being fluvial and subaerial.*

### **Hump Ridge Formation**

(QMAP database spelling: Hump Ridge Fmn)

“Sand Hill Point Formation is conformably overlain by Hump Ridge Formation (Eh), which includes conglomerate with granitic clasts, overlain by planar and **cross-bedded**, pebbly, quartzofeldspathic sandstone with macrofossil fragments (Fig. 50), and by further conglomerate. On the west flank of Hump Ridge, the fossiliferous sandstone grades laterally into sandy limestone (Eh). The formation represents a **fluvial** environment, grading upward into **deltaic** then **shallow marine** conditions” (Turnbull et al., 2010). “This conglomerate is a correlative of the Kaherekoau Formation in the Monowai Sub-basin... Rare sub-bituminous coal seams up to 0.5 m thick occur near Port Craig and at Lake Hauroko, where they overlie clast-supported conglomerate and are in turn overlain by bioturbated sandstone... The sedimentary setting of the Hump Ridge Formation is interpreted to be **fluvial and coastal plain** in the Late Eocene, changing to a **shallow marine shelf** in the earliest Oligocene” (Turnbull et al., 1993). “Originally described as a “coal measure” sequence with some marine sediments, the Hump Ridge Formation is now known to include a wide range of sediments representing several different depositional environments” (Turnbull and Uruski, 1995).

- **E0lh**

**Inferred age:** 36-29 Ma (King et al., 1999)

**EoD:** onshore to innermost shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone, coal; Description = conglomerate and overlying massive to graded sandstone; with minor coal and carbonaceous mudstone (QMAP database) – *this unit deepens from fluvial to deltaic and coastal plain to shallow marine shelf. The onshore period is considered too insignificant to be represented in this project. Mid-shelf may be an appropriate youngest depositional environment.*

- **E0lhc**

**Inferred age:** 36-29 Ma (King et al., 1999)

**EoD:** onshore to innermost shelf

**Basis for interpretation:** Main\_Rock = conglomerate; Sub\_Rocks = sandstone; Description = conglomerate with minor sandstone (QMAP database) – *this unit is initially onshore and deepens to an innermost shelf environment over time.*

- **E0lh1**

**Inferred age:** 36-29 Ma (King et al., 1999)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = sandstone; Description = calcareous sandstone and impure limestone (QMAP database). “The limestone facies is a shallow, clastic-dominated **deltaic to inner shelf** deposit, adjacent to the alluvial fans” (Turnbull and Uruski, 1995) – *EoD is after Turnbull and Uruski (1995).*

### **Blackmount Formation (Olwb)**

(QMAP database spelling: Blackmount Fmn; Waiau Gp)

“In the northeast [Waioe Formation] overlies a fault-bounded sliver of westerly-derived graded sandstone and mudstone of the Oligocene Blackmount Formation (Owb), a **submarine fan** sequence which probably extends at depth south towards Lake Hauroko (Turnbull et al. 2003; Carter and Norris 2005)” (Turnbull et al., 2010). “The Blackmount Formation, 2-3 km thick, grades from **mass-emplaced** breccias and sands of inferred **submarine fan** origin at the base, to **muddy turbidites and hemiterrigenous mudstone** of inferred **basin-floor** origin at the top” (Carter et al., 1982).

**Inferred age:** 34-26 Ma (King et al., 1999)

**EoD breakdown:** 34-32 Ma: upper bathyal

31-29 Ma: mid-bathyal

28-26 Ma: lower bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone (QMAP database) – *interpretations from the cited references combined with Fig. 3 indicate that the formation was initially deposited at upper bathyal depth, increasing over time to lower bathyal. Refer to “Blackmount Formation (Olwb)” on the Murihiku map area for further information.*

### **Hauroko Formation**

(QMAP database spelling: Hauroko Fmn; Waiau Gp)

“Hauroko Formation mainly comprises a fining-upward **submarine fan** sequence of Oligocene graded sandstone and mudstone, with conglomerate in large channels. It includes a **non-marine to shallow marine** sequence of boulder conglomerate, pebbly sandstone, rare carbonaceous mudstone and **coal**, and bioturbated laminated sandstone on the Lake Hauroko shoreline” (Turnbull et al., 2010). “...is defined as a complex sequence of predominantly **marine** conglomerate, sandstone, siltstone, and graded sandstone and mudstone which overlies Hump Ridge Formation, and underlies Waioe Formation mudstone... The Hauroko Formation is inferred to represent a series of small **proximal submarine fans or fan deltas** formed along the margin of the proto-Hump Ridge (Turnbull & Uruski et al. 1993). There is a well-preserved transition from **boulder beach** with back-beach peaty **lagoons**, to **shore face** and sandy bouldery beach in the sequences on the Lake Hauroko shoreline. The bioturbated facies represents a narrow, **shallow marine shelf**” (Turnbull and Uruski, 1995).

- **Olwu**

Main\_Rock = sandstone; Sub\_Rocks = mudstone conglomerate; Description = graded sandstone and mudstone with minor conglomerate shellbeds and limestone (QMAP database).

- **Olwuc**

Main\_Rock = conglomerate; Sub\_Rocks = sandstone, mudstone, coal; Description = pebble to boulder conglomerate with minor sandstone and coal (QMAP database).

**Inferred age:** 36-28 Ma (Turnbull and Uruski, 1995)

**EoD breakdown:** 36 Ma: onshore

35-29 Ma: innermost shelf

28 Ma: mid-shelf

**Basis for interpretation:** *EoD is based on descriptions in Turnbull and Uruski (1995) of the formation fining upwards, and the transition from beach and lagoons, to shore face and shallow shelf. Innermost shelf may be an appropriate final depth.*



### ***Mclvor Formation (eMiwv)***

(QMAP database spelling: Mclvor Fmn; Waiau Gp)

***Inferred age:*** 23-17 Ma (King et al., 1999)

***EoD:*** lower bathyal

***Basis for interpretation:*** Main\_Rock = limestone; Sub\_Rocks = mudstone; Description = graded bioclastic limestone interbedded with mudstone (QMAP database). “Northeast from Lake Hau-roko, graded bioclastic limestone and interbedded calcareous mudstone are mapped as the Miocene Mclvor Formation (Mwv)... Mclvor Formation is the **down-basin extension of a large submarine fan** that originated from a shallow shelf in the eastern Waiau Basin...” (Turnbull et al., 2010). “During the Early Miocene, a carbonate rich shelf (Clifden Subgroup) prograded into the Waiau Basin from the east (Figure 4). Carbonate detritus from this shelf was redeposited as a thick calc-**flysch** succession (Mclvor Formation) in a deep, centrally located SW-NE oriented trough... **deep-water**, mass emplaced sandstone of the Mclvor Formation” (Beggs et al., 2000). “The Mclvor Formation represents **deep water** deposition, on the **floor of a muddy flysch basin**” (Carter and Norris, 2005) – *EoD is based on the interpretations in the cited references, particularly the basin floor interpretation of Carter and Norris (2005).*

### ***Clifden Subgroup (OIMif)***

***Inferred age:*** 24-17 Ma (Turnbull and Allibone, 2003)

***EoD:*** mid-shelf

***Basis for interpretation:*** Main\_Rock = limestone; Sub\_Rocks = sandstone; Description = siltstone and calcareous sandstone overlain by variably pebbly bioclastic limestone (QMAP database). “In the Late Oligocene to Middle Miocene, this **shelf** extended southwestward across the Waiau Basin as far as Helmet Hill (Fig. 51) where sandstone and overlying sandy bioclastic limestone are mapped as Clifden Subgroup (Mwc)” (Turnbull et al., 2010) – *an average EoD of mid-shelf is nominated here. Refer to “Lower Clifden Subgroup (OIMiwc)” on the Murihiku map area for further information.*

#### **• Goldie Hill Formation (Miwcg)**

(QMAP database spelling: Goldie Hill Fmn; Clifden Sub-gp)

***Inferred age:*** 14-12 Ma (Turnbull et al., 2010)

***EoD:*** mid-bathyal

***Basis for interpretation:*** Main\_Rock = limestone; Sub\_Rocks = sandstone; Description = graded limestone and siltstone; with secondary cementation (QMAP database). “The limestone [Clifden Subgroup] is truncated by an unconformity and is overlain either by slightly younger (late Middle Miocene) graded, sandy to pebbly limestone and siltstone of the Goldie Hill Formation (Mwh)...” (Turnbull et al., 2010). “Depositional environment of the Goldie Formation is uncertain, but macrofauna indicate it was deposited in water depths shallowing to **inner shelf** at the type section. The unit may represent **shelf debris** infilling the channel in the underlying Forest Hill Formation” (Turnbull and Uruski, 1995) – *the description of the formation as graded limestone and siltstone in the QMAP database may indicate mass emplacement of the deposit on the slope. However, the sandy to pebbly nature of the limestone may indicate a more proximal shelf environment, or a proximal submarine fan deposit. The map unit is tentatively interpreted as a proximal submarine fan deposited at a mid-bathyal depth but it is emphasised that this interpretation is tentative and an innermost to mid-shelf environment could also be appropriate.*

### ***Rowallan Sandstone (Miwa)***

(QMAP database spelling: Rowallan Sandstone; Waiau Gp)

***Inferred age:*** 11-6 Ma (Turnbull and Uruski, 1995)

***EoD:*** innermost shelf

***Basis for interpretation:*** Main\_Rock = sandstone; Sub\_Rocks = shellbeds; Description = massive sandstone with rare shellbeds (QMAP database). “Massive sandstone with minor shellbeds of the Late Miocene Rowallan Sandstone (Mwa) is a lateral equivalent of Goldie Hill Formation to the southwest (Turnbull and Uruski 1995)” (Turnbull et al., 2010). “Most sediment was trapped in the Te Anau Basin, but some escaped southwards through the gap between the rising Takitimu Mountains and Fiordland, depositing the Rowallan Sandstone and Te Waewae Formation in the **shallow-marine** Waiau Basin... The interpreted depositional environment, from macrofaunas and

micro faunas, is a **shallow to very shallow (0–20 m)** restricted marine setting” (Manville, 1996) – *EoD is based on the Manville (1996) interpretation.*

### **Port Craig Formation (lMiwg)**

(QMAP database spelling: Port Craig Fmn; Waiau Gp)

**Inferred age:** 7-5 Ma (King et al., 1999)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = conglomerate, shellbeds, sandstone; Description = shelly limestone overlain by shelly sandstone with lenses of basal conglomerate (QMAP database). “At Port Craig this unit rests on Hunter Intrusives gabbro and consists of conglomerate, bioclastic pebbly limestone and sandy shellbeds” (Turnbull et al., 2010). “Rowallan Sandstone is laterally equivalent to the Port Craig Formation... is inferred to have been deposited in a **very shallow, wave-influenced near-shore** environment at Port Craig, deepening to the northeast” (Turnbull and Uruski, 1995) – *EoD is based on the interpretations of Turnbull and Uruski (1995) and the presence of shallow water macro-fauna.*

### **Te Waewae Formation**

(QMAP database spelling: Te Waewae Fmn; Waiau Gp)

“The limestone [Clifden Subgroup] is truncated by an unconformity and is overlain ... by the **very shallow marine** Pliocene Te Waewae Formation...” (Turnbull et al., 2010). “Most sediment was trapped in the Te Anau Basin, but some escaped southwards through the gap between the rising Takitimu Mountains and Fiordland, depositing the Rowallan Sandstone and Te Waewae Formation in the **shallow-marine** Waiau Basin... A sheltered, **shallow marine (0-20 m)** depositional environment is inferred” (Manville, 1996).

- **Plwe**

**Inferred age:** 6-4 Ma (Turnbull and Uruski, 1995)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = siltstone, shellbeds, conglomerate; Description = interbedded laminated siltstone and massive to crossbedded sandstone (QMAP database) – *EoD is based on the Manville (1996) and Turnbull et al. (2010) depositional depth interpretation.*

- **Plwec**

**Inferred age:** 6-4 Ma (Turnbull and Uruski, 1995)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = conglomerate; Sub\_Rocks = sandstone; Description = sandy pebble to cobble conglomerate with rare macrofossils (QMAP database) – *EoD is based on the Manville (1996) and Turnbull et al. (2010) depositional depth interpretation.*

### **Knife and Steel Formation (oIMiwks)**

(QMAP database spelling: Knife & Steel Fmn; Waiau Group)

**Inferred age:** 21-10 Ma (King et al., 1999)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone, conglomerate, limestone; Description = massive to pebbly mudstone with minor graded sandstone and limestone and mudstone olistoliths (QMAP database). “...consists of characteristic pebbly to boulder mudstone, massive mudstone, and interbedded graded sandstone and mudstone units up to 30 m thick. Clasts in bouldery mudstone include both Fiordland-derived plutonic rocks and locally derived mudstone blocks; the sandstone packets are often **slump-folded**. Recrystallised, pebbly to sandy, graded bioclastic limestone with Fiordland-derived clasts (Owl) occurs at Lake Poteriteri and beside the Hau-roko Fault on the south coast (Bishop 1986; Turnbull & Uruski 1995). Knife and Steel Formation, of Late Oligocene to Late Miocene age, is interpreted as largely redeposited on a **deep marine, east-facing slope**” (Turnbull et al., 2010) – *Turnbull et al. (2010) indicates a bathyal EoD for the Knife and Steel Formation. Based on this interpretation and the QMAP lithologic description the map unit is*

interpreted to represent upper fan sediments deposited at upper bathyal depths (Fig. 3). Owl is shown as a horizon on the map sheet. Mid-bathyal may be an appropriate alternative.

### **Kokopu Limestone (eMiwkp)**

(QMAP database spelling: Kokopu Limestone; Waiau Gp)

**Inferred age:** 18 Ma (King et al., 1999)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = mudstone, conglomerate; Description = graded limestone in calcareous mudstone; with limestone breccia; sandy limestone and pebbly limestone (QMAP database). "...includes sandstone, sandy limestone and rare breccia-bearing limestone" (Turnbull et al., 2010). "...is inferred to be a discrete **submarine fan** within the Waicoe Formation on the opposite side of the Waitutu Sub-basin to the Knife & Steel Formation. The intraformational limestone breccia, slump folding, and common floating clasts imply the Kokopu fan was on a relatively steep and unstable slope on the western flank of a rising Hump Ridge basement block" (Turnbull and Uruski, 1995) – *the QMAP description of the map unit indicates that graded limestone in calcareous mudstone is the main rock unit, implying that the sediments are mid-fan turbidites deposited at mid-bathyal depths (Fig. 3). Upper bathyal may be an appropriate alternative.*

### **Waikakapo Formation (eMiwop)**

(QMAP database spelling: Waikakapo Fmn; Waiau Gp)

**Inferred age:** 17 Ma (King et al., 1999)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = conglomerate; Description = sandstone; conglomerate and mudstone (QMAP database). "Waikakapo Formation (Mwo; Turnbull and Uruski 1995) comprises graded sandstone and mudstone, distinctive ridge-forming conglomerate, and lenses of breccia-conglomerate" (Turnbull et al., 2010). "...is inferred to represent a complex of small, coalescing **submarine fans** deposited from **turbidity currents** off an unstable shelf. Periodic **slumping** or **mass flow** events are represented by the breccia and conglomeratic facies" (Turnbull and Uruski, 1995) – *lithologic descriptions indicate that it is composed of upper and mid-fan sediment deposited at upper to mid-bathyal depths (Fig. 3).*

### **Crombie Conglomerate (Miwc)**

(QMAP database spelling: Crombie Conglomerate; Waiau Gp)

**Inferred age:** 15-13 Ma (King et al., 1999)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = conglomerate; Sub\_Rocks = sandstone; Description = pebble conglomerate pebbly sandstone and subordinate sandstone (QMAP database). "The Middle Miocene Crombie Conglomerate (Mwg) is enclosed within the Waicoe and Knife and Steel formations in the central Waitutu Sub-basin. It consists of sandy, pebble to cobble conglomerate and pebbly sandstone, and fills a channel eroded into mudstone... may be a distal equivalent of the Monowai Formation" (Turnbull et al., 2010) – *it is inferred here that the Crombie Conglomerate has been deposited at a bathyal depth because it is enclosed within the bathyal Waicoe and Knife and Steel formations. An upper bathyal EoD is nominated here based on the QMAP and Turnbull et al. (2010) descriptions and Fig. 3.*

### **Wairaurahiri Formation (IMiPlwr)**

(QMAP database spelling: Wairaurahiri Fmn; Waiau Gp)

**Inferred age:** 7-6 Ma (King et al., 1999)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone, siltstone, shellbeds; Description = siltstone; pebbly mudstone; sandstone conglomerate and shellbeds (QMAP database). "The youngest rocks in the onshore Waitutu Sub-basin are Late Miocene to Pliocene, fossiliferous siltstone, pebbly mudstone, conglomerate, sandstone, and rare shellbeds that are mapped as Wairaurahiri Formation... Wairaurahiri Formation represents depositional environments ranging from **bathyal basin** fill, through steep slopes with debris flows on proximal submarine fans, to

**intertidal shelf**" (Turnbull et al., 2010). "Macrofauna and microfauna suggest **deep water** conditions (C45/c107, Turnbull 1992), and the inferred depositional setting was at the narrow, northern end of the Waitutu Sub-basin. Conglomeratic sediments were deposited from **debris flows** or **proximal turbidity currents**, and structures in sandstone facies suggest deposition from both mass flow and traction currents. Quiet areas within the basin are indicated by massive siltstone and mudstone units. Eventual **shallowing to intertidal or even shoreface** depths is indicated by burrowed sandstone north of Trig. 16692" (Turnbull and Uruski, 1995) – *depositional environments ranging from bathyal to innermost shelf are represented in this formation. The map unit is defined as upper bathyal because the main rock type is mudstone, and this is interpreted as upper fan sediment deposited at upper bathyal depths (Fig. 3). Innermost shelf may be an appropriate final depth.*

## **Balleny Group**

"The Balleny Basin includes Eocene to Oligocene, **nonmarine** and **marine** sedimentary rocks of the Balleny Group, and is restricted to the area west of the Hauroko Fault in southern Fiordland" (Turnbull et al., 2010).

### **Macnamara Formation (E0lbm)**

(QMAP database spelling: Macnamara Fmn; Balleny Gp)

**Inferred age:** 41-36 Ma (King et al., 1999)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = conglomerate, carbonaceous mudstone, breccia; Description = pebble conglomerate and breccia overlain by sandstone with carbonaceous mudstone (QMAP database). "Macnamara Formation (Ebm) comprises basal conglomerate (Fig. 54) and pebbly sandstone, overlain by sandstone, carbonaceous mudstone and rare coal, and an upper unit of carbonaceous mudstone and sandstone [E0lbf]... It is unconformably overlain by the Chalky Island Formation (see below) as far east as Big River" (Turnbull et al., 2010). "An Eocene to earliest Oligocene **non-marine and shallow marine** sequence... Three lithofacies associations are recognised within the Macnamara Formation exposed onshore, and are equated with distinctive sedimentary environments, namely **alluvial fan, alluvial plain and a shallow marine, fan-delta** complex (Lindqvist 1990a)" (Turnbull et al., 1993) – *the EoD is defined as onshore after references cited in Turnbull et al. (1993). Innermost shelf may be appropriate in the upper part of the formation.*

### **Macnamara Formation (E0lbf)**

(QMAP database spelling: Balleny Gp)

**Inferred age:** 38-35 Ma (Turnbull et al., 2010)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone; Description = carbonaceous mudstone with minor sandstone and conglomerate (QMAP database). "...an upper unit of carbonaceous mudstone and sandstone..." (Turnbull et al., 2010) – *the unit is inferred to be part of the Macnamara Formation, so after interpretations in Turnbull et al. (1993) (see above in "E0lbm") the EoD is defined as innermost shelf.*

## **Balleny Group (E0lb)**

(QMAP database spelling: Balleny Gp)

"At Chalky Island (Fig. 55), a complex sequence that is indivisible at 1:250 000 scale is mapped as undifferentiated Balleny Group (Eb). This sequence includes Macnamara Formation and several other formations of granitic breccia, channelised sandstone, and mudstone, overlain by graded sandstone (Carter & Lindqvist 1975; Lindqvist 1975, 1990)" (Turnbull et al., 2010). "In the onshore Balleny Basin, subsidence was sufficiently rapid for the Eocene **fluvial and shallow marine** sequence of the lower Balleny Group to be succeeded by Early Oligocene **deep marine** sediments... At the Chalky Island type area, Balleny Group Oligocene rocks consist of a fining-upward succession of coarse-grained **terrigenous** sediments, and a thick **pelagic** marlstone or chalk. The various lithofacies associations at Chalky Island have been given formation status... The Group is a **retrogradational** succession, with a basal breccia (Nuggets Formation) overlain by thick-bedded sandstone (Sealers Formation) grading into a regularly bedded fining upward graded sandstone unit

(Munida Formation)... Lithofacies represent changing environments, from **near-shore submarine fans and channels**, through more **distal submarine fans to deep marine sea floor**... Nuggets Formation sediments were interpreted by Carter & Lindqvist (1975; 1977) to be mass flows in a submarine fan on an **inner shelf** setting, emplaced by slump-creep and high-density turbidity currents... The overlying Sealers Formation [...] sandstone lithofacies were also emplaced by mass-flow in a **proximal fan** environment, cut by fan channels... The Sealers Formation grades upward into the Munida Formation [...] **Bouma sequences** and bioturbation are common. The sandstones are slightly glauconitic (Carter & Lindqvist 1977). Interbedded calcareous silty mudstone contain scattered plant fragments, and have a moderately rich outer shelf microfauna. Macrofossils are rare. The depositional environment is interpreted as a broad fan fringe or fringes" (Turnbull et al., 1993).

**Inferred age:** 33-31 Ma (King et al., 1999)

**EoD breakdown:** 33 Ma: innermost shelf (Nuggets Formation)  
32-31 Ma: upper bathyal (Sealers and Munida formations)

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone, conglomerate, breccia. Description = basal fluvial breccia and conglomerate overlain by marine sandstone and mudstone (QMAP database) – *these sediments at Chalky Island are inferred to represent a sequence that deepens from innermost shelf (Nuggets Formation) to a proximal fan (Sealers Formation) that may have been deposited at upper bathyal depths, and the youngest formation (Munida Formation) which contains Bouma sequences. Mid-bathyal may be an appropriate final depth.*

### **Chalky Island Formation (E0lbc)**

(QMAP database spelling: Chalky Island Fmn; Balleny Gp)

**Inferred age:** 33-27 Ma (King et al., 1999)

**EoD:** lower bathyal

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = sandstone, chert; Description = nannofossil limestone with rare chert and graded sandstone beds (QMAP database). "These rocks represent submarine channel environments, **marginal to the deep marine basin** represented by the overlying Chalky Island Formation (Obc; Lindqvist 1990). Chalky Island Formation consists of thin-bedded, fine-grained, nannofossil limestone or marl, with rare thin cherts. Intercalated channel sandstone deposits occur at Gates Harbour and Big River..." (Turnbull et al., 2010). "**Bathyal** depths are indicated by the increased number of planktic foraminifera... The CIF environment is interpreted by Carter & Lindqvist (1977) and Lindqvist (1986) as **bathyal sea floor to very distal fan fringe**, periodically invaded by turbidity currents" (Turnbull et al., 1993). "...pass up gradationally into chalk marl with spaced thin **turbidites** (Chalky Island Formation) that represent **distal fan** and possibly **abyssal** sea-floor deposits" (Carter and Lindqvist, 1975) – *the Chalky Island Formation is described as a distal fan which implies lower bathyal depths (Fig. 3).*

### **Green Islets Formation (E0lbg)**

(QMAP database spelling: Green Islets Fmn; Balleny Group)

**Inferred age:** 29-27 Ma (King et al., 1999)

**EoD:** upper bathyal

**Basis for interpretation:** Main\_Rock = breccia; Sub\_Rocks = sandstone mudstone; Description = bouldery breccia with marly to coarse sandy matrix (QMAP database). "At Green Islets, a **submarine landslide** is intercalated with Chalky Island Formation (Fig. 56). This breccia deposit (Obg) consists of blocks, up to 2 m across, of locally derived granite, diorite, hornfels, mafic gneiss and amphibolite in a marly matrix reworked from Chalky Island Formation (Bishop & Howell 1985)" (Turnbull et al., 2010). "The Green Islets Breccia... was emplaced as several **submarine avalanche deposits** into the younger Chalky Island Formation..." (Turnbull et al., 1993) – *EoD is based on the interpretation in Turnbull et al. (2010) of mode of emplacement (submarine landslide), and Fig. 3, which implies that the map unit is an upper bathyal, upper fan deposit.*

### **Five Fingers Outlier (PleQff)**

**Inferred age:** 3-2 Ma (Turnbull et al., 1985)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = conglomerate, lignite, sandstone;

Description = conglomerate sandstone and minor lignite overlain by **marine** mudstone (QMAP database). “An unfaulted sliver of sedimentary rocks (Pwf) occurs at Five Fingers Peninsula on Resolution Island (Wellman 1954). This isolated outlier, largely obscured by a landslide, consists of conglomerate (Fig. 57), carbonaceous mudstone, and **lignite**, overlain by well-sorted, soft, fossiliferous sandstone and mudstone (Turnbull et al. 1985)” (Turnbull et al., 2010). “The sediments record rapid subsidence and a transgression from **alluvial plain to shallow marine environments**, and are fault bounded on both sides... The fauna appears to have lived in shallow water (about **20-50 m**) on an open continental shelf... The benthic assemblage lacks deep water forms and is most consistent with an **inner to possibly mid-shelf** environment” (Turnbull et al., 1985) – *the QMAP description appears to be describing a transgressive sequence, with onshore sediments overlain by shallow marine mudstones. Onshore may be an appropriate alternative EoD.*

## Quaternary – Sedimentary deposits

- **All Q deposits** (except – see below)

**EoD:** onshore

**Basis for interpretation:** Based on the QMAP database which includes alluvial, beach, dune, landslide, man-made fill, moraine, peat, scree, and till sediments in the Quaternary deposits.

- **Q17b, Q15b, Q13b, Q11b, Q9b, Q7b, Q5b, Q3b**

**EoD:** innermost shelf

**Basis for interpretation:** “Uplifted **marine** terrace surfaces...” (Turnbull et al., 2010).

- **Kisbee Formation (eQi)**

(QMAP database spelling: Kisbee Fmn)

**Inferred age:** 1 Ma (Turnbull et al., 2010)

**EoD:** outer shelf

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = conglomerate; Description = sparsely fossiliferous mudstone with rare dropstones; gravel and minor till (QMAP database). “The Kisbee Formation (eQi) consists of fossiliferous mudstone, gravel and till in the Wilson River gorge east of Puysegur Point (Turnbull et al. 2007)... It was deposited within a pre-existing submarine valley during a glacial period when the Puysegur area was still below sea level. Dropstones in the mudstone (Fig. 58) indicate the presence of floating ice above” (Turnbull et al., 2010). “The macrofauna and nannoflora indicate deposition within Castlegiffian time, somewhere between 0.5 and 1.2 Ma, at depths estimated to range between **50-150 and >200 m**” (Turnbull et al., 2007) – *Turnbull et al. (2007) interprets the depositional depth as mid-shelf to upper bathyal (Fig. 3). An average outer shelf depth is assigned here.*

## Quaternary – Volcanic deposits

- **Solander Island Volcanics (mQsv)**

**Inferred age:** < 0.5 Ma (Turnbull et al., 2010)

**EoD:** onshore intermediate eruptives

**Basis for interpretation:** “The Solander islands are formed of Solander Island Volcanics (mQv), which comprise porphyritic plagioclase-hornblende **andesite flows**, agglomerate and tuff, with minor **dikes** (Harrington & Wood 1958; Reay 1986; Reay & Parkinson (1997) (Fig. 15). There are rare intercalated lignites, and gabbroic, gneissic and dioritic xenoliths in some flows” (Turnbull et al., 2010) – *EoD is based on the main rock type of the map unit and the occurrence of, presumably, extrusive lava, as well as peat, implying terrestrial deposition. The occurrence of dikes implies minor intrusive emplacement.*

## WAKATIPU AREA (Geological Map 18)

### *Awarua Limestone (Oa)*

**Inferred age:** 25-24 Ma (King et al., 1999)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = conglomerate; Description = flaggy limestone with basal conglomeratic limestone (QMAP database). "...a hard, white, **bryozoan** limestone with basal conglomeratic and/or sandy facies resting unconformably on Greenland Group..." (Turnbull, 2000). "Where exposed onshore, Awarua Limestone is predominantly a thin (<20 m), **shallow-water** fragmental limestone, but locally has micritic facies interpreted to represent deposition in **deeper water** (Nathan 1978, p. 33 and fig. 7)" (Sutherland et al., 1996). "Such a widespread distribution of a thin, but uniform, unit immediately above an unconformity implies marine transgression over land ...Slow subsidence led to widespread deposition of **shallow-water** bryozoan limestone in the south, and deeper-water foraminiferal ooze in the north" (Nathan, 1978) – *the EoD is based on the predominantly shallow water interpretations of Sutherland et al. (1996) and Nathan (1978).*

### *Tititira Formation (mMt)*

(QMAP database spelling: Tititira Fmn)

"...mudstone, graded sandstone-mudstone, and graded conglomerate interbedded with sandstone... In the Kaipo valley one infaulted sliver of Tititira Formation includes volcanic flow rocks" (Turnbull, 2000). "...a **deep-water** sequence passing upwards from hemipelagic mudstone through **distal and proximal turbidites** (Kaipo Member) into a **mass-flow conglomerate-sandstone complex** (Long Reef Member)..." (Nathan, 1978).

**Inferred age:** 14-9 Ma (Sutherland et al., 1996)

**EoD breakdown:** 14-11 Ma: lower bathyal (Kaipo Member)

10-9 Ma: upper bathyal (Long Reef Member)

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = conglomerate, mudstone, limestone, volcanics; Description = interbedded sandstone and mudstone; rare conglomerate; in faulted lenses of limestone and volcanics (QMAP database) – *the lower part of the formation, represented by the Kaipo Member, is interpreted as being deposited in mid- to lower bathyal depths. The upper part of the formation, represented by the Long Reef Member, is interpreted as being an upper bathyal deposit. Refer to "Tititira Formation (mMt)" on the Haast map area for further information.*

### *Annick Group (Ea)*

**Inferred age:** 41-35 Ma (King et al., 1999)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = siltstone, conglomerate; Description = coarse sandstone; conglomerate and carbonaceous siltstone (QMAP database). "...predominantly **nonmarine** Eocene Annick Group in the north of the Te Anau Basin... Conglomerate, sandstone, carbonaceous mudstone, and rare coal (Ea) of the Annick Group form fault slivers along the Hollyford Fault System from the Eglinton valley to the Pyke River (Williams 1978; Ritchie 1980; Bishop et al. 1990). Conglomerate along the Wilmot Fault in the Skippers Range (Nauman 1973) may also be Annick Group" (Turnbull, 2000). "...the oldest Eocene sediments in the Te Anau Basin are **marine**... The Sandfly Formation fills paleovalleys eroded or downfaulted into basement... On the Franklin Mountains, pale grey **fluvial** representatives of the Earl Mountains Sandstone are interbedded with **marginal marine**, dark green sandstone, possibly of the Sandfly Formation. Near Northern Lake Te Anau, **fluvial** Earl Mountains Sandstone appear to grade laterally into **deltaic** facies then into **marine** Sandfly Formation mudstone (Turnbull 1986, 1991)... The Sandfly Formation includes both **non-marine** and **submarine fan** environments; the Earl Mountains Sandstone is mostly **fluvial**... The Sandfly sequence infilling the proto-Eglinton valley (Turnbull 1986) is interpreted to be a proximal, very high energy **fluvial** deposit, because of a lack of marine indicators and a higher proportion of coalified logs in the sediments. The fossil gully on the Earl Mountains is inferred to be subaerial on similar grounds" (Turnbull et al., 1993) – *Annick Group is located in the proto-Eglinton valley, so is defined as onshore, after Turnbull et al. (1993).*

### ***Sandfly Formation (Easc)***

(QMAP database spelling: Sandfly Fmn)

**Inferred age:** 41-39 Ma (King et al., 1999)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = conglomerate; Sub\_Rocks = sandstone; Description = massive conglomerate with minor sandstone interbeds (QMAP database). “Basal Annick Group sediments are Middle Eocene Sandfly Formation (Eas) conglomerate in the northern Te Anau Basin (Grindley 1958; Turnbull 1985, 1986, 1991), and infaulted along the Hollyford Fault System” (Turnbull, 2000). “At the northern end of Lake Te Anau, Sandfly Formation lithofacies are more complex and variable (Turnbull 1991). The basal lithofacies is m-bedded to massive, sandy, clast-supported cobble to boulder conglomerate up to 1000 m thick (D41/c103), with minor sandstone lenses, scattered coalified logs near the base, and rare macrofossil fragments or shellbeds towards the top (D41/c102)... Sandfly Formation lithofacies in Middle Fiord probably represent extremely rapid deposition, initially off the scarp of the Middle Fiord Fault as a scree breccia (Turnbull 1985) building into a **shallow marine** environment” (Turnbull et al., 1993) – *this conglomerate unit is likely the basal marine unit in the Te Anau Basin.*

### ***Sandfly Formation (Eas)***

(QMAP database spelling: Sandfly Fmn)

**Inferred age:** 41-39 Ma (King et al., 1999)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = conglomerate; Description = massive to graded or crossbedded sandstone; olistostromes of breccia-conglomerate (QMAP database). “Overlying the conglomerate are **fluvial to shallow marine** and **deltaic** conglomerate, **marine** sandstone, and boulder breccias in olistostromes” (Turnbull, 2000). “This basal lithofacies grades laterally over 1 or 2 km, and vertically over 100 to 200 m, into m-bedded massive and graded coarse sandstone. This in turn grades laterally and upwards into dark grey-brown massive mudstone... The conglomerate-sandstone-mudstone lithofacies in the northern Te Anau Basin is interpreted as a small-scale **submarine fan** complex deposited rapidly in a restricted marine basin. The probable southwestern margin of the basin is represented by the Franklin Mountain sequence (D41/c104) which may have been deposited in **shallower** water” (Turnbull et al., 1993) – *this unit is defined as a basinal deposit that rapidly filled and shallowed to inner shelf depths, followed by onshore deposition of Earl Mountains Sandstone. This is based on paleogeography maps by Turnbull et al. (1993).*

### ***Earl Mountains Sandstone (Eaa)***

(QMAP database spelling: Earl Mtns Sst)

**Inferred age:** 39-35 Ma (King et al., 1999)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = conglomerate, mudstone, coal; Description = sandstone with minor conglomerate; fines upward with mudstone and rare coal at top (QMAP database). “The basin-wide Late Eocene Earl Mountains Sandstone (Eaa) conformably overlies Sandfly Formation, or rests unconformably on basement” (Turnbull, 2000). “The Earl Mountains Sandstone is a major **fluvial** deposit, fining upwards from a relatively high energy, channel-dominated braided system to a distal **floodplain**-dominated environment... The upper carbonaceous mudstone is transitional from **brackish to marginal marine** and may be **lagoonal** as it rarely contains marine macrofossils and is overlain by definite marine units” (Turnbull et al., 1993) – *the unit is defined as onshore because it is described as fluvial and lagoonal.*

### ***Nightcaps Group (En)***

(QMAP database spelling: Nightcaps Group; Beaumont Fmn)

**Inferred age:** 42-35 Ma (King et al., 1999)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = conglomerate, mudstone, coal; Description = conglomerate; sandstone; rare coal; carbonaceous mudstone (QMAP database). “... dominated by granite-derived sandstone in channelled and cross-bedded units, with subordinate



carbonaceous mudstone and rare coal seams. They reflect regional subsidence and formation of an extensive **fluvial** system over much of western Southland (Turnbull & Uruski 1993)” (Turnbull, 2000) – *the group is defined as onshore because it appears to be a fluvial deposit. It has been defined here simply as Nightcaps Group, because this is how it is mapped on the geological map sheet and on the adjacent map (Murihiku). Refer to “Nightcaps Group (En)” on the Murihiku map area for further information.*

## Waiiau Group

“...basin-wide marine Oligocene to Miocene Waiiau Group... The Waiiau Group conformably overlies Annick Group, and includes formations representing three depositional settings: (1) **shallow marine** shelves on the west and southeastern flanks of the Te Anau Basin, (2) **submarine fans and fan deltas** infilling the main basin and adjacent sub-basins, and (3) Waicoe Formation (Oww), a background **deep water** mudstone facies that overlies and interfingers with fan deposits” (Turnbull, 2000). “In the Early Oligocene, the Te Anau Basin was inundated by 1000 m of **submarine fan** sandstone, which succeeded a diverse sequence of earliest Oligocene sandstone and mudstone deposited in several small basins. In the Middle to Late Oligocene, the Te Anau Basin was a **deep marine** depocentre with carbonate-dominated **shelf** environments established on its margins” (Turnbull et al., 1993).

### Waicoe Formation (OMw)

(QMAP database spelling: Waicoe Fmn)

Main\_Rock = mudstone; Sub\_Rocks = sandstone; Description = massive mudstone; subordinate sandstone units; rare graded limestone (QMAP database). “...Waicoe Formation (Oww), a background **deep water** mudstone facies which overlies and interfingers with fan deposits... Mudstone of the Waicoe Formation (Fig. 27c) conformably overlies or encloses all these fan sequences in the Te Anau Basin and adjacent sub-basins, and extends east to West Dome (Mackay 1982)” (Turnbull, 2000). “The main representative of Miocene sediments (Fig. 2) is the Horseshoe Mudstone (Wn, Turnbull, 1985), now called Waicoe Formation (Turnbull et al., 1989), which is dominated by **deep marine** mudstones similar to those of the Waiiau Basin. It includes thinly bedded, grey, **distal turbidite** sandstones...” (Uruski and Turnbull, 1990) – *the occurrence of Waicoe Formation has been aligned with descriptions in the Wakatipu, Fiordland and Murihiku QMAP bulletins, Turnbull et al. (1993), and the chronostratigraphic panels in King et al. (1999). Waicoe Formation on the Wakatipu map area occurs in Te Anau Basin and two sub-basins: the Burwood and Monowai sub-basins. NB: one polygon in the southwest of this map area is actually Tunnel Burn Formation (lOw).*

#### • Te Anau Basin

“This basin is simpler than the Waiiau Basin, and sedimentation patterns are less diverse... Fan sedimentation was replaced in the Late Oligocene by Waicoe Formation mudstone, which covers the whole central and northern Te Anau Basin... The mudstone contains macro- and microfauna indicating **gradually deepening** conditions, down to **bathyal** in the Early Miocene... The same Eo-Oligocene increase in regional subsidence that affected the Balleny and Waiiau basins also resulted in marine sedimentation over the greater Te Anau Basin. Another factor was activity on the Moonlight and Hollyford fault systems, which influenced sedimentation in local depocentres such as the Burwood and Dunton sub-basins, and along the Moonlight Fault itself past Lake Wakatipu... The lithostratigraphy of the Early and Middle Miocene Waiiau Group in the Waiiau and Te Anau basins resembles that of the Oligocene. Deposition of the basin-wide Waicoe Formation mudstone continued through the Miocene... No Middle Miocene sediments are preserved in the central Te Anau Basin... Throughout the Te Anau Basin, the Miocene Waicoe Formation mudstone was deposited in a **deep**, sheltered, marine basin with little coarse-grained clastic input. Planktic microfauna indicate **bathyal** depths in the west, and shallower **outer shelf** conditions in the north (D42/c102; R. Hoskins pers. comm. 1987). The formation coarsens eastwards into the Takaro Formation...” (Turnbull et al., 1993).

**Inferred age:** 29-19 Ma (Turnbull et al., 1993; 2010)

**EoD breakdown:**

29 Ma:	<u>upper bathyal</u>
28-26 Ma:	<u>mid-bathyal</u>
25-19 Ma:	<u>lower bathyal</u>

- **Burwood Sub-basin**

“The Burwood Sub-basin records the same Eocene and Oligocene **marine transgression** seen in the Waiau and Te Anau basins... By the Middle Whaingaroan (Middle Oligocene), the central Burwood Sub-basin had subsided to **outer shelf or upper slope** depths and a thick sequence of Waicoe Formation mudstone accumulated over the Spear Peak Formation sandstone. **Submarine fan** sedimentation then recommenced, and two distinct fan lithofacies invade the Waicoe mudstone” (Turnbull et al., 1993).

**Inferred age:** 34-12 Ma (Turnbull et al., 1993; 2010)

**EoD breakdown:** 34-33 Ma: innermost shelf  
32 Ma: mid-shelf  
31 Ma: outer shelf  
30-29 Ma: upper bathyal  
28-26 Ma: mid-bathyal  
25-12 Ma: lower bathyal

- **Monowai Sub-basin**

“The sequence [Point Burn, Tunnel Burn, and Hope Arm formations] is truncated by a Late Oligocene unconformity, and is overlain by Early Miocene Waicoe Formation mudstone... The planktic-dominated microfauna from the Waicoe and Borland formations indicates a **bathyal** environment of deposition of those formations... **subsided rapidly** in earliest Miocene times in response to the accelerating compressional tectonic regime... In the Early Miocene, the onshore western shelf area **abruptly subsided** and the basin-wide Waicoe Formation mudstone facies, already established in Oligocene time in the Waiau Basin, extended westwards over eastern Fiordland” (Turnbull et al., 1993).

**Inferred age:** 21-12 Ma (Turnbull et al., 1993; 2010)

**EoD breakdown:** 21-12 Ma: lower bathyal

### ***Stuart, Spear Peak and Point Burn formations (Ow)***

(QMAP database spelling: Point Burn; Spear Peak; Stuart f)

Includes Stuart, Spear Peak, and Point Burn formations.

“Undifferentiated Waiau Group (includes Point Burn, Stuart, and Spear Peak formations): Basal calcareous to carbonaceous mudstone; breccias lenses; cross-bedded bluff-forming sandstone units; fining and thinning upward graded sandstone-mudstone packets; minor conglomerate bands and fossiliferous conglomerate at Lake Gunn (Ow)” (Turnbull, 2000 geological map sheet). “The Waiau Group conformably overlies the Annick Group, and includes formations representing three depositional settings: (1) **shallow marine** shelves on the west and southeastern flanks of the Te Anau Basin, (2) **submarine fans and fan deltas** infilling the main basin and adjacent sub-basins...” (Turnbull, 2000).

- **Stuart Formation**

**EoD:** innermost shelf

**Basis for interpretation:** “At the north end of Lake Te Anau, **lagoonal marine** mudstone, cross-bedded sandstone, and graded sandstone sequences of the Stuart Formation (Ow), (Fig. 27b) rest on Annick Group...” (Turnbull, 2000) – *this formation is defined as innermost shelf based on “lagoonal marine”, however onshore may be an appropriate alternative.*

- **Spear Peak Formation**

**EoD:** upper bathyal

**Basis for interpretation:** “Southeast of the Moonlight Fault System adjacent to the Takitimu Mountains, the separate Burwood Sub-basin includes several graded sandstone-mudstone sequences mapped as Spear Peak (Ow)...” (Turnbull, 2000). “...Early Oligocene marine clastic unit, the Spear Peak Formation... is interpreted as a series of small coalescing **submarine fans**, building north-west from the Takitimu Mountains... By the Middle Whaingaroan (Middle Oligocene), the central Burwood Sub-basin had subsided to **outer shelf or upper slope** depths and a thick sequence of Waicoe Formation mudstone accumulated over the Spear Peak sandstone. Submarine fan sedimentation then recommenced, and two distinct fan lithofacies invaded the Waicoe mudstone. The

exact setting of these fans is unknown; microfauna indicate **outer shelf to upper slope** conditions” (Turnbull et al., 1993) – *this formation is defined as upper bathyal because it is series of submarine fans.*

- **Point Burn Formation**

*EoD:* innermost shelf

*Basis for interpretation:* “The western **shelf** sequence includes discontinuous basal Point Burn Formation sandstone (Ow)...” (Turnbull, 2000). “...shell beds with **shallow marine shelf** faunas” (Turnbull et al., 1993). “The Point Burn Formation is of **marginal and shallow marine origin**, as indicated by trace-fossils, cyclic sediments and the presence of calcareous algae *Lithophyllum*, *Lithothamnium* and *Lithoporella*...” (Carter et al., 1982) – *the Point Burn Formation is described as a shelfal deposit which is narrowed down here to innermost shelf. Mid-shelf may be an appropriate alternative.*

*Inferred age:* 36-27 Ma (King et al., 1999)

*EoD breakdown:* 36-35 Ma: innermost shelf (Stuart Formation)  
34-32 Ma: upper bathyal (Spear Peak Formation)  
31-27 Ma: innermost shelf (Point Burn Formation)

*Basis for interpretation:* Main\_Rock = sandstone; Sub\_Rocks = mudstone, conglomerate, limestone; Description = graded to massive sandstone and mudstone; minor conglomerate; rare limestone olistoliths (QMAP database) – *this unit includes three formations which are currently exposed around the edge of the Te Anau Basin. The EoD is broken down according to the comprising formations.*

### **Tunnel Burn Formation (lOw)**

(QMAP database spelling: Tunnel Burn Fmn)

*Inferred age:* 26-22 Ma (King et al., 1999)

*EoD:* innermost shelf

*Basis for interpretation:* Main\_Rock = limestone; Sub\_Rocks = sandstone; Description = massive to crossbedded sandy bioclastic limestone (QMAP database). “...distinctive blanket of Tunnel Burn Formation limestone (lOw) which is up to 100 m thick, and extends southwards from the Middle Fiord of Lake Te Anau. This bioclastic limestone is truncated in most places by the Marshall Paraconformity (unconformity) of latest Oligocene age (Carter et al. 1982), and is overlain by Waicoe Formation. Sandy limestone at Freestone Hill in the southwest corner of the map area may be a redeposited equivalent of the Tunnel Burn Formation” (Turnbull, 2000) – *an innermost shelf EoD is inferred. A mid-shelf interpretation could also be appropriate. Refer to “Tunnel Burn Formation (lOwt)” on the Fiordland map area for further information.*

### **Dunton and Takaro formations (OMd)**

(QMAP database spelling: Takaro; Dunton fmns)

“The eastern shelf sequence consists of variably fossiliferous, thick bedded marine sandstone, shellbeds, and thin bioclastic limestones of the Dunton and Takaro formations (Owd)” (Turnbull, 2000).

- **Dunton Formation**

*EoD:* upper bathyal

*Basis for interpretation:* “...consists of convoluted to parallel-laminated, often amalgamated, **dm-bedded**, coarse sandstone with scattered macrofossils, occasional **slump** horizons of fossiliferous pebbly mudstone, and some thick-bedded (2-3 m) massive and structureless sandstone (Turnbull 1986). The depositional environment of these sediments is interpreted to be a **subsiding shallow marine shelf**” (Turnbull et al., 1993) – *the EoD is defined as upper bathyal because this formation is assumed to have been transported/subsided to such depths.*

- **Takaro Formation**

*EoD:* innermost shelf

*Basis for interpretation:* “In the Upukerora area, a regressive sequence of Early Oligocene to Late Miocene age, the Takaro Formation... The Early Middle Miocene Takaro Formation **shelf** sediments

near the eastern side of the basin include up to 1000 m of muddy macrofossiliferous siltstone and fine grained sandstone, as well as shell beds and slightly pebbly bioclastic limestone units up to 30 m thick (Turnbull 1986; D42/c3, c106). Bioturbation has destroyed most sedimentary structures, although rare cross-lamination is still preserved. Many shell beds are concretionary and include coal clasts and slumped siltstone blocks... macrofauna and microfauna indicate that conditions shallowed from bathyal in the earliest Miocene, to **inner shelf** by late Early Miocene" (Turnbull et al., 1993) – *the EoD is defined as innermost shelf after Turnbull et al. (1993).*

**EoD breakdown:** 34-28 Ma: upper bathyal (Dunton Formation)  
23-12 Ma: innermost shelf (Takaro Formation)

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone, limestone, conglomerate; Description = variable massive to graded lithic sandstone; shell beds; limestone; mudstone; conglomerate (QMAP database) – *this unit code includes both Dunton and Takaro formations, so the EoD is divided based on the EoD of those two formations.*

### **Turret Peaks Formation (Owt)**

(QMAP database spelling: Turret Pks Fmn)

**Inferred age:** 34-26 Ma (King et al., 1999)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = siltstone conglomerate; Description = graded to massive to crossbedded fine to granular lithic sandstone and siltstone; Map\_Unit = **flysch** (QMAP database). "The overlying Oligocene to Middle Miocene **submarine fan** facies are mapped as Turret Peaks Formation (Owt)..." (Turnbull, 2000). "This sandstone unit is inferred to be a very large and active **submarine fan**, or series of fans, cut by major channels which at times were swept by traction-dominated sand-laden currents" (Turnbull et al., 1993). "Some 1800 m of sandstone-dominated **fan** deposits have infilled a major pull-apart depocentre within the northern Te Anau Basin... The basal 700-800 m of this succession, as observed in the Stuart Mountains, is made up of metre-bedded, often amalgamated sandstone beds (Fig. 5)... Also at around 1000 m, three conglomerate beds are found within the succession... Above 1300-1500 m, massive sandstone beds are very rare, and are replaced by mudstone intercalated with graded sandstone of a more classical **flysch facies** assemblage" (Zink and Norris, 2004) – *the fans and flysch deposits of this formation were deposited at bathyal depths, so an average depth of mid-bathyal is defined here.*

### **Borland Formation (Mwb)**

(QMAP database spelling: Borland Fmn)

**Inferred age:** 18-16 Ma (King et al., 1999)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone; Description = graded to massive sandstone with mudstone interbeds; Map\_Unit = **flysch** (QMAP database). "The overlying Oligocene to Middle Miocene **submarine fan** facies are mapped as ... Borland Formation (Mwb) in the main basin..." (Turnbull, 2000) – *EoD is based on the QMAP database and Turnbull (2000) defining the formation as flysch and submarine fans. Upper or lower bathyal may also be appropriate. Refer to "Borland Formation (Miwb)" on the Fiordland map area for further information. NB: the two southernmost polygons are mislabelled in the database and should be Duncraig Formation (Miwd on Fiordland).*

### **Army Hut Formation (Owt)**

(QMAP database spelling: Army Hut Fm)

**Inferred age:** 34-26 Ma (age of Turret Peaks Formation; King et al., 1999)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone, limestone, conglomerate; Description = variable massive to graded lithic sandstone; shell beds; limestone; mudstone; conglomerate (QMAP database). "The overlying Oligocene to Middle Miocene **submarine fan** facies are mapped as... Army Hut Formation (Owt) in the Dunton Sub-basin" (Turnbull, 2000) – *the Turnbull (2000) interpretation of the formation as a submarine fan implies a bathyal EoD. The main rock type of sandstone indicates a more proximal rather than distal deposit and thus the map unit is*

interpreted to have a mid-bathyal depth of deposition. However, the conglomerate could represent submarine channel fill in which case an upper bathyal EoD may be more appropriate (Fig. 3). No age data could be found for this formation, so it is given that of Turret Peaks Formation, because they have the same unit code and are included in the same unit on the geological map legend.

### **Weydon Burn Formation (Owe)**

(QMAP database spelling: Weydon Burn Fmn)

**Inferred age:** 30-22 Ma (King et al., 1999)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone; Map\_Unit = **flysch**; Description = graded sandstone and mudstone (QMAP database). "Southeast of the Moonlight Fault System adjacent to the Takitimu Mountains, the separate Burwood Sub-basin includes several graded sandstone-mudstone sequences mapped as... Weydon (Owe)... formations" (Turnbull, 2000). "**Submarine fan** sedimentation then recommenced, and two distinct fan lithofacies invaded the Waioce mudstone. The exact setting of these fans is unknown; microfauna indicate **outer shelf to upper slope** conditions. One fan on the northeast side of the basin is the Weydon Formation, which is characterised by coarse-grained, graded, biotite-rich quartzofeldspathic sandstone..." (Turnbull et al., 1993) – EoD is based on the QMAP database interpretation of the formation as flysch and an absence of submarine channels, conglomerates, or other proximal submarine fan deposits in the descriptions indicates a mid-bathyal EoD (Fig. 3). Upper bathyal may be an alternative EoD.

### **Haycocks Formation (Mwh)**

(QMAP database spelling: Haycocks Fmn)

**Inferred age:** 21-16 Ma (King et al., 1999)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone; Description = graded sandstone and mudstone; Map\_Unit = **flysch** (QMAP database). "Southeast of the Moonlight Fault System adjacent to the Takitimu Mountains, the separate Burwood Sub-basin includes several graded sandstone-mudstone sequences mapped as... Haycocks (Mwh) formations..." (Turnbull, 2000). "Microfaunas from mudstone interbeds indicate **outer shelf to bathyal** conditions" (Turnbull et al., 1993) – EoD is based on the QMAP database interpretation of the formation as flysch.

### **Bobs Cove Beds (Ob)**

**Inferred age:** 26-23 Ma (Turnbull, 2000)

**EoD:** outer shelf

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = sandstone, conglomerate; Description = limestone sandstone conglomerate and breccias (QMAP database). "At Bobs Cove they are up to 200 m thick, and include basal breccia, siltstone, limestone, sandstone, conglomerate, and olistostromes (Turnbull et al. 1975b). Elsewhere, only a few metres of indurated quartz-schist breccia, conglomerate, or fossiliferous sandstone or limestone are preserved" (Turnbull, 2000). "At the type locality at Bobs Cove, the basal part of the 450 m thick sequence represents **shallow marine** ("**shelf**") environments of deposition. The remainder of the sequence, from the limestone upwards, comprises redeposited sediment, deposited largely from mass-transport on a **submarine slope** leading to a deep marine flysch basin" (Turnbull et al., 1975). "Other published localities that fit a number of the criteria for **rocky shorelines** include those at Bobs Cove near Queenstown (Park 1909; Turnbull et al. 1975)..." (Scott et al., 1014) – *the depositional environment could range from innermost shelf to bathyal; it is narrowed down here to outer shelf, after the interpretation of shelfal for a significant portion of the unit in Turnbull et al. (1975).*

### **Prospect Formation (MPp)**

(QMAP database spelling: Prospect Fmn)

**Inferred age:** 11-3 Ma (King et al., 1999)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = conglomerate; Sub\_Rocks = sandstone, mudstone, lignite; Description = massive to crossbedded greywacke conglomerate; sandstone interbeds; mudstone units to 50 m thick (QMAP database). "The **nonmarine** Prospect Formation unconformably over-

lies the Waiuu Group... The marine sequence of the Te Anau Basin is erosively truncated by the Late Miocene to Pliocene Prospect Formation (Pp) (Fig. 27d). This **fluvial** conglomerate unit includes subordinate sandstone, carbonaceous mudstone, and minor lignite" (Turnbull, 2000). "The **largely nonmarine** Prospect Formation is wholly subdivided into five members on the basis of lithofacies associations and petrofacies. The basal Forest Burn and Umbrella Flat Members (new) were deposited by coarse grained **deltaic** systems which prograded across the marine Te Anau Basin from petrologically distinct uplifted basement terrains to either side. The upper part of the formation is dominated by gravelly braided **stream deposits**, subdivided into the Mt York, Little Creek, and Key Members on the basis of petrofacies and lithofacies assemblages" (Manville, 1996) – *EoD is based on Manville (1996)*.

### **Alpine Dike Swarm**

"Throughout northwest Otago, **lamprophyric intrusions** of the Alpine Dike Swarm intrude Haast Schist (Adams & Cooper 1996) (Fig. 29a). Dikes generally trend east-west, range from a few cm to over 5 m thick, and may extend for up to 1 km. They range from camptonite to tinguaitite, carbonatite, or limburgite (Fig. 29b), and have generally alkalic geochemistry. Volcanic vents or diatremes west of Lake Wanaka (Cook 1984; Clough 1988; Adams & Cooper 1996) consist of lamprophyric breccia (Ov) with a fresh to devitrified glass matrix, schist, lherzolite, harzburgite, and gabbro-norite clasts, and megacrysts of pyroxene, hornblende, and feldspar. Individual diatremes are up to 1 km in diameter, cut by lamprophyre dikes, and altered with abundant carbonate" (Turnbull, 2000). "**Lamprophyres**, occurring as **dikes** and high-level diatremes, intrude greenschist facies Haast Schist in the southern part of the Alpine Dike Swarm, near Wanaka, western Otago. Of 12 lamprophyres dated by conventional K-Ar techniques, 10 give whole-rock ages ranging between 25.2 and 31.9 Ma, with kaersutites separated from four samples forming a tighter group at 22.9-27.8 Ma" (Adams and Cooper, 1996).

- **Ov**

**Inferred age:** 32-25 Ma (Adams and Cooper, 1996)

**EoD:** mafic intrusives

**Basis for interpretation:** Main\_Rock = **lamprophyre**; Sub\_Rocks = agglomerate; Map\_Unit = volcanics; Description = brecciated and altered **lamprophyric** volcanics with schist inclusions (QMAP database) – *these dikes are defined as mafic intrusives after the main rock type.*

- **PMeOmi, PMLomi**

**Inferred age:** 32-28 Ma (Adams and Cooper, 1996)

**EoD:** mafic intrusives

**Basis for interpretation:** Main\_Rock = lamprophyre; OR camptonite (after Adams and Cooper, 1996) – *these polygons have been added into the database after Adams and Cooper (1996), where they are identified as lamprophyres or camptonites.*

- **Nevis Bluff dike (PMeMmi)**

**Inferred age:** 21 Ma (Hoernle et al., 2006)

**EoD:** mafic intrusives

**Basis for interpretation:** Main\_Rock = lamprophyre (after Hoernle et al., 2006). "A single basanitic sample from Nevis Bluff, regarded as a southern outlier of the Alpine–Northwest Otago lamprophyric dike swarm, produced an age of  $20.7 \pm 0.4$ , within the Waipiata age range and at the young end of the Alpine–Northwest Otago Dike Swarm range of ages..." (Hoernle et al., 2006) – *the dike at Nevis Bluff has been dated by Hoernle et al. (2006) and is identified as a lamprophyre. The polygon has been added into the database as such.*

### **Manuherikia Group**

"Throughout Central Otago, remnants of a sequence of **nonmarine** Miocene quartz conglomerate, sandstone, mudstone, and lignite up to 300 m thick are mapped as Manuherikia Group (mMm), divided by Douglas (1986) into the Bannockburn and Dunstan formations (not differentiated on the Wakatipu map)... These sediments were deposited in a **freshwater lake** which extended across

most of the Wakatipu map area east of The Remarkables from the Waikaia valley north to beyond the Lindis Pass... However extremely rare potash feldspar, ilmenite, and glauconite may be evidence for a marine sequence covering Central Otago (Youngson & Craw 1996)" (Turnbull, 2000). "The primary subdivision of Manuherikia Group sediments is twofold. A lower, **fluvial**, commonly coal-bearing succession (Dunstan Formation) is separated from an upper, **lacustrine** succession of typically non-carbonaceous fine grained **terrigenous** sediments (Bannockburn Formation)" (Douglas, 1986). "Following Douglas (1985b) the Manuherikia Group is divided into two formations, a lower Dunstan Formation, locally up to 150 m thick, and an overlying undifferentiated Bannockburn Formation, locally up to about 700 m thick" (Mildenhall and Pocknall, 1989). "The oldest sediments appear to have been deposited in the east around Gimmerburn, near Ranfurly, from a lower to middle Tertiary marine transgression which climaxed in the Late Oligocene. Earliest deposition began with quartz gravel deposited in narrow braided channels cut into the exposed schist basement. Eventually a **fluvial plain** developed with a complex of low gradient meandering channels and local back swamps, which accumulated considerable thicknesses of peat. Subsequently a large, longlived, **freshwater lake** was formed, Lake Manuherikia of Douglas (1985a, b), which covered over 5600 km<sup>2</sup>. In this sedimentary setting there were several sub-environments, ranging from stagnant freshwater bays (Nevis Oil Shale) to peat swamps (Roxburgh coal seam in Harliwich's Mine). Ultimately, the tectonic activity associated with the Kaikoura Orogeny resulted in an influx of sand and gravel from braided streams, causing Lake Manuherikia to shallow" (Mildenhall, 1989). "Outcrop and sediment preservation are too limited to define the margins of the paleolake(s), hence it is unclear whether lacustrine strata locally overlying Dunstan Formation in the Maniototo Basin (above) belong with Bannockburn Formation. This problem cannot be resolved without more rigorous definition and mapping of Bannockburn Formation" (Youngson et al., 1998).

- **mMm**

**Inferred age:** 19-15 Ma (Mildenhall and Pocknall, 1989)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = sand; Sub\_Rocks = gravel, silt, clay, lignite; Description = quartz sand and gravel with minor silt; clay; lignite; and sarsen stones (QMAP database) – *EoD is based on the cited literature. The duration of Lake Manuherikia is estimated from comments in Mildenhall and Pocknall (1989) and the initiation of faulting in this region from 8 Ma. The maximum extent of Lake Manuherikia during the Early Miocene is taken from the area that the present day out crop covers; it may have been larger than this.*

- **mMmc**

**Inferred age:** 19 Ma (Mildenhall and Pocknall, 1989)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = quartzite; Description = silica-cemented quartz sand and gravel (QMAP database). "In places the quartz gravel has been silica-cemented, and now forms lag deposits of sarsen stones" (Turnbull, 2000) – *EoD is based on the cited literature. The map legend implies that this unit code is a basal conglomerate in the group.*

## **Hawkdun Group (MPm, MPs)**

**Inferred age:** 11-4 Ma (Turnbull, 2000)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = gravel; Sub\_Rocks = sand, mud, breccia, gold; Description = weathered rounded greywacke or angular locally derived schist gravel with minor sand; may be auriferous (QMAP database). "The Hawkdun Group (Youngson et al. 1998) conformably or unconformably overlies the Manuherikia Group. The Hawkdun Group is discontinuously preserved along the margins of most fault-angle depressions of Central Otago, and is more widespread in the central Manuherikia valley. In the map area the group is represented by the Maniototo Conglomerate (IPdm) (previously Maori Bottom Formation or Group) and the Schoolhouse Fanglomerate (IPds) (Youngson et al. 1998). Maniototo Conglomerate is dominated by weathered, sandy conglomerate composed of well rounded, imbricated clasts of Rakaia terrane sandstone and schist. The Hawkdun Group also includes basal quartz-lithic sandstone at Cromwell (McPherson 1986) (not mapped), and weathered lithic gravel in the upper Clutha valley (Turnbull 1988). Schoolhouse Fanglomerate

consists of sandy to bouldery schist breccia resting on quartz-lithic Dell Sandstone in the Nevis valley (Williams 1974a). The Hawkdun Group represents **alluvial** braid plain deposits and proximal **alluvial** fans..." (Turnbull, 2000) – *EoD is based on Turnbull (2000) interpretation.*

## Quaternary – Sedimentary deposits

- **All Q deposits** (except – see below)

*EoD:* onshore

**Basis for interpretation:** Based on the QMAP database which includes alluvial, beach, dune, lacustrine, landslide, moraine, peat, scree, tailings, and till sediments in the Quaternary deposits.

- **Q1b**

*EoD:* innermost shelf

**Basis for interpretation:** "...a discontinuous **coastal marine** erosion surface..." (Turnbull, 2000) – *this unit has been assigned a marine EoD in keeping with Q1b on the adjacent Haast map area (Rattenbury et al., 2010).*



## WAITAKI AREA (Geological Map 19)

### Onekakara Group

This is the southern equivalent of the Eyre Group. Based on the GIS database the term “Eyre Group” is used to the north of the Waitaki River (i.e. northern half of Waitaki, Aoraki, Christchurch, and Kaikoura map areas), and “Onekakara Group” is used to the south of the Waitaki River (i.e. southern half of Waitaki, and Dunedin map areas).

#### ***Taratu Formation (KEot(e))***

(QMAP database spelling: Onekakara Gp Taratu Formation)

**Inferred age:** > 65-52 Ma (Boyes et al., 2012)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = conglomerate; Description = **Non-marine** quartz sand and conglomerate with clay matrix; lignite seams and carbonaceous mudstone; limonite and silica cemented (QMAP database). “The basal beds in eastern Otago include quartzose conglomerate and sandstone, mudstone and coal (Taratu Formation; lKt); north of the Waitaki River the lateral equivalent is Broken River Formation (Eeb)... Taratu and Broken River formations accumulated in valleys, **fluvial plains, swamps and estuaries** as the sea transgressed northwestwards. Sedimentary structures typical of **stream systems**, such as trough cross bedding, are common in the lower part, but towards the top of the units the better sorting, very low-angle crossbeds, hummocky cross stratification, increased bioturbation and presence of marine dinoflagellates indicate **marine influence** (Aitchison 1988; McMillan 1999)” (Forsyth, 2001). “Taratu Formation strata reflect their deposition in a **braided river** dominated environment (Aitchison 1981)” (Aitchison, 1988) – *the cited references all indicate that the Taratu Formation is a terrestrial deposit, however at the top a marginal marine influence occurred as the sea transgression began.*

#### ***Hogburn Formation (Eoh)***

(QMAP database spelling: Onekakara Gp Hogburn Formation)

**Inferred age:** 42-35 Ma (Bishop, 1974)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = sandstone; Description = **Non-marine** kaolinitic clay; quartz sandstone and conglomerate; mudstone and lignite (QMAP database). “...it is the inland equivalent of the youngest Taratu Formation” (Forsyth, 2001). “West of Oamaru the Bortonian quartz-rich **terrestrial** sediments of the Hogburn Formation...” (Field and Browne, 1989). “The Tertiary sequence at Naseby and Kyeburn consists of the Hogburn Formation, **terrestrial** quartzose sediments of probably Arnold age” (Bishop, 1974) – *the cited references all indicate that the Hogburn Formation is a terrestrial deposit.*

### Marine Onekakara Group

“The stratigraphically higher, **marine** formations (mapped as undifferentiated Onekakara Group marine units; Eo, Pom) are present in a coastal strip up to about 15 km wide, and up to 70 km inland in the Shag, Waitaki and Hakataramea valleys. The contact between the nonmarine and marine units is either an angular unconformity or disconformity, interpreted as a wave-cut surface (the Waipounamu Erosion Surface of LeMasurier & Landis 1996; see also Landis & Youngson 1996). Many local formation names are applied (Table 2). The more extensive rock types include limonitic and micaceous sandstone (Kauru Formation), concretionary silty sandstone, glauconitic sandstone and calcareous mudstone (Abbotsford Formation and Waihao Greensand; Fig. 24b and c), well sorted sandstone (Opawa Sandstone), glauconitic sandstone (Tapui Glauconitic Sandstone), calcareous mudstone and claystone (Burnside Mudstone), and impure limestone or marl (Amuri Limestone), Kapua Tuff, within Burnside Mudstone, is related the Waiareka Volcanics (see below). These rocks were deposited in a wide range of **shallow marine** environments, ranging from **shoreface to outer shelf** and offshore bars” (Forsyth, 2001). “**Paralic and shallow shelf and ramp** sediments deposited during a Late Cretaceous-Oligocene marine transgression” (Carter, 1988). “The Abbotsford and Moeraki Formations are correlatives, as are the Burnside Mudstone and Hampden Formation...” (Field and Browne, 1989).

## **Wangaloa Formation**

*EoD:* innermost shelf

*Basis for interpretation:* “Fossiliferous sandstone overlying or interbedded with Taratu Formation” (Bishop and Turnbull, 1996). “Douglas (1970) noted load casts and scour channels in the basal beds indicating a paleocurrent direction from the southwest (i.e. at right angles to the Waihemo Fault System). This suggests periodic ingress of relatively unsorted pebble detritus deposited by river floods off the schist hinterland and/or periodic storms affecting coastal gravelly sands” (Boyes et al., 2012) – *the formation is defined as innermost shelf because it is the first marine unit in the Onekakara Group to be deposited after the terrestrial Taratu Formation.*

## **Abbotsford Formation**

*EoD:* innermost shelf

*Basis for interpretation:* “The Otepopo Member of Abbotsford Formation comprises massive, dark green to greenish-black greensand thoroughly bioturbated by the Cruziana ichnofacies... The bioturbated texture, presence of phosphate and lag components (wood, pebbles and gravel) and abundant glauconite point to limited terrigenoclastic deposition on the **inner shelf**. Abundant gravel and coarse sand in the greensand in some areas may imply a more **nearshore** position” (Boyes et al., 2012) – *EoD is based on references in Boyes et al. (2012).*

## **Otepopo Formation**

*EoD:* innermost shelf

*Basis for interpretation:* “Deeper marine sediments are seen in the overlying Katiki Formation and Otepopo Greensand... The Otepopo Greensand consists of glauconitic medium- to fine-grained sandstones. The formation was proposed by Brown (1938) and is the senior synonym of Otepopo Formation (Brown, 1959b) and Waianakarua Greensand (Mutch, 1968)... The Otepopo Greensand was deposited in a **shallow marine, nearshore** environment below storm weather wave base. The high glauconite content suggests a slow sedimentation rate in an area with a low terrestrial sediment input” (Aitchison et al., 1993) – *the EoD is based on Aitchison et al. (1993) where the Otepopo Formation is described as being deposited in a shallow marine, nearshore environment. Mid-shelf may be an appropriate alternative.*

## **Moeraki Formation**

*EoD:* outer shelf

*Basis for interpretation:* “Microfaunas indicate outer neritic to **upper bathyal** settings at Clipper-1 and Galleon-1, but a **near shore** setting at Endeavour-1” (Boyes et al., 2012). “...deposited on a passive margin at **shelf**...” (Morgans, 2009) – *an EoD from upper bathyal (in the south, Shag River latitude) to innermost shelf (in the north, Oamaru latitude) could be appropriate, and it is averaged here to outer shelf.*

## **Kauru Formation**

*EoD:* innermost shelf

*Basis for interpretation:* “The crinoid-bearing facies probably represents earliest onlap or a storm surge onto a wave cut platform; sedimentological and paleontological evidence indicates a **moderate- to high-energy environment**... Gage (1957) proposed the name Kauru Formation for early transgressive, **shallow marine**, Early Paleogene sediments that crop out in North Otago” (Stilwell et al., 1994) – *this formation marks the transition between onshore and innermost shelf deposition, and as it is defined as a marine unit, innermost shelf is the inferred EoD.*

## **Kurinui Formation**

*EoD:* upper bathyal

*Basis for interpretation:* “The calcareous mudstone between the Moeraki Formation and the correlative of the Green Island Sand is known as the Kurinui Formation” (Boyes et al., 2012). “...the site deepened to at least **uppermost bathyal (>400 m)** depths during deposition of upper Kurinui Formation... Paleodepth interpretations based on benthic foraminifers, discussed above, suggest deeper paleodepths for the Kurinui and Hampden Formations than inferred by Field et al. (1989) and King et al. (1999)” (Morgans, 2009) – *EoD is after Morgans (2009).*

## **Green Island Sand**

*EoD:* mid-shelf

*Basis for interpretation:* “Fine to medium, cross stratified, silty sand” (Bishop and Turnbull, 1996). “In east Otago the Green Island Sand and Puketapu Formation mark an event of sea level rise, perhaps preceded by a fall” (Boyes et al., 2012) – *Bishop and Turnbull (1996) imply that the EoD (generally) increased during deposition of the Onekakara Group as a marine transgression occurred. Boyes et al. (2012) also imply that sea level rose during the Green Island Sand. Innermost shelf (or even outer shelf) may still be appropriate.*

## **Hampden Formation**

*EoD:* upper bathyal

*Basis for interpretation:* “The Hampden Formation consists of a moderately calcareous basal greensand, grading up into a calcareous siltstone... The Hampden Formation was deposited in **outer shelf to bathyal** settings, and probably contains a Porangan unconformity or condensed sequence (picked biostratigraphically) at the Clipper-1 drillhole, and possibly also at Endeavour-1” (Boyes et al., 2012). “...**outermost shelf to upper bathyal** paleodepths... Paleodepth interpretations based on benthic foraminifers, discussed above, suggest deeper paleodepths for the Kurinui and Hampden Formations than inferred by Field et al. (1989) and King et al. (1999)” (Morgans, 2009) – *EoD is after Morgans (2009), and outer shelf may be an appropriate alternative.*

## **Burnside Mudstone**

*EoD:* mid-shelf

*Basis for interpretation:* “Calcareous, grey-brown, plastic silty mudstone” (Bishop and Turnbull, 1996). “The Green Island Sand is succeeded by the calcareous **?mid shelf** Burnside Mudstone” (Field and Browne, 1989) – *the EoD is defined as mid shelf after Field and Browne (1989). Refer to “Burnside Mudstone (Ee\_b)” on the Aoraki map area for further information.*

## **Tapui Formation**

*EoD:* mid-shelf

*Basis for interpretation:* “Abundant hummocky cross stratification at the base of the Tapui Glauconitic Sandstone in the Livingstone-Maerewhenua area, North Otago, New Zealand, indicates a storm-dominated **shallow marine** environment” (Aitchison, 1988). “Between Oamaru and the Rangitata River the main Bortonian unit is muddy glauconitic sandstone (Waihao Greensand and its correlative, the Tapui Glauconitic Sandstone). While the lower part of the unit was deposited in **shallow shelf** conditions...” (Field and Browne, 1989). “The presence of glauconite, fossils, comminuted carbonaceous material, and quartz pebble layers and hummocky-cross stratified sandstone interpreted as storm deposits, point to a **shallow inner-middle shelf** setting” (Boyes et al., 2012) – *references cited in Field and Browne (1986) and Boyes et al. (2012) imply that most of the formation was deposited at inner to mid-shelf depths.*

## **South of Shag River**

- **Pom**

*Inferred age:* > 65-36 (Boyes et al., 2012)

*EoD breakdown:* > 65-51 Ma: innermost shelf (Wangaloa, Abbotsford formations)  
50-36 Ma: mid-shelf (Green Island Sand, Burnside Mudstone)

*Basis for interpretation:* Main\_Rock = siltstone; Sub\_Rocks = sandstone, greensand; Description = Marine quartzose and glauconitic sandstone and siltstone with shellbeds; nearshore to offshore environments; south of Waihemo FZ (QMAP database) – *refer to the above text which describes the marine members of the Paleogene Onekakara Group on the Waitaki map area. This unit code has the same EoD as Pom on the Dunedin map area.*

## **Between Shag River and Oamaru**

- **KOom(kp), KEom(e), KOom(e)**

*Inferred age:* 65-39 Ma (Boyes et al., 2012)

*EoD breakdown:* 65-64 Ma: innermost shelf (Otepopo Formation)

- 63-52 Ma: outer shelf (Moeraki, Kauru [in the north], Kurinui formations)  
 51-44 Ma: upper bathyal (Kauru [in the north], Kurinui formations)  
 43-39 Ma: outer shelf (Hampden, Tapui formations)

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = siltstone greensand; Description = shallow marine to outer shelf micaceous and glauconitic sandstone; siltstone; and mudstone (QMAP database) – refer to the above text which describes the marine members of the Paleogene Onekakara Group on the Waitaki map area.

### **Between Oamaru and Waitaki River**

- **KOom(eo)**

**Inferred age:** 55-39 Ma (Boyes et al., 2012)

**EoD breakdown:** 55-43 Ma: innermost shelf (Kauru Formation)  
 42-39 Ma: mid-shelf (Tapui Formation)

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = siltstone, greensand; Description = deepening facies sequence from shallow marine glauconitic sandstone; siltstone; marl; to biope-lagic chalk (QMAP database) – refer to the above text which describes the marine members of the Paleogene Onekakara Group on the Waitaki map area.

## **Eyre Group**

### **Broken River Formation (Eeb)**

(QMAP database spelling: Eyre Gp Broken River Formation)

“Taratu and Broken River formations accumulated in valleys, **fluvial plains, swamps and estuaries** as the sea transgressed northwestwards. Sedimentary structures typical of **stream systems**, such as trough cross bedding, are common in the lower part, but towards the top of the units the better sorting, very low-angle crossbeds, hummocky cross stratification, increased bioturbation and presence of marine dinoflagellates indicate **marine influence** (Aitchison 1988; McMillan 1999)” (Forsyth, 2001). “Fine-grained **fluvio-deltaic** quartzose coal measures...” (Field and Browne, 1989).

**Inferred age:** 65-46 Ma (Boyes et al., 2012)

**EoD breakdown:** 65-56 Ma: onshore  
 55-46 Ma: innermost shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = conglomerate; Description = **Non-marine** quartz sand and conglomerate with clay matrix; lignite seams and carbonaceous mudstone; limonite and silica cemented; (QMAP database) – the EoD is initially defined as onshore because it is described as being a non-marine, fluvial deposit containing coal measures. In the upper part it has a marginal marine influence as the sea transgresses westwards; this boundary is nominated as the beginning of the Waipawan. The Broken River Formation is younger in the south than in the north (i.e. on Christchurch map), where the minimum age is older than 65 Ma. It is only younger than 65 m.y. on the Waitaki and Aoraki (IKe\_b, Pe\_b) map areas (Boyes et al., 2012).

### **Eyre Group (Ee)**

Includes Kauru Formation, Waihao Greensand, Ashley Mudstone, and Amuri Limestone.

This is the northern equivalent of the Onekakara Group. The stratigraphic names are after Field and Browne 1986 and 1989. Based on the GIS database the term “Eyre Group” is used to the north of the Waitaki River (i.e. northern half of Waitaki, Aoraki, Christchurch, and Kaikoura map areas), and “Onekakara Group” is used to the south of the Waitaki River (i.e. southern half of Waitaki, and Dunedin map areas).

### **Kauru Formation**

**EoD:** innermost shelf

**Basis for interpretation:** “The crinoid-bearing facies probably represents earliest onlap or a storm surge onto a wave cut platform; sedimentological and paleontological evidence indicates a **moderate- to high-energy environment**” (Stilwell et al., 1994). “This unit marks the transition between the terrestrial Haumurian-Waipawan Papakaio and Broken River Formations and the marine Bor-

tonian Tapui Glauconitic Sandstone and Waihao Greensand” (Field and Browne, 1989). “The unit is locally concretionary; plant debris is locally abundant in lower to mid-sequence while glaucony is evident in the middle to upper sequence... The abundance of terrigenous clastics and sedimentary structures related to traction currents is consistent with an **inner** to perhaps **mid-shelf** setting. The age is Waipawan or Mangaorapan (Maxwell 2003), but possibly older (see below)” (Fordyce and Thomas, 2011) – *this formation marks the transition between onshore and marine deposition, and as it is defined as a marine unit, innermost shelf is the nominated EoD.*

### **Waihao Greensand**

*EoD:* mid-shelf, deepening over time to outer shelf

*Basis for interpretation:* “The abundance of glaucony, dearth of coarser terrigenous clastic grains and generally massive bedding indicate that the Waihao Greensand was probably deposited in a **middle to outer shelf** setting” (Fordyce and Thomas, 2011). “Between Oamaru and the Rangitata River the main Bortonian unit is muddy glauconitic sandstone (Waihao Greensand and its correlative, the Tapui Glauconitic sandstone). While the lower part of the unit was deposited in **shallow shelf** conditions the top part in the Waihao area was probably deposited at depth of **150-200 m** (Maxwell 1975)” (Field and Browne, 1989) – *the EoD is defined as mid-shelf because the cited references describe it as a shallow shelf deposit, including a relative rise in sea level to 150-200 m, which corresponds to outer shelf.*

### **Ashley Mudstone**

*EoD:* outer shelf

*Basis for interpretation:* “The assemblage is interpreted as having lived in a low energy marine environment on the **outer shelf or upper slope**... The occurrence of many trachyleberids possessing eyes suggests a paleodepth within the **photic zone** and is evidence for a maximum lower depth limit of approximately **200 m**. This interpretation of a quiet, moderately **deep water outer shelf** depositional environment is consistent with other sedimentological and macrofaunal evidence that indicate overall transgressive conditions over much of the South Island during late Eocene times” (Ayress, 1995) – *the EoD is defined here as outer shelf, although upper bathyal may also be appropriate. Further to the north (i.e. Kaikoura, Christchurch) the Ashley Mudstone (or Formation) is a deeper, lower bathyal deposit.*

### **Amuri Limestone**

*EoD:* outer shelf

*Basis for interpretation:* “...impure limestone or marl...” (Forsyth, 2001). “Although originally defined as a stand-alone formation (Field & Browne et al. 1989), on this map [Aoraki] Amuri Limestone is included within the uppermost part of the Eyre Group. Amuri Limestone is characteristically a pale, fine-grained, muddy limestone or very calcareous mudstone, which is generally less than 10 m thick but reaches 80 m in the upper Hinds River and Castle Hill basin (Gage 1970; Field & Browne 1986; Oliver & Keene 1990). This limestone is absent in several locations, probably due to erosion before the overlying beds were deposited” (Cox and Barrell, 2007). “Much of Canterbury was submerged in the Oligocene, when micrite (Amuri Limestone) [...] was deposited... The Amuri generally has an **outer neritic to bathyal** microfauna and this, coupled with its fine texture, suggests an **outer shelf or slope** paleoenvironment” (Field and Browne, 1989) – *EoD is based on comments in Field and Browne (1989). Amuri Limestone is younger and shallower here than in the north on the Kaikoura map area.*

**Inferred age:** 55-34 Ma (Boyes et al., 2012)

**EoD breakdown:** 55-43 Ma: innermost shelf (Kauru Formation)

42-39 Ma: mid-shelf (Waihao Greensand)

38-34 Ma: outer shelf (Ashley Mudstone, Amuri Limestone)

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone; Description = shallow marine to outer shelf micaceous and glauconitic sandstone; siltstone; and mudstone (QMAP database) – *the EoD is based on members of the Eyre Group that occur in this map area, based on the chronostratigraphic transects of Boyes et al. (2012).*

## Eyre Group (Eeb+Ee)

(QMAP database spelling: Eyre Gp)

**Inferred age:** 65-34 Ma (Boyes et al., 2012)

**EoD breakdown:** 65-56 Ma: onshore (Broken River Formation)  
55-43 Ma: innermost shelf (Broken River Formation, Kauru Formation)  
42-39 Ma: mid-shelf (Waihao Greensand)  
38-34 Ma: outer shelf (Ashley Mudstone, Amuri Limestone)

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone conglomerate; Description = Non-marine to shallow marine to outer shelf deposits (QMAP database) – *this unit code appears to include Broken River Formation and the Eyre Group. The EoD is based on members of the Eyre Group that occur in this map area, based on the chronostratigraphic transects of Boyes et al. (2012). Refer to “Broken River Formation (Eeb)” and “Eyre Group (Ee)” on the Waitaki map area for interpretations of the members.*

## Alma Group

“Waiareka and Deborah volcanics, together with the associated Ototara Limestone, form the Alma Group (Gage 1957)... The volcanoes near Oamaru apparently erupted on the relatively **shallow continental shelf** (Coombs et al. 1986; Cas et al. 1989). **Surtseyan** eruptions projected ash, lapilli and blocks into the atmosphere from vents **below sea level**. Much of the ejected material was re-worked by mass flows and by wave and current action” (Forsyth, 2001). “The Oamaru Volcanics (40 ± 2 to 32 Ma) are the products of largely **shallow submarine** eruption and include **pillow lavas, hyaloclastite** breccias and tuffs, pyroclastic surge deposits and **marine volcanoclastic sediments**. They range in composition from tholeiitic to strongly alkali, though most of the Eocene volcanism was tholeiitic” (Field and Browne, 1989). “Tertiary volcanism in the Kakanui area began during the Late Eocene with **submarine eruptions** of **basaltic tuff** and emplacement of **hypabyssal intrusives** of the Waiareka Volcanic Formation. This formation is succeeded by the Totara Limestone, an upper Eocene, tuffaceous biomicrite. The Deborah Volcanic Formation lies on the Totara Limestone and is overlain by a middle Oligocene biosparrudite, the McDonald Limestone. Additional details on the regional geology will be found in Gage (1957) and Coombs and Dickey (1965)” (Dickey, 1968). “The rarity in Alma Group strata of non-winged pollen and spores (W.F. Harris, pers comm., 1966) and of terrigenous debris other than very fine silt-sized quartz and clay-rich fecal pellets is fully compatible with the hypothesis that the **coastline was some considerable distance** from Oamaru during Alma Group time” (Edwards, 1991).

## Ototara Limestone (EOlo)

(QMAP database spelling: Alma Ototara limestone)

**Inferred age:** 36-31 Ma (Edwards, 1991)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = tuff; Description = Bryozoan grain-supported calcarenite with volcanogenic and marly layers (QMAP database). “Ototara Limestone (Elo) includes Gage’s Totara and McDonald limestones and is equivalent to the expanded Totara Limestone of Field & Browne (1986). Ototara Limestone is massive or indistinctly bedded and mainly comprises bryozoan remains with little terrigenous matter; in places it contains tuff and pebbles of basalt... The limestone is interbedded with rocks of the Waiareka and Deborah Volcanic formations... It was deposited on **submarine platforms**, in a **shallow marine, shelf** setting” (Forsyth, 2001). “The available evidence indicates that the bryozoan facies of the Ototara Limestone were produced (and often deposited) at depth of about **30 to 60 m** but also resulted from ‘over the bank’ redeposition at depths of up to **150 m**” (Edwards, 1991) – *the depth range stated in Edwards (1991) is equivalent to innermost shelf, but redeposition may have occurred as deep as outer shelf.*

## Waiareka Volcanics

“The Waiareka Volcanics (Elw) are present close to the coast between Moeraki and Oamaru and as far inland as Maerewhenua. Correlative thin tuffs are present as far afield as Kapua in South Canterbury... Waiareka Volcanics comprise **basaltic tuff, agglomerate and pillow lavas, basaltic to doleritic dikes and sills**, and layers of coeval sediment; the dominant lithology is tuff... Tuffs

are well bedded and well sorted; they include planar-laminated ash beds, current-bedded tuff, and reworked units containing brachiopods and molluscs. Volcanic debris flows with fragments of pillows, dikes and bombs are well exposed at Bridge Point south of Kakanui, and pyroclastic surge deposits occur near Cape Wanbrow" (Forsyth, 2001).

- **Waiareka Volcanics (Elw)**

(QMAP database spelling: Alma Waiareka volcanics undiff)

**Inferred age:** 40-34 Ma (Hoernle et al., 2006)

**EoD:** submarine mafic eruptives

**Basis for interpretation:** Main\_Rock = **basalt**; Sub\_Rocks = tuff, agglomerate; Description = Tholeiitic alkalic tuff; agglomerate; basaltic **dikes sills** and **pillow lava** (QMAP database) – *the Waiareka Volcanics are defined as submarine because they are described as occurring on a shallow marine shelf.*

- **Waiareka Pyroclastics (Elwp)**

(QMAP database spelling: Alma Waiareka pyroclastics)

**Inferred age:** 40-34 Ma (Hoernle et al., 2006)

**EoD:** submarine mafic eruptives

**Basis for interpretation:** Main\_Rock = **tuff**; Sub\_Rocks = agglomerate; Description = Volcanic breccia; agglomerate; tuff and tuff-derived mudstone with richly fossiliferous horizons (Lorne and Upper Pyroclastics) (QMAP database). "...the Lorne Pyroclastics comprise **breccia, tuff, agglomerate and mudstone** and are up to 120 m thick. Fossiliferous horizons contain molluscs, brachiopods, echinoderms, corals, bryozoa and foraminifera" (Forsyth, 2001) – *based on the presence of shallow marine fossils, the pyroclastics are defined as submarine eruptives, although a sedimentary deposit interpretation may be appropriate, perhaps at mid-shelf.*

- **Oamaru diatomite (Elwd)**

(QMAP database spelling: Alma Oamaru diatomite)

**Inferred age:** 35-34 Ma (Edwards, 1991)

**EoD:** outer shelf

**Basis for interpretation:** Main\_Rock = diatomite; Description = Calcareous and siliceous massive diatomite with tuff interbeds (QMAP database). "Oamaru Diatomite, up to 45 m thick, includes massive, soft, pale grey siltstone composed of diatoms with other micro-organisms, and intercalated tuff beds. It is overlain by, and grades laterally into, the Ototara Limestone" (Forsyth, 2001). "The diatomite overlies tuff of the Lorne Pyroclastics and usually underlies, and is considered a lateral equivalent to the lower part of, the bryozoan-rich Ototara Limestone (Edwards 1991)..." (O'Connor, 1999). "...in a basin located some 50 km offshore... was probably deposited in depths ranging from **100 to 150 m** at the base to about **75 m** at the top" (Edwards, 1991) – *100-150 m water depth corresponds to outer shelf conditions. Edwards (1991) also describes the formation as shallowing to mid-shelf at the top.*

- **Waiareka Volcanics (Tokarahi Sill) (Elws)**

(QMAP database spelling: Alma Waiareka Volcanics (Tokarah))

**Inferred age:** 40-34 Ma (Hoernle et al., 2006)

**EoD:** mafic intrusives

**Basis for interpretation:** Main\_Rock = olivine **basalt**; Description = Olivine tholeiite **sill** of Waiareka Volcanics (QMAP database). "The olivine tholeiite Tokarahi **Sill** (Gage 1957) was **intruded** into wet, unconsolidated sediment of Middle Eocene (Bortonian) age, concordant with bedding. It has prominent columnar jointing and associated **pillow lavas**" (Forsyth, 2001) – *the EoD is defined as intrusive, because the unit is named a "sill", however the mention of pillow lavas implies an extrusive, submarine mode of emplacement as well. Therefore submarine mafic eruptives may be appropriate for part of the unit.*

## **Deborah Volcanics**

"The Deborah Volcanics (Old) are recognised between Oamaru and Kakanui (Edwards 1991)... Deborah Volcanics comprise pyroclastic deposits, including the Kakanui Mineral Breccia, and several

**intrusive dolerite or basalt** masses in the area between Oamaru and Kakanui (Edwards 1991). Tuffs at Kakanui were deposited in **shallow water** by **mass flow** processes, the youngest being the Kakanui Mineral Breccia (Fig. 25c)" (Forsyth, 2001). "Despite the name, the Mineral Breccia rarely has sufficient coarse clasts to qualify as a breccia; most consists of **lapilli tuff**... In examining the surge-bedded deposits here, an important possibility for consideration is that they may have been formed subaerially, but then relocated by partial flank collapse of the volcanic edifice to a subaqueous final resting place. Another possibility is that the unconformity separating them from the overlying bioclastic deposits and then pillow lavas was initiated subaerially, and the surge-bedded facies formed on an emergent part of the volcano" (White and Hicks, 2009). "Bombs and blocks of lava in the tuffs indicate that the Mineral Breccia Member formed from a melanephelinite magma..." (Dickey, 1968). "The predominance of sediment gravity-flow deposits with well-defined beds and the steep-sided geometry of the cones support the interpretation that the Kakanui deposits comprise **Surtseyan-type** volcanoes (cf. White et al. 2003). The **subaqueous** nature of the deposits is indicated by bounding limestone units..." (Corcoran and Moore, 2008).

- **Deborah Volcanics (Old)**

(QMAP database spelling: Alma Deborah volcanics)

**Inferred age:** 40-34 Ma (Hoernle et al., 2006)

**EoD:** submarine mafic eruptives

**Basis for interpretation:** Main\_Rock = tuff; Description = Tholeiitic alkalic scoria; crystal tuff; lapilli and breccia including Kakanui Mineral Breccia (QMAP database) – *the Deborah Volcanics, including the Kakanui Mineral Breccia, are described as being Surtseyan-type deposits, which occur in submarine settings. Parts of these deposits, particularly of the mineral breccia, may be reworked and an EoD of shelfal, perhaps innermost or mid-shelf may be appropriate.*

- **Deborah basalt, dikes and intrusives (Oldb)**

(QMAP database spelling: Alma Deborah basalt, dikes and)

**Inferred age:** 40-34 Ma (Hoernle et al., 2006)

**EoD:** submarine mafic eruptives

**Basis for interpretation:** Main\_Rock = **basalt**; Sub\_Rocks = basanite; Description = Basanitic and basaltic **flows; dikes; plugs** and **intrusive** masses of Deborah Volcanics (QMAP database) – *the EoD is defined as an eruptive rather than intrusive because "flow" is mentioned first before intrusive forms in the QMAP database description. Mafic intrusive is an alternative EoD.*

## **Kekenodon Group (eMk)**

**Inferred age:** 27-22 Ma (Boyes et al., 2012)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = greensand; Description = Calcareous greensand and cemented bioclastic limestone (QMAP database). "The Kekenodon Group (eMk), of latest Oligocene to earliest Miocene age, typically consists of the Kokoamu Greensand and overlying Otekaike Limestone... Kekenodon Group beds in the Waitaki Valley and eastern Maniototo basin may represent the maximum inland extent of marine transgression... The Kekenodon Group rocks are a condensed sequence, deposited in **shallow**, sediment-starved platform environments" (Forsyth, 2001). "Duntroonian–Waitakian limestone at Kokonga in the Maniototo district, Central Otago, New Zealand is interpreted to be a **rocky shoreline** facies formed near the time of maximum Cenozoic marine transgression across Zealandia. The limestone, which is correlated with the Otekaike Limestone of North Otago, contains **shallow** and warm water indicators such as coralline algae, oysters, echinoderms, bryozoa and a foraminiferal assemblage composed almost entirely of *Amphistegina*" (Scott et al., 2014) – *the Kokoamu Greensand and Otekaike Limestone have been interpreted as mid-shelf in the Aoraki Area (refer to "Kekenodon Group (eMk)"). However, Forsyth (2001) interprets the group as possibly representing the maximum inland extent of marine transgression in parts of the Waitaki area, which could imply that it is a proximal unit (innermost shelf).*



## Otakou Group (Mo)

**Inferred age:** 22-16 Ma (Boyes et al., 2012)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = limestone, siltstone; Description = Blue-grey siltstone sandstone and carbonaceous mudstone in shallowing-up sequence (north of Waihemo FZ); outer shelf sandstone a (QMAP database). “The predominantly **marine** Otakou Group (Mo) occurs in coastal areas except between the Waihemo Fault System and Waianakarua River. The sequences are somewhat different on either side of this gap... To the south, well sorted medium- to fine-grained sandstone (Caversham Sandstone) and impure limestone (Goodwood Limestone) were deposited in an **outer shelf** setting; to the north, **mid-shelf** sandstone and siltstone (Mt Harris Formation) are succeeded by **shallow marine** sandstone (Southburn Sand) and the **paralic** quartz sandstone, carbonaceous mudstone and lignite of the White Rock Coal Measures” (Forsyth, 2001). “Otakou Group represents a continental **shelf and slope** wedge which prograded eastwards as it was fed with sediment from the Southern Alps from the Early Miocene onwards” (Carter, 1988) – *EoD is based on Forsyth (2001) which gives an outer shelf EoD in the south, and a mid-shelf EoD in the north of the map area. The map unit is defined as mid-shelf here because it appears to be the average depositional depth for the group. Deeper deposition could be expected in the south, and shallower deposition in the north. This is the southern (and deeper) equivalent of the Motunau Group (see eMn on the Aoraki map area).*

## Kekenodon & Otakou Group (eMk+Mo)

**Inferred age:** 30-16 Ma (Boyes et al., 2012)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = limestone, greensand, siltstone; Description = Siltstone, sandstone, carbonaceous mudstone, calcareous greensand and cemented bioclastic limestone (QMAP database) – *this unit code appears to include undifferentiated Kekenodon and Otakou Groups. Refer to “Kekenodon Group (eMk)” and “Otakou Group (Mo)” for further interpretations.*

## Manuherikia Group

“**Fluvial** and **lacustrine** sediments of the Manuherikia Group...” (Forsyth, 2001). “Outcrop and sediment preservation are too limited to define the margins of the paleolake(s)...” (Youngson et al., 1998).

- **mMm**

**Inferred age:** 19-15 Ma (Mildenhall and Pocknall, 1989)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = siltstone; Sub\_Rocks = sandstone, lignite; Description = Lacustrine clay, silt and sand with lignite seams; basal fluvial quartz sand and conglomerate (QMAP database) – *EoD is based on the cited literature. The duration of Lake Manuherikia is estimated from comments in Mildenhall and Pocknall (1989) and the initiation of faulting in this region from 8 Ma. The maximum extent of Lake Manuherikia during the Early Miocene is taken from the area that the present day out crop covers; it may have been greater than this. Refer to “Manuherikia Group” on the Wakatipu map area for further information.*

- **mMmc**

**Inferred age:** 19 Ma (Mildenhall and Pocknall, 1989)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = quartzite; Description = silica-cemented fluvial quartz sand and conglomerate generally at base of Manuherikia Group (QMAP database) – *EoD is based on the cited literature. The map legend implies that this unit code is a basal conglomerate in the group. Refer to “Manuherikia Group” on the Wakatipu map area for further information.*

## Dunedin Volcanic Group

“Within the area of the Waitaki map are many small volcanic centres formerly mapped as Waipiata Volcanics and Molehill Basalt (e.g. Mutch 1963; Gage 1957) which are now included in the Dunedin Volcanic Group (Md)... Most of the vents were small, with activity short-lived, producing only a few **flows** or a **tuff ring**... Tuffs and agglomerates underlie the lowermost flows... Bedded surge deposits in the Waihemo and Karitane districts probably originated during **phreatomagmatic** eruptions, and there is a possible pumice ignimbrite near Waikouaiti... The rocks range from basanites and alkalic olivine basalts through a range of intermediate rock types to nephelinites and phonolites” (Forsyth, 2001). “In contrast to the DVC, the WVF consists of the remains of numerous non-contiguous individual monogenetic volcanoes, inferred to have erupted **subaerially** (Coombs et al., 1986)” (Németh and White, 2003).

- **Mdv**

**Inferred age:** 25-9 Ma (McDougal and Coombs, 1973; Hoernle et al., 2006; Coombs et al., 2008; Timm et al., 2010)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = **basalt**; Sub\_Rocks = agglomerate, tuff; Description = Alkali basalt lava **flows**, plugs, agglomerate, tuff and **shallow intrusions** including those offshore (Mdv) (QMAP database) – *EoD is based on the interpretation of Németh and White (2003) that the majority of Waipiata volcanics were erupted subaerially. However, the early stages of Dunedin Volcanic Group deposition was submarine. There is also mention of phreatomagmatic eruptions in Forsyth (2001), which indicates interaction with water. Refer to “Dunedin Volcanic Group” on the Dunedin map area for further information.*

## Foulden Diatomite (Mdd)

**Inferred age:** 23 Ma (Lindqvist and Lee, 2009)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = diatomite; Sub\_Rocks = agglomerate, tuff; Description = dikes, or diatomite and carbonaceous sapropel as **lake deposits** in maar crater at Foulden Hills (QMAP database). “The **nonmarine** diatomite (Mdd) of Miocene age at Foulden Hills is over 75 m thick and possibly accumulated in a volcanic maar lake...” (Forsyth, 2001). “The diatomite accumulated in a small ~1.5 km diameter maar-floored lake that formed during basaltic volcanism” (Lindqvist and Lee, 2009) – *EoD is after Forsyth (2001).*

## Hawkdun Group (MPld)

**Inferred age:** 11-4 Ma (Forsyth, 2001)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = conglomerate; Sub\_Rocks = sand, silt; Description = Deformed weathered sandy conglomerate derived from Rakaia terrane greywacke and schist; basal quartz-lithic gravel and sand (QMAP database). “Hawkdun Group represents **alluvial** braid plain deposits and proximal **alluvial fans**... Schmitt (1984) considered that mudstone in the western Maniototo basin were distal fluvial and lacustrine facies within the same depositional setting” (Forsyth, 2001) – *EoD is based on Forsyth (2001) EoD interpretation.*

## Kowai Formation

“Weathered red, orange and brown gravel, sand and mud present on the flanks of the Hunters Hills, from the Hakataramea valley in the west to the coast at Timaru and Makikihi, and as far south as the Waitaki River are mapped as Kowai Formation (Pk; Field & Browne 1986); they include the Cannington Gravels (Gair 1959) and the Elephant Hill Gravels (Riddolls 1966)... At Makikihi the **lower part of the formation is marine** (Collins 1953) and the foreset bedding of intercalated sand and gravel indicates deposition in shallow water, with strong currents (Field and Browne 1986). Macrofossils of Late Pliocene age include crabs, oysters and cetacean bones. Marine gravels are also present at Timaru (Gair 1961) and possibly elsewhere, as shells have been reported from drill holes at Pareora” (Forsyth, 2001). “...**predominantly nonmarine** Kowai Formation” (Feldmann et al., 2008). “To the east, at Makikihi the unit includes **marine** fossils...” (Field and Browne, 1989).

- **Cannington Gravel (Plkc)**

Main\_Rock = conglomerate; Sub\_Rocks = sand, silt; Description = Deformed weathered greywacke gravel with silt and sand beds; marine at base (Makikihi and Timaru) (QMAP database).

- **Elephant Hill Gravels (Plke)**

Main\_Rock = conglomerate; Sub\_Rocks = sand, silt; Description = Deformed weathered greywacke gravel with silt and sand beds (QMAP database).

**Inferred age:** 5-1 Ma (Boyes et al., 2012)

**EoD:** onshore

**Basis for interpretation:** *EoD is based on the comments in the literature which suggest that the Kowai Formation was initially deposited in a shallow marine (i.e. innermost shelf) environment which became progressively more estuarine and fluvial. It is unlikely that there was an instantaneous transition from marine to non-marine, but for this project, it is assumed to have taken place between 5 and 4 Ma. On the paleogeography maps these gravels are included in the onshore area as the marine part of them was probably only a brief inundation, the detail of which is beyond the scope of this project.*

## **Timaru Basalt (IPlt, IPlt~)**

**Inferred age:** 3 Ma (Hoernle et al., 2006)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = **basalt**; Sub\_Rocks = tuff; Description = Olivine and hypersthene basalt in several flows in Timaru area, extending slightly offshore (QMAP database). "At Mt Horrible it is about 25 m thick, while on the coast it may be just over a metre thick. It was apparently extruded **subaerially** from a vent near Mt Horrible... There are a number of individual flows – up to five in any one outcrop – of olivine, hypersthene and olivine-hypersthene basalts (Duggan & Reay 1986)" (Forsyth, 2001). "Palagonite is the first stable product of volcanic glass alteration... Palagonite forms rinds of variable thickness on every mafic glass surface exposed for some time to aquatic fluids" (Stroncik and Schmincke, 2002) – *EoD is based on Forsyth (2001) subaerial interpretation. However palagonite indicates interaction with seawater, so submarine may also be appropriate in parts.*

## **Quaternary – Sedimentary deposits**

- **All Q deposits** (except – see below)

**EoD:** onshore

**Basis for interpretation:** Based on the QMAP database which includes alluvial, lacustrine, loess, peat, scree, tailings, and till sediments in the Quaternary deposits.

- **mQb, Q5b, Q1b**

**EoD:** innermost shelf

**Basis for interpretation:** "Recent and mobile **beach** deposits... Deposits of shelly gravel and sand... Remnants of higher **beach** deposits (shelly sand)..." (Forsyth, 2001).

## MURHIKU AREA (Geological Map 20)

### Nightcaps Group (En)

(QMAP database spelling: Nightcaps Gp; Mako Coal Measures)

**Inferred age:** 42-35 Ma (King et al., 1999)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone, lignite; Description = sandstone and carbonaceous mudstone with minor lignite (QMAP database). “The Nightcaps Group reflects regional subsidence and formation of an extensive **fluvial then lacustrine** system over much of western Southland (Turnbull & Uruski 1993)” (Turnbull and Allibone, 2003). “In the Waiau Basin, Eocene sediments are represented by the largely **non-marine** Nightcaps Group, consisting of Beaumont and Orauea formations in the east...” (Turnbull et al., 1993). “The Beaumont Coal Measures and Orauea Mudstone were deposited in **fluvio-deltaic** and **lacustrine** environments, respectively” (Pocknall and Turnbull, 1989) – *this unit is considered here to be undifferentiated Nightcaps Group based on the geological map sheet. Innermost shelf may be an appropriate final depth.*

### Beaumont Formation (Enb)

(QMAP database spelling: Beaumont Fmn; Nightcaps Gp)

**Inferred age:** 42-35 Ma (King et al., 1999)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone; coal; oil shale; Description = sandstone with minor conglomerate; mudstone; coal and oil shale (QMAP database). “The basal Beaumont Coal Measures (Enb), up to 250 m thick, include arkosic sandstone in channelled and cross-bedded units, subordinate carbonaceous mudstone, rare coal seams and, at Orepuki, oil shale (Willett & Wellman 1940)” (Turnbull and Allibone, 2003). “Palynoflora, in-situ stumps, rootlets and abundant driftwood logs were used by Pocknall & Turnbull (1989) to infer a probable **upper delta plain or flood plain** deposit in the Waiau River. An overlying cyclic, coarsening-upward, mudstone-sandstone lithofacies is interpreted as a prograding **delta facies** (Pocknall & Turnbull 1989). Marine indicators are lacking, and the deltas prograded into an extensive lake or lagoon represented by the Orauea Mudstone” (Turnbull et al., 1993) – *this formation is the basal fluvial formation of the Nightcaps Group.*

### Orauea Formation (Eno)

(QMAP database spelling: Orauea Fmn; Nightcaps Gp)

“Beaumont Coal Measures are conformably overlain by up to 350 m of Orauea Mudstone (Eno), a **lacustrine to lagoonal** carbonaceous mudstone with rare graded sandstone interbeds” (Turnbull and Allibone, 2003). “...an extensive **lake** or **lagoon** represented by the Orauea Mudstone... Sparse microfauna, dinoflagellates and **freshwater** bivalves in the Orauea Mudstone show that it formed in a **brackish lagoonal** or **lacustrine** environment (Lake Orauea), which **became restricted marine** at the top (Arafin 1982; Griffith 1983; Pocknall 1984a)... The Orauea Mudstone facies represents basin-wide subsidence, a precursor to the more extensive marine transgression at the close of the Eocene. The way in which the Orauea lake came under marine influence is not known; it may have been due to rising sea level backing up the lake outlet to the southwest, or to breaching a barrier in the Hump Ridge area” (Turnbull et al., 1993).

**Inferred age:** 35-33 Ma (King et al., 1999)

**EoD breakdown:** 35 Ma: onshore  
34-33 Ma: innermost shelf

**Basis for interpretation:** Main\_Rock = mudstone; Description = carbonaceous mudstone to siltstone with rare sandstone beds (QMAP database) – *Lake Orauea became marine, probably in the latest Eocene, at the beginning of a marine transgression.*

### Mako Coal Measures (Em)

(QMAP database spelling: Nightcaps Gp; Mako Coal Measures)

**Inferred age:** 42-36 Ma (Cahill, 1995)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone, lignite; Description = sandstone and carbonaceous mudstone with minor lignite (QMAP database). “The Eocene Mako Coal Measures (Em) formation is preserved along the southwestern side of the Hokonui Hills (Rout 1947; McKellar 1968). It rests unconformably on Murihiku Supergroup and consists of about 20 m of silty mudstone, claystone and sandstone overlain by 15-20 m of sandstone with thin seams of sub-bituminous **coal**” (Turnbull and Allibone, 2003). “The TE Weilly-1 and JW Laughton-1 wells were drilled on or near basement highs, and both intersected **terrestrial** sands, and quartzose and lignitic sediments of the Mako Formation over basement” (Cahill, 1995) – *these coal measures are defined as onshore, after Cahill (1995).*

### **Lignite measures (Elm)**

**Inferred age:** 42-35 Ma (Bishop, 1974)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = lignite; Description = mudstone and carbonaceous mudstone with **lignite** seams (QMAP database). “The unit consists of lignite, white to brown variably carbonaceous clay, and rare fine-grained sand” (Turnbull and Allibone, 2003). “Lignite and clay in Pomahaka Coalfield, locally limonite- or silica-cemented” (Turnbull and Allibone, 2003, geological map sheet) – *it is inferred that this unit is the coal measures of the Pomahaka Coalfield.*

### **Hogburn Formation (IEh)**

**Inferred age:** 42-35 Ma (Bishop, 1974)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = lignite, conglomerate; Description = quartz sandstone and quartz conglomerate with lignite (QMAP database). “Tiny remnants of quartz sandstone and mudstone (IEh), in places silica-cemented, are preserved adjacent to the Tuapeka Fault Zone, and are correlated with the Hogburn Formation of Central Otago” (Turnbull and Allibone, 2003) – *refer to “Hogburn Formation (Eoh)” on the Waitaki map area for further information.*

### **Hogburn Formation (IEhc)**

**Inferred age:** 42-35 Ma (Bishop, 1974)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = quartzite; Description = hard silica-cemented quartz sandstone and conglomerate (QMAP database) – *this unit code likely represents that which is described in Turnbull and Allibone (2003) as “in places silica-cemented”. Following from IEh, it is assumed to also be a terrestrial deposit.*

## **Waiau Group**

### **Stuart, Spear Peak and Point Burn formations (eOw)**

(QMAP database spelling: Waiau Gp; Spear Peak Fmn)

“...undifferentiated lower Waiau Group rocks (eOw) comprising graded sandstone with olistostromes, channelised breccia and conglomerate and local limestone, overlain by graded sandstone and mudstone” (Turnbull and Allibone, 2003).

**Inferred age:** 36-27 Ma (King et al., 1999)

**EoD breakdown:**

36-35 Ma:	<u>innermost shelf</u> (Stuart Formation)
34-32 Ma:	<u>upper bathyal</u> (Spear Peak Formation)
31-27 Ma:	<u>innermost shelf</u> (Point Burn Formation)

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone conglomerate; Description = graded sandstone and mudstone with conglomerate and limestone blocks (QMAP database) – *this unit code appears to include undifferentiated Waiau Formation around the edge of the Te Anau Basin. The EoD is based on that of the adjacent polygon in the Wakatipu map area (refer to “Stuart, Spear Peak and Point Burn formations (Ow)” in the Wakatipu map area). The EoD is broken down according to the comprising formations.*

## **Waioce Formation**

(QMAP database spelling: Waioce Fmn)

- **OIMiww**

Main\_Rock = mudstone; Sub\_Rocks = sandstone, limestone; Description = mudstone with graded limestone; breccia and sandstone interbeds (QMAP database).

- **Intraformational fan (OIMiul)**

Main\_Rock = limestone; Sub\_Rocks = sandstone; Description = well bedded sandy limestone with calcareous sandstone interbeds within Waioce Fmn (QMAP database). “Waioce Formation hosts numerous other named formations in the Waiiau Basin; it encloses graded limestone beds (Muf) of a **submarine fan** sequence in the upper Aparima River (Mutch 1972)” (Turnbull and Allibone, 2003).

“...Waioce Formation, of massive, sometimes concretionary calcareous mudstone (Oww), rests on Nightcaps Group (or possibly basement, east of Mt Hamilton)” (Turnbull and Allibone, 2003). “Facies range from very proximal rock-fall and debris flow deposits, including clasts several metres in size, through thick sand-dominated **fluvial** and **submarine fan** successions, to **hemipelagic** mudstone (Waioce Formation of Fig. 3)” (Zink and Norris, 2004) “...in the Waiiau Basin is the Waioce Formation, which Turnbull et al. (1989) suggested is generally **deep marine** and merges eastward into the shallower Winton Hill Formation” (Cahill, 1995). “The main representative of Miocene sediments is the Horseshoe Mudstone (Wn, Turnbull, 1985), now called Waioce Formation (Turnbull et al., 1989), which is dominated by **deep marine** mudstone similar to those of the Waiiau Basin. It includes thinly bedded, grey, **distal turbidite** sandstone...” (Uruski and Turnbull, 1990). “In its typical development, the fine grain size, abundant bioturbation and wispy parallel lamination of the Waioce Formation suggests deposition in a quiet **deepwater marine** location which was transverse by gentle bottom currents. We conclude, therefore, that the typical Waioce formation represents a **hemipelagic basin fill** facies. At the same time, **distal turbidity currents** emplaced interdigitating fan fringe and basin floor sediments associated with the Taylor Member of the Blackmount Formation fan” (Carter and Norris, 2005) – *the occurrence of Waioce Formation has been aligned with descriptions in the Wakatipu, Fiordland and Murihiku QMAP bulletins, Turnbull et al. (1993), and the chronostratigraphic panels in King et al. (1999). Waioce Formation on the Murihiku map area occurs in Waiiau Basin and Burwood Sub-basin (of Te Anau).*

- **Waiiau Basin**

“During the Oligocene, the Waiiau Basin with its constituent sub-basins was a complex, tectonically active area, where a wide variety of sediments accumulated from several source areas... In earliest Oligocene time the area came under **marine** influence, but there were no major lithologic changes, and the Waioce Formation mudstone gradually succeeded the Orauea Formation... The Waioce Formation mudstone in the Waiiau Basin is a blue-grey, slightly calcareous to non-calcareous, slightly carbonaceous pelite (Arafin 1982), of Early Oligocene to Pliocene age. The Oligocene part lacks sedimentary structures and coarse clastic sediment, and was deposited in quiet water conditions. Microfauna indicate a **steadily deepening** environment, from **inner to outer shelf or upper slope** conditions, sheltered from full open-ocean influence... The lithostratigraphy of the Early and Middle Miocene Waiiau Group in the Waiiau and Te Anau basins resembles that of the Oligocene. Deposition of the basin-wide Waioce Formation mudstone continued through the Miocene” (Turnbull et al., 1993).

**Inferred age:** 34-12 Ma (Turnbull et al., 1993)

**EoD breakdown:**

34-33 Ma:	<u>innermost shelf</u>
32 Ma:	<u>mid-shelf</u>
31 Ma:	<u>outer shelf</u>
30-29 Ma:	<u>upper bathyal</u>
28-26 Ma:	<u>mid-bathyal</u>
25-12 Ma:	<u>lower bathyal</u>

- **Burwood Sub-basin**

“The Burwood Sub-basin records the same Eocene and Oligocene **marine transgression** seen in the Waiau and Te Anau basins... By the Middle Whaingaroan (Middle Oligocene), the central Burwood Sub-basin had subsided to **outer shelf or upper slope** depths and a thick sequence of Waicoe Formation mudstone accumulated over the Spear Peak sandstone. **Submarine fan** sedimentation then recommenced, and two distinct fan lithofacies invade the Waicoe mudstone” (Turnbull et al., 1993).

**Inferred age:** 34-12 Ma (Turnbull et al., 1993; 2010)

**EoD breakdown:** 34-33 Ma: innermost shelf  
32 Ma: mid-shelf  
31 Ma: outer shelf  
30-29 Ma: upper bathyal  
28-26 Ma: mid-bathyal  
25-12 Ma: lower bathyal

### ***Tunnel Burn Formation (lOw)***

(QMAP database spelling: Tunnel Burn Fmn)

**Inferred age:** 26-22 Ma (King et al., 1999)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = sandstone, mudstone; Description = condensed sequence of bioclastic limestone overlying sandstone and below mudstone (QMAP database). “A tiny but important outcrop of Tunnel Burn Formation limestone (lOw), at the foot of Pad-dock hill west of the Hauroko Fault (Carter et al., 1982), represents a condensed **shelf** sequence on the margin of the Te Anau Basin” (Turnbull and Allibone, 2003) – *an innermost shelf EoD is inferred. A mid-shelf interpretation could also be appropriate. Refer to “Tunnel Burn Formation (lOw)” on the Fiordland map area for further information.*

### ***Borland Formation (mMiwb)***

(QMAP database spelling: Borland Fmn)

**Inferred age:** 18-16 Ma (King et al., 1999)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone; Description = graded sandstone and mudstone (QMAP database). “Southwest of the Takitimu Mountains, the Black-mountain Fault separates two further Waiau Group sequences of predominantly **submarine fan** sediments... West of the fault, near Monowai in the southernmost Te Anau Basin, Miocene **graded sandstone and mudstone** of the Borland Formation (Mwb) overlie Waicoe Formation” (Turnbull and Allibone, 2003) – *EoD is based on the interpretations and descriptions in Turnbull and Allibone (2003). A lower bathyal EoD may be an appropriate interpretation. Refer to “Borland Formation (Miw)” on the Fiordland map area for further information.*

### ***Monowai Formation (mMiwm)***

(QMAP database spelling: Monowai Fmn)

**Inferred age:** 16-15 Ma (King et al., 1999)

**EoD:** mid-bathyal

**Basis for interpretation:** Main\_Rock = conglomerate; Sub\_Rocks = sandstone, mudstone; Description = conglomerate and pebbly mudstone in slump sheets with graded sandstone and mudstone (QMAP database). “Borland Formation is overlain by northward-derived Middle Miocene conglomerate and sandstone of the Monowai Formation (Mwm)...” (Turnbull and Allibone, 2003). “...interpreted as a shallow marine delta-top and delta-slope deposit, with significant **redeposition by submarine slumping** (Carter and Norris 1977b)” (Turnbull et al., 2010) – *based on the summary of Carter and Norris 1977 in Turnbull et al. (2010), the Monowai Formation is defined here as shallow marine sediments redeposited at bathyal depths. Upper bathyal may be an appropriate alternative. Refer to “Monowai Formation (mMiwm)” on the Fiordland map area for further information.*

## ***Duncraigen Formation (mMiwd)***

***Inferred age:*** 14-12 Ma (King et al., 1999)

***EoD:*** lower bathyal

***Basis for interpretation:*** Main\_Rock = sandstone; Sub\_Rocks = mudstone conglomerate; Description = graded sandstone and mudstone (QMAP database). "...succeeded in turn by graded sandstone and mudstone and rare conglomerate of the Duncraigen Formation (Mwd) **submarine fan**" (Turnbull and Allibone, 2003). "The flysch that underlies (McIvor Formation) and overlies (Duncraigen Formation) the Monowai conglomerates contains diverse foraminiferal assemblages and **deep-water** benthic invertebrate assemblages" (Carter and Norris, 1977). "The gradational nature of this sedimentary change, and the appearance of dark terrigenous mud in Tep subdivisions, suggest that basal Duncraigen sediments represent a **deeper water delta-front** slope as the Monowai conglomerate delta retreated northwards consequent upon tectonic subsidence. The gradual vertical disappearance of bottom-current emplaced rippled sands and reworked tops to the thicker turbidites, the increasing calcite content of the interbedded mudstone, and the appearance of homogenous muds with deep water molluscan faunas all suggest that higher in the Duncraigen Formation **deep marine lower slope or basin floor** environments are again represented" (Carter and Norris, 2005) – *the cited references indicate a range of depositional depths for the formation from deeper water delta-front to lower bathyal. The EoD is defined as lower bathyal here based primarily on Carter and Norris (1977, 2005).*

## ***Blackmount Formation (Olwb)***

(QMAP database spelling: Blackmount Fmn)

"East of the Blackmount Fault, a westerly-derived **submarine fan** sequence (Blackmount Formation, Olwb) with locally-derived basal dioritic breccia (Ligar Breccia) rests on dioritic basement and grades up through thick-bedded lithic sandstone into graded sandstone and mudstone, and then into Waioe Formation" (Turnbull and Allibone, 2003). "The Blackmount Formation, 2-3 km thick, grades from **mass-emplaced** breccias and sands of inferred **submarine fan** origin at the base, to **muddy turbidites and hemiterrigenous mudstone** of inferred **basin-floor** origin at the top" (Carter et al., 1982). "Clearly, faulting and regional depression had created a major sedimentary depocentre, which received more than 2000 m of broadly fining-upward, **fan to basin floor** sediments during the remainder of the Oligocene (Blackmount Formation, Fig. 3)" (Norris and Carter, 1982). "These submarine fans occupied **slope** and **base of slope** settings along the entire north-western side of the Waiiau Basin by Middle Oligocene time, and merged eastward into deep marine Waioe Mudstone in the centre of the basin" (Turnbull et al., 1993).

***Inferred age:*** 34-26 Ma (King et al., 1999)

***EoD breakdown:*** 34-32 Ma: upper bathyal

31-29 Ma: mid-bathyal

28-26 Ma: lower bathyal

***Basis for interpretation:*** Main\_Rock = sandstone; Sub\_Rocks = breccia, mudstone; Description = graded sandstone and mudstone with basal breccia; fining upward to mudstone (QMAP database) – *interpretations from the cited references combined with Fig. 3 indicate that the formation was initially deposited at upper bathyal depth, increasing over time to lower bathyal.*

### **• Ligar Breccia (Olwbl)**

(QMAP database spelling: Ligar Breccia; Blackmount Fmn)

***Inferred age:*** 34-32 Ma (King et al., 1999)

***EoD:*** upper bathyal

***Basis for interpretation:*** Main\_Rock = breccia; Sub\_Rocks = sandstone, conglomerate; Description = breccia and conglomerate with sandstone matrix (QMAP database). "The breccia facies, the Ligar Breccia Member (Carter & Norris 1977a), overlies Fiordland basement and in places is extremely coarse-grained with boulders up to 10 m across. It is massive to crudely m-bedded, extremely poorly sorted, fines upward, and contains rare macrofossils near the top. It is interpreted by Carter & Norris (in prep.) as a fanglomerate deposited by **mass flow**" (Turnbull et al., 1993) – *this basal member of the Blackmount Formation is defined as an upper bathyal deposit on account of its coarse nature and that it was deposited by mass flow.*



### ***Birchwood Formation (Olwi)***

(QMAP database spelling: Birchwood Fmn)

***Inferred age:*** 30-29 Ma (King et al., 1999)

***EoD:*** mid-bathyal

***Basis for interpretation:*** Main\_Rock = limestone; Sub\_Rocks = sandstone; Description = graded bioclastic limestone interbedded with sandstone and mudstone (QMAP database). “An easterly-derived Oligocene redeposited graded limestone – mudstone facies, Birchwood Formation (Owi) (Arafin 1982) is enclosed within Waioe Formation mudstone west of Ohai” (Turnbull and Allibone, 2003). “The Birchwood Formation is inferred to be a discrete **submarine fan lobe** which prograded westward into the eastern Waiau Basin (Arafin 1982)” (Turnbull et al., 1993) – *the EoD is defined as mid-bathyal because Arafin 1982 (in Turnbull et al., 1993) infers that it is a discrete submarine fan lobe, which based on Fig. 3, implies a minimum depth of mid-bathyal, maybe even lower bathyal.*

### ***Mclvor Formation (eMiww)***

(QMAP database spelling: Mclvor Fmn)

***Inferred age:*** 23-17 Ma (King et al., 1999)

***EoD:*** lower bathyal

***Basis for interpretation:*** Main\_Rock = limestone; Sub\_Rocks = mudstone; Description = graded bioclastic limestone interbedded with mudstone (QMAP database). “A younger easterly-derived **submarine fan** of graded limestone beds isolated within Waioe mudstone, the Miocene Mclvor Formation (Mwv), was probably derived from the westward-prograding limestone-dominated Clifden Subgroup” (Turnbull and Allibone, 2003). “The Mclvor Formation represents **deep water** deposition, on the **floor of a muddy flysch basin**” (Carter and Norris, 2005) – *EoD is based on the interpretations in the cited references, particularly the basin floor interpretation of Carter and Norris (2005). Refer to “Mclvor Formation (eMiww)” on the Fiordland map area for further information.*

### ***Waihoaka Formation***

(QMAP database spelling: Waihoaka Fmn)

“In the southeast of the Waiau Basin around the Longwood Range, **shallow marine** facies overlying basement include conglomerate, fossiliferous sandstone, limestone and mudstone of the Waihoaka Formation (Owk), limestone (Oul, Mul); and conglomerate and sandstone (Oc) in the Pourakino Valley and near Otautau (Harrington & Wood 1947; Forsyth 1992)” (Turnbull and Allibone, 2003). “A 100 to 300 m thick shallow **marine** sequence... Micro- and macrofaunas from the formation indicate **very shallow, inner shelf** conditions at the base, deepening to **mid-outer shelf**, then probably to upper slope at the top, in the Early Miocene (R. Hoskins pers. comm. 1987)” (Turnbull et al., 1993).

- **Olwk**

***Inferred age:*** 34-26 Ma (King et al., 1999)

***EoD:*** innermost shelf

***Basis for interpretation:*** Main\_Rock = sandstone; Sub\_Rocks = limestone, mudstone; conglomerate; shellbeds; Description = fossiliferous sandstone with basal conglomerate; limestone lenses and shellbeds (QMAP database) – *the lithologic description in the database and the shallow marine interpretation in Turnbull and Allibone (2003) indicate a shelfal EoD for the map unit. An innermost shelf EoD is nominated here based on the main rock type of sandstone (QMAP database), combined with Fig. 3. It could also be appropriate to breakdown the EoD, beginning with innermost shelf, and deepening over time to outer shelf.*

- **Olul (Oul on mapsheet)**

***Inferred age:*** 29-25 Ma (Turnbull and Allibone, 2003)

***EoD:*** mid-shelf

***Basis for interpretation:*** Main\_Rock = limestone; Sub\_Rocks = sandstone; Description = limestone and fossiliferous sandstone with basal conglomerate; siltstone and shellbeds (QMAP database) – *EoD is based on the QMAP description and Fig. 3.*

- **Miul (Mul on mapsheet)**

*Inferred age:* 19-16 Ma (Turnbull and Allibone, 2003)

*EoD:* mid-shelf

*Basis for interpretation:* Main\_Rock = limestone; Description = soft to cemented shelly limestone (QMAP database) – *EoD is based on the QMAP description and Fig. 3. Innermost shelf could also be appropriate.*

- **Oc**

*Inferred age:* 34-31 Ma (Turnbull and Allibone, 2003)

*EoD:* innermost shelf

*Basis for interpretation:* Main\_Rock = conglomerate; Sub\_Rocks = sandstone; Description = weathered pebble conglomerate and pebbly sandstone (QMAP database) – *the lithologic description in the database and the shallow marine interpretation in Turnbull and Allibone (2003) indicate a shelfal EoD for the map unit. An innermost shelf EoD is nominated here based on the main rock type of conglomerate (QMAP database), although an onsshore interpretation may be more appropriate based on Fig. 3.*

## **Clifden Subgroup**

- **Lower Clifden Subgroup (OIMiwc)**

(QMAP database spelling: lower Clifden Subgp)

*Inferred age:* 24-17 Ma (Turnbull and Allibone, 2003)

*EoD:* mid-shelf

*Basis for interpretation:* Main\_Rock = limestone; Sub\_Rocks = sandstone; Description = sandy to bioclastic limestone with local basal conglomerate overlying sandstone (QMAP database). “The Clifden Subgroup of the Waiiau Group represents the western part of a **shallow marine shelf** which covered much of Southland in the Late Oligocene to Middle Miocene (F. Hyden 1979, 1980), extending into the Waiiau Basin through the tectonically-controlled Ohai depression. Clifden Subgroup includes several formations and the type localities of several New Zealand stages (Fig. 32A) and is described in detail by Wood (1969). Two informal subdivisions are mapped: a lower Clifden Subgroup (Mwc) of basal sandstone overlain by pebbly conglomeratic limestone (Hyden 1980), and thick limestone of the Forest Hill Formation (Ouf) (Fig. 32B); and an upper Clifden Subgroup (Mwc)...” (Turnbull and Allibone, 2003). “Across the Early Miocene peak of the transgression, bryozoan calcirudites and calcarenites of **mid-outer shelf** depths dominated completely and reached their greatest purity (95-98% CaCO<sub>3</sub>) (top Takaka Limestone; Forest Hill Limestone)” (Kamp and Nelson, 1988) – *the map unit is interpreted here as mid-shelf based primarily on the mid- to outer shelf interpretation for the Forest Hill Limestone (of the lower Clifden Subgroup) in Kamp and Nelson (1988), and the main rock type for the map unit being bioclastic limestone, combined with Fig. 3. Water depths of up to 200 m in this report is considered to be outer shelf or shallower. Alternatively an innermost shelf interpretation may be appropriate in areas dominated by sandy limestone.*

- **Forest Hill Formation (OIMif)**

(QMAP database spelling: Forest Hill; Castle Downs fmns)

*Inferred age:* 24-17 Ma (Turnbull and Allibone, 2003)

*EoD:* mid-shelf

*Basis for interpretation:* Main\_Rock = limestone; Sub\_Rocks = sandstone; Description = sandy to bioclastic limestone with local basal conglomerate; variably glauconitic (QMAP database). “... scarp-forming bioclastic bryozoan limestone of the Late Oligocene to Early Miocene Forest Hill Formation (see Figs 30, 31, 32B). Forest Hill Formation commonly has a basal conglomeratic facies (not mapped) (F. Hyden 1979, 1980)” (Turnbull and Allibone, 2003). “Macro- and microfauna from the Clifden Subgroup indicate a **shallow inner shelf** marine setting, in water depths probably less than **200 m** (Fleming and others 1969; Hyden & Forest 1980; Arafin 1982) for both the Forest Hill Formation and the overlying sequence” (Turnbull et al., 1993). “These facies were supplanted by a combination of bivalve-bryozoan-barnacle-foraminiferal-algal calcarenites (middle Takaka Limestone, Nelson; Castle Downs Formation, Southland). Across the Early Miocene peak of the transgression, bryozoan calcirudites and calcarenites of **mid-outer shelf** depths dominated completely and reached their greatest purity (95-98% CaCO<sub>3</sub>) (top Takaka Limestone; Forest Hill Limestone)”

(Kamp and Nelson, 1988). “Deposition of Forest Hill Limestone on the continental **shelf** occurred in the early Miocene during a relatively quiet tectonic period with reduced clastic sediment supply” (Cahill, 1995) – *the map unit is interpreted here as mid-shelf based primarily on the mid- to outer shelf interpretation for the Forest Hill Limestone in Kamp and Nelson (1988), and the main rock type for the map unit being bioclastic limestone, combined with Fig. 3. Alternatively an innermost shelf interpretation may be appropriate.*

- **Upper Clifden Subgroup (Miwc)**

**Inferred age:** 16-11 Ma (King et al., 1999)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = claystone, shellbeds, lignite; Description = sandstone with shellbeds; laminated siltstone; locally with lignite (QMAP database). “... upper Clifden Subgroup (Mwc) of laminated siltstone and mudstone, shellbeds, massive fossiliferous bioturbated sandstone, and locally lignite at the top of the sequence” (Turnbull and Allibone, 2003). “Microfauna from Helmet Hill and Goldie Hill indicate dramatic shallowing in the Early Miocene, from bathyal through outer shelf or upper slope, to **inner shelf** depths in the Middle Miocene (R. Hoskins pers. comm. 1987)” (Turnbull et al. 1993) – *EoD is based on the shallow marine shelf interpretation for the Clifden Subgroup in Turnbull and Allibone (2003), combined with the main rock type for the map unit being sandstone, and Fig. 3. The upper Clifden Subgroup is approximated as being the Middle Miocene part of the Clifden Subgroup.*

### **Rowallan Sandstone (Miwa)**

(QMAP database spelling: Rowallan Sandstone; Waiau Gp)

**Inferred age:** 11-6 Ma (Turnbull and Uruski, 1995)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = shellbeds; Description = massive sandstone with rare shellbeds (QMAP database). “The Clifden Subgroup is unconformably overlain by further Waiau Group rocks, including massive **shallow marine** sandstone with minor shellbeds...” (Turnbull and Allibone, 2003). “Most sediment was trapped in the Te Anau Basin, but some escaped southwards through the gap between the rising Takitimu Mountains and Fiordland, depositing the Rowallan Sandstone and Te Waewae Formation in the **shallow-marine** Waiau Basin... The interpreted depositional environment, from macrofaunas and micro faunas, is a **shallow to very shallow (0–20 m)** restricted marine setting” (Manville, 1996) – *EoD is based on the Manville (1996) interpretation.*

### **Te Waewae Formation (Plwe)**

(QMAP database spelling: Te Waewae Fmn; Waiau Gp)

**Inferred age:** 6-4 Ma (Turnbull and Uruski, 1995)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = siltstone, shellbeds, conglomerate; Description = interbedded laminated siltstone and massive to crossbedded sandstone (QMAP database). “...**very shallow marine** Pliocene Te Waewae Formation (Pwt) (Turnbull and Uruski 1995), composed of laminated siltstone, cross-bedded sandstone and local shellbeds and conglomerate, forming the cliffs behind Te Waewae Bay” (Turnbull and Allibone, 2003) – *EoD is based on the Turnbull and Allibone (2003) depositional depth interpretation. Refer to “Te Waewae Formation” on the Fiordland map area for further information.*

### **Orepuki Formation (PleQa)**

**Inferred age:** 3 Ma (Turnbull and Allibone, 2003)

**EoD:** innermost shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = conglomerate, siltstone, mudstone; Description = sandstone siltstone and variably carboniferous mudstone with conglomerate lenses (QMAP database). “Orepuki Formation (PQa) is slightly younger, **very shallow to marginal marine and possibly fluvial** sandstone, lignite, and conglomerate, in paleovalleys and dissected high terraces on the southern Longwood Range near Orepuki” (Turnbull and Allibone, 2003) – *EoD is based on the Turnbull and Allibone (2003) interpretation for the formation, combined with the main*

rock type, and Fig. 3. An *onshore* EoD may be appropriate (Turnbull and Allibone, 2003).

### **Winton Hill Formation (Olwh)**

(QMAP database spelling: Winton Hill Fmn)

**Inferred age:** 34-26 Ma (Turnbull and Allibone, 2003)

**EoD:** *mid-shelf*

**Basis for interpretation:** Main\_Rock = mudstone; Sub\_Rocks = sandstone, limestone; Description = mudstone with graded limestone; breccia and sandstone interbeds (QMAP database). “Basal Eocene non-marine sedimentary rocks are overlain by massive calcareous mudstone of the Oligocene Winton Hill Formation (Owh), the lateral equivalent of the Waioce Formation” (Turnbull and Allibone, 2003). “...massive calcareous mudstone (Early Oligocene (Whaingaroan), Winton Hill Formation) which contain well preserved **mid neritic** faunas” (Hyden, 1980). “According to recent analysis of the original biostratigraphic slides from the Winton wells, the formation is predominantly a **mid-outer shelf and bathyal facies** (Strong 1991a, b) and marks the onset of the marine transgression. The stratigraphic equivalent unit in the Waiau Basin is the Waioce Formation, which Turnbull et al. (1989) suggested is generally deep marine and merges eastward into the **shallower** Winton Hill Formation... By the late Early Oligocene, the marine Winton Hill Formation was being deposited widely. This is mainly a **shelf** facies (Strong 1991a, b), although at JW Laughton-1 an outer shelf to upper bathyal environment was determined from foraminifera” (Cahill, 1995) – *the majority of this formation is inferred to be a mid-shelf deposit, although some parts may be outer shelf to upper bathyal.*

### **East Southland Group**

“Non-marine East Southland Group rocks overlies Forest Hill Formation west of Forest Hill (Isaac & Lindqvist 1990). The East Southland Group (Isaac & Lindqvist 1990) underlies the area east of the Oreti River, and the Waimea Plains and basins north of Gore, and is time-equivalent to both Chatton and Forest Hill formations. The group consists of discontinuous **basal marine** and **estuarine** facies (Chatton and Pomahaka formations), conformably overlain (and in places underlain) by **non-marine** Gore Lignite Measures” (Turnbull and Allibone, 2003).

### **Chatton Formation (Miec)**

(QMAP database spelling: Chatton Fmn)

**Inferred age:** 26-16 Ma (Turnbull and Allibone, 2003)

**EoD:** *innermost shelf*

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone, conglomerate, shellbeds; Description = fossiliferous sandstone with mudstone and shellbeds (QMAP database). “Chatton Formation (Mec) as mapped includes the Castle Downs Formation of Hyden (1980), following Isaac & Lindqvist (1990). It consists of up to 150 m of fossiliferous sandy limestone and variably glauconitic sandstone, representing **inner to mid-shelf** environments” (Turnbull and Allibone, 2003). “The succeeding glauconitic sandy mudstones, shelly sandstone and oolitic greensand of the Late Oligocene (Duntroonian) Chatton Formation (and its lateral equivalent, the Castle Downs Formation) are distinctive **shallow water** sediments containing **inner neritic** faunas. Locally they are highly bioturbated and four discrete burrowed omission surfaces can be distinguished at Woody Knoll” (Hyden, 1980). “The diverse abraded macrofauna and associated foraminifera indicate **inner shelf** depths, and ages between Late Oligocene (Duntroonian-Waitakian) in the north near Croydon to Early Miocene (Otaian-Altonian) in the south at Kapuka (N. De B. Hornibrook pers. comm.)” (Pocknall and Mildenhall, 1984). “Chatton Formation was named from **shallow marine** sandy shellbeds exposed in the Chatton district some 25 km north of Cosy Dell (Chatton beds of Marwick 1929)... These shelly sands within the Chatton Formation at Cosy Dell contain abundant fine-grained degraded **plant litter**... Several lines of evidence confirm that the Chatton Formation at Cosy Dell is Late Oligocene in age... However, nannofossil assemblages provide a more precise age range of between 25.4 and 24.4 Ma, close to the boundary between the Duntroonian and Waitakian local stages (Conran et al. 2014)” (Lee et al., 2014) – *EoD is based on the Turnbull and Allibone (2003) and Hyden (1980) interpretations for the formation, combined with the main rock type, and Fig. 3.*

## ***Pomahaka Formation (Miep)***

(QMAP database spelling: Pomahaka Fmn)

***Inferred age:*** 26-23 Ma (Turnbull and Allibone, 2003)

***EoD:*** onshore (estuarine)

***Basis for interpretation:*** Main\_Rock = claystone; Sub\_Rocks = sandstone, shellbeds; Description = claystone with carbonaceous mudstone and minor shellbeds and sandstone (QMAP database). “Pomahaka Formation (Mep), between the Blue Mountains and a basement high northeast of Gore, consists of interbedded fossiliferous claystone, sandstone, lignite and carbonaceous mudstone. It was deposited in a Late Oligocene-Early Miocene **estuary**” (Turnbull and Allibone, 2003). “...a ~30 m thick assemblage of shallow marine and freshwater swamp deposits, is the basal unit of the Late Oligocene-Miocene East Southland Group (Isaac & Lindqvist 1990). It is inferred to have accumulated in a **tidal interdistributary bay** setting. As well as providing an example of coal accumulation in a **coastal marsh** environment, Pomahaka Formation contains an important record of New Zealand’s brackish water mollusc fauna (e.g. Beu & Maxwell 1990)” (Lee et al., 2009) – *EoD is based on the Turnbull and Allibone (2003) estuarine interpretation for the formation. Innermost shelf may also be appropriate.*

## ***Gore Lignite Measures***

“Three lithofacies were differentiated by Isaac & Lindqvist (1990): a lower sandstone-dominated unit, a middle unit hosting thick coal seams (Fig. 33), and an upper sandstone-siltstone-carbonaceous mudstone unit with little coal. The Gore Lignite Measures were deposited in lower **coastal plain, delta plain and alluvial plain** environments, in a progradational setting” (Turnbull and Allibone, 2003). “[The lowest unit of the Gore Lignite Measures] was probably deposited in environments ranging from **delta front distributary bars and channels to lower delta plain channel fills, point bars, and interdistributary flood basins...** The persistent seams, [of the middle unit] (**lacustrine** carbonaceous and non-carbonaceous mudstones, channel and crevasse splay sands, and **flood plain** silts and clays), are envisaged as having accumulated in a middle to lower **delta plain** setting... The upper unit [was] probably deposited in upper **delta plain-fluvial plain** environments. In summary, the Gore Lignite Measures and associated marine and estuarine beds are interpreted as a **prograding deltaic to fluvial** sequence. Marine transgression in the Late Oligocene resulted in deposition of estuarine to inner shelf sediments over Permian-Jurassic basement. Progradation, or possibly falling sea level, resulted in the successive deposition of delta front and lower delta plain sediments over the marine beds and basement. Subsidence and progradation continued, and laterally persistent middle delta plain clastics and peats resulted. Continued progradation throughout the Early and Middle Miocene resulted in the middle delta plain sediments being overlain by upper delta to fluvial plain gravels, sands, and muds” (Pocknall and Mildenhall, 1984). “Other published localities that fit a number of the criteria for **rocky shorelines** include those... on Bluff Peninsula (Bosel & Coombs 1984)” (Scott et al., 2014).

- **Mieg**

***Inferred age:*** 24-13 Ma (Cahill, 1995; Turnbull and Allibone, 2003)

***EoD:*** onshore

***Basis for interpretation:*** Main\_Rock = sandstone; Sub\_Rocks = lignite, claystone, mudstone, conglomerate; Description = sandstone with lignite and carbonaceous mudstone; mudstone; claystone and minor conglomerate (QMAP database) – *EoD is based on the interpretations in Pocknall and Mildenhall (1984).*

- **Miegc**

***Inferred age:*** 24-13 Ma (Cahill, 1995; Turnbull and Allibone, 2003)

***EoD:*** onshore

***Basis for interpretation:*** Main\_Rock = quartzite; Description = silicified quartz sandstone and conglomerate (QMAP database). “On Landslip Hill the quartz gravel and sand facies are silica-cemented and form extensive horizons (Wood 1956; Lindqvist 1990)” (Turnbull and Allibone, 2003) – *this quartzite is assumed to be an onshore deposit.*

## **Manuherikia Group (mMmc)**

**Inferred age:** 19 Ma (Mildenhall and Pocknall, 1989)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = quartzite; Description = silica-cemented quartz sandstone and conglomerate as sarsen stones (QMAP database). “Scattered silcrete boulders in the Millers Flat Basin (mMm; Wood 1966) are correlated with the equivalent Miocene Manuherikia Group of Central Otago” (Turnbull and Allibone, 2003). “Throughout Central Otago, remnants of a sequence of **nonmarine** Miocene quartz conglomerate, sandstone, mudstone, and lignite up to 300 m thick are mapped as Manuherikia Group... In places the quartz gravel has been silica-cemented, and now forms lag deposits of sarsen stones” (Turnbull, 2000) – *EoD is based on the cited literature. Refer to “Manuherikia Group” on the Wakatipu area for further information.*

## **Prospect Formation (MiPlp)**

(QMAP database spelling: Prospect Fmn)

**Inferred age:** 11-3 Ma (King et al., 1999)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = conglomerate; Sub\_Rocks = sandstone; Description = massive to crossbedded conglomerate with minor sandstone and local breccia (QMAP database). “In Te Anau Basin, the Waiau Group marine sequence is truncated by the Late Miocene to Pliocene Prospect Formation (Pp) (Fig. 34)... The formation consists of clast-supported conglomerate with subordinate cross-bedded sandstone” (Turnbull and Allibone, 2003) – *EoD is based on the Manville (1996). Refer to “Prospect Formation (MPp)” on the Wakatipu map area for further information.*

## **Pebbly Hill Quartz Gravel (lMiPlq)**

“Pebbly Hill Gravels (MPq) consists of up to 150 m of Late Miocene to Pliocene sandy pebbly quartz conglomerate with a clayey matrix, interbedded with rare claystone, quartz sand and **lignite**” (Turnbull and Allibone, 2003).

**Inferred age:** 12-4 Ma (Turnbull and Allibone, 2003)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = gravel; Sub\_Rocks = sand lignite; Description = quartz gravel with minor quartz sand carbonaceous mudstone and lignite (QMAP database) – *EoD is based on the main rock type of gravel and sub-rock types of sand and lignite.*

**Inferred age:** 12-4 Ma (Turnbull and Allibone, 2003)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = gravel; Sub\_Rocks = sand; Description = quartz and quartz-greywacke gravel with minor sand and carbonaceous mudstone (QMAP database) – *EoD is based on the main rock type of gravel and sub-rock types of sand and lignite.*

## **Quaternary – Sedimentary deposits**

- **All Q deposits** (except – see below)

**EoD:** onshore

**Basis for interpretation:** Based on the QMAP database which includes alluvial, beach, dune, lacustrine, landslide, loess, moraine, peat, scree, swamp, and tailings sediments in the Quaternary deposits.

- **Q5b, Q7b**

**EoD:** innermost shelf

**Basis for interpretation:** “...marginal **marine** origin...” (Turnbull and Allibone, 2003).

## DUNEDIN AREA (Geological Map 21)

### Onekakara Group (Pom)

“The **marine** part of the transgressive Onekakara Group (distinct from the basal non-marine Taratu Formation) is mapped as a single unit which includes the Wangaloa, Brighton, Fairfield, Saddle Hill, Steele, Abbotsford, Green Island, and Burnside formations. McMillan (1993), and McMillan and Wilson (pers. comm.), suggest that the Fairfield, Steele, and Saddle Hill units are best considered members of a revised Abbotsford Formation... These rocks were deposited in a wide range of depositional environments ranging from **shoreface and inshore bars and shellbeds, to inner and outer shelf** mudstone and **offshore bars...**” (Bishop and Turnbull, 1996). “**Paralic and shallow shelf and ramp** sediments deposited during a Late Cretaceous-Oligocene marine transgression” (Carter, 1988). “Sediments were deposited during a transgression which progressed westwards across the South Island during the late Cretaceous and early Tertiary. The basal sediments of this transgression are the conglomerate and shelly sandstone and limestone present in the Brighton Limestone, basal Saddle Hill Siltstone, and Mitchells Point Facies of the Wangaloa Formation. They are replaced upwards, in most successions, by **relatively deeper water**, sandy siltstone and siltstone such as occur in the Trig C Facies of the Wangaloa Formation, the upper part of the Saddle Siltstone, and the overlying Abbotsford Mudstone. Most of these sediments are characterised by varying amounts of glauconite, limonite, siderite, pyrite, and gypsum” (Webb, 1973).

### **Wangaloa Formation**

*EoD:* innermost shelf

*Basis for interpretation:* “Fossiliferous sandstone overlying or interbedded with Taratu Formation” (Bishop and Turnbull, 1996). “Bored, calcite-cemented, and partly carbonised Araucariaceae logs (?*Agathis* sp.) occur within a concretionary shellbed in Wangaloa Formation **shallow marine** sandstone exposed near Mitchells Rocks, southeast Otago” (Lindqvist, 1986). “Douglas (1970) noted load casts and scour channels in the basal beds indicating a paleocurrent direction from the southwest (i.e. at right angles to the Waihemo Fault System). This suggests periodic ingress of relatively unsorted pebble detritus deposited by river floods off the schist hinterland and/or periodic storms affecting coastal gravelly sands” (Boyes et al., 2012) – *the formation is defined as innermost shelf because it is the first marine unit in the Onekakara Group to be deposited after the terrestrial Taratu Formation.*

### **Brighton Limestone**

*EoD:* innermost shelf

*Basis for interpretation:* “Thin shelly limestone, calcareous and glauconitic sandstone in the Brighton-Fairfield area” (Bishop and Turnbull, 1996) – *based on Webb (1973) this member appears to be a basal unit in the Onekakara Group, and is assigned an EoD of innermost shelf.*

### **Abbotsford Formation (Fairfield, Saddle Hill, Steele)**

*EoD:* innermost shelf

*Basis for interpretation:* “Massive, slightly micaceous and glauconitic siltstone in the Brighton-Fairfield area (Saddle Hill Siltstone). Greensand at the base of and within the Abbotsford Formation at Brighton (Steele Greensand and Fairfield Greensand). Extensive, rarely concretionary glauconitic silty sandstone or mudstone including greensand (Abbotsford Formation; Ngarara Formation, Carter 1988a)” (Bishop and Turnbull, 1996). “The Otepopo Member of Abbotsford Formation comprises massive, dark green to greenish-black greensand thoroughly bioturbated by the *Cruziana* ichnofacies... The bioturbated texture, presence of phosphate and lag components (wood, pebbles and gravel) and abundant glauconite point to limited terrigenoclastic deposition on the **inner shelf**. Abundant gravel and coarse sand in the greensand in some areas may imply a more **nearshore** position” (Boyes et al., 2012) – *EoD is based on Boyes et al. (2012).*

### **Green Island Sand**

*EoD:* mid-shelf

*Basis for interpretation:* “Fine to medium, cross stratified, silty sand” (Bishop and Turnbull, 1996).

“In east Otago the Green Island Sand and Puketapu Formation mark an event of sea level rise, perhaps preceded by a fall” (Boyes et al., 2012) – *Bishop and Turnbull (1996) imply that the EoD (generally) increased during deposition of the Onekakara Group as a marine transgression occurred. Boyes et al. (2012) also imply that sea level rose during the Green Island Sand. Innermost shelf (or even outer shelf) may still be appropriate.*

### **Burnside Mudstone**

*EoD: mid-shelf*

*Basis for interpretation: “Calcareous, grey-brown, plastic silty mudstone” (Bishop and Turnbull, 1996). “The Green Island Sand is succeeded by the calcareous **?mid shelf** Burnside Mudstone” (Field and Browne, 1989) – *the EoD is defined as mid shelf after Field and Browne (1989). Refer to “Burnside Mudstone (Ee\_b)” on the Aoraki map area for further information.**

**Inferred age:** > 65-36 Ma (Boyes et al., 2012)

**EoD breakdown:** > 65-51 Ma: innermost shelf (Wangaloa Formation, Brighton Limestone, Abbotsford Formation)  
50-36 Ma: mid-shelf (Green Island Sand, Burnside Mudstone)

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = conglomerate, siltstone, mudstone, limestone, shellbeds; Description = quartzose and glauconitic sandstone siltstone shellbeds and limestone (QMAP database) – *the EoD is broken down according to the formations named in Bishop and Turnbull (1996) for the Dunedin map area. Based on the Great South Basin Chronostratigraphic Transects NS-2 and -3 there appears to be a depositional hiatus from 44-43 Ma; it may be appropriate to include this as an unconformity. This unit code has the same EoD as Pom on the Waitaki map area.*

### **Hogburn Formation (IEh)**

**Inferred age:** 42-35 Ma (Bishop, 1974)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = mudstone, siltstone, conglomerate, coal; Description = **non-marine** quartz pebble conglomerate (locally silica-cemented) sandstone siltstone mudstone coal (QMAP database). “Fault-bounded slivers of quartz conglomerate, carbonaceous mudstone, and lignite unconformably overlying schist, occur discontinuously along the Tuapeka Fault Zone near Lawrence. These sequences are correlated with the Hogburn Formation (Bishop 1974a) of eastern Central Otago (D. Craw and J.H. Youngson pers. comm.), and are of Middle to Late Eocene age (J.I. Raine, unpublished data)” (Bishop and Turnbull, 1996) – *the Hogburn Formation is a terrestrial deposit. Refer to “Hogburn Formation (Eoh)” on the Waitaki map area for further information.*

### **Hogburn Formation (IEhc)**

**Inferred age:** 42-35 Ma (Bishop, 1974)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = quartzite; Description = hard silica-cemented quartz sandstone and conglomerate (QMAP database) – *this unit code likely represents that which is described in Turnbull and Allibone (2003) as “in places silica-cemented”. Following from IEh, it is assumed to also be a terrestrial deposit.*

### **Kekenodon Group (eMk)**

**Inferred age:** 23-22 Ma (Boyes et al., 2012)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = limestone; Sub\_Rocks = greensand; Description = limestone and greensand (QMAP database). “The Kekenodon Group (Carter 1988a) overlies the Marshall Unconformity, and predominantly consists of greensand or limestone of latest Oligocene to earliest Miocene age... Lithofacies and formations recognised onshore within the Kekenodon Group are: 1) Coarse glauconitic sandstone with phosphatic concretions (Concord Greensand); 2) White or yellow, fine-grained, crystalline, variably sandy or glauconitic limestone (Milburn and Scroggs Hill limestones). These rocks were deposited in **shallow, starved shelf to inner shelf** carbonate plat-



form environments” (Bishop and Turnbull, 1996) – *EoD is based on the Bishop and Turnbull (1996) description and interpretation of the map unit combined with Fig. 3. An innermost shelf interpretation may also be appropriate. Refer to “Kekenodon Group (eMk)” on the Waitaki map area for further information.*

## Otakou Group (Mo)

Includes Caversham Sandstone, Clarendon Sandstone, and Dowling Bay Limestone.

**Inferred age:** 21-20 Ma (Boyes et al., 2012)

**EoD:** mid-shelf

**Basis for interpretation:** Main\_Rock = sandstone; Sub\_Rocks = limestone, tuff; Description = calcareous sandstone, sandy limestone and minor tuff (QMAP database). “Early to Middle Miocene sedimentary rocks of the regressive Otakou Group (Carter 1988a) overlie the Kekenodon Group, or where it is absent, the Marshall Unconformity... Constituent lithofacies and formations are: 1) Variably calcareous and glauconitic sandstone (Caversham Sandstone, Fig. 16f). 2) Medium to fine-grained, weakly phosphatic sandstone (Clarendon Sandstone). 3) Sandy Limestone and tuffaceous limestone (Dowling Bay Limestone, Fig. 16g). The residual phosphatic Clarendon Sandstone overlies Milburn Limestone, the contact being marked by paleokarst topography on the limestone. This surface is inferred to result from subaerial leaching following a drop in sea level and marine regression in the Early Miocene (Carter 1969; Bishop 1994b). The tuffaceous sediments represent the Middle Miocene initiation of the subaerial Dunedin Volcano (e.g. Benson 1968; Coombs et al. 1986)” (Bishop and Turnbull, 1996). “To the south, well sorted medium- to fine-grained sandstone (Caversham Sandstone) and impure limestone (Goodwood Limestone) were deposited in an **outer shelf** setting” (Forsyth, 2001) – *EoD is based on Forsyth (2001) which gives a shelfal depth for the group. The map unit is defined as mid-shelf here because it appears to be the average depositional depth for the group. Outer shelf may be appropriate on this map area. Refer to “Otakou Group (Mo)” on the Waitaki map area for further information.*

## Dunedin Volcanic Group

“The Dunedin Volcano is a partly-eroded shield volcano which was intermittently active in late Middle Miocene time (13-10 Ma; Coombs et al. 1986). Scattered smaller volcanic centres, some of which are significantly older (up to 21 Ma; Coombs et al. 1986), occur up to 100 km northwest and southwest of the Dunedin Volcano. Within the main volcano, rocks of the Dunedin Volcanic Group have been assigned to four eruptive episodes (Md0, Md1, Md2, and Md3)... The initial, dominantly trachytic phase of activity of the Dunedin Volcano was centred on the Port Chalmers area and, like the first and second main eruptive phases which followed, produced **tuff, breccia, agglomerate, dikes, plugs, shallow intrusives, and flows** (Fig. 17). The third and last phase produced extensive **flows of basalt and phonolite**, as well as steep-sided lava domes which now form many prominent peaks around Otago Harbour” (Bishop and Turnbull, 1996). “Miocene marine sediments on the Peninsula give evidence of a **submarine setting for the early phases of the volcanic activity**... A wide range of pyroclastic deposits is found on the Otago Peninsula, including tephra erupted from **shoaling** volcanoes, and fully **subaerial** tephra (**Strombolian** deposits), which erupted commonly from small volcanoes. Most of the small volcanoes seem to have been short-lived eruption centres but locally there are also eruptive centres that were active for quite a substantial time or were reactivated during their history” (Martin, 2000). “...the Dunedin Volcanic Group was formed. It includes the Alpine Dyke Swarm, the Dunedin Volcanic Complex (DVC) and the Waipiata Volcanic Field (WVF). The DVC is located at the coast and nearby inland a few tens of kilometres from the shoreline, adjoining a half-circular area containing the WVF volcanic rocks. The WVF is a several hundred metres thick accumulation of alkali volcanic rocks erupted **subaerially** in the middle Miocene over a period of at least 3 million years (Benson, 1969; Coombs et al., 1986; Reay et al., 1991)... In contrast to the DVC, the WVF consists of the remains of numerous non-contiguous individual monogenetic volcanoes, inferred to have erupted **subaerially** (Coombs et al., 1986)” (Németh and White, 2003). “Dunedin Volcano (here given formal lithostratigraphic status) lasted from  $16.0 \pm 0.4$  to c.  $10.1$  Ma, and that of the surrounding Waipiata Volcanics lasted from  $24.8 \pm 0.6$  to  $8.9 \pm 0.9$  Ma... The geographical separation between the Waipiata Volcanics and the Dunedin Volcano is drawn arbitrarily at the outer limit of preserved lava flows erupted from the central volcano” (Coombs et al., 2008).

## ***Initial eruptive phase***

- **Md0e**

***Inferred age:*** 14-13 Ma (McDougal and Coombs, 1973)

***EoD:*** submarine silicic eruptives

***Basis for interpretation:*** Main\_Rock = **trachyte**; Description = trachytic flows and tuffs (QMAP database) – *EoD is based on the interpretations that the earliest activity was in a shallow marine environment.*

- **Md0i**

***Inferred age:*** 14-13 Ma (McDougal and Coombs, 1973)

***EoD:*** silicic intrusives

***Basis for interpretation:*** Main\_Rock = **trachyte**; Description = **dikes and plugs** of anorthoclase trachyte (QMAP database) – *the QMAP lithologic description describes the map unit as dikes and plugs indicating that the EoD was subterranean.*

- **Md0p**

***Inferred age:*** 14-13 Ma (McDougal and Coombs, 1973)

***EoD:*** submarine silicic eruptives

***Basis for interpretation:*** Main\_Rock = **trachyte**; Sub\_Rocks = trachytic breccia; Description = breccia and basaltic agglomerate (QMAP database) – *EoD is based on the interpretations that the earliest activity was in a shallow marine environment.*

## ***First main eruptive phase***

- **Md1e**

***Inferred age:*** 15-12 Ma (Bishop and Turnbull, 1996; Hoernle et al., 2006; Coombs et al., 2008)

***EoD:*** onshore mafic eruptives

***Basis for interpretation:*** Main\_Rock = **basalt**; Sub\_Rocks = benmoreite phonolite basanite trachyandesite; Description = extensive flows of olivine basalt plagioclase basalt basanite kaiwekite and trachyandesite (QMAP database) – *EoD is based on the Main\_Rock type of basalt. There is no mention of evidence for marine emplacement, so the setting is taken to be onshore, although submarine may still be appropriate at this stage.*

- **Md1i**

***Inferred age:*** 13-12 Ma (Bishop and Turnbull, 1996)

***EoD:*** intermediate intrusives

***Basis for interpretation:*** Main\_Rock = **phonolite**; Sub\_Rocks = **trachyandesite** tinguaitite nepheline syenite; Description = shallow **intrusions** of nepheline syenite porphyry tinguaitite and trachyandesite (QMAP database) – *phonolite and trachyandesite indicate intermediate intrusives.*

- **Md1p**

***Inferred age:*** 13-12 Ma (Bishop and Turnbull, 1996; Hoernle et al., 2006)

***EoD:*** onshore mafic eruptives

***Basis for interpretation:*** Main\_Rock = breccia; Sub\_Rocks = **basaltic** agglomerate; Description = vent filling breccia and agglomerate (QMAP database) – *there is no mention of evidence for marine emplacement, so the setting is taken to be onshore, although submarine may still be appropriate at this stage.*

## ***Second main eruptive phase***

- **Md2e**

***Inferred age:*** 14-11 Ma (McDougal and Coombs, 1973; Coombs et al., 2008)

***EoD:*** onshore mafic eruptives

***Basis for interpretation:*** Main\_Rock = **basalt**; Sub\_Rocks = phonolite dolerite benmoreite; Description = extensive flows of trachybasalt olivine dolerite basalt phonolite (QMAP database) – *EoD is based on the Main\_Rock type of basalt. There is no mention of evidence for marine emplacement, so the setting is taken to be onshore, although submarine may still be appropriate at this stage.*

- **Md2i**

**Inferred age:** 12-11 Ma (McDougal and Coombs, 1973; Timm et al., 2010)

**EoD:** mafic intrusives

**Basis for interpretation:** Main\_Rock = **dolerite**; Sub\_Rocks = tinguaita phonolite; Description = plugs of dolerite porphyrite phonolite and tinguaita (QMAP database) – *the QMAP lithologic description describes the map unit as plugs indicating that the EoD was subterranean. Intermediate intrusives may also be appropriate.*

- **Md2p**

**Inferred age:** 12-11 Ma (Bishop and Turnbull, 1996)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = breccia; Sub\_Rocks = **basaltic** agglomerate; Map\_Unit = second main eruptive phase; Description = vent filling breccia (QMAP database) – *there is no mention of evidence for marine emplacement, so the setting is taken to be onshore, although submarine may still be appropriate at this stage.*

### **Third main eruptive phase**

- **Md3e**

**Inferred age:** 13-10 Ma (Bishop and Turnbull, 1996; Coombs et al., 2008)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = **basalt**; Sub\_Rocks = phonolite trachybasalt basanite tuff; Description = extensive flows of phonolite basalt trachyandesite minor tuff (QMAP database) – *EoD is based on the Main\_Rock type of basalt. There is no mention of evidence for marine emplacement, so the setting is taken to be onshore.*

- **Md3p**

**Inferred age:** 12-10 Ma (McDougal and Coombs, 1973; Coombs et al., 2008; Timm et al., 2010)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = **basalt**; Sub\_Rocks = tuff phonolite; Description = lapilli tuff agglomerate volcanic breccia minor trachytic flows (QMAP database) – *EoD is based on the Main\_Rock type of basalt. There is no mention of evidence for marine emplacement, so the setting is taken to be onshore.*

### **Beyond the main volcano**

“Beyond the main volcano, Dunedin Volcanic Group rocks include diatremes filled with **volcaniclastic sediments**, a differentiated **sill** at Lake Waihola (Reay & Walls 1994), **flow** remnants, **dikes**, and **plugs**. These are mapped either as volcanic sediments, flows or pyroclastics (Md), or as undifferentiated volcanic rocks (Mdv). Subordinate volcanogenic sediments are interbedded with the volcanic rocks. The most widespread are boulder conglomerates considered to represent local alluvial valley fill formed during the life of the volcano (cf. Benson 1968). Other sedimentary rocks include scattered local diatomite, carbonaceous shale, and lignite interpreted as ephemeral lake deposits” (Bishop and Turnbull, 1996).

- **Mdc**

**Inferred age:** 15-10 Ma

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = conglomerate; Sub\_Rocks = tuff diatomite leaf beds carbonaceous shale; Map\_Unit = **flood plain alluvium**; Description = generally lenticular deposits of conglomerate in formed stream channels finer deposits in ephemeral lakes (QMAP database) – *EoD is based on the map unit’s classification as flood plain alluvium.*

- **Mdp**

**Inferred age:** 13-10 Ma

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = breccia; Sub\_Rocks = **basaltic** agglomerate; Description =

basaltic breccia and agglomerate in outliers to Dunedin volcanic complex (QMAP database) – *EoD is based on the Sub\_Rock type of basalt. There is no mention of evidence for marine emplacement, so the setting is taken to be onshore.*

- **Mdv**

**Inferred age:** 23-10 Ma (Hoernle et al., 2006; Coombs et al., 2008)

**EoD:** onshore mafic eruptives

**Basis for interpretation:** Main\_Rock = **basalt**; Sub\_Rocks = tuff pyroclastics; Description = undifferentiated flows pyroclastics and intrusives peripheral to the Dunedin volcanic complex (QMAP database) – *Waipiata Volcanics, part of the Dunedin Volcanic Group, occurred over a longer time and wider area than activity of the main Dunedin Volcano. Refer to “Dunedin Volcanic Group” on the Waitaki map area for further information.*

### **Lignite (mMl)**

**Inferred age:** 16-15 Ma (Bishop and Turnbull, 1996)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = **lignite**; Sub\_Rocks = sandstone tuff; Description = lignite minor sandstone and tuff (QMAP database). “**Non-marine** lignite, minor quartz sandstone, and tuff (mMl)... They are inferred to be a maar deposit which formed immediately prior to eruption of Dunedin Volcanic Group rocks (Youngson 1993)” (Bishop and Turnbull, 1996) – *EoD is based on the Bishop and Turnbull (1996) interpretation.*

### **Fluvial deposits (IMc)**

**Inferred age:** 6-4 Ma (Bishop and Turnbull, 1996)

**EoD:** onshore

**Basis for interpretation:** Main\_Rock = gravel; Sub\_Rocks = sand mud gold; Description = weathered schist- and quartz-derived gravel sand and mud locally auriferous (QMAP database). “Deposits of weathered quartz-schist conglomerate, sandstone, mudstone, and local lignite are discontinuously preserved in the Lake Mahinerangi area, west of Maungatua... They are inferred to represent **river deposits** in proto-Taieri and Waipori river channels...” (Bishop and Turnbull, 1996) – *EoD is based on the Bishop and Turnbull (1996) interpretation.*

## **Quaternary – Sedimentary deposits**

- **All Q deposits** (except – see below)

**EoD:** onshore

**Basis for interpretation:** Based on the QMAP database which includes alluvial, dune, peat, reclaimed land, and tailings sediments in the Quaternary deposits.

- **Q11b, Q9b, Q7b, Q5b, Q1b, Q1b~**

**EoD:** innermost shelf

**Basis for interpretation:** “A series of **marine** erosion surfaces...” (Bishop and Turnbull, 1996).

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