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**Title**                    **Hawke's Bay forearc basin (eastern North Island, New Zealand):  
Stratigraphy, biostratigraphy, chronology, geological maps and  
paleogeography**

**Operator**

**Author**                Kyle J. Bland and Peter J.J. Kamp

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**Summary**            This report documents the results of analysis of the late Neogene forearc basin in central Hawke's Bay, eastern North Island (Hikurangi subduction margin), New Zealand. This analysis is based on new 1:50,000-scale geological maps of the succession exposed in outcrop in central Hawke's Bay, which are reproduced here as six sheets (Enclosures 3 & 4). The analysis builds on detailed stratigraphic and facies descriptions of the Late Miocene (Tongaporutuan) to Pleistocene (Castlecliffian) basin fill (see also Bland et al. 2007; Kamp et al. 2008), its biostratigraphy and chronology, which are integrated here. The history of Late Neogene basin development is summarised in a series of paleogeographic maps.

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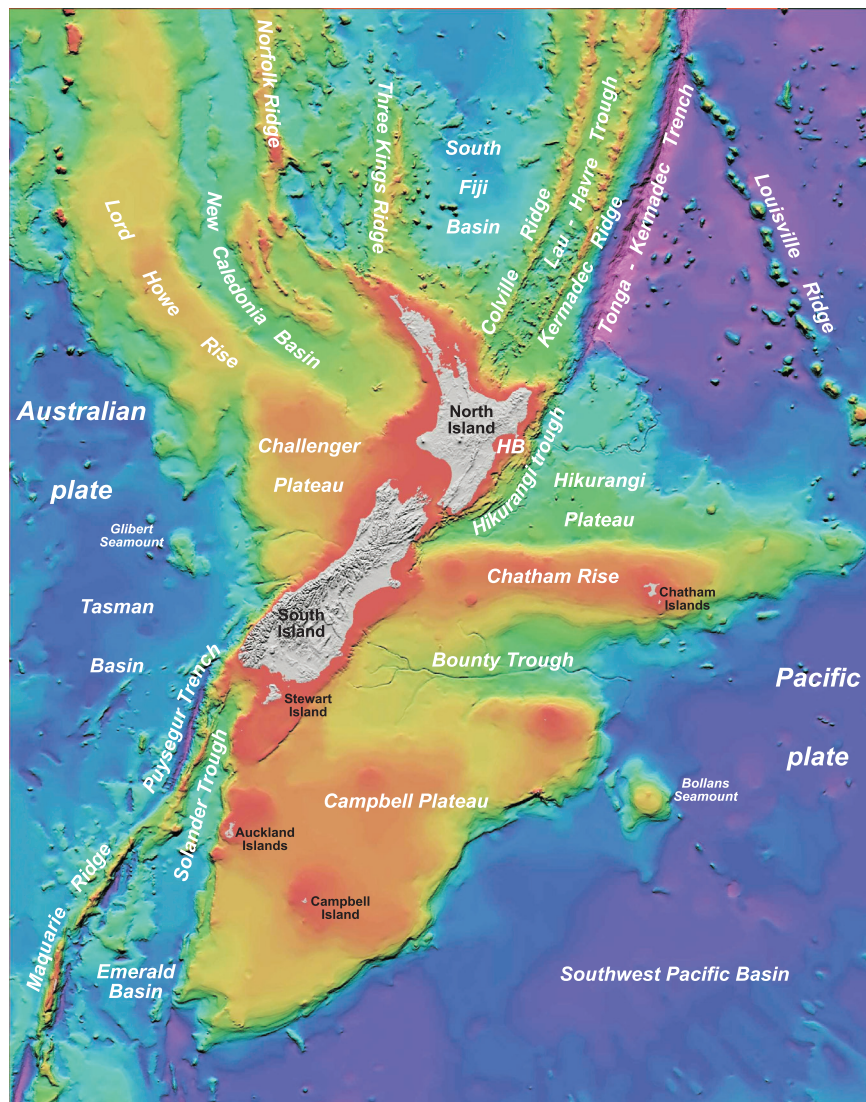
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## Introduction

Hawke's Bay is a province in eastern North Island, New Zealand. It lies within the Hikurangi margin, which is an ocean-continent subduction zone at the northern end of the New Zealand sector of the Australia-Pacific plate boundary zone (Fig. 1). Much of Hawke's Bay, the provinces to the north (Poverty Bay) and to the south (Wairarapa), are underlain by sedimentary successions of Neogene age that accumulated in a forearc position along the inboard margin of the accretionary wedge (Figs 2–4). A forearc basin configuration is best developed in Hawke's Bay, west of the marine embayment known as Hawke Bay (Fig. 4). Immediately south of Cape Kidnappers in the eastern part of the basin, Pliocene and Pleistocene strata dip northwest, being underlain by the

highest part of the accretionary wedge, whereas to the west, strata of the same age dip southeast off elevated Jurassic basement (Ruahine Range; Kaweka Range). North of Wairoa (Fig. 4) the modern basin configuration is not so clear and deformed mid-Miocene and older strata occur at the surface, variably eroded. It is possible that during the Early and Middle Miocene the basin had a NW-SE orientation rather than the present NE-SW structural grain (Kamp & Xu, 2002). In Wairarapa the highest part of the accretionary wedge increasingly impinges to the south upon the North Island axial range (Fig. 3) limiting the development of a forearc basin, and in southernmost Wairarapa the modern valley appears to be a foreland basin where elevated basement (Rimutaka Range) overthrusts Pliocene and Pleistocene strata.



*Fig. 1:* New Zealand subcontinent showing the main bathymetric and tectonomorphic features. HB, Hawke Bay. Base image is the NIWA Undersea New Zealand map.

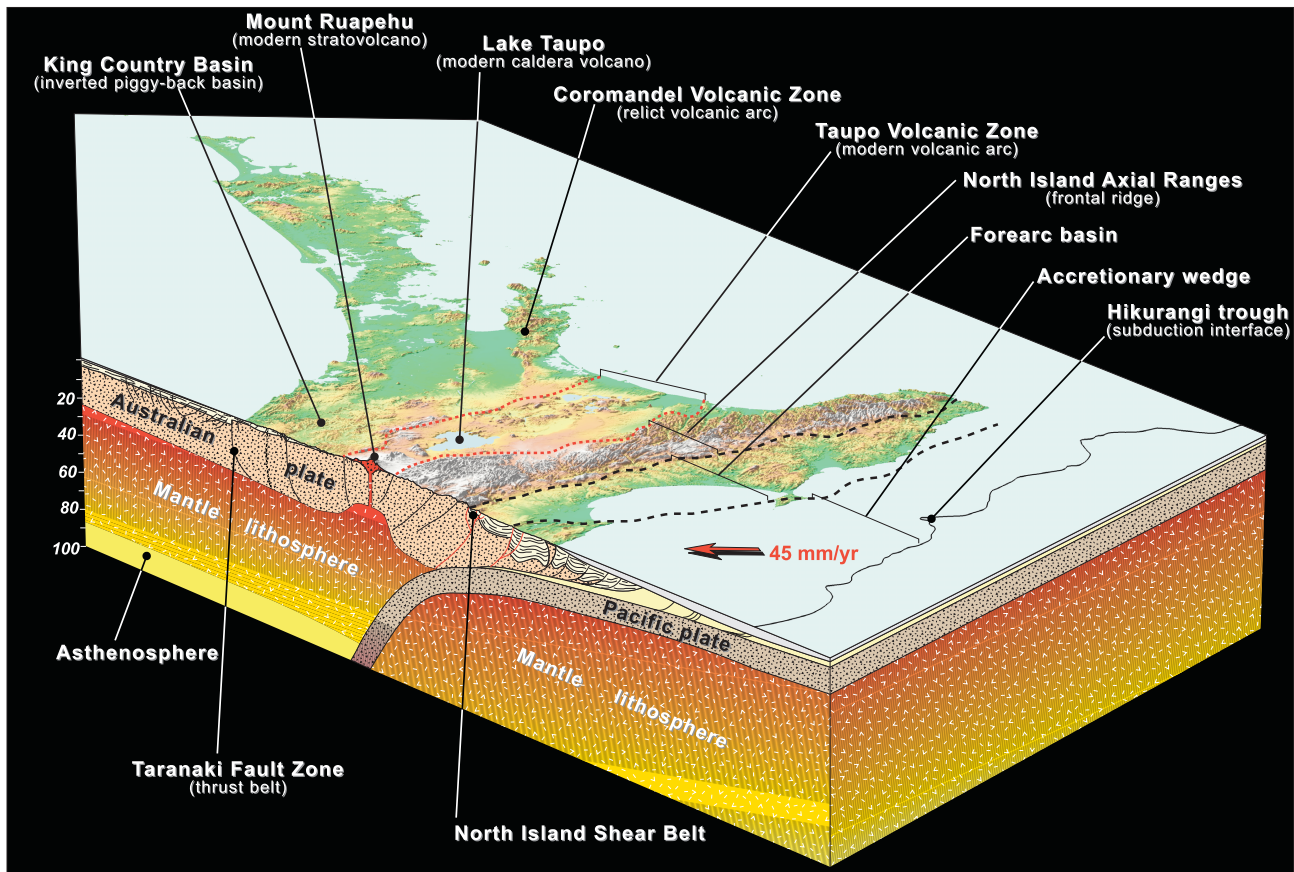


Fig. 2: Illustration of the tectonic setting of eastern North Island, New Zealand. Data used in this figure were derived from Beanland (1995), Field et al. (1997), Barnes and Nicol (2002), and Barnes et al. (2002).

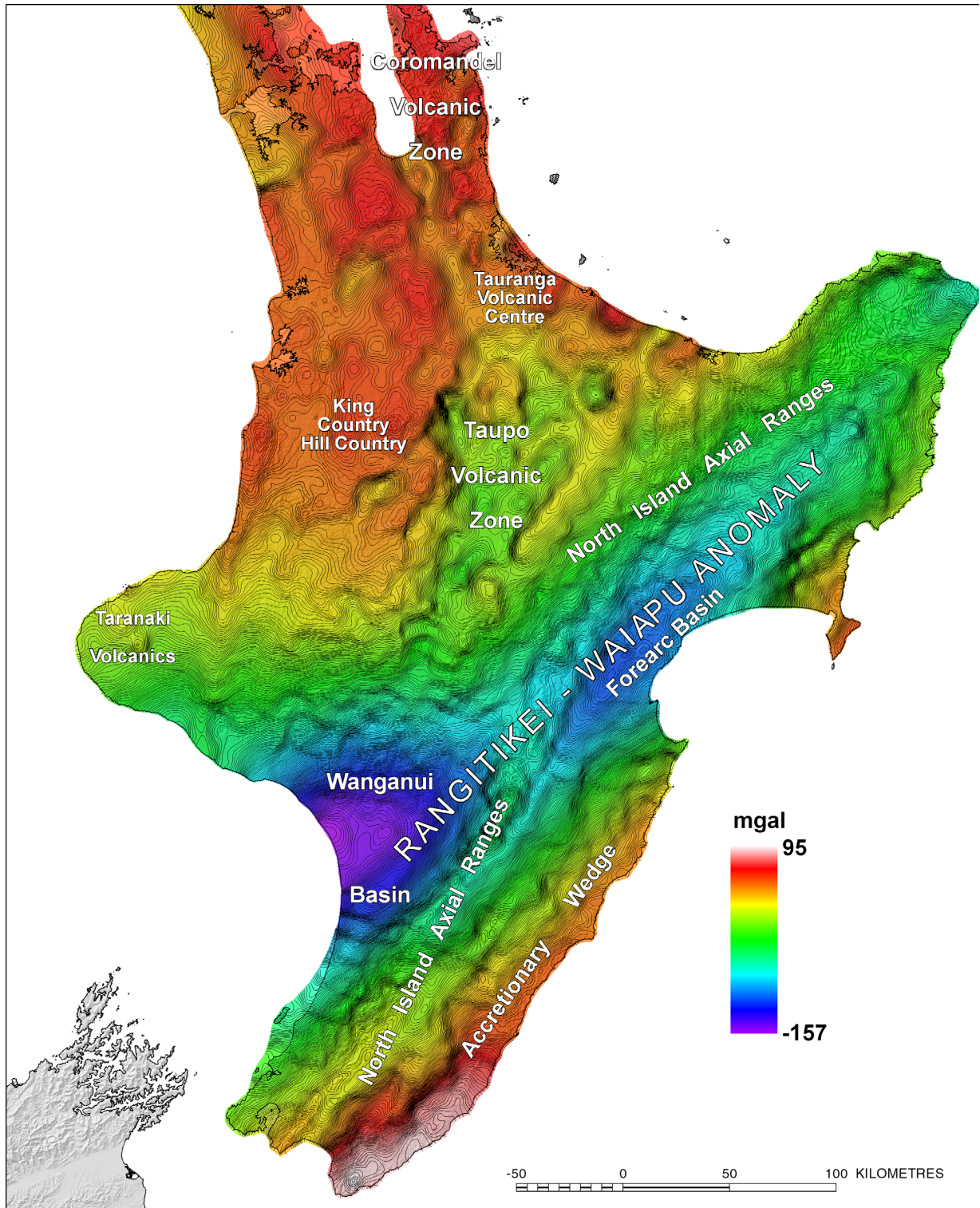
The Bouguer gravity anomaly map for North Island (Fig. 3) has positive values for the accretionary wedge and negative values for the Pliocene – Pleistocene depocentres of Hawke’s Bay and Wanganui Basin. The negative gravity values are inferred to derive mainly (two-thirds) from the deeper lithosphere structure (Pacific plate crust displacing Australia plate upper mantle) and one-third from upper crustal structure including the low-density (modelled as 2.4 g/cc) basin succession within five km of the surface (Stern and Davey, 1985; Stern et al. 2010).

The focus of this report is on basin analysis of Hawke’s Bay Basin. The report includes new 1: 50 000 scale geological maps derived from surface (outcrop) mapping and a series of enclosures that summarise the stratigraphy and paleogeography of the basin. Subsurface stratigraphy derived from exploration drillholes has been integrated into the basin stratigraphy. The structure of the basin, including a series of structural cross-sections, is outlined in a companion PR report No: 4884 (Kamp and Bland 2014). The forearc basin remains a frontier basin for hydrocarbon

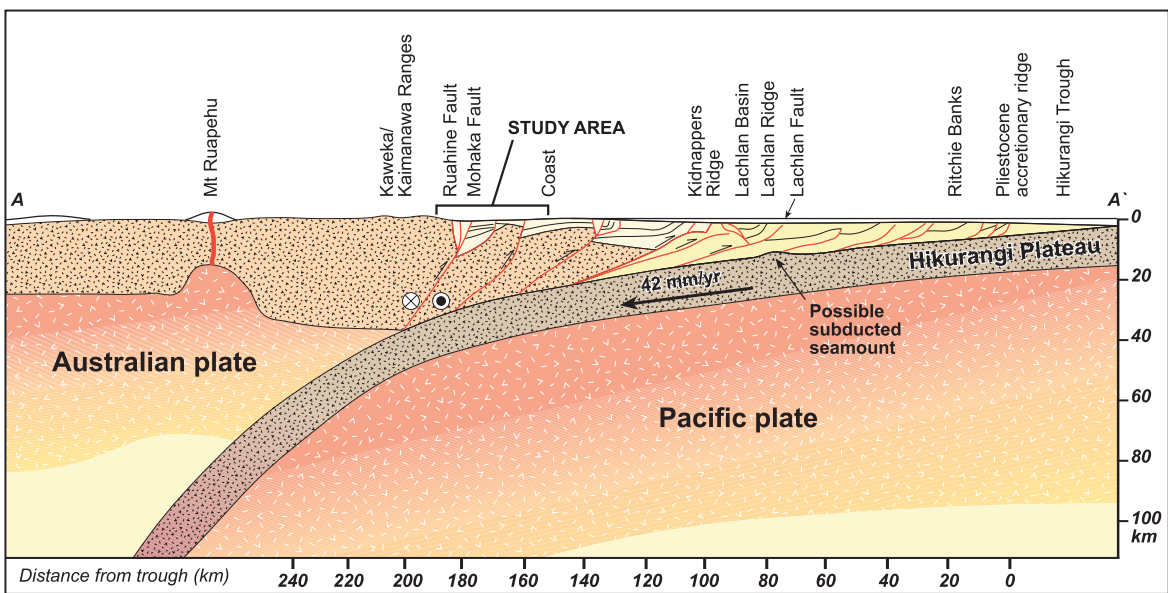
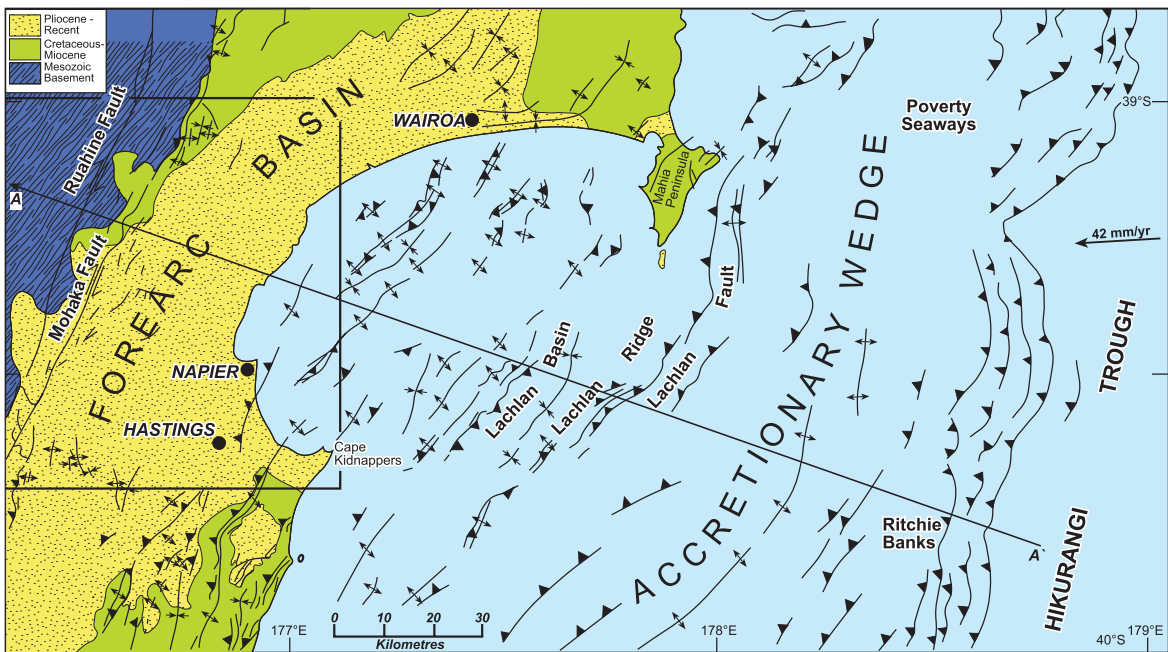
exploration, numerous seeps on land showing that it has an active hydrocarbon system, and it can be considered prospective for conventional and unconventional hydrocarbon accumulations.

## Tectonic setting

Seismic reflection and seismicity data indicate that the top of the subducted oceanic Pacific plate lies at shallow depth beneath Hawke Bay and dips to the northwest at a shallow angle (6°) increasing to about 12° beneath the forearc basin and the axial ranges, beyond which it dips at 55° (Ansell and Bannister, 1996; Barnes et al., 2002). The term Hikurangi margin is used to include all elements of the modern subduction zone between the Hikurangi Trough and the back-arc region to the northwest of the Taupo Volcanic Zone (Figs 2 - 4). The Hikurangi margin is the southern continuation of the Tonga-Kermadec subduction system (Fig. 1) and differs from it in having an overriding plate comprised of continental crust. The Hikurangi margin has evolved over the last 27 m.y. (Furlong and Kamp, 2009; 2012).



**Fig. 3:** Distribution of bouguer gravity anomalies, North Island. Anomaly values are in mgal ( $10^{-5}$  N/kg); contour interval 1 mgal. Gravity values are in terms of the New Zealand Potsdam System (1959). Assumed density of topography (land)  $+2.67$  Mg/m<sup>3</sup>, ocean  $-1.64$  Mg/m<sup>3</sup>. Data compiled from DSIR 1:250 000 bouguer anomaly maps (Sheets 3-12; Woodward (1971a, b); Woodward and Boyle (1972); Reilly (1972); Woodward and Ferry (1973, 1974); Doone and Ferry (1974); Ferry et al. (1974); Whiteford (1974); Whiteford and Woodward (1974)). The position of the Rangitikei-Waiapu gravity low (Robertson and Reilly 1958) is indicated. Note the strong coincidence of positive values with the accretionary wedge, and negative values with the Pliocene-Pleistocene forearc basin and Wanganui Basin (Rangitikei-Waiapu anomaly).



**Fig. 4:** Regional tectonic setting of the Hawke's Bay area and the central part of the Hikurangi margin (subduction zone). Location of the crustal section is indicated by line A-A'. The central Hawke's Bay map area is shown by the black box on the figure map. Adapted from Barnes et al. (2002).

The present day vector describing the relative motion between the two plates trends 40° (at 50 mm/y) to the general strike of the margin at the northern end and 70° (at 38 mm/y) at the southern end, meaning that there is greater obliquity to the convergence towards the south. Traditionally, this motion has been considered to be partitioned into margin-parallel motion (expressed on strike-slip faults along the axial ranges) and margin-normal motion accommodated on reverse faults within the accretionary wedge (Walcott, 1978; Beanland, 1995). More recent detailed mapping (Begg and Lee, 2002; Lee et al., 2011; Kamp and Bland, 2014)

does not support the model of partitioning the motion into different styles in different parts of the subduction zone; in addition, the strike-slip displacement along and within the axial ranges is now viewed as related to oblique extension within the Taupo Volcanic Zone (Wallace et al., 2004).

The Hikurangi Trough (Figs 1, 2 & 4) is effectively the structural trench but it is substantially infilled with sediment, especially in the south, and is more akin to a trough. It is approximately four km deep in the north and decreases to one km deep

at its southwest end near Marlborough (Beanland 1995). The Hikurangi Trough comprises two separate zones: (i) a northern, sediment-flooded, volcanic knoll-studded, SSW trending structural continuation of the Kermadec Trench; and (ii), a southern, more east-west trending transform boundary between central New Zealand and the Chatham Rise (Lewis, 1980; 1985). The presence of seamounts indicates that the Pacific plate is oceanic lithosphere (Uruski and Wood 1993).

An accretionary wedge 100-180 km wide has developed on the landward side of Hikurangi Trough (Fig. 4). The extent to which this wedge is genuinely made up of accreted sediments, as opposed to pre-Late Oligocene (pre-subduction initiation) strata that have undergone a kneading process driven by reverse fault imbrication, is unclear and requires more exploration by seismic reflection methods. The geometry of the wedge south of Cape Kidnappers (Fig. 4) suggests that outer parts of the wedge comprise accreted sediments (Lewis and Pettinga 1993), although the sediments have derived from erosion of the Australia plate and have cascaded down the shelf and slope to the trough rather than having been derived from off-scraping of sediment coming in on the Pacific plate. The wedge is least developed north of Hawke Bay where its structure is dominated by the subduction of seamounts and associated collapse of the slope (Barker et al. 2009). Inboard parts of the wedge are emergent in the coastal hill country between Cape Kidnappers and Cape Palliser at the eastern end of Cook Strait (Pettinga 1982; Kamp 1982; Pettinga and Lewis 1985; Ballance 1993; Lewis and Pettinga 1993).

The accretionary wedge comprises four geological units: (i) Mesozoic basement undermass, (ii) "passive margin" sediments, (iii) frontally-accreted trench-fill and (iv), slope basin fill. Deep seismic profiling offshore off Poverty Bay indicates that most of the section is comprised of basement undermass. This will be part of the L. Jurassic and E. Cretaceous subduction wedge that formed prior to the mid- to Late Cretaceous end of the previous phase of subduction accretion (Mazengarb and Harris 1994; Kamp 1999; Adams et al. 2013). This section is overlain by associated Late Cretaceous slope basin strata

that accumulated up to the end of the subduction phase (e.g. George 1992), which are difficult to separate from a thin succession (1-2 km) of so-called passive margin sediments that accumulated between the end of Cretaceous subduction (about 90 Ma) and the Late Oligocene start of the modern phase of subduction (Furlong and Kamp 2009, 2012). The blanket of Late Cretaceous and Paleogene sediments are terrigenous, fine grained and accumulated in bathyal environments, becoming calcareous (marl) during the Oligocene (Weber Formation). The width of the frontally accreted sediments is variable along the margin from negligible to 10s of km wide and up to 7 km thick (Lewis, 1980; Lewis and Pettinga, 1993). The main part of the wedge is being shortened by imbricate reverse faults that form structural highs defining the seaward margin of a series of trench-slope basins that contain progressively tilted slope sediments (Lewis and Pettinga, 1993). These slope basins are best developed in the central section offshore of Southern Hawke's Bay and Wairarapa where they are typically 5 - 30 km wide and contain fills 200 - 2200 m thick (Lewis, 1980; Lewis and Pettinga, 1993). Some of these basins have been uplifted on land as part of the inboard margin of the wedge, including the Late Miocene Makara Basin (van der Lingen and Pettinga, 1980; Pettinga 1982). Deformation styles in this area include tight recumbent and isoclinal folds, and reverse and/or thrust faults (Pettinga 2004). The latter is often accompanied by narrow anastomosing zones of tectonic melange and broken formation. The slope basin fill exposed on land includes Miocene turbidites, hemipelagic mudstone and Pliocene shelf limestone (Pettinga 1982; Harmsen 1985; Kamp et al. 1988).

Late Quaternary landscape features over the inboard margin of the accretionary wedge in the coastal hill country indicate that folding, faulting and uplift of the accretionary wedge continues to the present day. Such landscape features include uplifted and commonly tilted marine terraces, deeply incised and rejuvenating streams and rivers, and surface expression of active folds and faults (Pettinga 2004). Rates of Late Quaternary uplift of this region are variable, and range from <1 m/ka to about 3 m/ka (Lewis 1971; Hull 1985, 1987; Pillans 1986). The offshore part of the accretionary prism contains many

actively growing fault-controlled anticlines and associated faults (Field et al. 1997; Barnes and Nicol 2002; Barnes et al. 2002). These are mechanically linked to the structural telescoping of the accretionary prism. One tectonically active ridge is the Lachlan Ridge (Barnes et al. 2002; Ricketts and Nelson 2004) (Fig. 4). Lachlan Ridge is the submarine extension of Mahia Peninsula and is an antiformal structure located above the hanging wall of an east-verging thrust, the Lachlan Fault. The fault itself extends to a detachment in Cretaceous or older strata (Field et al. 1997; Barnes et al. 2002).

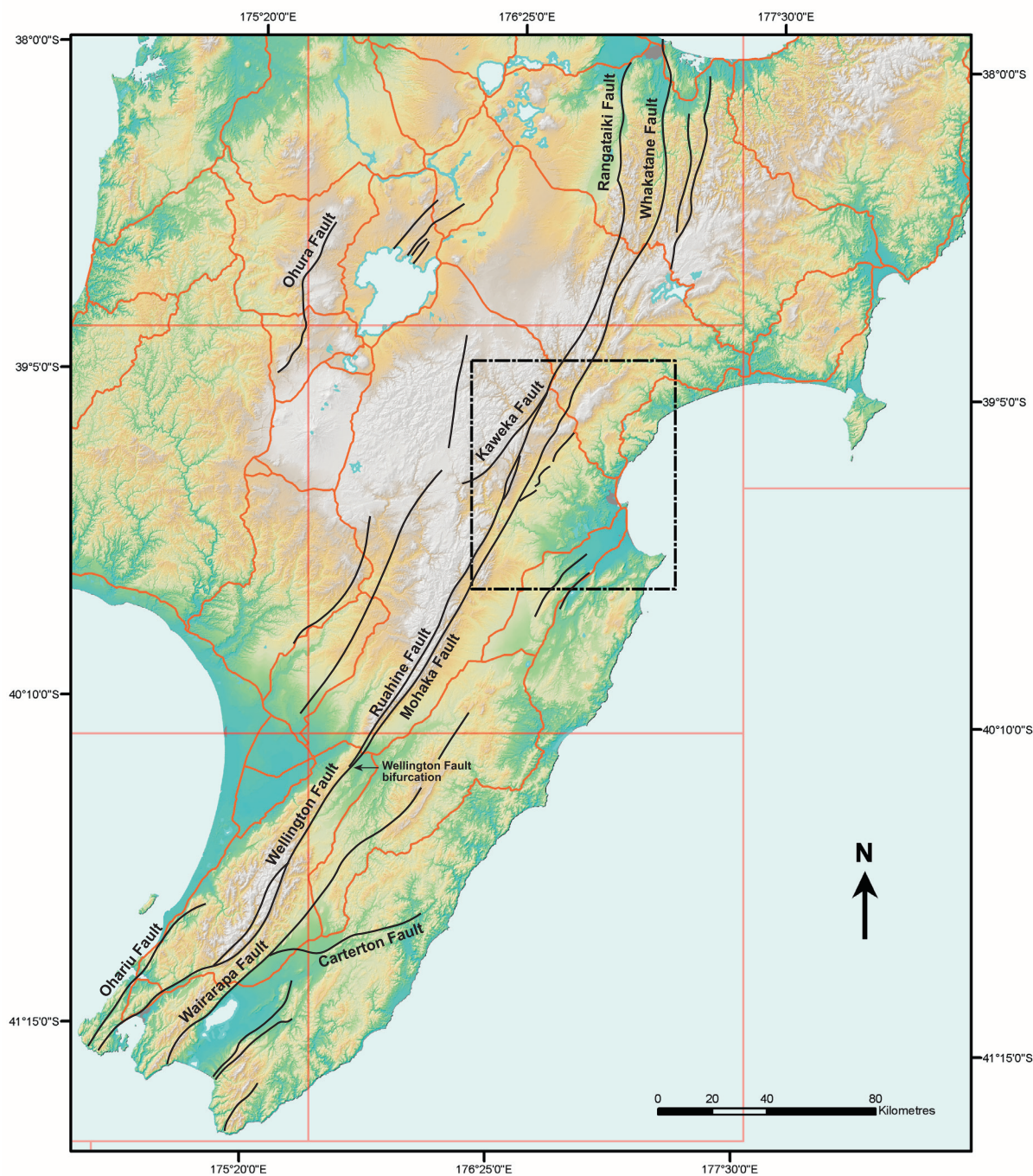
The forearc basin (Figs 2 - 4) represents a major topographic and structural depression on the arc side of the active accretionary wedge described above. In Hawke's Bay the western boundary is another structural ridge underlain by basement of L. Jurassic age. The forearc basin contains a Mio-Pliocene sedimentary fill that is mildly deformed by reverse and oblique-slip faults. The least deformed region is a zone through the central part of the basin. Deformation is most pronounced in the east along the accretionary borderland, which has reverse faulted and tilted the basin fill; deformation is also pronounced along the western margin, which lies within the North Island Shear Belt, a zone of active dip-slip and dextral faulting (Wallace et al. 2004).

Hawke Bay between Cape Kidnappers and Mahia Peninsula (Fig. 4) is part of the forearc basin. Water depths are typically less than 120 m, with the 250 m isobath defining the edge of the continental shelf (Field et al., 1997). The Neogene succession within it has been mildly deformed into anticlines and a few reverse faults (Barnes et al. 2002) (Fig. 4). Seismological data indicate that the top of the subducted Pacific plate lies ~12 km beneath Hawke Bay, with the plate interface dipping at a shallow angle of about 6° northwest (Bannister 1988; Ansell and Bannister 1996; Barnes and Nicol 2002).

Mesozoic basement has been encountered in Te Hoe-1, Ongaonga-1, and Takapau-1 hydrocarbon exploration drill holes in western parts of the forearc basin. Drilling in the eastern part of the basin has not been deep enough to

intercept basement (Hawke Bay-1, Hukarere-1, Whakatu-1), although it is considered to occur at depth beneath Miocene, Paleogene and possibly latest Cretaceous sedimentary successions. The frontal ridge bordering the Hawke's Bay forearc basin to the west is up to 1700 m high and composed mainly of L. Jurassic indurated greywacke basement. Continuous dextral oblique-slip faults occur within and along the eastern margin of the exposed basement ridges. Near and north of Woodville the Wellington Fault bifurcates into the Ruahine and Mohaka Faults, which continue northeastward into Hawke's Bay (Fig. 5). These faults commonly juxtapose basement against Miocene-Pliocene sedimentary rocks of the forearc basin. Displacement since the Early Pleistocene along the bounding faults is possibly as much as 2000 m (Berryman, 1988). The North Island Shear Belt acts to accommodate some of the modern plate motion through the North Island (Cashman et al. 1992; Beanland et al. 1998; Nicol and Van Dissen 2002; Wallace et al. 2004). Offset on the major dextral faults (e.g. Ruahine and Mohaka Faults) is possibly related to opening of the Taupo Volcanic Zone (Wallace et al. 2004), whereas the Wakarara, Tukituki, and Poukawa Faults appear to have mainly reverse dip-slip displacement (Erdman and Kelsey 1992; Beanland et al. 1995; Nicol and Van Dissen 2002). Large areas of the axial ranges are characterised by summit height concordance or smooth topography, which has been interpreted as representing a remnant erosion surface (Wellman 1948; Kamp 1982; Berryman 1988).

The Taupo Volcanic Zone (TVZ; Figs 2 & 3) is the youngest and most active (eastern) part of the Central Volcanic Region (Beanland 1995; Stratford and Stern 2006). It is a seismically active zone of Quaternary calc-alkaline volcanism and intra-arc rifting (Spinks et al. 2005) containing numerous closely spaced northeast-southwest striking normal faults, half-grabens and volcanic centres (Wilson et al. 1984; Leonard et al. 2010). The TVZ marks the present location of intra-arc rifting related to an overall convergent setting within the North Island, and associated with a highly thinned crust of 15 km thickness (Bibby et al. 1995; Stratford and Stern 2006).



**Fig. 5:** Distribution of some major faults in southern and central North Island. The location of Wellington Fault, which bifurcates near Woodville is indicated. Dashed box indicates the central Hawke’s Bay map area. Orange lines are QMAP sheet cut-ups; red lines are state highways.

Volcanic activity commenced in the TVZ at about 2 Ma (Houghton et al. 1995; Briggs et al. 2005) and the present area of active volcanism is concentrated in a NNE-SSW trending zone 250 km long from White Island in the northeast to Mount Ruapehu in the southwest (Spinks et al. 2005). This area includes all activity in the past 300,000 y. (Houghton et al. 1995; Wilson et al. 1995; Leonard et al. 2010). It can be divided into three parts along its length: a central region

with several calderas from Okataina to Taupo including associated rhyolitic volcanism at the surface; and two sections of Whakatane-White Island in the northeast and Tongariro-Ruapehu in the southwest with andesite-dacite stratovolcanoes (Houghton et al. 1995; Wilson et al. 1995; Leonard et al. 2010). The central area is productive in terms of rhyolitic volcanics (~ 0.28 m<sup>3</sup> s<sup>-1</sup>) and geothermal fluxes (c. 4200 MW) (Wilson 1996).

## Forearc basin physiography

The part of the Hawke's Bay forearc basin mapped here (Fig. 6) covers about 5,600 km<sup>2</sup> of central parts of Hawke's Bay between the Ruahine and Kaweka Ranges in the west and Hawke Bay in the east, and bounded approximately to the north and south by Waikare and Havelock North respectively. The region is administered by the Hawke's Bay Regional Council, Hastings District Council, Wairoa District Council, and Napier City Council. The main human population is centred about the twin cities of Napier and Hastings (combined population of approximately 110,000 people), of which Hastings is the largest. Other towns include Havelock North, Flaxmere

and Taradale, settlements include Te Haroto, Kotemaori, Putorino, Bayview, Puketapu, Bridge Pa, Clive, Haumoana, and Te Awanga, and small farming communities include Maraekakaho, Tutira, Te Pohue, Rissington, Patoka, Puketitiri, Sherenden, Kuripapango and Kereru (Fig. 7).

The highest points in the study area occur on the Kaweka Range (Kaweka J, 1724 m), and the Maungaharuru Range (Taraponui, 1308 m) (Enclosure 1). The Te Waka Range (highest point 1029 m) is also mostly over 900 m in elevation. The high ranges in western parts of Hawke's Bay are under snow for about 3 months during winter and experience exceptionally strong winds during much of the year and particularly the



Fig. 6: Location of cultural features referred to in the text of this report.



The Ohara Depression (Fig. 7) lies between the active Ruahine and Mohaka Faults. While Recent slip on these faults is dominated by strike-slip to oblique-slip displacement, long-term dip-slip displacement is responsible for the presence of the depression and the bounding Ruahine and Wakarara Ranges.

The Heretaunga Plains represent the flood plains of the Tutaekuri, Ngaruroro and Tukituki River systems, which enter Hawke Bay within several kilometres of each other (Fig. 7). The major population centres of Hawke's Bay are all located on the Heretaunga Plains.

The eastern hill country (Fig. 7) represents the highest parts of the accretionary wedge. It typically comprises an area of hills, often capped by Pliocene Te Aute limestone beds. The Maraetotora Plateau is the dominant landform of coastal central Hawke's Bay. It is an area with an average elevation of around 500 m a.s.l. and rising in places up to 600 m a.s.l. (Pettinga 2004). The plateau is capped by relatively flat-lying Early Pliocene limestone and calcareous sandstone (Lillie 1953; Pettinga 1980; Harmsen 1985; Beu 1995).

The fluvial terrace (Fig. 7) country comprises a series of gently dipping, relatively flat hills underlain by fluvial deposits derived from erosion of the adjacent Wakarara and Ruahine Ranges.

## **Lithostratigraphy (Late Miocene – Early Pleistocene)**

Lithostratigraphic schemes at different levels of comprehensiveness and for different parts of Hawke's Bay have been proposed in the past by McKay (1886a, b, 1887), Lillie (1953), Kingma (1971), Haywick (1990), Beu (1995), Field et al. (1997), Mazengarb and Speden (2000), and Lee and Begg (2002), amongst others. A systematic lithostratigraphy of the Neogene succession exposed in central parts of Hawke's Bay was published in a petroleum report by Bland et al. (2007). The objective of this section of the report is to provide an overview of the stratigraphy of the late Neogene succession in central parts of

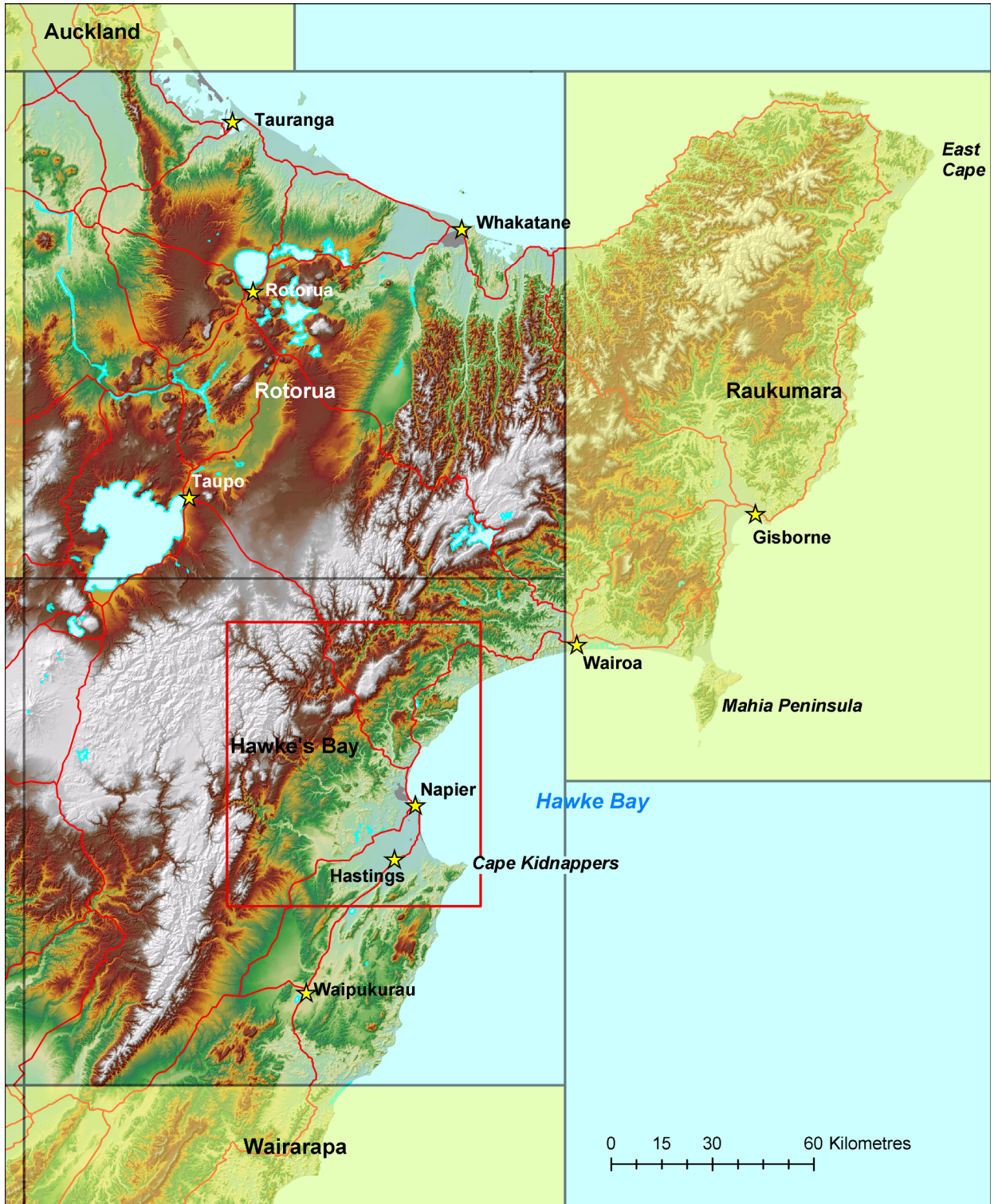
the forearc basin in Hawke's Bay (Enclosure 2: Stratigraphic correlations; Enclosure 3: Legend) to underpin the publication here of new geological maps produced at 1:50 000 (Enclosure 4, Sheets 1 - 6). Readers are referred to Bland et al. (2007) PR3724 for comprehensive description of all of the stratigraphic units appearing on these geological maps.

## **Geological maps**

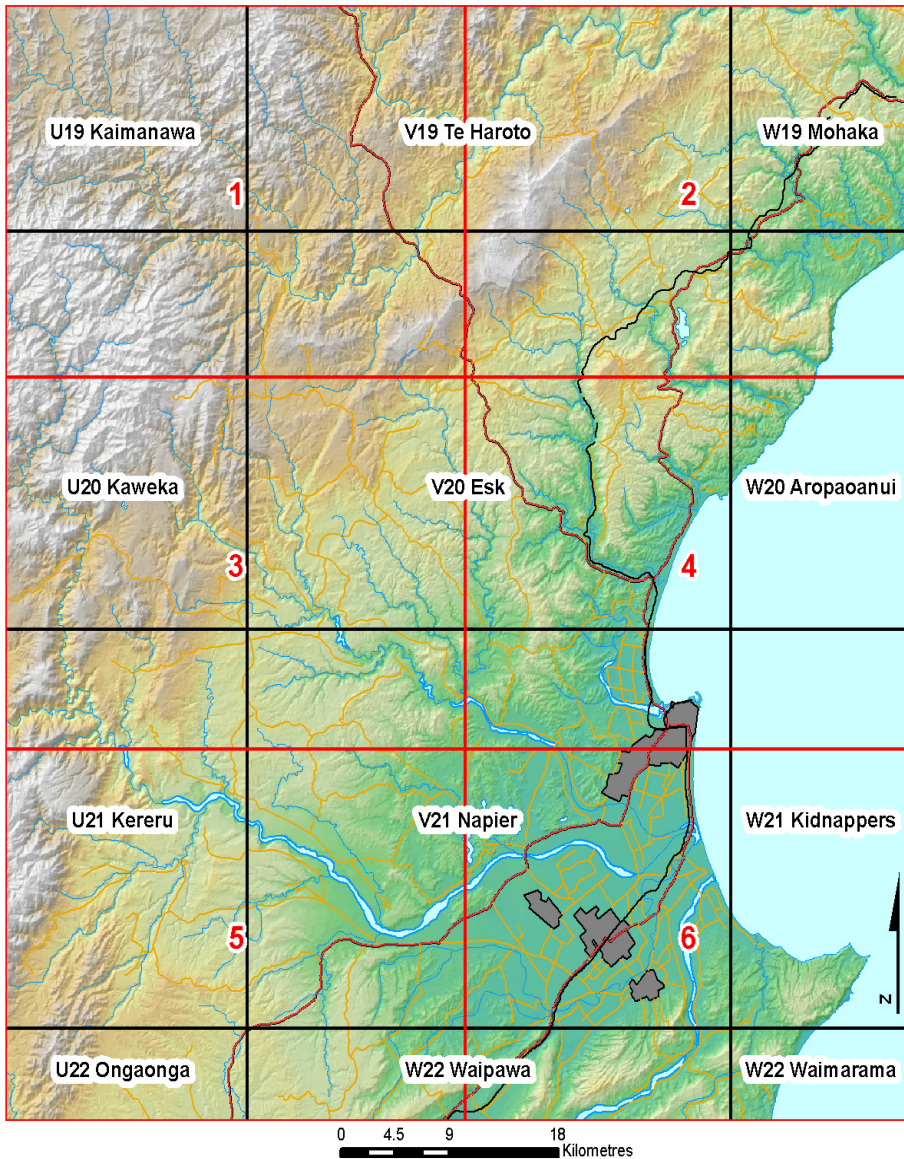
New geological maps (the extent of which are shown on Fig. 8) and the associated Legend builds on earlier investigations, including Lillie (1953), Kingma (1957, 1958a, b, 1962, 1971), Grindley (1960), Beu et al. (1980), Browne (1981), Haywick (1990), Haywick et al. (1991), Erdman and Kelsey (1992), Kelsey et al. (1993), Beu (1995), Bland (2001), Graafhuis (2001), Baggs (2004), Bland et al. (2004), Browne (2004a), and Dyer (2005).

The geological maps were developed using Geographic Information System (GIS) technology. A GIS database contains all relevant geological and topographical information, in effect a seamless digital coverage of the geology of the basin. The geological maps have been produced such that they can be printed at 1:50 000 scale, cut-up into six sheets (Fig. 9). Elements of the design of these maps sheets were derived from published GNS Science QMAP sheets, and Land Information New Zealand (LINZ) NZMS 260 series topographic map sheets.

The geological maps portray the surface distribution of geological units, faults and folds. The lowermost unit comprises basement of Mesozoic age. This is followed by Tolaga Group, Mangaheia Group, Kidnappers Group and sediments of Late Quaternary age. Units of the Tolaga Group are thick (tens to hundreds of metres), whereas there is a high degree of differentiation in the upper part of the Mangaheia Group, individual units typically having thicknesses of 40 - 70 m. Both of these group names have been adopted from Northern Hawke's Bay (Mazengarb et al. 1991; Mazengarb and Speden 2000). The three groups mark the development of the forearc basin. The Tolaga Group represents shelf to middle bathyal environments of deposition. The Mangaheia Group is mostly shelfal succession whereas the



*Fig. 8:* Digital elevation and hillshade relief models of eastern North Island showing the location of the map area and regions from which lithostratigraphic group names have been derived. Red box is the extent of Enclosure 4. Red lines are state highways. Black boxes are the boundaries of GNS Science QMAP sheets (sheet names indicated in larger font). Light yellow fill in these boxes indicate completed QMAP sheets at the time the work in this report was undertaken. The Raukumara QMAP Sheet (Mazengarb and Speden 2000) is where the Tolaga and Mangaheia Group names were derived. The Hawke's bay sheet is now published (Lee et al. 2011)



**Fig. 9:** Relationship between NZMS 260 series topographic map sheets and the geological map sheet cut-up in Enclosure 4 (this work) overlying a digital elevation model (DEM) and hillshade relief model. Black lines are NZMS topographic sheets and red boxes are map area geological map sheets. Black labels with white halos are NZMS topographic sheet names. Large red numbers are the geological map sheets in Enclosure 4.

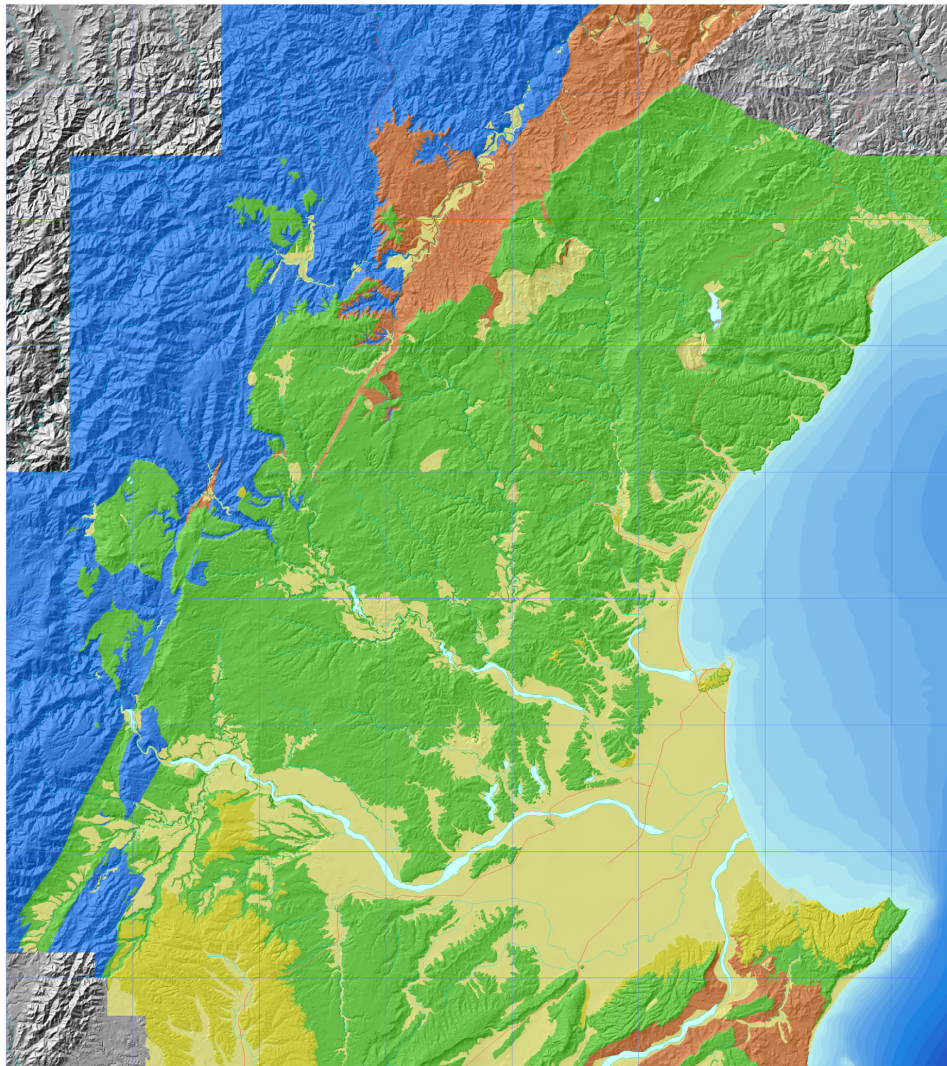
Kidnappers Group represents marginal-marine to non-marine succession.

Where possible, historical usage of unit names has been continued. However, in many parts of the basin different names have been applied in the past to what we have demonstrated are the same stratigraphic unit. Thus the lithostratigraphy, particularly in the Mangaheia Group, has been substantially simplified and many unit names have been abandoned. Geological cross-sections illustrating the sub-surface distribution of units and deformation are in Kamp & Bland (2014, PR4884).

### Mesozoic Basement

Mesozoic basement rocks underlie the axial ranges in western parts of the map area (Fig. 10).

Basement rocks also crop out in a few places west of Mohaka Fault near Patoka and in the Wakarara Range at Kereru. Grindley (1960) subdivided basement rocks into two stratigraphic units, Kaweka Greywacke and Urewera Greywacke. Kaweka Greywacke (Jurassic) was mapped west of Kaweka Fault and Urewera Greywacke (Jurassic) to the east. Basement rocks underlying the East Coast region are now assigned to the Torlesse composite terrane (e.g. Lee and Begg 2002). Mortimer (1995) subdivided the Torlesse of eastern North Island on the basis of differences in sandstone petrography, age, bulk chemical composition and the known and inferred extent of mélangé belts. Two major basement units have been mapped in the Hawke's Bay and Bay of Plenty areas, namely the Pahau Terrane and a Kaweka Terrane. Both are of Late Jurassic to



**Fig. 10:** Distribution of major rock units (groups) mapped in central Hawke's Bay superimposed on a hillshade relief model. Blue lines are 10 km NZMS 260 series gridlines. State Highways - red lines; significant water bodies - blue lines and light-blue polygons.

Early Cretaceous age. The boundary between the two has been placed along the Mohaka Fault (Lee et al. 2011).

Basement rocks are greywacke-dominated flysch, although argillite, chipwacke, conglomerate and minor chert facies are also present. Flysch facies are common in the Wakarara Range, Pakaututu, and Puketitiri areas where they are moderately to highly deformed. Basement rocks are highly shattered and fractured proximal to major faults, with varying degrees of folding common (Kamp and Bland 2014).

### **Tolaga Group**

Tolaga Group was named and defined by Mazengarb et al. (1991) for sedimentary rocks of Waitakian to Upper Tongaporutuan (Miocene) age in the Tauwhareparae area inland from Tolaga Bay (Raukumara Peninsula). In the Tolaga Bay area the beds accumulated in outer shelf to upper bathyal environments of deposition (Mazengarb et al. 1991, p. 33). Mazengarb and Speden (2000) extended the definition of Tolaga Group to include strata of Early to Late Miocene age in the area of the Raukumara QMAP sheet. In the construction of the new geological maps presented here the following reports were

useful: Cutten (1988); Moore (1987); Francis (1993); Grindley (1960); Scott et al. (1990a); and Cutten (1994). Tolaga Group strata crop out in the western parts of the map area from Waitere Station in the northwest to Kuripapango in the central southwest (Enclosure 4). As the strike of the group is oblique to the North Island Shear Belt, the Mohaka Fault at the southern end of Te Waka Range offsets the group. A small outlier of Tolaga Group (Te Ipuohape Sandstone Member, Waitere Formation) overlies basement at Opau and Waipunga Streams near Patoka. At these sites there is a spectacular angular unconformity with overlying Te Waka Formation (Late Pliocene, Mangaheia Group). An outlier of Tolaga Group is also preserved in a fault-bounded block in the Kuripapango area. This is the southernmost occurrence at the surface of Tolaga Group. The lithology and Tongaporutuan age of this outlier associates it with Waitere Formation.

Tolaga Group contains five formations and seven members (Figs 11 & 12) of Upper Otaian to Lower Opoitian (Early Miocene to Early Pliocene) age.

Whakamarino Formation (Otaian) is the lowermost formation in the Tolaga Group (Figs 12, 13A). It is overlain by Poamoko Formation of Clifdenian to Upper Lillburnian age and includes Ngatapa Sandstone Member, Arapaepae Alternating Member and Kingma Peak Mudstone Member (Fig. 12). Ngatapa Sandstone (Fig. 13B, C) is a moderately to well cemented, highly fossiliferous sandstone containing abundant shallow-water macrofossils (Fig. 13C).

Te Haroto Formation is mapped on Tarawera Station and in the Te Haroto area (Fig. 13D; Column Th-1). This unit comprises basal concretionary highly fossiliferous sandstone (Fig. 13D) that passes into siltstone to sandy siltstone (Fig. 13E, F). Te Haroto Formation unconformably overlies basement (Fig. 12). It is unconformably overlain by Tarawera Limestone Member (Fig. 13E; Column Wi-2), the basal unit of Waitere Formation.

Tarawera Limestone Member comprises several metres of moderately well cemented pebbly fossiliferous limestone to shelly conglomerate

rich in the gastropod *Zeacolpus*. In the Tarawera Station area Tarawera Member overlies Te Haroto Formation across an unconformable surface that displays decimetre-scale relief (e.g. V19/247220, Column Wi-2). Elsewhere the member may overlie basement, the Whakamarino Formation, or any member of the Poamoko Formation.

Tarawera Limestone Member passes conformably into Te Ipuohape Sandstone Member, a 300 m-thick interval of non-to slightly cemented, variably concretionary sandstone to sandy siltstone. Where Tarawera Limestone Member is absent, as in Crohane Forest, Te Ipuohape Sandstone Member unconformably overlies Torlesse basement. Te Ipuohape Sandstone Member passes conformably into Rakaita Siltstone Member via the Auroa Alternating Member, which comprises flysch facies.

Mokonui Sandstone is the stratigraphically highest formation in the Tolaga Group and in most sections conformably overlies Rakaita Siltstone (Waitere Formation). It is unconformably overlain by Titiokura Formation (Mangaheia Group). The base of the Mokonui Sandstone is well exposed on the Napier-Taupo Road (V20/278152, Column V20-38) and comprises a 0.5 m-thick well cemented concretionary bed followed by a 0.2 m-thick sandstone with abundant glauconite, small phosphate nodules and phosphatised macrofossils, including gastropods, bivalves, brachiopods, and shark teeth. A contact of this type has not been observed anywhere else in the map area. Cutten (1994) reported observing an angular unconformity between Rakaita Siltstone and Mokonui Sandstone at the Pohokura Road-Woodstock Road intersection on the Maungaharuru Range (V19/375276), but we find this contact to be conformable. Mokonui Sandstone is regressive shoreface sandstone in the map area.

Throughout the map area, the base of the Titiokura Formation comprises a 0.5 - 6 m-thick conglomerate that usually displays decimetre-scale relief on its lower contact (e.g. Column Tw-3). At Hell's Hole on the Te Waka Range up to 30 m of relief is present on this contact (V20/235127).

## Mangaheia Group

Mazengarb et al. (1991) introduced the name Mangaheia Group in a geological map of the Tauwhareparae area north of Gisborne, elevating its prior formation status (Steineke 1934). The Mangaheia Group in the type area comprises shallow-water sandstone and limestone facies, with some deeper water bathyal mudstone of Kapitean to at least Opoitian age (Mazengarb et al. 1991, p. 33). Mazengarb and Speden (2000) applied the name Mangaheia Group to the Wairoa and Mahia areas to include strata of similar lithology and age (Kapitean-Waipipian). In this usage Mangaheia Group included the youngest Cenozoic marine rocks present in their map area.

Pallentin and Nelson (2001) identified similarities between Mangaheia Group strata in the Wairoa-Mahia area and strata in the Maungaharuru-Willowflat-Putere Lakes area to the south. Bland (2001) and Graafhuis (2001) included rocks of this area in a Maungaharuru Group, elevating the name Maungaharuru Formation of Cutten (1994). Our investigations show continuity of limestone units from our map area to the Raukumara QMap sheet area, indicating that the two regions have linked stratigraphies. The Mangaheia Group in the map area includes rocks previously assigned to the Maungaharuru Subgroup (Bland et al. 2004), the Petane Group of Haywick et al. (1991) and Beu (1995), and the Napier, Poporangi, and Hawke's Bay groups of Beu (1995). Mangaheia Group has been adopted as a high level stratigraphic unit in the Hawke's Bay QMap Sheet (Lee et al. 2011)

The Mangaheia Group is widespread throughout the study area, cropping out in a NE-SW trending belt from Maungaharuru Range and Tangoio Block in the north to Ohara Depression and Matapiro Syncline in the south (Fig. 10).

Twenty-two formations and 40 members of Kapitean to Upper Nukumaruan (Late Miocene to Early Pleistocene) age have been mapped and characterised in the Mangaheia Group in this work. The group is dominated by shelfal lithofacies indicating that subsidence mostly matched sediment accumulation rates. Formation and

member boundaries are frequently also sequence or systems tract boundaries underlining their origin due to relative sea level change.

The stratigraphic nomenclature for the Mangaheia Group varies throughout the map area, as shown in Fig. 11. The most complete stratigraphic record occurs in the north (Waikare, Esk, and Mangaone river sections) where the strata have ages from Upper Opoitian to Upper Nukumaruan (Early Pliocene-Early Pleistocene). In other areas significant parts of the Mangaheia Group are absent due to non-deposition or erosion.

The following sections outline the broad stratigraphic trends in the Mangaheia Group for each of several geographic areas (Fig. 11). For detailed information about each stratigraphic unit readers are referred to Bland et al. (2007).

### *Waikare, Waikoau, Esk and Mangaone River areas (Maungaharuru Range, Te Waka Range, and Tangoio Block)*

In Maungaharuru and Te Waka Ranges, Titiokura Formation is the lowermost unit in the Mangaheia Group (Figs 14, 15, 16). The base of Titiokura Formation is diachronous from northeast to southwest, being Upper Opoitian in age in the northern Maungaharuru Range and Waipipian in age in the Te Waka Range (Bland et al. 2004). Local relief on the contact can be minimal or up to 30 m at Hell's Hole in Te Waka Range. The formation dramatically thickens to the northeast (Fig. 15). In the Maungaharuru Range Titiokura Formation is conformably overlain by Pohue Formation, a thick interval of sandstone that grades into siltstone to the northeast (Willowflat Road, V19/518369). In the Te Waka Range the Titiokura Formation is conformably overlain by sandstone of Te Waka Formation. Te Waka Formation comprises up to 80 m of fine sandstone with 20 m of interbedded concretionary sandstone and limestone (Fig. 16F). The thickest limestone bed at the type section is 8 m thick (V20/256129, Column V20-50). Laterally (down-dip) this sandstone passes into a 40 m-thick broadly channelized limestone (Fig. 18) in bluffs above Te Pohue village (V20/271106, Column V20-51).



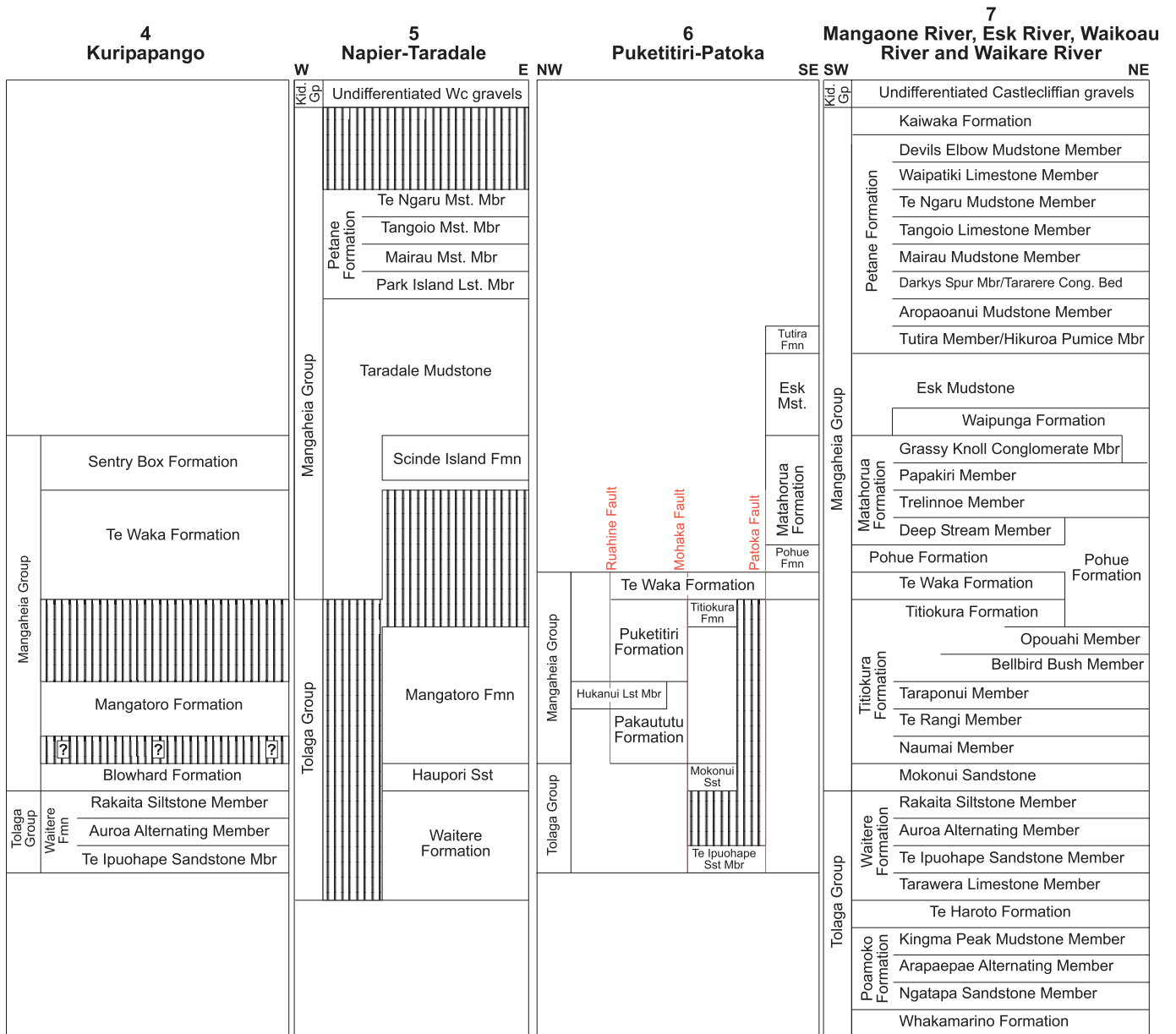
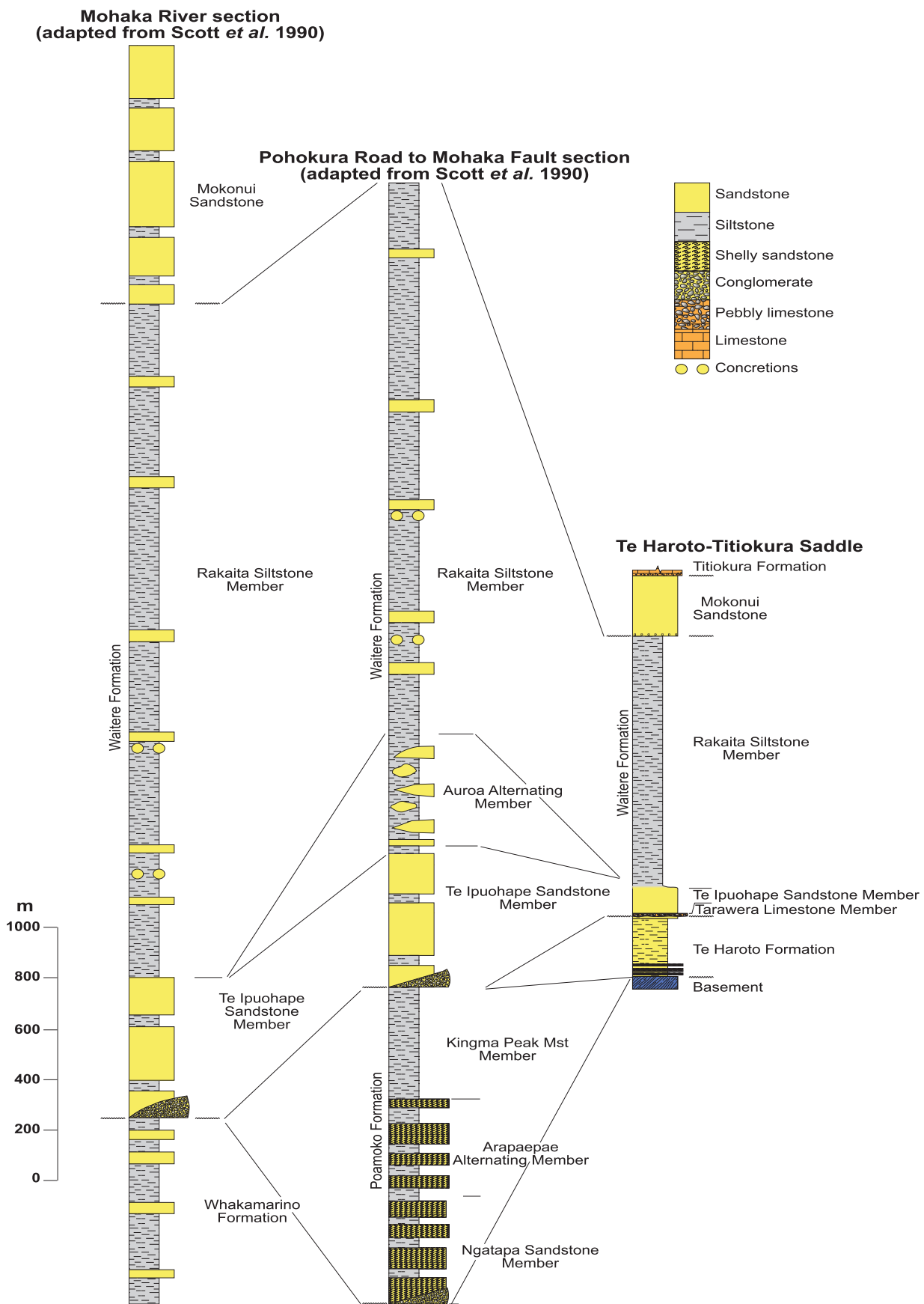
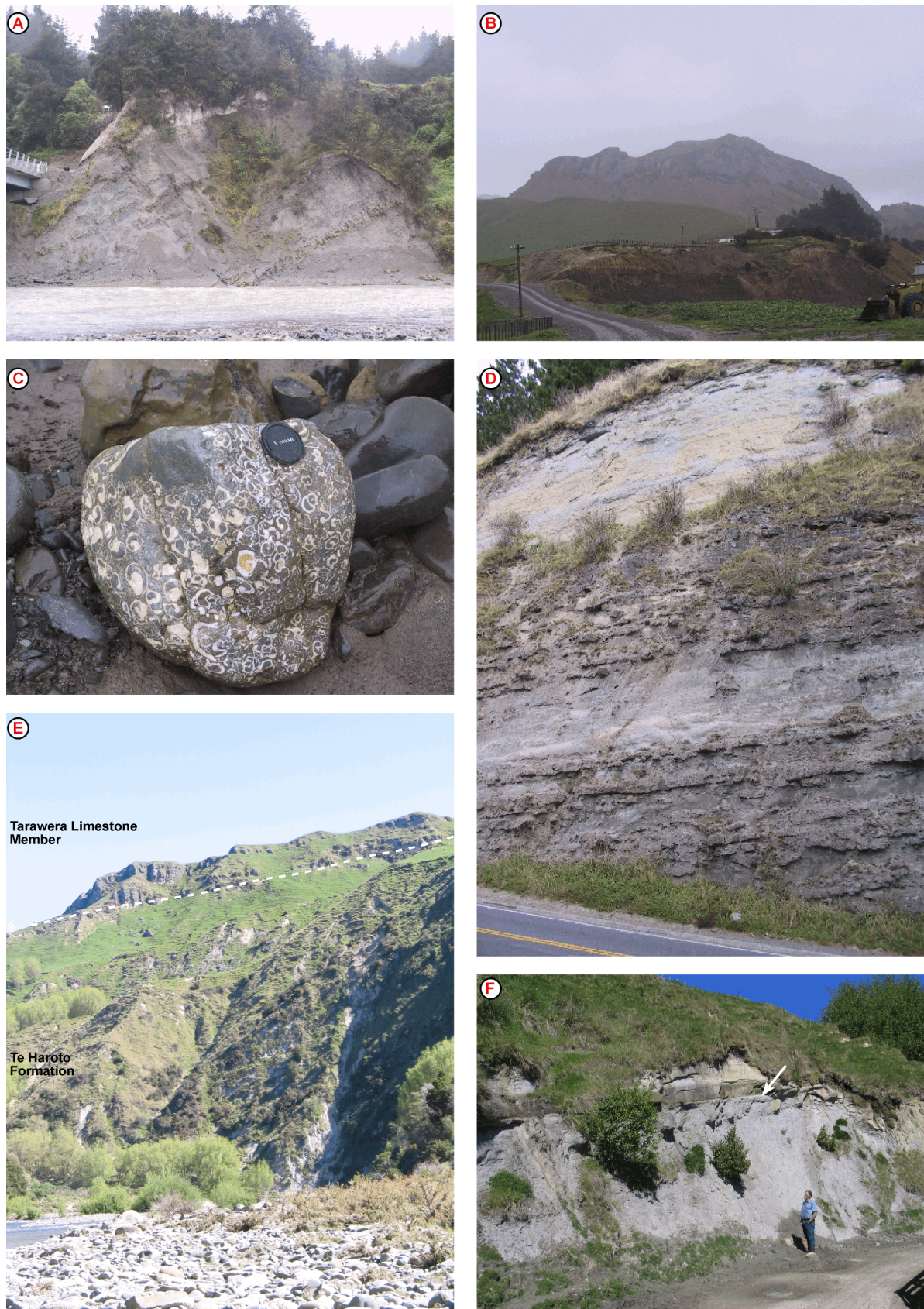


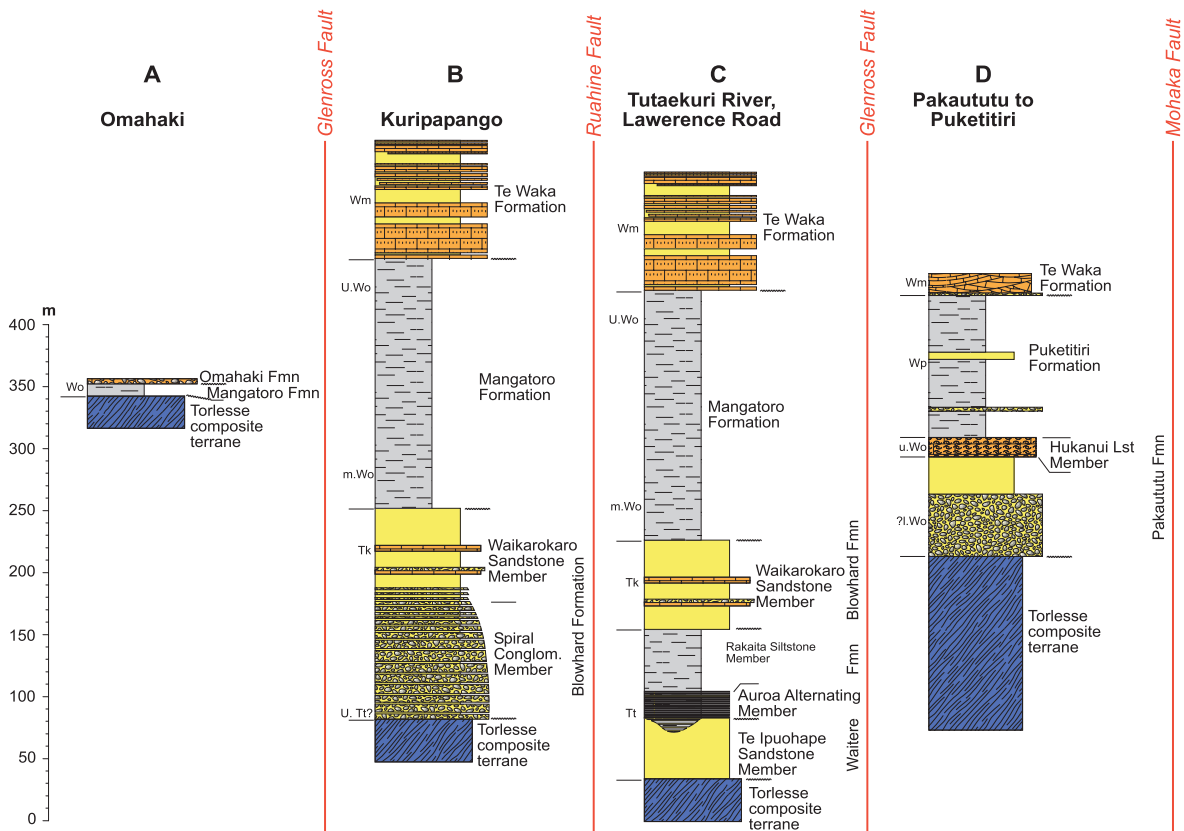
Fig. 11: (Two page spread) Summary of lithostratigraphic nomenclature for central Hawke's Bay.



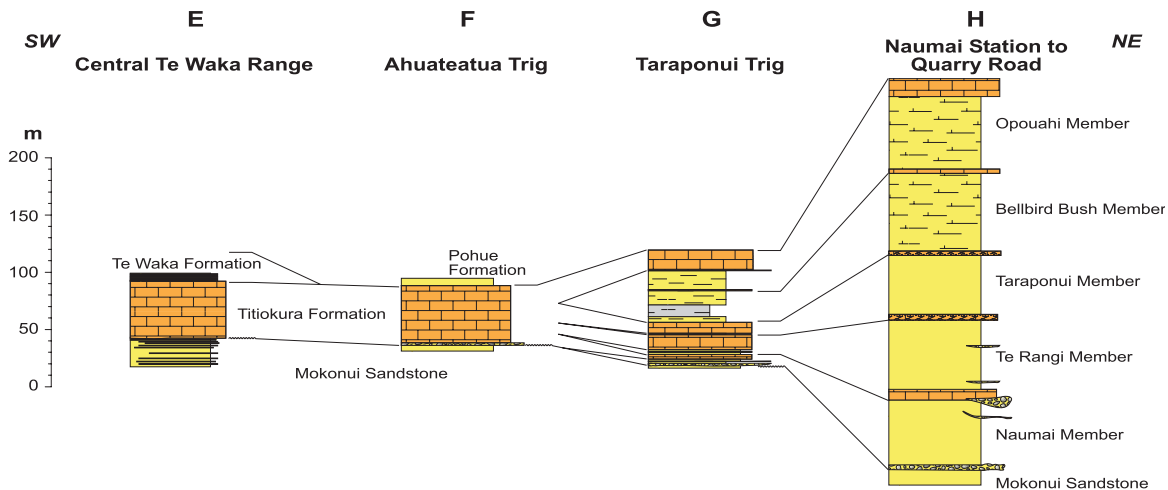
**Fig. 12:** Schematic stratigraphic columns illustrating the general stratigraphy of Tolaga Group rocks in the study area. Beds range in age from Otaian (Early Miocene, Whakamarino Formation) to Lower Opoitian (Early Pliocene, Mokonui Sandstone). Note how not all formations occur in all areas. The Waitere Formation and Mokonui Sandstone are the most widespread formations in the Tolaga Group.



**Fig. 13:** Field photographs of representative stratigraphic units within the Tolaga Group in western Hawke's Bay. A) Whakamarino Formation exposed in the Mohaka River, Waitere Station (V19/400356). B) Bluffs of Ngatapa Sandstone Member, Waitere Station (V19/400351 looking southwest). C) Highly fossiliferous boulder from Ngatapa Sandstone Member (Poamoko Formation), Waitere Station (V19/402354). D) Highly fossiliferous concretions within sandstone, cropping out on the Napier-Taupo Road near Te Haroto, basal Te Haroto Formation (V19/196265). E) Te Haroto Formation underlying Tarawera Limestone Member, Tarawera Station (V19/271246 looking south). F) Te Haroto Formation, Tarawera Station. White arrow denotes sharp contact between (lower) siltstone and (upper) sandstone parts of the formation (V19/246221).

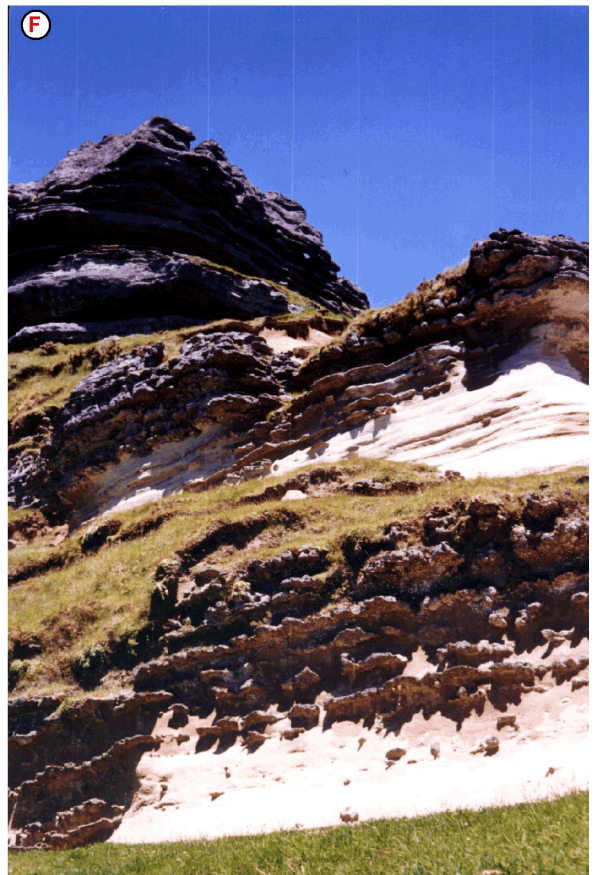


**Fig. 14:** Schematic stratigraphic columns (from southwest to northeast) of upper Tolaga Group and lower Mangaheia Group cropping out west of Mohaka Fault in the North Island Shear Belt. Note how the basal formation of the group varies between locations. This figure highlights how Te Waka Formation is the only unit present persistently across the shear belt. Column locations are shown on Fig. 11.



**Fig. 15:** Schematic distribution of the Titiokura Formation from the type section on Te Waka Range northeast to northern Maungaharuru Range. Note the formation thickening from southwest to northeast, reflecting the increase in thickness of siliciclastic interbeds.

**Fig. 16:** (facing page): Field photographs of typical lithofacies within lower formations of the Mangaheia Group. A) Basal contact of the Mangaheia Group in Kuripapango quarry with Torlesse basement overlain by Waikarokaro Sandstone Member (Blowhard Formation). Note the prominent relief on the contact (U20/047927). B) Waikarokaro Sandstone Member exposed in the lower slopes of Mount Miroroa, near Kuripapango. Person circled for scale (U20/008927). C) Hukanui Limestone Member (Pakaututu Formation), basal Mangaheia Group in Pakaututu and Puketitiri areas). The bivalves are *Tucetona laticostata* (V20/118113). D) Cross-bedded calcareous sandstone and minor limestone of Te Rangii Member, Titiokura Formation, cropping out on Naumai Station, Maungaharuru Range (V19/390273). E) Thick limestone facies of Opouahi Member, Titiokura Formation, cropping out beside Pohokura Road, Maungaharuru Range. Master weathering surfaces in the outcrop are arrowed (V19/410221). F) Concretionary sandstone and limestone beds of Te Waka Formation cropping out at the type section, northern end of Te Waka Range. Carbonate content increases up through this section (V20/252129).



The Te Waka Formation is conformably overlain by Pohue Formation, which in the Te Pohue area consists mainly of shelfal sandstone with occasional shellbeds. Matahorua Formation conformably overlies Pohue Formation and its base is marked by the first occurrence of greywacke conglomerate (Enclosure 2). Matahorua Formation is thickest in the Te Pohue and Patoka districts, particularly in Mangaone River and Glengarry Forest areas. 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, Trelinoe, and Papakiri members, Grassy Knoll).

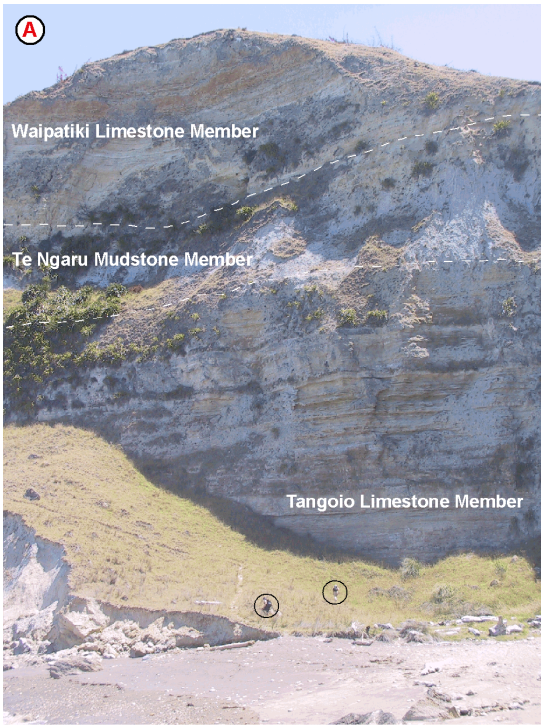
In the Waikare, Waikoau and Esk River areas, Waipunga Formation, an interval of shelfal sandstone and siltstone, overlies Matahorua Formation. It thins rapidly south of the Esk River section, and from Kaiwaka Stream southward Matahorua Formation is overlain by Esk Mudstone. Esk Mudstone (Fig. 17D) is in turn overlain by Petane Formation (redefined from Petane Group of Haywick et al. 1991), a unit that contains up to five cyclothems in the well-documented (e.g. Beu and Edwards 1984) Darkys Spur and Devils Elbow sections in the Tangoio Block (Columns V20-46 and V20-45, respectively). Members defined in Petane Formation in this area are Tutira Member (Fig. 17F), Hikuroa Pumice (Fig. 17E), Aropaoanui Mudstone, Darkys Spur Member, Tararere Conglomerate, Mairau Mudstone, Tangoio Limestone (Fig. 17A), Te Ngaru Mudstone (Fig. 17A), Waipatiki Limestone (Fig. 17A, B), and Devils Elbow Mudstone.

#### *Puketitiri, Patoka, and Rissington*

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; Fig. 16C) 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 (Column V19-22). The thick conglomerate interval thins rapidly away from Ruahine Fault. The Hukanui Limestone Member is distinctive for its abundant valves of the large dog cockle *Tucetona laticostata* (Fig. 16C), among other thick-shelled molluscs. The presence of small *Phialopecten marwicki* supports an Opoitian age for this unit. Puketitiri Formation overlies Pakaututu Formation, a 120 m-thick massive to slightly laminated siltstone to sandy siltstone of inferred Waipipian age that is punctuated by occasional 2-3 m-thick beds of greywacke conglomerate and breccia. The underlying contact with Pakaututu Formation is inferred to be conformable, but field exposure is poor. Puketitiri Formation is unconformably overlain by Te Waka Formation (Fig. 14D), with the contact exposed in several places including at Hukanui Station (V20/155114, Columns V20-62 and V20-63), Rocky Hill Station (V20/139059, Column V20-67) and near Puketitiri (V20/173068, Columns V20-69 and V20-70). On Hukanui Station Te Waka Formation at its base has a 0.5 m-thick very coarse-grained and poorly sorted breccia with common large *Crassostrea ingens* oyster shells. While the basal breccia is similar to that at the base of Titiokura Formation, the presence of the Mangapanian index pectinid *Phialopecten thomsoni* in the limestone above the basal breccia confirms that this unit is Te Waka Formation. Te Waka Formation in the Puketitiri area is characterised by the presence of giant-scale cross-beds up to 20 m across. Near the axial ranges to the west of Mohaka Fault, Te Waka Formation comprises highly fossiliferous pebbly limestone that unconformably overlies Torlesse basement.

**Fig. 17:** (*facing page*): Field photographs of typical lithologies in upper parts of Mangaheia Group. A) Sea-cliff outcrop of Tangoio Limestone, Te Ngaru Mudstone and Waipatiki Limestone Members of Petane Formation. People circled for scale. Photo location W20/521229, south of Waipatiki Beach. B) Herringbone, trough and tabular cross-stratification in Waipatiki Limestone Member, Okawa Stream, V21/250781. C) Highly fossiliferous greywacke conglomerate, Flag Range Conglomerate Member (Petane Formation), Kikowhero Stream, V21/192726. D) Esk Mudstone with interbedded tephra layers (arrowed). Lower reaches of Mangaone River above Rissington, V21/305897. E) Cross-stratified tephric interval in Hikuroa Pumice Member (Petane Formation), cropping out near Beattie Road, V20/360968. F) Trough cross-stratified greywacke conglomerate, Tutira Member (Petane Formation) near Glengarry Road, Tiokapu Station, V20/136987.



East of Mohaka Fault in the Puketitiri and Patoka areas the basal formation of the Mangaheia Group is usually Te Waka Formation, which unconformably overlies Mokonui Sandstone, although it may overlie Torlesse basement or Te Ipuohape Sandstone Member (Opau Stream, Fig. 18H; V20/207049, Column V20-73a; Katz 1973). In one locality near Patoka at “The Gorges” (Fig. 18I; V20/186011, Column V20-86 and V20-87) inferred Titiokura Formation crops out and although the base is not exposed it probably unconformably overlies Mokonui Sandstone and is conformably overlain by a cyclothemic interval of Te Waka Formation (Fig. 18I). Te Waka Formation is the oldest Mangaheia Group unit to crop out either side of Ruahine and Mohaka faults (Fig. 14, 18), and therefore has important implications for determining the displacement history of faults in the North Island Shear Belt (Kamp and Bland 2014).

Te Waka Formation crops out in a nearly continuous NE-SW belt from the type section at Te Waka Trig through Patoka, Mangatutu Station, Kuripapango, and Glenross Range to Awapai Station. In the Kuripapango area Te Waka Formation unconformably overlies Torlesse basement, Blowhard Formation (Kapitean) or Mangatoro Formation (Upper Opoitian) (Fig. 14). No Waipipian beds are present in this area. On Awapai Station the formation interfingers with Puketitiri Formation (Mangapanian) and eventually passes laterally into it (Fig. 18A). In most cases, however, Te Waka Formation is conformably overlain by Pohue Formation, which is then conformably overlain by Matahorua Formation. Matahorua Formation is in turn overlain by Esk Mudstone (Fig. 17D). In the Patoka, Puketitiri, and Rissington areas no Tutira Member, Aropoanui Mudstone, or Darkys Spur Member is present, having passed laterally into Esk Mudstone. Esk Mudstone grades into Mairau Mudstone, which is in turn overlain by Flag Range Conglomerate Member (Fig. 17C), a lateral but coarser-grained and shallower water equivalent of Tangoio Limestone Member (Fig. 17A). Flag Range Limestone Member is overlain by Te Ngaru Mudstone and then Waipatiki Limestone Member (Fig. 17B), Devils Elbow Mudstone Member and a variably fossiliferous

coarse-grained conglomerate that marks the base of Kaiwaka Formation.

#### *Napier-Taradale*

The stratigraphy in the Napier-Taradale area (Fig. 11) is related to the stratigraphy in the Rissington area and Tangoio Block. The oldest exposed unit is Scinde Island Formation of Lower Nukumaruan age (Beu 1995). The stratigraphy below Scinde Island Formation was determined from Hukarere-1 Drillhole (Westech Energy New Zealand Ltd 2001, PR 2656). Scinde Island Formation is a lens within Taradale Mudstone, which has a minimum thickness of 860 m. Taradale Mudstone is of Waipipian to mid-Nukumaruan age and unconformably overlies Eocene succession in Taradale-1 drillhole (Darley and Kirby 1969). In outcrop, Taradale Mudstone is gradationally overlain by Park Island Limestone Member (correlative of Darkys Spur Member), Mairau Mudstone Member, Tangoio Limestone Member and a thin erosional remnant of Te Ngaru Mudstone Member.

#### *Sherenden-Matapiro*

The succession cropping out in the Sherenden-Matapiro area (Fig. 19) is transitional stratigraphically between Tangoio Block and the Ohara Depression. The oldest unit exposed is the Te Waka Formation (Mangapanian) on the upthrown (south-eastern) side of Mohaka Fault near Willowford and Waiwhare. Te Waka Formation is overlain by, and interfingers with Pohue Formation, which is much thinner here than in the Maungaharuru Range and Te Pohue areas. Pohue Formation is in turn overlain by Grassy Knoll Conglomerate Member, the only member of the Matahorua Formation to occur in this area, and then by Esk Mudstone and Okauawa Formation.

Okauawa Formation contains two conglomerate-siltstone-sandstone cycles (Kikowhero and Whakamarumaruru members) and is overlain by Mairau Mudstone Member, and in turn by Flag Range Conglomerate Member, both of Petane Formation. The Flag Range Conglomerate Member (Fig. 17C) dips below the surface in the Matapiro area on the western limb of Matapiro Syncline and resurfaces near Omahu and

Puketapu as Tangoio Limestone Member. These correlatives are overlain by Te Ngaru Mudstone Member, Waipatiki Limestone Member (Fig. 17A), Devils Elbow Mudstone Member, Kaiwaka Formation and Puketautahi Limestone Member (a thick, well cemented limestone).

#### *Kuripapango*

The stratigraphy for the succession in the Kuripapango area is summarised in Fig. 20. The Blowhard Formation of Kapitean age (Fig. 16A, B) unconformably overlies basement, or more rarely Rakaita Siltstone Member (Waitere Formation, Tolaga Group). The Spiral Conglomerate and Waikarokaro Members were mapped by Browne (2004a) (Fig. 14B). Spiral Conglomerate Member comprises >100 m of poorly sorted greywacke conglomerate with thinner fine to medium sandstone and rare siltstone beds (Browne 2003). It is overlain by Waikarokaro Sandstone Member (Fig. 16B), which comprises up to 70 m of very well sorted sandstone with conglomerate and limestone interbeds. Blowhard Formation is inferred to be unconformably overlain by Mangatoro Formation of Upper Opoitian age (Browne 2004a). Mangatoro Formation consists of mudstone and is probably in part a correlative of Puketitiri Formation (Fig. 11). The exact thickness of the unit is unknown as the base is not exposed, being in fault contact with older units. It is estimated from geological cross-sections to be at least 200 m thick.

Te Waka Formation (Mangapanian age) comprises a thick limestone unit overlying basement on Glenross Range and on Sandy Ridge, as well as Waikarokaro Sandstone Member, Mangatoro Formation (Mount Kohinga) and Puketitiri Formation (central and southern Glenross Range). This limestone passes up into a succession of at least three cyclothems consisting of mixed siliciclastic-bioclastic sandstone and shellhash sandy limestone (Fig. 18B, C). These cyclic units form the crest of The Lizard (U20/034911, Column U21-107) and the summit of the Glenross Range (U20/040903, Column U21-105). The youngest Mangaheia Group unit in the Kuripapango area is Sentry Box Formation of lowermost Nukumaruan age (Beu et al. 1977; Beu 1995), which comprises fine sandstone to

gravelly limestone and fossiliferous sandstone with abundant concretions and carbonaceous debris (Browne 2003). It crops out at Gentle Annie (U20/953954) in a fault-bounded sliver on Mount Kohinga (U20/981948) and along the summit ridge of Mount Miroroa below the Miroroa Thrust (U20/006923) (Browne 1986, 2004). At Gentle Annie it rests on basement (Browne 2004a, b) and on Mount Miroroa unconformably over Waikarokaro Sandstone Member (Fig. 18B). The Lower Nukumaruan age of Sentry Box Formation derived from the occurrence of *Zygochlamys patagonica delicatula* and *Jacquinotia edwardsii* (Beu et al. 1977, 1981; Beu 1995; Browne 2004a). In the Ngaruroro River around Kuripapango, deposits of Holocene Taupo Pumice are common.

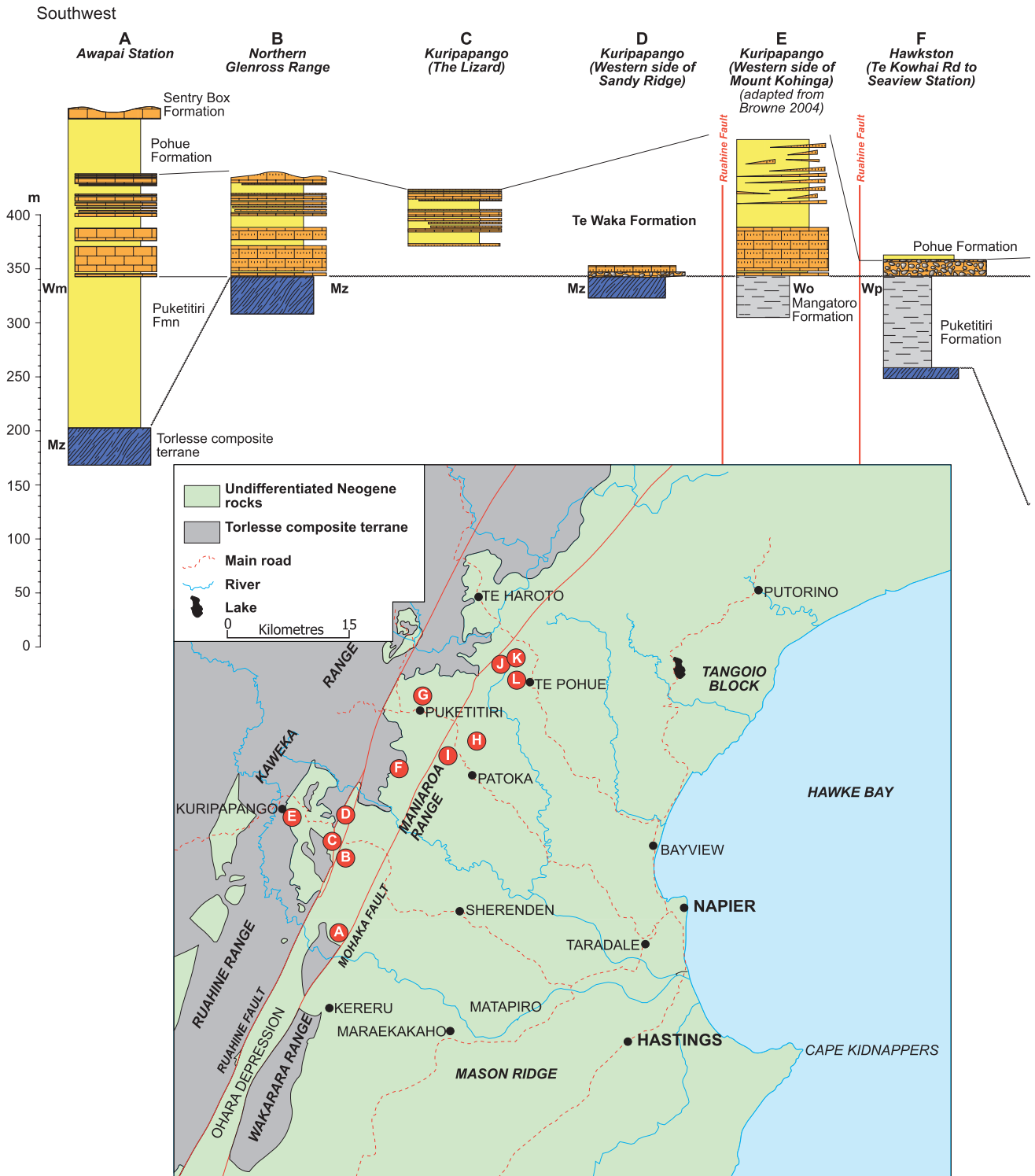
#### *Omahaki Depression*

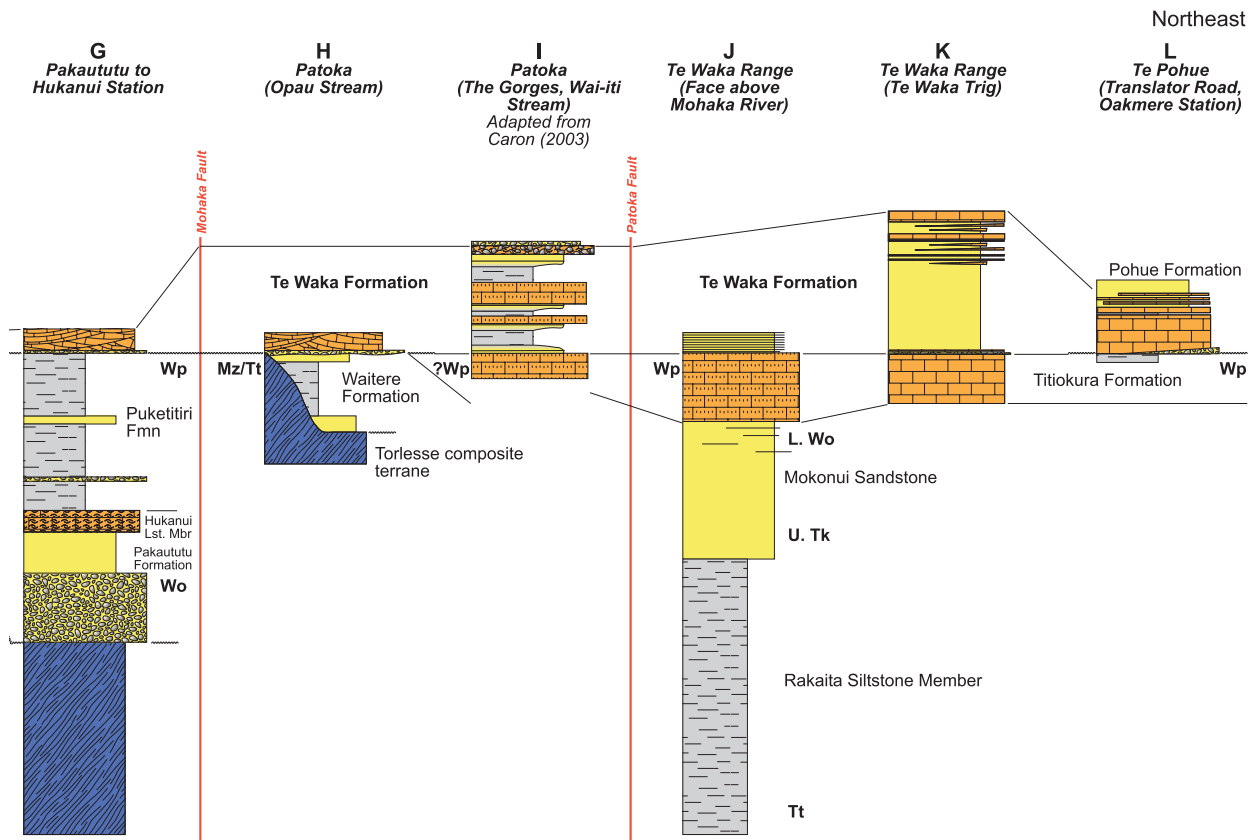
The Omahaki Depression contains a limited thickness of Early Pliocene (Opoitian) succession over basement (Fig. 14A). Approximately 20 m of Mangatoro Formation overlies basement and is in turn unconformably overlain by conglomeratic limestone of the Omahaki Formation (Column U21-106).

#### *Ohara Depression-Kereru*

Limestone beds are developed around the margins of Ohara Depression on the flanks of the Ruahine and Wakarara Ranges recording the positions of contemporary paleohighs away from high siliciclastic sediment input ((Fig. 21, 22A, B, 23). The stratigraphic record in the Ohara Depression also contains greywacke conglomerate and thick mudstone and sandstone beds. The stratigraphic nomenclature of Erdman and Kelsey (1992) has been emended based on correlations from our mapping (Figs 22 & 23).

Puketitiri Formation (Figs 22 & 23) is at least 100 m thick and comprises massive sandy mudstone with interbedded sandstone, pebbly limestone and conglomerate (Kelsey et al. 1993). This formation occurs in Kereru-1 east of Mohaka Fault (Johnston and Francis 1996). In southern and central Ohara Depression Puketitiri Formation is conformably overlain by Sentry Box Formation (e.g. U21/934665, Column U21-121) whereas it has an unconformable contact in





**Fig. 18:** (two page spread): Schematic stratigraphic columns illustrating the distribution of Te Waka Formation from the type section on Te Waka Range (northeast) to Awapai Station (southwest). Note how Te Waka Formation overlies a number of stratigraphic levels from Mesozoic basement to “middle” Pliocene limestone.



### Ohara Depression-Kereru stratigraphic history

Beu <i>et al.</i> (1980)	Erdman and Kelsey (1992)	Beu (1995)		This Study (Bland 2006)
	Salisbury gravel lithofacies	Salisbury gravel lithofacies	Kidnappers Group	Salisbury Gravel
	Poutaki Pumiceous Fmn	Poutaki Formation		Poutaki Formation
	Okauawa Formation	Okauawa Formation	Mangaheia Group	Whakamarumaru Mbr Okauawa Formation
				Kikowhero Member
Kereru Limestone	Kereru Limestone	Kereru Limestone		Kereru Formation
	Ohara Mudstone	Ohara Mudstone		Esk Mudstone
	Mount Mary Limestone	Mount Mary Limestone		Mount Mary Pebbly Lst
	Sentry Box Limestone	Sentry Box Lst.    Seconds Ridge Conglom. Mbr		Sentry Box Formation    Seconds Ridge Cong. Mbr
	Kaumatua Formation	Kaumatua Formation	Puketitiri Formation	

**Fig. 21:** Summary of the history of stratigraphic nomenclature of the Ohara Depression from Beu *et al.* (1980) to the present work. The diagram illustrates the stratigraphic nomenclature adopted, mainly from Erdman and Kelsey (1992).

On Mount Mary (the type section, U21/981948) the formation crops out as a single pebbly unit, although laterally towards the centre of the Ohara Depression there are three interbedded conglomerate and limestone beds separated by mudstone, reflecting interfingering with Esk Mudstone. Mount Mary Pebbly Limestone occupies a similar stratigraphic position to that of Sentry Box Formation but lacks its diagnostic Lower Nukumaru taxa. This could be because it is slightly younger than Sentry Box Formation or the paleoenvironments in those places were unsuitable (too shallow).

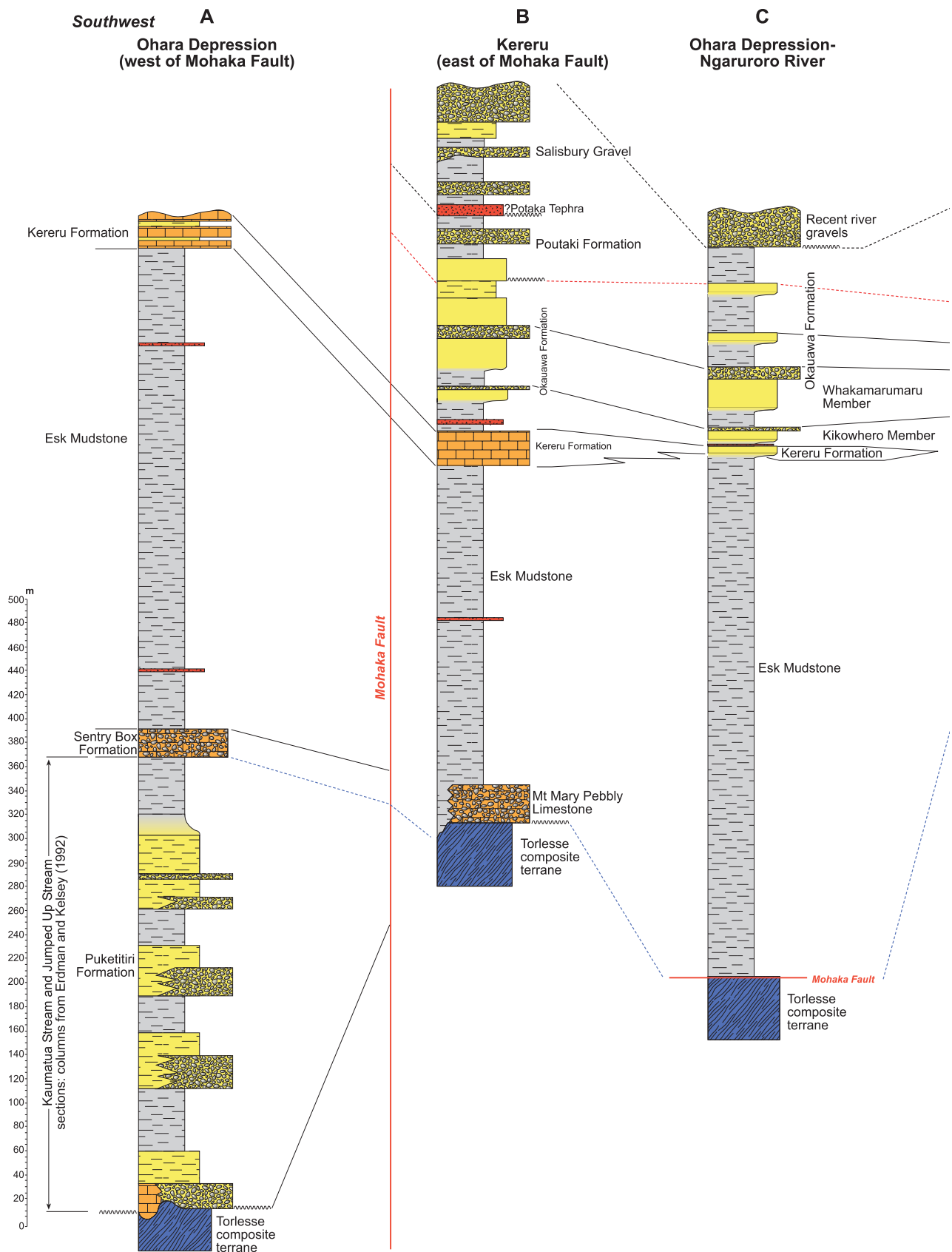
Esk Mudstone in Ohara Depression is up to 412 m thick (Erdman and Kelsey 1992) conformably overlain by Kereru Formation, three pebbly limestone and sandy oyster beds forming strongly dipping ridges along much of the eastern edge of Wakarara Range and on several small platforms and ledges west of Mohaka Fault on the western edge of Wakarara Range (e.g. U21/968684). On the eastern side of Wakarara Range, Kereru Formation dips up to 90° due to displacement on Wakarara Fault (Enclosure 4) (Kamp and Bland 2014).

Kereru Formation is conformably overlain by Okauawa Formation east of Mohaka Fault (Erdman and Kelsey 1992) where it is at least 150 m thick comprising highly fossiliferous sandstone, siltstone, and variably fossiliferous conglomerate. The two principal conglomerate beds (upper parts of the Kikowhero and Whakamarumaru

members, respectively) are restricted to lower parts of the formation and crop out from Ohara Stream (Columns U21-114, -115 and -116) to Ngaruroro River and to the Sherenden-Flag Range area. These conglomerates are inferred to be lateral correlatives of Tutira Member and Tararere Conglomerate (Darkys Spur Member) in Petane Formation (Fig. 21). Okauawa Formation is overlain by Poutaki Formation, which consists of 60 - 100 m of coarse pumiceous sandstone, pumice granule to cobble conglomerate, siliciclastic sandstone and mudstone. The lower contact of Poutaki Formation is defined as the first occurrence of 1-1.5 m-thick pumiceous sandstone at the top of Okauawa Formation (Beu 1995). Poutaki Formation is unconformably overlain by Salisbury Gravel of Kidnappers Group. The Salisbury Gravel is the only mapping unit differentiated in the Kidnappers Group in the map area. Salisbury Gravel comprises thick conglomerate and pumiceous sandstone beds overlying 6 m-thick Kidnappers Ignimbrite (Wilson *et al.* 1995).

#### *Mason Ridge-Maraekakaho*

The stratigraphy of this area has been documented by Dyer (2005) and her scheme is adopted here (Fig. 24). The lowest unit cropping out in the wider Mason Ridge area is Raukawa Mudstone, which is in turn overlain by Te Onepu Limestone, the classic “Te Aute Limestone” facies. The Te Onepu Limestone is overlain by Makaretu Mudstone, which in turn is overlain by Mason Ridge Formation, a cyclothem succession of



**Fig. 22 :** (two page spread): Summary stratigraphic columns for the Nukumaruan succession in central parts of Hawke's Bay from Ohara Depression (southwest) to the Esk River catchment (northwest, Tangoio Block). Geological mapping in this work has confidently correlated rocks from the Tangoio area to the Ohara Depression, resulting in a unified Nukumaruan lithostratigraphy for this part of central Hawke's Bay. The blue broken line marks the Mangapanian-Nukumaruan boundary and the red line the Pliocene-Pleistocene boundary.

**D**  
Sherenden-Flag Range

Southeast

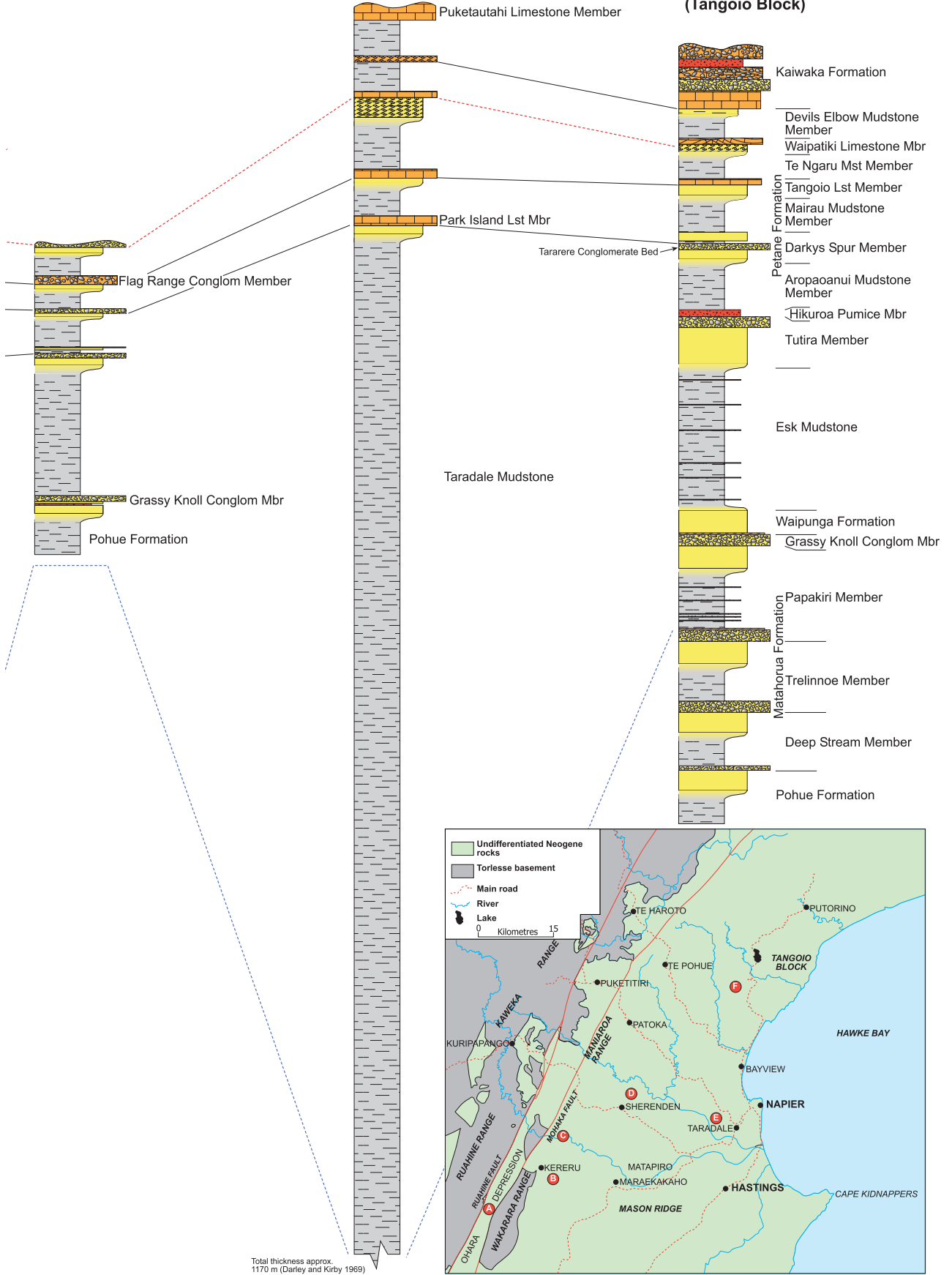
**E**

Matapiro-Taradale

**F**

Esk Catchment  
(Tangoio Block)

Northeast



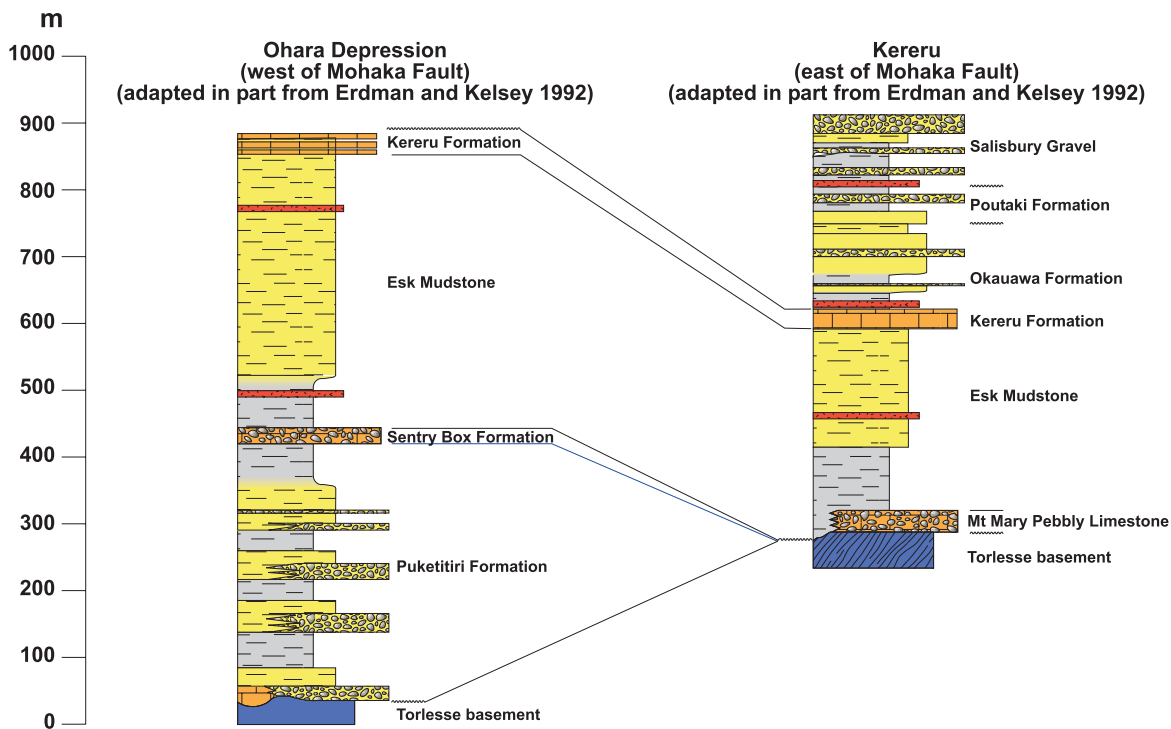


Fig. 23: Correlation of Mangapanian to Castlecliffian units cropping out in Ohara Depression with those east of the Mohaka Fault. Within the Ohara Depression Kereru Formation (Mangaheia Group) is the stratigraphically highest unit. East of Mohaka Fault the Salisbury Gravel (Castlecliffian, Kidnappers Group) forms the stratigraphically highest beds.

limestone and mudstone. The basal member of Mason Ridge Formation is Mahana Limestone Member, which gradationally overlies Makaretu Mudstone. This unit is overlain by Maharakeke Mudstone Member, Torran Limestone Member, Whakapirau Mudstone Member and Pakihirua Limestone Member. Mason Ridge Formation is unconformably overlain by Okauawa Formation, Poutaki Formation and in places a thin veneer of Kidnappers Group conglomerate.

*Maraetotara Plateau-Raukawa Range*

Formations in this south-eastern map area accumulated on a growing accretionary wedge (Caron et al. 2004a). They are eastern equivalents to the Pliocene succession cropping out along the western margin of the forearc basin area. The basal unit is the “lower to middle” Mangatoro Formation, which is in turn overlain by the Upper Opoitian Kairakau Limestone (equivalent to lowermost parts of Titokura Formation,

**Mason Ridge-Maraekakaho stratigraphic history**

		Kingma (1971)	Beu et al. (1980)	Harmsen (1985)	Kelsey et al. (1993)	
Kid. Gp		Salisbury gravels			Salisbury gravel lithofacies	
		Roys Hill Siltstone			Poutaki Pumiceous Formation	
	Roys Hill Siltstone	Upper Scinde Island pebbly limestone		Petane Limestone	Petane Formation	Okauawa Formation
		Waitio pumiceous siltstone				Mason Ridge limestones and interbedded mudstone
		Lower Scinde Island limestone				
		Roys Hill Siltstone				Makaretu Mudstone
	Te Aute Limestone	Te Aute Limestone	Te Aute Limestone	Te Onepu Limestone	Te Onepu Limestone	

Fig. 24: (two page spread): Summary of historical stratigraphic nomenclature for the Mason Ridge and Maraekakaho areas by Kingma (1971), Beu et al. (1980), Harmsen (1985), Kelsey et al. (1993), Beu (1995), Dyer (2005), and this work.

and Hukanui Limestone Member). Kairakau Limestone is overlain by a succession comprising Mokopeka Sandstone, Tuki Bell limestone (informal, Caron 2002), Mokopeka Sandstone, (mid-Waipipian) Awapapa Limestone (which forms Te Mata Peak), Pukekura Calcarenite, (upper Waipipian) Rotookiwa Limestone, Raukawa Mudstone, (Mangapanian) Te Onepu Limestone, Makaretu Mudstone, Mahanga Mudstone, (lower Nukumaruan) Pakipaki Limestone, and Mason Ridge Formation. For more detailed descriptions of these units readers are referred to Beu (1995), Caron (2002), and Caron et al. (2004a).

### Kidnappers Group

Kidnappers Group is the stratigraphically highest lithostratigraphic group in the basin. It records the development of terrestrial environments across the earlier forearc basin seaway during the Middle to Late Pleistocene (Early Quaternary). Kidnappers Group incorporates all rocks of Castlecliffian age in the on land part of the forearc basin (Fig. 10).

Kidnappers Group is named after Cape Kidnappers at the southern end of Hawke Bay. Kingma (1971) formalised the long usage of the name “Kidnappers” in reference to the well-exposed section between Clifton and Black Reef. The name itself was introduced by Hill (1887) who referred to the strata in this area as the Kidnapper Beds or Kidnappers Section, and in 1891 as the Kidnapper Conglomerates and the Kidnapper Pumice and Conglomerate Beds. The definition of Kingma (1971) is retained, and

extended to incorporate the prominent thick Castlecliffian gravel beds cropping out adjacent to the northern Ruahine and Wakarara Ranges (Erdman and Kelsey 1992).

The Kidnappers Group mostly crops out in two widely separated areas: the Salisbury Terraces at Kereru in the west, and the Maraetotara Plateau and Cape Kidnappers area in the east (Fig. 10). Isolated thin veneers of Castlecliffian conglomerate crop out in central parts of the basin, particularly above Nukumaruan strata. The Salisbury Gravel dips at a few degrees to the east and is relatively undeformed by faulting and folding. Beds cropping out in the Kidnappers section dip northwest, forming the eastern limb of the Napier Syncline and lie to the west of the Kidnappers Anticline. Beds in the Kidnappers section are commonly offset by normal faults having throws of less than 10 m. Remnants of Kidnappers Group conglomerate occur at significant elevations particularly on Mason Ridge and in the Dartmoor area. Kidnappers Group also crops out sporadically in coastal areas, such as at Scinde Island, Petane Corner, and Whirinaki Bluff.

Two hundred and thirty-two metres of Kidnappers Group were intercepted in Whakatu-1 drillhole where it unconformably overlies Taradale Mudstone of Mangapanian age (Ozolins and Francis 2000). Although no Kidnappers Group was intercepted in Taradale-1 (Darley and Kirby 1969), steeply dipping beds of undifferentiated Kidnappers Group crop out nearby at Waiohiki in a small outlier beside Tutaekuri River.

**Mason Ridge-Maraekakaho stratigraphic history**

Beu (1995)		Dyer (2005)		This Study (Bland 2006)	
Poporangi Group	Salisbury gravel lithofacies	Kid. Gp	Salisbury Gravel Formation	Kid. Gp	Salisbury Gravel
	Poutaki Pumiceous Formation		Poutaki Pumiceous Formation		Poutaki Formation
	Okauawa Formation		Okauawa Formation		Okauawa Formation
Petane Group		Petane Group	Pakihirua Limestone Member	Mangaheia Group	Pakihirua Limestone Member
			Whakapirau Mudstone Member		Whakapirau Mudstone Member
	Park Island Limestone		Torran Limestone Member		Torran Limestone Member
Napier Gp		Mason Ridge Formation	Maharakeke Mudstone Member	Mason Ridge Formation	Maharakeke Mudstone Member
	Scinde Island Limestone		Mahana Limestone Member		Mahana Limestone Member
Hawke's Bay Gp		Hawke's Bay Gp	Makaretu Mudstone	Hawke's Bay Gp	Makaretu Mudstone
	Te Onepu Limestone		Te Onepu Limestone		Te Onepu Limestone

Kidnappers Group unconformably overlies Mangaheia Group in high-level terraces east of Kereru and Wakarara Range. The lower part of Salisbury Gravel is marked by pumice deposits including Kidnappers Ignimbrite (Kamp 1990; Wilson et al. 1995). The Salisbury Gravel is therefore of comparable age to Kidnappers Group rocks of non- and marginal-marine origin cropping out in the coastal section between Clifton and Black Reef.

The Kidnappers Group in the coastal section has been subdivided into several formations (Kingma 1971; Kamp 1978) but in this work has been mapped as undifferentiated Kidnappers Group. In the Kidnappers section the basal formation of the Kidnappers Group is the Maraetotara Sandstone, which unconformably overlies Late Pliocene (Waipipian) Black Reef Calcareous Sandstone.

### Late Quaternary Deposits

Late Quaternary deposits are thickest and best developed beneath the Heretaunga Plains (Fig. 10). Late Quaternary deposits are 75 m thick in Whakatu-1 (Ozolins and Francis 2000) and 45

m thick in Taradale-1 (Darley and Kirby 1969). Hukarere-1 drilled through approximately 8 m of port reclamation fill and no Late Quaternary sediments (Westech Energy New Zealand Ltd 2001). Extensive terraces in the Ohara Depression and Kereru areas are underlain by greywacke gravel. Flights of well-developed terraces are also present in the lower reaches of Waikare River.

### Discussion

Mangaheia Group stratigraphy: Beu's (1995) scheme versus this report.

Beu (1995) attempted to reconcile the stratigraphic relationships between limestone units of Late Miocene-Early Pleistocene age throughout eastern North Island. In the process he formally defined many new groups, formations and members. His work was underpinned by a new Late Neogene pectinid (*Phialopecten*, *Mesopeplum*, *Sectipecten*) biostratigraphy. In the course of the mapping undertaken here it has become necessary to emend Beu's 1995 stratigraphy (Fig. 25). This is mainly the case for the Nukumaruan part of the basin record.

Beu (1995) Sherenden-Otamauri				This Study (Bland 2006) Sherenden-Otamauri				
SW		NE		SW		NE		
Kidnappers Group	Salisbury gravel lithofacies			Kidnappers Group	Salisbury Gravel			
	Puketautahi Limestone				Petane Formation	Kaiwaka Formation Puketautahi Limestone Member		
	Moteo Mudstone					Devils Elbow Mudstone Member		
	Matapiro Limestone					Waipatiki Limestone Member		
	Waitio Mudstone				Te Ngaru Mudstone Member			
	Sherenden Cong. Mbr		Flag Range Lst		Tangoio Lst	Flag Range Conglom Mbr		Tangoio Lst Mbr
	Crownthorpe Mudstone				Mairau Mst		Mairau Mst Mbr	
					Park Island Lst		Park Island Lst Mbr	
	Waiwhare Lst/Willowford Mst				Taradale Mudstone		Okauawa Formation	Whakamarumaruru Member
								Kikowhero Member
Esk Mudstone								
			Matahorua Fmn		Grassy Knoll Conglom Mbr			
			Pohue Formation					
			Te Waka Formation					
				Mangaheia Group				
				Petane Formation				

Fig. 25: (two page spread) Comparison of the stratigraphy of Beu (1995) and this work for the Sherenden-Otamauri and Tangoio Block areas.

All formations defined and mapped by Beu (1995) have now been incorporated in the Mangaheia Group as defined in this report in Bland et al. (2007) and in Lee et al. (2011).. This has reduced the number of lithostratigraphic groups in this interval from four to one, reasons and justification being given in Bland et al. (2007). Beu (1995) renamed the Blowhard Formation of Browne (1981, 1986) as Owhakao Limestone, but we return to the use of the name Blowhard Formation. The lower limestone-bearing part of the Maungaharuru Formation of Beu (1995) is now mapped as Titiokura Formation and five members have been formally defined within it (Naumai, Te Rangi, Taraponui, Bellbird Bush, and Opouahi members) (Bland et al. 2004). Middle and upper parts of Maungaharuru Formation are now mapped as Pohue and Matahorua formations.

Beu (1995) defined new nomenclature for much of the Nukumaruan stratigraphy in the forearc basin. This stratigraphy included previously defined formations (mostly from Beu and Edwards (1984) and Haywick et al. (1991)) together with new groups, formations,

and members, as summarised in Fig. 25. This arose from the development of stratigraphic subdivisions in each of three parts of central Hawke's Bay. Our geological mapping has demonstrated stratigraphic continuity across this part of the basin. The Poporangi, Napier, and Petane Groups of Beu (1995) are now all included in the Mangaheia Group. We also suggest that his Hawke's Bay Group be incorporated within the Mangaheia Group. The Tutira, Aropaoanui, Darkys Spur, Mairau, Tangoio, Te Ngaru, Waipatiki, and Devils Elbow formations of Beu's Petane Group are now all mapped as members of the Petane Formation. The Waipunga, Esk and Kaiwaka Formations, also part of Beu's Petane Group, are retained as discrete formations within Mangaheia Group. Flag Range Limestone and Sherenden Conglomerate Member of Beu (1995) are mapped together as Flag Range Conglomerate Member (Petane Formation). Puketautahi Limestone of Beu (1995) is included here as a member of Kaiwaka Formation (Puketautahi Limestone Member). Whanawhana Limestone and Seconds Ridge conglomerate (informal) are mapped as Sentry Box Formation, with Seconds Ridge Conglomerate now defined as a member. Crownthorpe Mudstone is included in both the Okauawa Formation and Mairau Mudstone Member. Ohara Mudstone is now incorporated into Esk Mudstone. Matapiro Limestone is now mapped as part of Waipatiki Limestone Member. Willowford Mudstone is included in Esk Mudstone. Park Island Limestone is emended to Park Island Limestone Member and included as part of Petane Formation. Waitio Mudstone is now mapped as Te Ngaru Mudstone Member and Moteo Mudstone is now mapped as Devils Elbow Mudstone Member. Readers are referred to Bland et al. (2007) for systematic description of the basin stratigraphy and the rationale for it.

Beu (1995) Tangoio Block/Esk-Waikoau Rivers		This study (Bland 2006) Tangoio Block/Esk-Waikoau Rivers	
SW	NE	SW	NE
Undifferentiated Castlecliffian gravels		Undifferentiated Castlecliffian gravels	
Petane Group	Kaiwaka Formation	Petane Formation	Kaiwaka Formation
	Devils Elbow Mudstone		Devils Elbow Mudstone Member
	Waipatiki Limestone		Waipatiki Limestone Member
	Te Ngaru Mudstone		Te Ngaru Mudstone Member
	Tangoio Limestone		Tangoio Limestone Member
	Mairau Mudstone		Mairau Mudstone Member
	Darkys Spur Formation		Tararere Conglomerate Bed Darkys Spur Member
	Aropaoanui Mudstone		Aropaoanui Mudstone Member
	Tutira Conglomerate		Tutira Member Hikuroa Pumice Member
	Esk Mudstone		Esk Mudstone
Waipunga Sandstone	Waipunga Formation		
Maungaharuru Formation		Mangaheia Group	Grassy Knoll Conglomerate Mbr
			Papakiri Member
			Trelinnoe Member
			Deep Stream Member
	Pohue Formation	Pohue Formation	
Te Waka Formation	Te Waka Formation		
Titiokura Limestone	Titiokura Formation		
	Opouahi Member		
	Bellbird Bush Member		
	Taraponui Member		
	Te Rangi Member		
	Naumai Member		
Maungaharuru Formation			

# Biostratigraphy

## Introduction

Here we report the biostratigraphy for the forearc basin fill. This is chiefly based on molluscan macrofossil biostratigraphy, supported by microfossil biostratigraphy. In New Zealand the Miocene to Recent succession is subdivided into several local stages (Fig. 26) defined on the basis of foraminiferal and molluscan bioevents (Fig. 27).

Because no one section contains all age datums identified within the basin, lithostratigraphy and geological mapping provide the correlation framework for the integrated biostratigraphy and chronology. This is aided by the occurrence of cyclothem in the Pliocene part of the succession. A limitation of using molluscan bio-events for determining a relative stratigraphy in the study area is facies control on their distribution. Most biostratigraphically useful bio-events occur within shellbeds in cyclothem strata. However, they are separated by mudstone and sandstone facies that form most of the thickness of the cyclothem. This means that the location of a stage boundary can be imprecise, as the bio-events that mark a particular stage boundary may not have occurred while accumulation of the shellbed took place. A consequence is that stage boundaries could either be placed at the base of a shellbed containing the first occurrence of a new species or at the top of the preceding shellbed where the last occurrence of an older species occurs. Both the Waipipian-Mangapanian (Wp-Wm) and Mangapanian-Nukumaruan (Wm-Wn) Stage boundaries in the basin are placed at the base of shellbeds containing the lowest occurrence (L.O.) of new species (e.g. L.O. of *Phialopecten thomsoni* and *Phialopecten triphooki/Zygochlamys patagonica delicatula*, respectively) and the dual occurrence of lowest and highest (H.O.) occurrences together in the same shellbed (e.g. H.O. *Crassostrea ingens* and *P. thomsoni* with

L.O. *P. triphooki* and *Z. delicatula* in the Sentry Box Formation).

While the latest Pliocene-Pleistocene (uppermost Mangapanian-Nukumaruan) part of the basin fill is richly fossiliferous with numerous bio-events, the remainder of the succession is generally sparsely fossiliferous, and bio-events useful for identifying stages in other New Zealand sedimentary basins (e.g. L.O. *P. marwicki*, H.O. *Sectipecten grangei*, *S. wollastoni*) are unsuitable

Ma	International				New Zealand		
	Era	Period	Epoch	Age	Series	Stage	
0	Cenozoic	Neogene	Pleistocene	Late	Quaternary	Haweran	
0.5				Middle		0.34	
1				Early		Castlecliffian	
1.5							
2			Pliocene	Early	1.81	Wanganui	Nukumaruan
2.5					Gelasian		2.40
3					Late		Mangapanian
3.5					Piacenzian		3.00
4							Waipipian
4.5			Miocene	Tortonian	7.12	Taranaki	Upper
5							Zanclean
5.5		5.28					Upper
6	Messinian						Kapitean
6.5					Lower		
7						6.50	
7.5							Upper
8							
8.5							Tongaporutuan
9							
9.5							
10					Lower		
10.5							
11			Late		Southland	10.92	
			Middle	Serravallian		Waiauian	

Fig. 26: Summary of part of the Neogene geological time scale showing the relationship between International Ages and the New Zealand Stage Classification scheme. Adapted from Cooper (2004).



in central Hawke's Bay. An example of this is *P. marwicki*, which is not known in rocks older than Upper Opoitian in eastern North Island, even though it is important in defining the base of the Opoitian in Wanganui and Taranaki basins.

### Assignment of biostratigraphic stages

This section describes bio-events that aid the identification of relative age of stratigraphic units in the basin fill. Only the Tongaporutuan to Nukumaruan part of the basin fill is described here. For biostratigraphic events in pre-Tongaporutuan stratigraphy in the basin, readers are referred to Scott et al. (1990a), Cutten (1994) and Field et al. (1997). Rapidly evolving macrofauna such as the pectinid genus *Phialopecten*, and gastropoda such as *Austrofusus*, *Pelicaria*, and *Struthiolaria* have proven to be very useful taxa for determining Pliocene-Pleistocene New Zealand biostratigraphic stages in the map area.

A limited number of microfossil samples have been collected and analysed in this investigation,

supplemented by microfossil records from both paleontological reports and the New Zealand Fossil Record Electronic Database (FRED). Microfossil analysis of the Tolaga Group north of SH5 (Napier-Taupo Road) was undertaken by Scott et al. (1990a). Microfossil samples collected during this study have come from siltstone exposed in the outcrop belt from Puketitiri to Omahaki.

### Tongaporutuan

Most rocks of Tongaporutuan age in the study area are of deep-water (outer shelf to bathyal) origin and age diagnostic macrofossils are not common. The Tongaporutuan Stage in the study area is identified by the presence of *Sectipecten grangei*. It has only been observed and collected from shallow-water concretionary sandstone beds in the Tutaekuri River in Kaweka Forest Park (Fig. 28).

Microfossil samples U20/f150 and V20/f442 (Bland 2006 Appendix V) collected in this investigation contain typical planktic and benthic



**Fig. 28:** *Sectipecten grangei* (circled), a Tongaporutuan index scallop in a strongly cemented highly fossiliferous shellbed in Te Ipuohape Sandstone Member, Tutaekuri River, Kaweka Forest Park. The bulk of the fossiliferous material in this shellbed comprises shellhash and *Crepidula radiata* and *Patro undatus* of no biostratigraphic value.

foraminifera, including *Globoconella miotumida*, *Neogloboquadrina pachyderma*, *Bolivinita* c.f. *plioobliqua* and *B. pohana*. The relative abundance of *Globigerinoides* and the apparent absence of *Globoquadrina dehiscens* in V20/f442 led analyst M. Crundwell to suggest an age of 8.8 - 8.0 Ma for this sample (Upper Tongaporutuan). These results complement those of Scott et al. (1990a) - the presence of *Bolivinita pohana* in poorly preserved, low-diversity foraminiferal assemblages near the base of Te Ipuohape Sandstone Member and of *Globoquadrina dehiscens* in higher levels, indicates Lower Tongaporutuan accumulation for this unit (Cutten 1994). The absence of *Globoquadrina dehiscens* in middle and upper parts of Waitere Formation supports accumulation after the Lower Tongaporutuan (Cutten 1994).

### Kapitean

Kapitean rocks are generally non to sparsely fossiliferous in the basin. The Waikarokaro Sandstone Member (Blowhard Formation) in the Kuripapango area does contain a sparse molluscan macrofauna including the Kapitean index *Sectipecten wollastoni* and also *Maorimactra chrydaea*.

A paucity of foraminiferal events near the base of the Kapitean Stage reflects a period of relatively stable oceanic conditions and evolutionary stasis amongst planktic foraminifera (Crundwell et al. 2004). No microfossil analysis has been undertaken on strata of Kapitean age during this investigation. Scott et al. (1990a) and Cutten (1994) undertook microfossil analysis of the Tolaga Group succession in the north of the study area where they sampled the upper beds of Waitere Formation (upper part of Rakaita Siltstone Member) and the lower part of Mokonui Sandstone. Sample V19/f80 from upper parts of Rakaita Siltstone Member near The Organs was assigned a Kapitean age based on the presence of *Bolivinita pliozea* and *Globoconella miotumida* (Scott et al. 1990a). Collections V19/f46, f47 and f113 from Mokonui Sandstone in the Mohaka River section contained poorly preserved variants of *G. miotumida*. Some individuals with elevated umbilical faces (axial orientation) resembled *conomiozea* morphotypes, and other small

compact specimens resembled *G. puncticulata sphericomiozea*. A peripheral keel was observed on adequately preserved specimens and this population was assigned to *G. miotumida*. These three collections were dated as Lower Kapitean, possibly adjacent to the Upper Kapitean datum marked by the entry of *G. puncticulata sphericomiozea* (Scott et al. 1990a).

### Opoitian

Opoitian strata are widespread along western margins of the study area from Maungaharuru Range to Omahaki Depression. They are identified mostly by the presence of *Phialopecten marwicki*, often in association with *Struthiolaria (Callusaria)* spp. (Table 1). The first occurrence of *Phialopecten marwicki* in the study area is inferred to have occurred in the Upper Opoitian (Early Pliocene) (Beu 1995) and is recorded in the base of Te Rangi Member of Titiokura Formation at Naumai Station, and in Hukanui Limestone Member (Pakaututu Formation) near Puketitiri and Ripia River. It is also inferred to have appeared coevally in the Upper Opoitian Kairakau Limestone along the eastern margin of Hawke's Bay (Beu, 1995).

Microfossils identified in samples collected from Opoitian rocks in the study area include planktic foraminifera *Globoconella puncticulata*, *G. pliozea* and *Truncorotalia juanai* (U21f87). A collection (V19/f160) from about 100 m above the base of Mokonui Sandstone on Pohokura Road but still within it, included *Truncorotalia crassiformis*, *Globoconella pliozea*, and *G. puncticulata* and was assigned a Lower Opoitian age (Scott et al. 1990; Cutten 1994).

### Waipipian

The Waipipian succession in the forearc basin typically comprises mudstone facies punctuated by occasional limestone beds. The most useful macrofossil for identification of the Waipipian Stage in the forearc basin is *P. marwicki*. Although this species first evolved in the Lower Opoitian (in Wanganui-Taranaki Basins), it progressively became larger through time, with Waipipian forms typically bigger than Opoitian forms. Opoitian *P. marwicki* are rarely over 100 mm high while Waipipian *P. marwicki* are larger

**Table 1:** Molluscan taxa most useful for identifying the Opoitian Stage in the map area. The list is adapted from Beu and Maxwell (1990), Beu (1995) and Beu et al. (2004). \* Denotes taxa of highest biostratigraphic utility and reliability.

Restricted	Last occurrence	First occurrence
<i>Towaipecten ongleyi</i> *	<i>Myrtea</i>	<i>Phialopecten marwicki</i> *
<i>Zethalia russelli</i> *	<i>Struthiolaria (Callusaria)</i> *	<i>Mesopeplum (Borehamia)</i>
<i>Pellicaria parva</i> *	<i>Struthiolaria (Callusaria) obesa</i> *	<i>crawfordi</i>
	<i>Xenostrobus altijugatus</i>	<i>Zethalia</i> *
		<i>Perna</i>
		<i>Lutraria solida</i> *
		<i>Dosinia (Phacosama)</i>
		<i>Pellicaria canaliculata</i> *
		<i>Polinices waipipiensis</i>
		<i>Semicassis (Kahua) fibrata</i>
		<i>Austrofusus pagoda</i>
		<i>Maoricolpus roseus</i>
		<i>Zeacolpus vittatus</i>
		<i>Pteromyrtea dispar</i>

than 115 mm high (Beu 1995, p. 64). Typical Waipipian forms of *P. marwicki* have only been collected from the top of the Titiokura Formation along the crest of Te Waka Range.

The H.O. of *Phialopecten marwicki*, marking the end of the Waipipian, has been identified along the crest of Te Waka Range near Te Waka Trig. *Phialopecten marwicki* is common in the uppermost beds of Titiokura Formation in this area.

Microfossil samples collected from rocks of Waipipian age in the study area are constrained by the presence of several planktic foraminifera, including *Truncorotalia crassaformis*, *Globocornella inflata*, *G. inflata triangula*, *G. puncticulata*, *G. subconomiozea* and *G. pliozea* (Bland 2006 Appendix V).

### Mangapanian

The base of the Mangapanian Stage is defined by the L.O. of *Phialopecten thomsoni*. It is common and widespread in limestone facies of Te Waka Formation, particularly from the Patoka area southwest to Awapai Station. It has not, however, been observed in the shallow-water sandstone facies of Pohue Formation.

No successful microfossil analysis of Mangapanian rocks has been undertaken in this investigation. One microfossil sample (V20/f444) was collected from Puketitiri Formation near Puketitiri, but it contained no calcareous material (M. Crundwell, pers. comm. 2004).

### Nukumaruan

Fossiliferous shellbeds are common in the Nukumaruan succession within the forearc basin and have contributed to development of a molluscan biostratigraphy (Beu et al. 2004). Nukumaruan strata are very widespread in central and southern Hawke's Bay and significant effort has been put into analysis of their molluscan macrofossil content in this investigation.

The most important and distinctive faunal characteristic of the Nukumaruan is the basal Nukumaruan migration to central New Zealand of a cold water fauna characterised by the subantarctic scallop *Zygochlamys patagonica delicatula* and the large subantarctic crab *Jacquiniotia edwarssi* (Table 2). During this migration, plankto-trophic larvae of *Zygochlamys* were transported passively in ocean currents at least 600 km north of the present northern limit of common specimens off Otago Peninsula (Orpin et al. 1998; Beu et al. 2004). Fossils of *Zygochlamys* are abundant as far north as Dannevirke and are variably present in the map area (Beu et al. 1981; Beu 1995).

The base of the Nukumaruan Stage is well defined across the study area as it is marked by both the extinction and appearance of many molluscan macrofauna. Genera first recorded in New Zealand in the Nukumaruan include *Semicassis (sensu stricto)* and *Paracomitas*, as well as common species such as *Mesopeplum convexum*, *Austrovenus crassitesta*, *Xymene expansus*, *Zethalia zelandica*, *Austrofusus*

**Table 2:** Taxa most useful for identifying the Nukumaruan Stage in the study area. The list is adapted from Beu and Maxwell (1990), Beu (1995) and Beu et al. (2004). \* Denotes taxa of highest biostratigraphic utility and reliability. l.n., lowermost Nukumaruan; u.n., Upper Nukumaruan.

Restricted	Last occurrence	First occurrence
<i>Phialopecten triphooki</i> * <sup>l.n.</sup>	<i>Crassostrea ingens</i> * <sup>l.n.</sup>	<i>Pratulium pulchellum</i>
<i>Towaipecten mariae</i> *	<i>Patro undatus</i> *	<i>Bassina parva</i> *
<i>Zygochlamys patagonica</i>		<i>Pellicaria</i> n.sp. aff. <i>zelandiae</i>
<i>delicatula</i> * <sup>l.n.</sup>		<i>Alcithoe brevis</i>
? <i>Mesopeplum</i> ( <i>M.</i> ) <i>convexum</i>		<i>Alcithoe arabica</i>
<i>Struthiolaria frazeri</i>		<i>Aoteadrillia alpha</i> *
<i>Glycymeris</i> (s.s.) <i>shrimptoni</i> *		<i>Austrofusus glans</i>
<i>Spisula</i> ( <i>Spisuloma</i> ) <i>crassitesta</i> *		<i>Xymene expansus</i>
<i>Pellicaria acuminata</i> *		<i>Zethalia zelandica</i> *
<i>Pellicaria convexa</i> * <sup>u.n.</sup>		<i>Austrovenus crassitesta</i>
<i>Pellicaria rugosa</i> *		
<i>Aoteadrillia finlayi</i>		
<i>Cominella kereruensis</i>		
<i>Austrofusus taitae</i>		

*taitae* and *Aeneator marshalli*. Nukumaruan restricted species include *Glycymeris shrimptoni*, *Towaipecten mariae*, *Phialopecten triphooki*, *Struthiolaria frazeri*, *Pellicaria acuminata*, *Pellicaria convexa* and *Paracomitas protransenna* (Table 3). The many common mollusca becoming extinct at the end of the Nukumaruan include the genera *Glycymeris* (*sensu stricto*), *Towaipecten*, *Patro*, *Neopanis*, *Pteromyrtea*, *Spisula* (*Spisularia*), *Lutraria*, *Dosinia* (*Raina*), *Eumarcia* (*Eumarcia*), *Eumarcia* (*Atamarcia*) and *Taxonia* and the species *Marama murdochi*.

Of particular note in Nukumaruan biostratigraphy are the numerous species that either became extinct or first appeared during the Nukumaruan. A characteristic basal Nukumaruan molluscan fauna includes *Zygochlamys delicatula*, *Phialopecten triphooki*, and the last recorded examples of *Crassostrea ingens*, *Maoricardium spatiosum* and *Phialopecten thomsoni*. A distinctive Upper Nukumaruan molluscan macrofauna was reported by Beu (1995) and include *Amalda mucronota forma erica*, *Aeneator comptus*, *Glaphyrina plicata* and *Cominella excoriata*.

The L.O. of three pectinid species are important in determining the position of the Mangapanian-Nukumaruan boundary; namely *Phialopecten triphooki*, *Z. delicatula* and *Towaipecten mariae*. Other notable first occurrences in the Nukumaruan include *Glycymeris shrimptoni*, *Dosinia* (*Austrodosinia*) *anus*, *Pellicaria convexa*, *Austrofusus taitae*, *Struthiolaria frazeri* and

*Zethalia zelandica*. Although reported as having been in New Zealand waters since the Tongaporutuan (Late Miocene) (Beu and Maxwell 1990), the extant small pectinid *Mesopeplum convexum* appears as a very common component in coarse shellbed facies from the basal parts of the Nukumaruan, whereas it appears to be absent in rocks older than Nukumaruan. McIntyre (2002) and Beu et al. (2004) regarded the appearance of *M. convexum* as an indicator of the Nukumaruan.

The first occurrences of *Phialopecten triphooki* and *Towaipecten mariae* have been accurately located at several sites through the map area. In the Esk River section the L.O. of *P. triphooki* (V20/371084, Column V20-48) is underlain by sandstone containing the H.O. of the Mangapanian-restricted gastropod *Struthiolaria* n.sp. aff. *frazeri* (A. Beu, GNS Science pers. comm. 2004). The L.O. of *P. triphooki* has also been observed in Deep Stream (V20/361073, Column V20-47); the Napier-Taupo Road at Glengarry Hill (V20/309038, Column V20-77); Glengarry Forest (V20/293023); Huiarangi Road near Patoka (Fig. 29; V20/259002, Column V20-84); the base of the Scinde Island Formation at Scinde Island, Napier (type locality of *Phialopecten triphooki*, V21/460843; Beu 1995); Mason Ridge; Sentry Box Formation at Awapai Station, Whanawhana (U21/040806, Column V21-110; and the base of the Sentry Box Formation in Jumped Up Stream (U21/934665, Column U21-121).

The L.O. of *Z. delicatula* has only been observed in the base of Sentry Box Formation in



**Fig. 29:** Shellbed in Papakiri Member (Matahorua Formation) containing the L.O. of *Phialopecten triphooki* and *Glycymeris shrimptoni* in the map area, exposed beside Huiarangi Road near Patoka (GR NZMS260/259002). A basal Nukumaruan age of 2.4 Ma is assigned to this horizon. The black dotted line marks the abrupt transition from shallow-water *G. shrimptoni*-dominated conglomerate into shelfal pebbly siltstone dominated by *Neilo* and *Dosinia (Kereia) greyi*. This shellbed has been geologically mapped into the Te Pohue area and the Esk River catchment. The locations of some *P. triphooki* valves are circled.

the Jumped Up Stream section (U21/934665, Column U21-121), although it has been reported at other sites in the map area (Beu et al. 1977; Beu 1995; Browne 2004a). The L.O. of *Phialopecten triphooki* occurs in several horizons across the map area. This is inferred to reflect changing facies and habitats through the Lower Nukumaruan, indicating that the persistence of *P. triphooki* in the study area may be strongly facies controlled. In the area around Deep Stream, Esk River and Kaiwaka Stream, including the top of the Grassy Knoll Conglomerate Member in Deep Stream, the L.O. of *P. triphooki* occurs in the base of Papakiri Member and the H.O. in the Grassy Knoll Conglomerate Member. In the Glengarry and Patoka areas, both the L.O. and H.O. of *P. triphooki* occur in the Papakiri Member and have been located at Glengarry Hill, in Glengarry Forest, and beside Huiarangi Road (Fig. 29). The overlying Grassy Knoll Conglomerate Member in these areas comprises lithofacies that were

unsuitable for *Phialopecten* (e.g. non-marine to estuarine). In the Ohara Depression the H.O. of *Phialopecten triphooki* coincides with the top of the Sentry Box Formation. In the Mason Ridge area the H.O. occurs in the Pakihirua Limestone Member (Mason Ridge Formation).

The extinction of the large oyster *Crassostrea ingens* occurred during the lowermost Nukumaruan (Beu 1995). Co-occurrence of *Z. delicatula* and *P. triphooki* with *P. thomsoni* and *Crassostrea ingens* in Jumped Up Stream demonstrates a reliable very basal Nukumaruan age (Beu 1995). McIntyre (2002) also noted this co-occurrence in Hautawa Shellbed in Wanganui Basin.

The lineage of species of the gastropod genus *Pellicaria* has proven to be useful in understanding Nukumaruan stratigraphy of the map area (Beu 1995). Two species and one form of

*Pellicaria* occur in siltstone facies in Nukumaruan strata in the map area, these being *P. acuminata* and its successors, *P. convexa* and *P. convexa* form *fossa*. *Struthiolaria frazeri* is a large distinctive Nukumaruan-restricted gastropod that characterises shallow-water sandstone facies of Nukumaruan age. It is most common in sandstone beds of middle to Upper Nukumaruan age in the Tangoio Block and in the Kereru area. Prominent *S. frazeri*-rich shellbeds crop out in Darkys Spur Member at Darkys Spur and in Okauawa Formation opposite Whanakino Station entrance gate.

An interesting point of pectinid biostratigraphy identified in the map area is the lack of *Phialopecten* and *Towaipecten* in rocks younger than Lower Nukumaruan. *Phialopecten* has preferentially occupied environments associated with the accumulation of coarse-grained limestone to conglomeratic facies. Specimens of *Phialopecten triphooki*, the youngest *Phialopecten* species, have been collected from three cyclothems into the Nukumaruan Stage. Although apparently suitable substrates and depositional settings were present for *Phialopecten* in the mid and Upper Nukumaruan (such as the Flag Range Conglomerate Member), no *Phialopecten* or *Zygochlamys* have been observed. The extinction of the two genera in Hawke's Bay seems to have occurred during lowermost Nukumaruan time, perhaps 120 000 years into the stage. This may be due to one of two reasons. Firstly, the base of the Nukumaruan marks an influx of subantarctic faunas such as *Zygochlamys* and *Jacquinotia*, among others. The influx of cooler waters coincided with the speciation from *P. thomsoni* (Mangapanian) to *P. triphooki*, as well as *Towaipecten katieae* to *T. mariae*. It appears that the subantarctic faunas only survived in Hawke's Bay for a short interval, perhaps only 80 to 120 k.a., similar to the length of time that *Phialopecten triphooki* survived in the Nukumaruan in Wanganui Basin. It may be that as waters warmed slightly after the lowermost Nukumaruan they became intolerable for *Phialopecten* and *Zygochlamys*. A second factor is the availability of suitable substrate for the pectinids. After the Lower Nukumaruan a rapid basin-wide deepening occurred, recorded by the accumulation of Esk Mudstone. Shelf limestone

of Sentry Box Formation in Ohara Depression rich in *Phialopecten triphooki* and *Zygochlamys delicatula* is abruptly overlain by mudstone containing an upper bathyal fauna (Beu 1995). In the areas from the Tangoio Block south through the Esk Catchment to the Ngaruroro River, non- to marginal-marine conglomerate beds (with common *Phialopecten triphooki*) of the Matahorua Formation are overlain by outer shelf mudstone facies. Immediately north of the map area, shelfal rocks of Upper Mangapanian age are overlain by upper bathyal mudstone of Lower Nukumaruan age at the Mohaka River viaduct. Throughout the map area *Zygochlamys*, *Phialopecten*, and *Towaipecten* of Nukumaruan age have only been observed and collected from coarse-grained pebbly limestone to shelly conglomerate facies. In the Esk and Mangaone catchments such facies only occur for two cycles into the lower part of the Nukumaruan. It could be that a dramatic change in environment occurred in the Lower Nukumaruan that was unfavourable for *Phialopecten* and other scallops, and that these genera became extinct in the Hawke's Bay part of the forearc basin. Even though suitable facies are widespread in the mid and Upper Nukumaruan in the study area, they were not recolonised by *Phialopecten* as it was already extinct. *Zygochlamys* could not re-colonise these beds, as water temperatures were probably too warm for it to migrate northward as it had done during the lowermost Nukumaruan. It is important to keep in mind that while *Phialopecten* is extinct in the modern environment, *Z. delicatula* is still widespread on the East Otago slope where it is commercially harvested.

*Notorotalia zelandica* is typical of foraminifera in Nukumaruan strata in eastern North Island, although it is rare in the Nukumarua Coast section of Wanganui Basin (Beu et al. 2004). Hornibrook et al. (1989) nominated the first occurrence of *Truncorotalia crassula* as the best available proxy for the base of the Nukumaruan Stage (Fig. 27). Beu et al. (2004) comment, however, that while the L.O. of *T. crassula* is still used as a stage proxy in deep-water sequences where age-diagnostic benthic foraminifera and mollusca are lacking, the biostratigraphic events on which the stage correlation is based are subject to facies control and may not necessarily be homotaxial.

Planktic and benthic foraminifera identified in Nukumaruan rocks in this study include *Globoconella inflata*, *Globoconella inflata triangula*, *Truncorotalia crassaformis*, *T. truncatulinoides*, *T. crassula*, *T. cf. crassula* and *Notorotalia zelandica* (M. Crundwell, GNS Science pers. comm. 2004) (Bland 2006, Appendix V).

## A Magnetostratigraphic Datum

Beu and Edwards (1984) inferred the Pliocene-Pleistocene boundary to lie within Waipatiki Limestone Member (Petane Formation) in the Tangoio Block on the basis of the first occurrence of *Gephyrocapsa sinuosa* in the base of the underlying Te Ngaru Mudstone Member. Waipatiki Limestone Member has been mapped across the map area from the Tangoio Block south into the Matapiro district as far as Ngaruroro River. Waipatiki Limestone is conformably, although abruptly, overlain by Devils Elbow Mudstone Member. The top of the Olduvai paleomagnetic subchron (1.78 Ma) has been located in this mudstone (P. Kamp and G. Turner, unpublished data). The position of this paleomagnetic transition correlates well with the inferred position of the Pliocene-Pleistocene boundary.

The next most useful paleomagnetic transition to locate within the forearc basin succession would be the Gauss-Matuyama boundary (2.58 Ma). No attempts have been made to determine its position by the authors, as it will lie in the map area mainly within sandstone facies of Pohue Formation and Te Waka Formation. Puketitiri Formation, which may carry this transition in part of the basin, is very poorly exposed.

## Integrated Biostratigraphy and Chronology

An integrated biostratigraphy and chronology for the Neogene forearc basin succession in central Hawke's Bay is shown in Fig. 30. It shows chiefly the stratigraphic positions of macrofossil and microfossil datums used in establishing the age of the sedimentary succession exposed within the forearc basin.

The oldest Neogene rocks (Tolaga Group) cropping out in the map area occur in the Te Hoe and Te Haroto areas. Foraminifera and a few macrofossils underpin the biostratigraphy (Scott et al. 1990a; Cutten 1994). Te Haroto Formation is of Lower Tongaporutuan to possibly Waiauan age cropping out only in the Te Haroto and Tarawera Station area. It is unconformably overlain by Tarawera Limestone Member (Waitere Formation), which contains a distinctive macrofauna of *Zeacolpus* sp. and *Struthiolaria (Callusaria)* sp. Tarawera Limestone passes up into Te Ipuohape Sandstone Member containing concretionary beds rich in *S. (Callusaria)* in places. Te Ipuohape Sandstone Member (Tongaporutuan) passes through the Auroa Alternating Member into the Rakaita Siltstone Member, the top of which is at least as old as Upper Tongaporutuan based on microfossil content. The overlying Mokonui Sandstone, the highest unit in Tolaga Group, is Kapitean to Lower Opoitian (Late Miocene to Early Pliocene) in age (Scott et al. 1990a; Cutten 1994). Microfossil sample V19/f46 from Mokonui Sandstone in the Mohaka River (V19/432321) contains *Globoconella miotumida* (with *conomiozea morphotypes*) and is dated as Lower Kapitean, possibly near the Lower to Upper Kapitean boundary. Sample V19/f160 from Pohokura Road near Woodstock Road (V19/376274) includes *Truncorotalia crassaformis*, *Globoconella puncticulata* and *G. pliozea* with a Lower to "Middle" Opoitian age (Cutten 1994).

Mokonui Sandstone is unconformably overlain by the "early to middle" Pliocene Titiokura Formation. The L.O. of *Phialopecten marwicki* in this part of the basin occurs in Te Rangi Member of Titiokura Formation at Naumai Station on the Maungaharuru Range. These specimens resemble the typical Opoitian form characterised by small size and numerous ribs, placing them in the Opoitian field of Beu (1995, Fig. 9, p. 27). An Upper Opoitian age for the base of Titiokura Formation in the Maungaharuru Range is supported by the Kapitean to Lower Opoitian age of the underlying Mokonui Sandstone.

The position of the Opoitian-Waipipian boundary in the Maungaharuru and Te Waka ranges remains uncertain, although it is inferred

to lie in Bellbird Bush Member of Titiokura Formation. Three microfossil samples collected from the Bellbird Bush and Opouahi Members (Titiokura Formation) along Pohokura Road provide mixed Upper Opoitian and Lower Waipipian ages (Beu et al. 1980; Beu 1995; V19/f8529 collected by N. de B. Hornibrook, A.G. Beu, and T.L. Grant-Taylor; V19/f8615 and f8616 collected by R. Stonely). Sample V19/f8529 was assigned an Opoitian-Waipipian age, although comments on this sample suggest the age is more probably Waipipian. Sample V19/f8615 was assigned a Waipipian age and sample V19/f8616 a “Waitotoran” (Waipipian/Mangapanian) age. These ages suggest that the Opouahi Member is Lower Waipipian in age and that the underlying Bellbird Bush Member is of Upper Opoitian-Lower Waipipian age.

The base of Te Waka Formation at its type section on Te Waka Range (V20/258133) may be of uppermost Waipipian age. Sparse scallops observed in middle to upper beds of Te Waka Formation at the type section resembled typical Waipipian *Phialopecten marwicki* rather than the expected Mangapanian *Phialopecten thomsoni* (Bland 2001). Additionally, small specimens of *Phialopecten* observed in these beds share morphological characteristics of both *P. marwicki* and *P. thomsoni* (A. McIntyre, pers. comm. 2000; Bland 2001). Uppermost beds of Te Waka Formation in the Te Waka Range are of Mangapanian age, based on the occurrence of the Mangapanian index *Phialopecten thomsoni* (Beu 1995). These beds also contain *Maoricardium spatiosum* (Bland 2001), and therefore cannot be younger than Mangapanian.

Pohue Formation in the Maungaharuru Range is of uppermost Waipipian to Mangapanian age. In Te Waka Range and in the Patoka area Pohue Formation is wholly of Mangapanian age. The decrease in age of the base of Pohue Formation towards the south reflects its interfingering with Te Waka Formation.

The stratigraphy of these areas lies across the North Island Shear Belt and is punctuated by common unconformities. No absolute ages have been determined in these areas and the relative chronology developed is based entirely on

micro- and macrofossil biostratigraphy.

In the Kuripapango area Tongaporutuan strata are restricted to a small area around the Tutaekuri River near its confluence with Donald River. The Tongaporutuan age is determined from the common presence of *Sectipecten grangei* and by both planktic and benthic foraminifera, including *Globoconella miotumida*, *Neogloboquadrina pachyderma* and *Bolivinita pliobliqua* (U20/f150). These Tongaporutuan beds are unconformably overlain by Kapitean shallow marine sandstone of Blowhard Formation, which contain *Sectipecten wollastoni*, the Kapitean index scallop. Mangatoro Formation of “middle” to Upper Opoitian age (M. Crundwell, GNS Science, pers. comm. cited in Browne 2004a) probably unconformably overlies Blowhard Formation. Mangapanian Te Waka Formation based on the presence of common *Phialopecten thomsoni* unconformably overlies Mangatoro Formation. No Waipipian rocks are known or exposed in either the Kuripapango or Omahaki Depression areas.

Preserved in several fault-bounded blocks in Ohara Depression and upon basement in northern Ruahine Range are small areas of lowermost Nukumaruan Sentry Box Formation. The age of this formation is tightly constrained by the presence of common *Z. delicatula* and *J. edwarssi*. The stratigraphy of the Tangoio Block (Fig. 31) was regarded by Beu and Edwards (1984), Haywick et al. (1991) and Beu (1995) as a 550 m-thick succession of “middle” to Upper Nukumaruan age. These beds accumulated during a known period of obliquity-controlled sea-level cycles with durations of 41 k.a. (Haywick et al. 1991, Haywick and Henderson 1991 and Haywick 2000).

Following work by Beu and Edwards (1984), Haywick et al. (1991) and Beu (1995), we have given close attention to geological mapping of Nukumaruan strata in the Tangoio Block and the underlying conglomerate-bearing succession (Fig. 31). The conglomerate bed at the base of Papanui Member (Matahorua Formation) contains the L.O. of *Phialopecten triphooki* and *Towaipecten mariae*, marking the base of the Nukumaruan Stage at c. 2.40 Ma. Sandstone underlying this conglomerate contains the H.O. of

## Integrated Biostratigraphy and Chronology summary

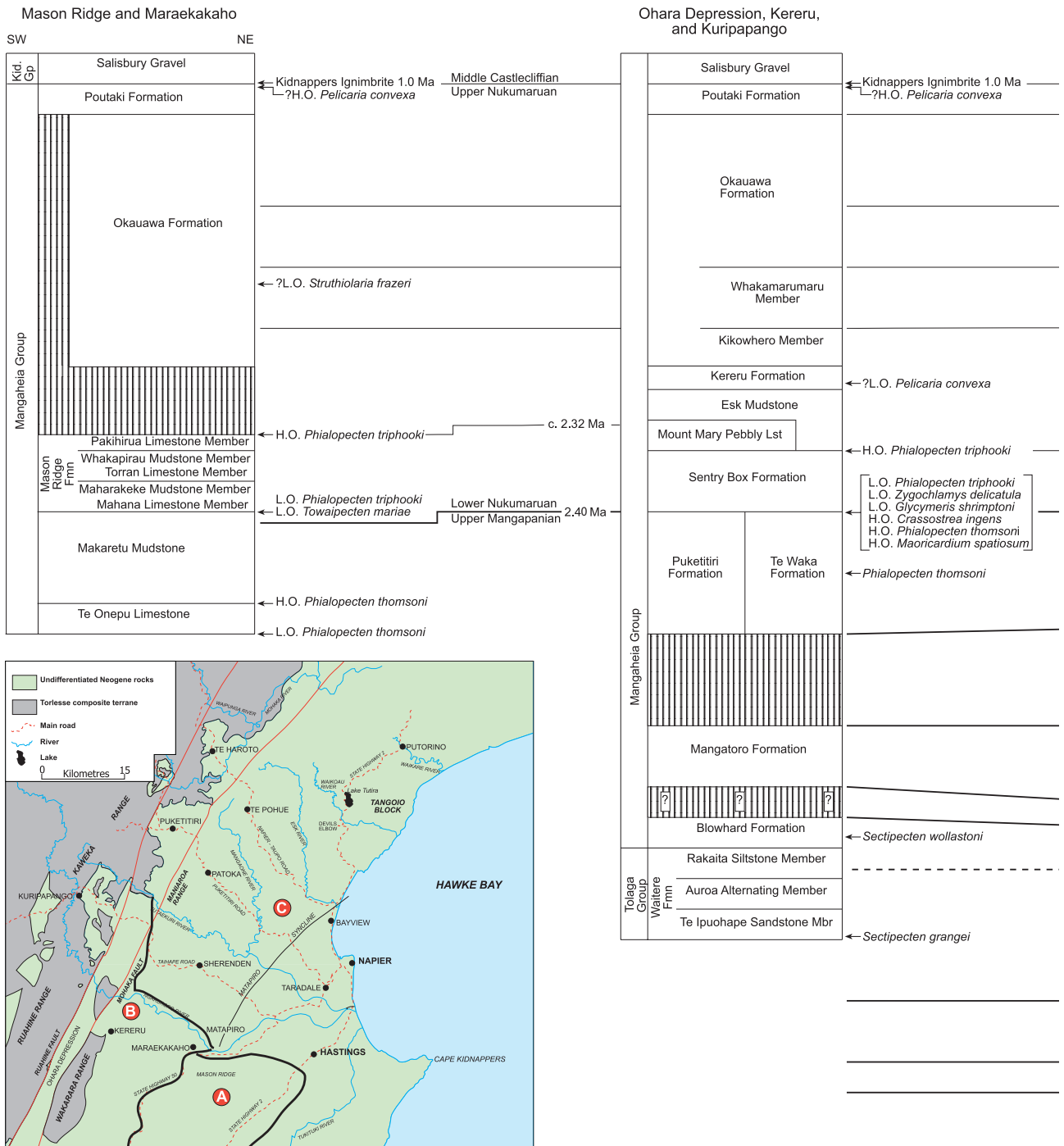
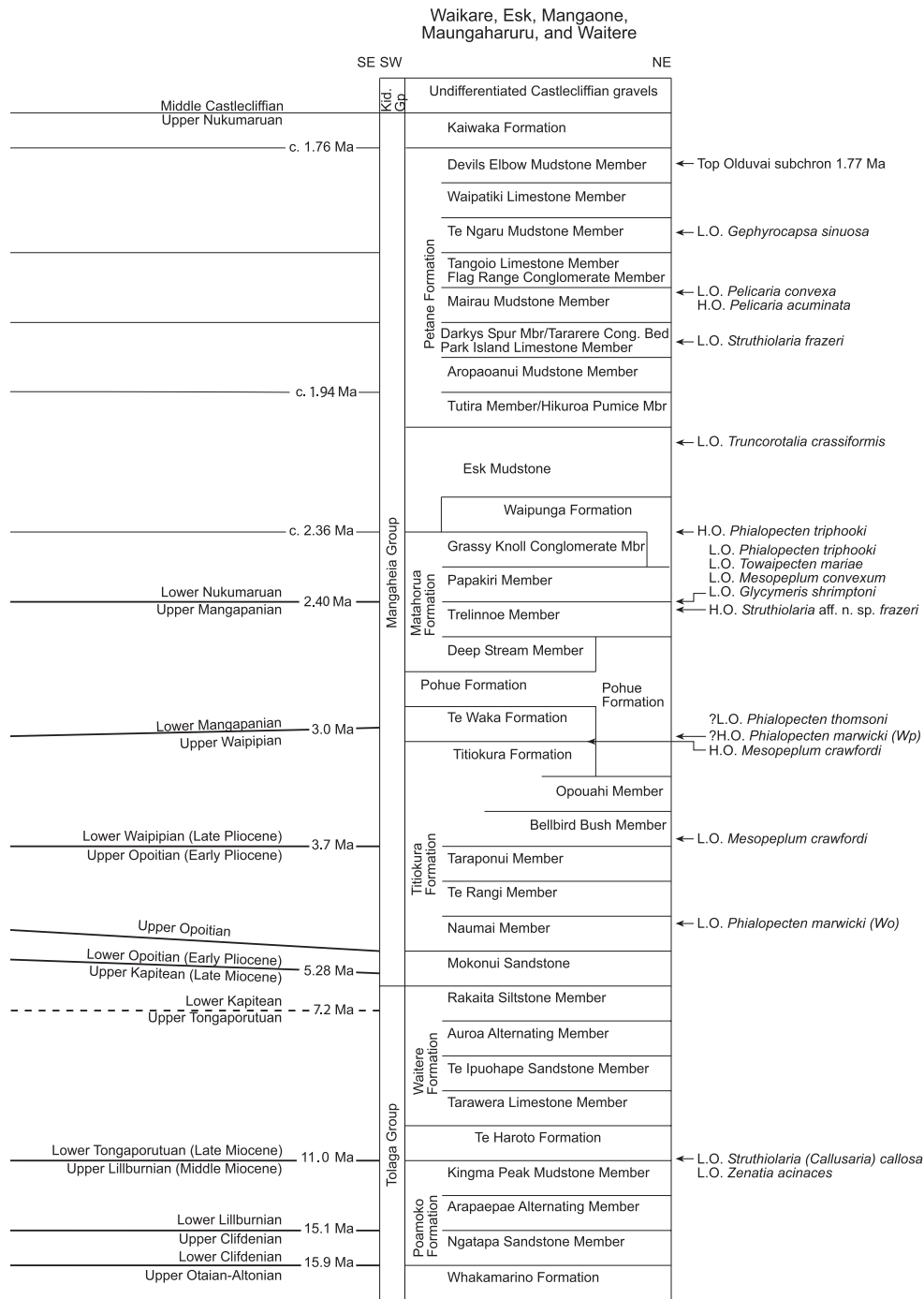
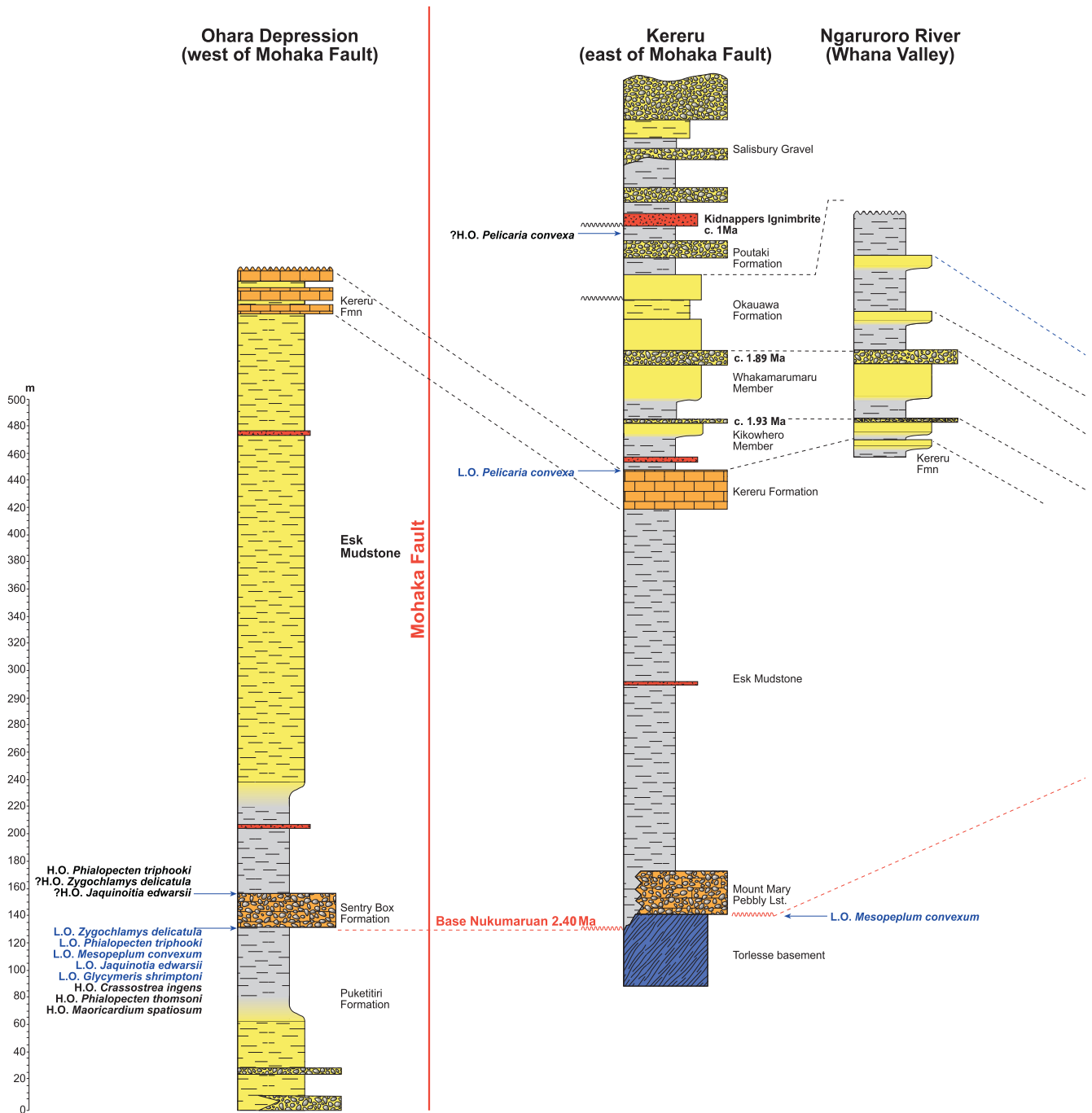


Fig. 30 : (two page spread) Summary of integrated biostratigraphy and chronostratigraphy for the forearc basin in central Hawke's Bay.

# Integrated Biostratigraphy and Chronology summary



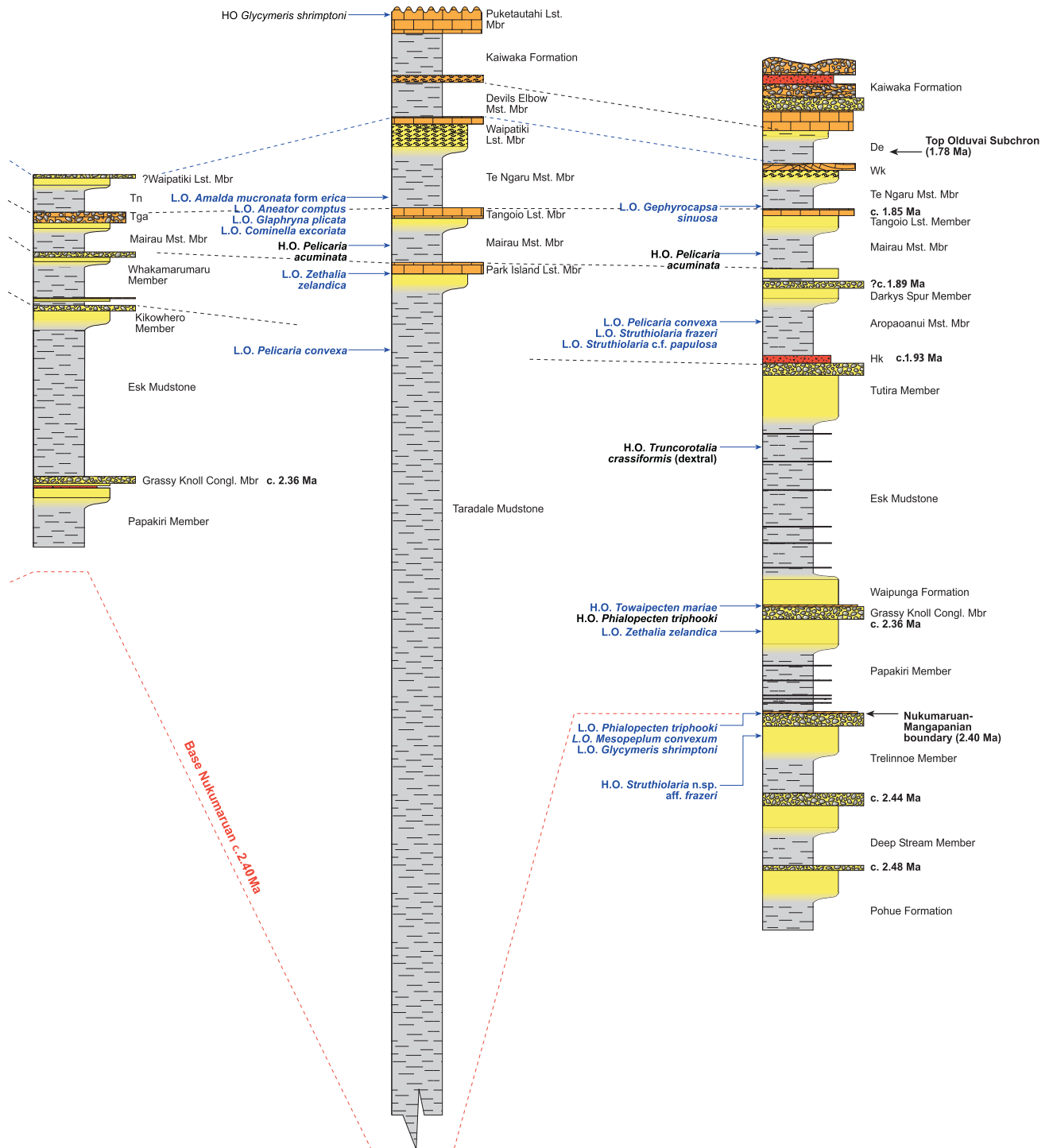


**Fig. 31:** (two page spread): Simplified stratigraphic columns of Nukumaruan stratigraphy described for the map area. The positions of biostratigraphic lowest occurrences are shown in blue font; biostratigraphic highest occurrences are shown in black font. Other markers are shown in black bold font. The red dashed line is the Nukumaruan-Mangapanian boundary. De, Devils Elbow Mudstone Member; Hk, Hikuroa Pumice Member; Tga, Flag Range Conglomerate Member; Tn, Te Ngaru Mudstone Member; Wk, Waipatiki Limestone Member. Some fossil datums in the Esk Catchment section are based on Beu and Edwards (1984) and Haywick et al. (1991). Ohara Depression and Kereru stratigraphic columns are adapted from Erdman and Kelsey (1992).

**Sherenden-Flag Range**

**Omahu-Taradale**

**Esk Catchment (Tangoio Block)**



the large gastropod *Struthiolaria n. sp. aff. frazeri* (Beu 1995; A. Beu, GNS Science, pers. comm. 2001) (Fig. 31). The Grassy Knoll Conglomerate Member also contains *P. triphooki* and the top of this member is assigned an age (2.36 Ma) some 41 k.a. younger than the Papakiri Member. If the age of the base of the Nukumaruan adopted here changes, then the interpolated ages will correspondingly need to change.

The L.O. of *Gephyrocapsa sinuosa* is located near the base of the Te Ngaru Mudstone Member (Beu and Edwards 1984; Beu 1995). This agrees well with the position of the top of the Olduvai paleomagnetic subchron (1.78 Ma) in Devils Elbow Mudstone.

The Grassy Knoll Conglomerate Member has been confidently mapped from the Waikoau River section southwest through the Te Pohue, Patoka, and Waihau areas, into the Tutaekuri River section and from there to Taihape Road near Willowford. The stratigraphic position of this bed is well established in the Esk River section where it is one sequence above the base of the Nukumaruan Stage (2.40 Ma), defined by the L.O. of *Phialopecten triphooki*. A 2.36 Ma age for the Grassy Knoll Conglomerate helps constrain the age of the overlying Esk Mudstone in the Sherenden and Waihau areas. It is overlain by Kikowhero Member (Okauawa Formation), which itself has been correlated through geological mapping to the Tutira Formation, which is four 41 k.a. duration sequences older than the former Pliocene-Pleistocene boundary (1.81 Ma), and therefore will have an age of about 1.94 Ma (Fig. 31). This implies that the Esk Mudstone and underlying Waipunga Formation accumulated over some 420,00 y in the Tangoio Block. Esk Mudstone will have a similar duration in the part of the basin to the south in the Sherenden-Flag Range and Kereru districts and in Ohara Depression (Fig. 31).

Geological mapping reported here demonstrates that Waipatiki Limestone Member cropping out in the Tangoio Block is the same stratigraphic unit as Matapiro Limestone of Beu (1995) and Baggs (2004). Throughout the Matapiro area strata are broadly folded as Matapiro Syncline. Waipatiki Limestone Member is often the stratigraphically

highest unit involved in Matapiro Syncline. Because Waipatiki Limestone Member remains in outcrop throughout the syncline, it provides a horizon that can be used to correlate stratigraphy on both limbs of the syncline. On the eastern limb, Waipatiki Limestone Member is underlain by Te Ngaru Mudstone, Tangoio Formation, Mairau Mudstone and Park Island Limestone members (Petane Formation). The ages of these units are the same as those assigned to the formations and members cropping out in the Tangoio Block. On the western limb of the syncline, Waipatiki Limestone is underlain by Te Ngaru Mudstone Member, Flag Range Conglomerate Member (Petane Formation), Whakamarumaruru and Kikowhero members of Okauawa Formation and Esk Mudstone.

Geological mapping of horizons from the Tangoio Block southwest into the Kereru area and Ohara Depression has refined the age of the succession there (Fig. 31). The Darkys Spur Member has been correlated with the top of the Whakamarumaruru Member (Okauawa Formation). The top of the Tutira Member (marked by the Hikuroa Pumice Member) has been correlated with the top of Kikowhero Member of Okauawa Formation.

Previous workers have attempted to correlate Lower Nukumaruan limestone at Scinde Island with limestone cropping out at Mason Ridge (e.g. Beu et al. 1980; Beu 1995). Unlike the Scinde Island Formation where only the lowermost of the three limestone members contain *Phialopecten triphooki* (Beu 1995), both the lowermost and uppermost of the three limestone members of Mason Ridge Formation contain *P. triphooki* (Caron 2002; Dyer 2005). The Mason Ridge Formation is therefore entirely of Lower Nukumaruan age based on the presence of *P. triphooki*. It is probable that the uppermost member of Mason Ridge Formation is equivalent to the lowermost limestone member of Scinde Island Formation (Member A).

## Basin development and paleogeography

The Neogene geological history of central and western parts of Hawke's Bay can be usefully subdivided into three major phases, each of which

is represented by one of three lithostratigraphic groups. The first phase, of Early Miocene - Early Pliocene (Otaian - Lower Opoitian) age is represented by the Tolaga Group. This group comprises four deepening-upward packages (each a separate formation), with shelfal beds at the base passing upsection into bathyal units. A thick sandstone formation (Mokonui Sandstone) at the top of the group is unconformably overlain by Mangaheia Group. Mangaheia Group represents the second Neogene phase of sedimentation and comprises cyclothemical shelfal sequences. Intervals of probable upper bathyal beds do occur within the cyclothemical succession. The uppermost Neogene phase of sedimentation is represented by the Middle Pleistocene (Castlecliffian) Kidnappers Group, which is characterised by thick non- to marginal-marine greywacke conglomerate and associated fluvial and innermost shelf deposits.

The basin has been inverted along its western margin with deformation focused on faults of the North Island Shear Belt. Paleogeographic maps of the Hawke's Bay area for the Neogene (Enclosure 5) illustrate the eastward migration of the western basin margin throughout time, and the progressive uplift of the inboard margin of the accretionary wedge during the Late Neogene. There may also be late Neogene migration of dextral dip-slip faults into the basin from the west. The formation of the North Island Shear Belt has occurred since the Late Pliocene and has been attributed to clockwise rotation of East Cape associated with oblique rifting in the Taupo Volcanic Zone (Beanland and Haines 1998; Wallace et al 2004; Reyners et al. 2006).

The stratigraphic record along the eastern margin of the forearc basin records the progressive encroachment of the accretionary wedge into the forearc basin concurrent with sedimentation in the basin. Late Miocene sediments in Makara Basin (Pettinga 1982) accumulated in bathyal environments. Shoaling of this basin to shelf depths had occurred by the Upper Opoitian as shown by accumulation of Opoitian Kairakau Limestone (Beu 1995). This has been attributed to uplift of the inboard margin of the accretionary wedge, the semi-emergent ridge extending from Te Mata Peak to at least as far south as Cape

Turnagain (Beu 1995). The outcrop pattern of westward-younging Pliocene limestone units east of Te Mata Peak demonstrates the involvement of forearc basin sedimentation concurrent with growth of the inboard margin of the accretionary wedge. Nukumaruan Mason Ridge Formation presently crops out close to the forearc basin axis and at lower elevations compared with older Pliocene limestone beds (e.g. Kairakau Limestone and Awapapa Limestone) located to the east.

This pattern of uplift and sedimentation formed a tidal seaway, which was most extensive during the Mangapanian. It was characterised by the development of limestone formations (Te Aute lithofacies) along both margins of the seaway. Although large volumes of siliciclastic sediment were sourced to the basin, thick limestone beds accumulated, possibly due to strong tidal currents that swept elevated parts of the seafloor clear of siliciclastic sediment. Breaches in the seaway were present at times near Kuripapango and Manawatu Gorge. The interior seaway became constricted in Wairarapa (Mount Bruce) during the upper Nukumaruan and after that embayments to the north (Hawke Bay) and south (Palliser Bay) developed.

While the Late Miocene-Pleistocene part of the basin fill (Mangaheia Group) accumulated during a period of known regular sea-level oscillations, terrigenous sediment supply seems to have been an important factor driving stratigraphic architecture in the forearc basin and it has largely overprinted the role of eustatic sea-level change, which has been shown to be a key control on depositional architecture in the adjacent Wanganui Basin (Naish and Kamp 1997). Consequently, limited correlation can be achieved between units in Mangaheia Group and the  $\delta O^{18}$  record contained in ODP records. The identification of sequences in parts of Mangaheia Group is mostly due to the presence of bioclastic shellbeds within much thicker siliciclastic intervals and without them the identification of sequence and systems tract boundaries would be very difficult. At the same time, where siliciclastic beds are absent, sequence architecture can be equally difficult to identify. For example, in Titiokura Formation at Te Pohue, the winnowing of bioclastic deposits during their accumulation

has condensed the sedimentary succession into a relatively thin carbonate interval, making field-based identification of cyclothems difficult. Such condensation and stacking within limestone lithofacies has also occurred along and above the accretionary wedge in Pliocene formations such as the Awapapa Limestone and Te Onepu Limestone (Caron et al. 2004a, 2004b).

## Summary

A revised lithostratigraphy is proposed for the Neogene sedimentary succession in central Hawke's Bay, which rationalises many previously named units, particularly shellbeds and limestones, and as much as possible, group and formation nomenclature has been unified with that for regions to the north (Raukumara QMap sheet). Neogene rocks of Early Miocene to Middle Pleistocene (Otaian to Castlecliffian) age crop out over an area of about 5,700 km<sup>2</sup> and have been described and geologically mapped at 1:50 000 scale (Enclosure 3; Enclosure 4, Sheets 1-6). This report also includes stratigraphic correlations (Enclosure 2).

Torlesse composite terrane basement rocks have been mapped here without internal differentiation. The Neogene succession exposed adjacent and over the basement has been subdivided into three stratigraphic groups: Tolaga Group (Otaian - Lower Opoitian), Mangaheia Group (Upper Opoitian - Upper Nukumaruan) and Kidnappers Group (Castlecliffian).

The Tolaga Group nomenclature has been adopted from QMAP Raukumara (Mazengarb and Speden 2000) and comprises Whakamarino Formation, Poamoko Formation (Ngatapa Sandstone Member, Arapaepae Alternating Member, and Kingma Peak Mudstone Member), Te Haroto Formation (new), Waitere Formation (Tarawera Limestone Member (new)), Te Ipuohape Sandstone Member, Auroa Alternating Member, Rakaita Siltstone Member and Mokonui Sandstone.

A significantly revised lithostratigraphy has been presented here for the Early Pliocene - Early Pleistocene Mangaheia Group in central and

western parts of the forearc basin. Mangaheia Group nomenclature has been adopted from QMAP Raukumara. The Hawke's Bay, Petane, Napier, and Poporangi Groups, as defined by Haywick et al. (1991) and Beu (1995), are incorporated into the Mangaheia Group. Petane Group is demoted to Petane Formation. Most formations previously defined within Petane Group are redefined as members of Petane Formation. Due to their thickness and lateral extent, Esk Mudstone and Kaiwaka Formation are maintained as separate formations. The stratigraphy cropping out in Ohara Depression-Kereru area, as mapped by Erdman and Kelsey (1992) and Beu (1995), has been correlated with beds to the north and east. Kaumatua Formation of Erdman and Kelsey (1992) is now included in Puketitiri Formation. Sentry Box Formation is defined to include Whanawhana Limestone and Seconds Ridge Conglomerate of Beu (1995). Ohara Mudstone is now mapped as Esk Mudstone.

An integrated chronostratigraphy has been developed for the forearc basin fill. This is based mostly on macrofossil biostratigraphy, particularly the established pectinid biostratigraphy, with support where possible from paleomagnetism. The lineage of pectinid species of the genera *Sectipecten*, *Mesopeplum*, *Phialopecten*, and *Towaipecten* has proven to be useful in the identification of New Zealand Late Cenozoic stages in shelfal parts the basin fill. Calcareous foraminifera have yielded biostratigraphic ages in intervals where macrofauna are rare, particularly in the Tolaga Group.

The Titiokura and Te Waka Formations become younger from northeast to southwest within the basin. Titiokura Formation in the northern Maungaharuru Range is of Upper Opoitian-lowermost Waipipian age, whereas it is mostly Waipipian in the Te Waka Range to the south. Te Waka Formation is of uppermost Waipipian to Lower Mangapanian age at the northern end of Te Waka Range, whereas it is uppermost Mangapanian age in the Glenross Range to the south. In addition, the age of overlying Pohue Formation decreases from Lower Waipipian-Mangapanian in the Maungaharuru Range to uppermost Mangapanian in the Waiwhare area

to the south.

Cyclothems in the Upper Mangapanian - Upper Nukumaruan part of the Mangaheia Group assist in developing an integrated chronology based mainly on molluscan biostratigraphy. The continuous succession exposed in the Esk River catchment has enabled the development of this chronostratigraphy; extended to others parts of the basin by detailed geological mapping of horizons, commonly sequence boundaries. The Mangapanian-Nukumaruan boundary (c. 2.4 Ma) is characterised by the L.O. of *Phialopecten triphooki* and less commonly by the L.O. of *Zygochlamys delicatula*. It is also marked by the H.O. of *Crassostrea ingens*, and *Maoricardium spatiosum*, among extinction of several other taxa. This boundary occurs at the base of the lower shellbed in Papakiri Member, the base of the Sentry Box Formation and at or near the base of Scinde Island Formation. Mason Ridge Formation is also of Lower Nukumaruan age based on the occurrence of *P. triphooki* in all three limestone members. Grassy Knoll Conglomerate Member has an inferred age of about 2.36 Ma. Geological mapping of this horizon into the Sherenden and Waiwhare area has provided an approximate age for the base of Esk Mudstone in these areas.

Geological mapping suggests a correlation between Tutira and Hikuroa Pumice Members (Petane Formation) in the Esk River/Tangoio Block area, and Kikowhero Member (Okauawa Formation) in Ohara Depression and at Flag Range. The Darkys Spur Member (Esk-Tangoio Block) has been correlated with Park Island Limestone Member (Taradale-Puketapu) and the upper parts of Whakamarumaruru Member (Ohara Depression-Flag Range). Tangoio Limestone Member (c. 1.76 Ma) is correlative with Flag Range Conglomerate Member and has been mapped into upper beds of Okauawa Formation. The former Pliocene-Pleistocene boundary (1.81 Ma) occurs within Waipatiki Limestone Member (Beu and Edwards 1984; Haywick et al. 1991) and correlated into upper beds of Okauawa Formation. The top of the Olduvai paleomagnetic subchron (1.78 Ma) is located in Devils Elbow Mudstone Member. It probably also occurs within Okauawa Formation or Poutaki Formation, but

its position has not been defined due to a lack of lithofacies suitable for paleomagnetic dating or stratigraphic correlation. Kaiwaka Formation is equivalent to uppermost beds of Okauawa Formation and Poutaki Formation.

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## **Appendix I: Paleogeography of forearc basin stratigraphy and sedimentation in central Hawke's Bay**

### **Otaian-Waiauan (21.7 - 10.92 Ma)**

The oldest Neogene strata cropping out in the map area is the Otaian Whakamarino Formation. It accumulated in shelfal to upper bathyal environments. It includes thin turbidites. Whakamarino Formation is unconformably overlain by Poamoko Formation. Submergence resumed during the Clifdenian with deposition of Ngatapa Sandstone Member in shelf environments. It is overlain by mid-bathyal Arapaepae Alternating Member and Kingma Peak Mudstone Member of Upper Lillburnian age (Cutten 1994).

No Waiauan rocks are known to crop out in the map area, indicating emergence and erosion. While western parts of the basin were emergent at this time, Waiauan sediments occur in the Wairoa-Mahia area (Makaretu-D Sandstone, Tunanui Formation; Mazengarb and Speden 2000), in Tuhara-1 (Ian R Brown and Associates 1998d) and Tangihau Mudstone and Makaretu-D sandstone in Opoho-1 (Ian R Brown and Associates Ltd 1999c). No Waiauan rocks are reported in other exploration wells in the Wairoa area, although they do crop out in the Lake Waikaremoana area, and inland from Wairoa and Ruakituri (Mazengarb and Speden 2000). In central parts of Hawke's Bay, Waipipian Taradale Mudstone overlies steeply dipping Waiauan flysch in Mason Ridge-1 (Leslie 1971b). Waiauan Waipuna Limestone was recorded in Whakatu-1 by Ozolins and Francis (2000), and shelfal sandstone of Waiauan age was reported from Hawke Bay-1 (BP Shell Aquitaine Todd Petroleum Development Ltd 1976). Rocks of Upper Whaingaroan to possibly Upper Tongaporutuan age are absent in Hukarere-1 (Westech Energy New Zealand Ltd 2001), and beds of Mangaorapan to Waipipian age are absent in Taradale-1 (Darley and Kirby 1969). It is likely therefore that western parts of the map area were subaerial for much of the Waiauan and remained so until Lower Tongaporutuan. Central and eastern parts of the basin were at bathyal depths, with flysch and other redeposited

beds accumulating. It is inferred that the absence of Waiauan rocks in Hukarere-1 and Taradale-1 reflect either condensation or a younger phase of uplift and erosion.

### **Tongaporutuan (10.92 - 7.2 Ma)**

Tongaporutuan rocks are widespread in northwestern parts of the map area and in the subsurface throughout the Hawke's Bay part of the forearc basin. The Tongaporutuan was marked by subsidence in the Te Hoe-Mohaka area with accumulation of shelf sandstone followed by bathyal marine conditions, with emergence during the Upper Kapitean to Lower Opoitian with accumulation of Mokonui Sandstone.

Most of the southern part of the map area was emergent during the lowermost Tongaporutuan, with the exception of the Tarawera Station and Te Haroto areas where Te Haroto Formation accumulated. A short period of emergence followed deposition of this unit, followed during the mid-Tongaporutuan by subsidence with accumulation of shelfal Tarawera Limestone Member and coarse grained highly fossiliferous lower beds of Te Ipuohape Sandstone Member (both Waitere Formation). The overlying Auroa Alternating and Rakaita Siltstone Members accumulated in bathyal environments.

A similar pattern of Tongaporutuan subsidence occurred in the Wairoa area where several hydrocarbon exploration wells (Kiakia-1, Makareao-1, Kauhauroa-1, -2, -5, Awatere-1, Tuhara-1) have intercepted late-Lower and Upper Tongaporutuan strata. Middle bathyal Pindari Mudstone was intercepted in all the wells as well as middle bathyal Poha Formation. These formations are most probably correlatives of Waitere Formation. Intermittent development of turbidite fan complexes is represented by Makareao Sandstone Member in Poha Formation. Ratios of planktic to benthic foraminifera in this member from Makareao-1 led Ian R Brown and Associates Ltd (1998) to suggest that a shelf barrier east of Hawke's Bay existed somewhere between Mahia Peninsula and Cape Kidnappers that partially restricted the water mass. Hawke Bay-1 is located in this area, and foraminifera from Tongaporutuan mudstone in this hole indicate an

outer shelf environment (BP Shell Aquitaine Todd Petroleum Development Ltd 1976).

Along the eastern margin of the map area Tongaporutuan beds are recorded in Whakatu-1 (Ozolins and Francis 2000) and in the Makara Basin, inferred to be a slope basin (Pettinga 1982). It is uncertain whether Tongaporutuan rocks are recorded in Hukarere-1 due to poor paleontological data, although they are certainly absent in nearby Taradale-1 (Darley and Kirby 1969) and Mason Ridge-1 (Leslie 1971b). It is likely that Tongaporutuan beds were deposited over the sites of all four of these wells and that a post-Tongaporutuan erosion event, probably in the Opoitian (Beu et al. 1980) removed them from Taradale-1 and Hukarere-1.

### **Kapitean (7.2 - 5.28 Ma)**

The Kapitean in the forearc basin was characterised by a transition from mostly deep marine facies of the Tolaga Group to shelfal facies of the Mangaheia Group. Accumulation of bathyal Rakaita Siltstone Member (Waitere Formation) transitioned to innermost shelf Mokonui Sandstone. Mokonui Sandstone accumulated in the vicinity of Maungaharuru and Te Waka Ranges from the “middle” Kapitean into the Lower Opoitian as shoreline facies. During the Upper Kapitean Blowhard Formation, which is a correlative of Mokonui sandstone, accumulated over basement in the Kuripapango area to the south.

### **Opoitian (5.28 - 3.6 Ma)**

Stratigraphic units of Mangaheia Group accumulated as diverse facies during the Pliocene in the forearc basin. The Opoitian records the development of Te Aute lithofacies limestone along the margins of an interior seaway (“Ruataniwha Strait”). The eastern margin of this seaway probably comprised a series of shoaling, shelfal ridges, perhaps with a small number of islets. The western shelf of the basin was narrow, and probably only several kilometres wide. It was bounded by a Torlesse basement hinterland of relatively low gradient.

During the Upper Opoitian, Titiokura Formation accumulated along northwestern margins of

the map area as part of a continent-attached carbonate depositional system (Bland et al. 2004; Caron et al. 2004a, Caron et al. 2012). Titiokura Formation was deposited from at least Putere Lakes in the northeast to the central parts of Maungaharuru Range in the southwest. Concurrently, Kairakau Limestone accumulated along the eastern margin of the seaway from Te Mata Peak to as far south as Cape Turnagain. Accumulation of Pakaututu Formation (including the Hukanui Limestone Member) in the Puketitiri area, occurred adjacent to a rocky coastline, probably in a large embayment. Mangatoro Formation continued to accumulate at Kuripapango, Omahaki, Maraetotara Plateau and southern parts of Hawke’s Bay (Lillie, 1953; Harmsen 1985). Upper Opoitian shallowing is recorded in the Omahaki Depression, where upper bathyal Mangatoro Formation is overlain by shallow water Omahaki Formation. Mangatoro Formation at Kuripapango remained shelfal through this time.

Lower Opoitian Haupori Sandstone crops out in the Maraetotara Plateau and in the Cape Kidnappers area (Francis 1993) and was reported in Hukarere-1 (Westech Energy New Zealand Ltd 2001). Haupori Sandstone was deposited at about middle shelf depths in the Maraetotara area (Francis 1993) and near the shelf break in Hukarere-1 (Westech Energy New Zealand Ltd 2001). Haupori Sandstone was then overlain by Mangatoro Formation, which represents the remainder of Opoitian sedimentation in these areas. During the Opoitian, outer-shelf to upper bathyal mudstone was deposited over Hawke Bay-1 (BP Shell Aquitaine Todd Petroleum Development Ltd 1976).

### **Waipipian (3.6 - 3.0 Ma)**

The Waipipian was characterised by the development of carbonate banks in the northwest and southeast of the map area. Waipipian beds are not very widespread in outcrop in the study area, reflecting limited terrigenous sediment supply. The interior seaway became well developed by this time. The shoreline along the western margin was irregular and rocky with an emerging basement hinterland. A continental shelf developed during the Waipipian

in the northwest of the map area. Basement was exposed in the area of Ongaonga-1 and Takapau-1 as Mangapanian limestone overlies Torlesse basement. Extensive carbonate banks developed along western and eastern margins of the basin to the north. Fold structures formed in the Wairoa area, with Whakapunake Limestone and Tahaenui Limestone being developed about the flanks of antiforms.

During the lower Waipipian deposition of Puketitiri Formation over Pakaututu Formation occurred in the Puketitiri area and Pohue Formation began to accumulate east of Maungaharuru Range. Around Napier and Taradale, the Taradale Mudstone began to accumulate, overlying Eocene rocks (Darley and Kirby 1969). Erosion occurred in the Ohara Depression. Sedimentation occurred east of the Wakarara Range as Waipipian rocks were recorded in Kereru-1 (Johnston and Francis 1996).

The accretionary wedge continued to shoal, resulting in tidal currents becoming more constricted in the seaway. There was probable emergence along parts of the accretionary wedge at this time. Along this rising ridge the Awapapa Limestone and Rotookiwa Limestone accumulated as detached carbonate factories atop reverse fault-cored anticlines and thrust ridges (Caron et al. 2004). Awapapa Limestone accumulated during the lower Waipipian and Rotookiwa Limestone during the upper Waipipian, with Pukekura Calcareous Sandstone deposited between the two units. Black Reef Calcareous Sandstone was deposited as inner shelf facies around the Black Reef (Cape Kidnappers) area at the northern end of Maraetotara Plateau.

### **Mangapanian (3.0 - 2.4 Ma)**

During the Mangapanian the interior seaway was at its most extensive, with significant areas of carbonate banks accumulating along both margins. Greywacke conglomerate and sandstone entered the basin during the Mangapanian in northwestern parts of the map area. The inboard margin of the accretionary wedge was well exposed and probably constituted an archipelago of islands. The

continent-attached western shelf became more extensive due to uplift and progradation of siliciclastic sediments. Western parts of the basin were swept by strong tidal currents, with giant cross-bedded limestone deposited at Hukanui Hill (Puketitiri). Continent-detached carbonate factories developing on structural highs off the accretionary wedge were also swept by tidal currents. Seaway connections were open between East Coast Basin and Wanganui Basin through the Kuripapango and Manawatu Straits, with a semi-emergent basement island present around the present-day Ruahine Range. The Kaweka Range was probably partially exposed and basement around the Ahimanawa, Ikawhenua, and Huiarau Ranges was also emergent. The strong tidal currents through the basin acted to transport significant amounts of siliciclastic sediment north into Waikare and Raupunga areas. These areas remained depocentres throughout the Mangapanian, with outer shelf to uppermost bathyal sedimentation.

In the lower Mangapanian, a rocky greywacke coastline extended from the Ohara Depression to at least as far north as Hawkston Station (Patoka). Northeast of these areas the coastline was probably more regular, with uplifted late Neogene sediments exposed in the hinterland. Puketitiri Formation was deposited on basement from the Ohara Depression to the Glenross Range. This reflects submergence of the basement underlying Ohara Depression and infers displacement on the Ruahine, Glenross, and Mohaka Faults. The Puketitiri Formation in the Ohara Depression accumulated at shelf depths until the Sentry Box Formation was deposited during the earliest Nukumaruan.

Te Waka Formation represents a succession of carbonate banks that migrated southwestward through time so that the oldest beds occur at the type section at Te Waka Trig and the youngest beds occur in the southwest at Awapai Station. At Sandy Ridge (Kuripapango), Hawkston Station, and Opau Stream, Te Waka Formation accumulated over basement, as well as overstepping underlying formations to the north. Along the Glenross Range, Te Waka Formation also overlies parts of Puketitiri Formation before grading into it at Awapai Station at the southern

end of the Glenross Range. No Te Waka Formation is evident south of Ngaruroro River. While Te Waka Formation continued to accumulate into the Upper Mangapanian around Kuripapango and Awapai Station, Puketitiri Formation accumulated in the Ohara Depression. During this time Pohue Formation was deposited in the northeast of the map area. Te Waka Formation continued to accumulate along Te Waka Range.

In the axis of the forearc basin to the south of the map area Lower Mangapanian limestone accumulated over basement in the vicinity of Ongaonga-1 and Takapau-1. In Hawke Bay-1, middle shelf deposition continued uninterrupted from the Waipipian into the Mangapanian. Mangapanian strata in this well section are mostly sandy siltstone lithofacies, although a 12 m-thick interval of coquina limestone was reported, suggesting the development of a carbonate factory on the structure (BP Shell Aquitaine Todd Petroleum Development Ltd 1976).

During the Upper Mangapanian (c. 2.48 Ma) the first influx of Torlesse greywacke conglomerate occurred in the basin, represented by the Deep Stream Member (Matahorua Formation). The four conglomerate beds in the formation mark basinward progradation of a fluvial braidplain during sea level lowstand conditions. By the earliest Nukumaruan the braidplain extended from Tutaekuri River in the south to Willowflat Road in the north.

Te Waka Formation is overlain by Pohue Formation and both formations young to the southwest. Pohue Formation began accumulating during the lower Waipipian in the Maungaharuru Range area, while Titiokura Formation accumulated around the Te Waka Range area. By the Lower Mangapanian, Te Waka Formation in the Te Waka Range area was being overlain by Pohue Formation. Te Onepu Limestone was deposited along the Raukawa Range area during this time.

Although cyclothemetic succession are evident in Upper Opoitian - lower Waipipian parts of Titiokura Formation (Bland et al. 2004), prominent cyclothemetic intervals became evident in the sedimentary record in the Te Waka and

Pohue Formations, although they are difficult to map.

### **Nukumaruan (2.4 - 1.63 Ma)**

The Nukumaruan was characterised by the development of cyclothemetic intervals in parts of the basin succession and uplift in the North Island Shear Belt and accretionary wedge. Regular sea-level oscillations of about 60 - 70 m occurred throughout this stage (Naish and Kamp 1997). The eastern margin was probably a continuous ridge during this time. The seaway was open at its northern and southern ends during lower parts of the Nukumaruan, although the southern end was closed during the Upper Nukumaruan. Limestone deposition is recorded from both the lowermost and upper parts of the stage, although it is absent from middle parts. Terrigenous sediment flux was high throughout this stage at 0.3 - 2.6 m/ka. The basal Nukumaruan records the short-lived northward migration of elements of sub-antarctic fauna into southern North Island.

In the lowermost Nukumaruan, limestone of the Sentry Box Formation was deposited along the western margin of the basin from Ohara Depression to Kuripapango. Further north, cyclothemetic shelfal beds of the Matahorua Formation (Papakiri and Grassy Knoll Conglomerate Members) were deposited. The presence of shallow-marine Sentry Box Formation preserved on the Ruahine and Kaweka Ranges demonstrates that these basement areas were mostly submarine during the lower Nukumaruan. In the Ohara Depression, Sentry Box Formation overlies Puketitiri Formation. The contact is gradational in central parts of the depression and unconformable in northern parts, indicating shallower water conditions in the northern area (Erdman and Kelsey 1992). The deposition of thick greywacke conglomerate beds in the Matahorua Formation during this time indicates that a substantial area of basement hinterland must have been at the surface. The fluvial braidplain of Matahorua Formation was at its greatest extent during the lowermost Nukumaruan, extending from Waiwhare in the southwest to at least Willowflat Road in the northeast. Coevally, along the eastern side

of the basin, Scinde Island Formation, Mason Ridge Formation, and Pakipaki Limestone were deposited on and around structural highs inferred to be associated with the accretionary wedge. Taradale Mudstone accumulated at shelf water depths in axial parts of the basin.

During the Lower Nukumaruan the Wakarara Range was semi-emergent and deposition of Mount Mary Pebbly Limestone occurred around its flanks. Rapid subsidence occurred across this part of the map area during 2.36 - 2.3 Ma. The focus of subsidence appears to be around the Ohara Depression, where shallow marine Sentry Box Formation is abruptly overlain by upper bathyal (c. >200 m) Esk Mudstone (Beu et al 1977). Subsidence of the northern part of the Wakarara Range allowed Esk Mudstone to accumulate over both Mount Mary Pebbly Limestone and Torlesse basement. In the Esk River area, Grassy Knoll Conglomerate Member was overlain by Esk Mudstone and farther north Esk Mudstone accumulated over Waipunga Formation. Sedimentation rates of c. 2.6 m/ka in the Ohara area during accumulation of Esk Mudstone decreased to c. 0.5 m/ka in the Tangoio Block. Immediately northeast of the map area, Upper Mangapanian inner shelf sandstone in the lower reaches of Mohaka River are overlain by Lower Nukumaruan redeposited sandstone indicating high rates of subsidence in the basin axis north of the map area. Shelf carbonate accumulated during the lower Nukumaruan on antiforms as Scinde Island Formation, Mason Ridge Formation and Pakipaki Limestone. Taradale Mudstone continued to accumulate around the Napier and Maraekakaho areas in axial parts of the forearc basin until about 2.15 Ma.

Esk and Taradale mudstones accumulated across the axial parts of the basin through the Lower Nukumaruan. The Wakarara Range was partially emergent by 2.15 Ma, however the main uplift of this range probably didn't occur until after deposition of the Poutaki Formation (Erdman and Kelsey 1992), estimated to be about 1.7-1.6 Ma. Uplift of the Wakarara Range centred on displacement on the Big Hill-Ohara Depression section of the Mohaka Fault, resulted in deposition of Kereru Formation around and

upon the range flank. During sea-level lowstands after 2.15 Ma a braidplain extended from Ohara Depression northeast to Flag Range and Mount Cameron, accumulating as Kikowhero and Whakamarumaruru Members (Okauawa Formation). At the same time another fluvial system prograded across the Tangoio Block as far southwest as Glengarry Road. Conglomerate beds in the Tutira and Darkys Spur Members were deposited by this alluvial fan. It is inferred that the two systems then merged into one system resulting in the Flag Range Conglomerate Member (Petane Formation; c. 1.84 Ma). 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).

The Tutira Member is overlain by Hikuroa Pumice Member, recording the influx of volcanoclastic material into the basin. It is possible that the Hikuroa Pumice Member may be the result of the eruption of either the Waiteariki Ignimbrite from the Kaimai Volcanic Centre, or one of the Papamoa Ignimbrites from the Tauranga Volcanic Centre, both described by Briggs et al. (2005).

Along the inboard parts of the accretionary wedge, structural highs at Taradale, Fern Hill and Roys Hill began to rise. By c. 2.1 Ma the Taradale, Fern Hill, and Roys Hill areas had reached a point where carbonate factories developed upon them and the Park Island Limestone Member was deposited during regressive and transgressive parts of a sea-level oscillation. It is inferred that the highs became subaerially exposed during sea-level lowstand. Around the location of Whakatu-1, Taradale Mudstone continued to accumulate, although to the north and west shelfal beds of Okauawa and Petane Formations accumulated.

By the Upper Nukumaruan, the western shoreline was probably heavily indented, with numerous bays, estuaries and harbours, particularly during periods of sea-level lowstand when the braidplains were at maximum basinward extent.

Marine sedimentation in much of the map area ended during the Upper Nukumaruan (about 1.7 - 1.6 Ma), the emergence recorded by the varied lithofacies in the Kaiwaka and Poutaki Formations. The Matapiro area probably remained marine longer than in the Tangoio Block and Napier-Puketapu areas, judged by the presence of thick Puketautahi Limestone Member of Kaiwaka Formation.

### **Castlecliffian (1.63 - 0.34 Ma)**

The Castlecliffian was characterised by the deposition of thick, non- to marginal-marine beds, dominated by thick conglomerate beds.

The Big Hill Fault had developed in the Lower Castlecliffian, elevating the Big Hill block. At about 1.1 Ma the Ruahine Ranges began to be uplifted and eroded. This coincides with the time the Big Hill Fault started to accommodate some strike-slip displacement (Erdman and Kelsey 1992). Herricks Syncline and Anticline, and the Matapuna Fault are other contractional structures in Ohara Depression. The Balcony Syncline probably formed due to uplift of the Wakarara Range on the Big Hill-Ohara section of Mohaka Fault. The Wakarara Fault slipped as the Wakarara Range was uplifted. Rocks along the eastern margin of Wakarara Range became involved in the Wakarara Monocline. To the north in the Kuripapango area, the Miroroa Thrust (described by Browne 1986) was probably active during this time. It was interpreted by Beanland (1995) as a cross-fault or relay structure between Comet Fault and Ruahine Fault.

The Uplift of Ruahine and Kaweka Ranges led to an influx of greywacke detritus into the forearc basin, itself being mildly folded and uplifted. The depocentre in the Kidnappers area, which was emergent during the Nukumaruan (expressed as an angular unconformity between the Waipipian Black Reef Calcareous Sandstone (Mangaheia Group) and the Castlecliffian Maraetotara Sandstone (Kidnappers Group)), became a subsidiary basin to the principal forearc basin during the Middle Pleistocene from about 1 Ma. River systems with catchments in the Ruahine Range and Kaweka Range also formed during the Middle Pleistocene and transported gravel

to form the beds within the Kidnappers Group in the Ruataniwha Plains area, on the western flank of Te Mata Peak and across the Heretaunga Plains.

