STRATIGRAPHY AND SEDIMENTOLOGY OF PLIOCENE LIMESTONES IN NORTHERN HAWKE'S BAY: THE OPOITI, WHAKAPUNAKE AND TAHAENUI LIMESTONES

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"The true geologist will never spare himself when his work is in question. He must be prepared to work long hours, to endure cold and heat and wet and hunger, and at times risk life and limb (though not without consideration of the advantage to be gained). He should allow no difficulty that can be overcome to stop him. Streams must be forded, precipices climbed, tent and clothes and food swagged many miles up and down stream, through bush, up mountain sides…"

Percy Gates Morgan, 1920, *Instructions to the field officers.*

Everything I am, Everything I long to be,

I lay it down at Your feet

-Song lyrics by Matt Maher

ABSTRACT

The Opoiti, Whakapunake and Tahaenui Limestone formations (Opoitian to Waipipian; Pliocene) crop out extensively in northern Hawke's Bay between Wairoa and Mahia Peninsula where they are encased within mudstone dominated Wairoa Formation. The limestones are shallow cool-water carbonates that formed about tectonically active antiform structures inboard from the convergent subduction plate margin along eastern North Island. Their coarse skeletal fraction is dominated by barnacle plates with common brachiopod, pectinid and oyster remains. The carbonate factory for prolific skeletal production was likely sited in shoal water (30-60 m deep), high energy conditions atop the antiforms, with deposition from carbonate shedding down the flanks of the antiforms and even into the bounding synforms.

The individual limestone units are laterally discontinuous and perceived as large lenses (up to c.3-4 km long by c.2 km wide). The enclosing thick mud-rich (M1-M4) to locally sandy (S1-S4) lithofacies, along with occasional volcaniclastic beds (V1), are here informally recorded as Wairoa Formation A, B, C or D, depending on their stratigraphic position with respect to the three limestone units.

Stratigraphic logging of sections at Nuhaka (Tahaenui/Clonkeen), Mt Moumoukai and on Mahia Peninsula established 12 sedimentary lithofacies based on field texture and composition, namely limestones (L1-L3), sandstones (S1-S4), mudstones (M1-M4), and a volcaniclastite (V1). The lithofacies discriminate well on triangular plots involving carbonate content and insoluble sand, silt and clay grain sizes and typically show vertical similarities between field sites for each limestone, suggestive of similar depositional patterns and controls operating at the different localities.

Opoiti Limestone occurs on Mahia Peninsula and Mt Moumoukai as a bedded, c.30 m thick, moderately dipping (25^{o} W), siliciclastic sand-rich unit with common brachiopods and mudstone clasts (L1, L2, L3) that unconformably overlies late Miocene mudstone (M1). Petrography ranges from a sandy biomicrite to a variably sandy, poorly washed rounded biosparite or bioclastic arenite in which interskeletal space is occupied mainly by microbioclastic micrite with some isopachous sparite. Carbonate content is up to c.75%; siliciclastic grains range from very fine to fine sand size. The Opoiti Limestone is likely a

transgressive event deposit (TST), fining upwards into sandstone and mudstone (HST) of Wairoa Formation B, and largely under tectonic control.

Whakapunake Limestone within the field area is restricted to the west coast of Mahia Peninsula where it is c.40 m thick and comprises limestone (L3) units (10-100 cm thick) interbedded with unique mudclast-bearing shelly sandstone (S4) units (20-100 cm thick). These couplets may be related to storm emplacements although their origin, and that of the mudclasts, remains problematic. The elongated mudclasts possibly mark the positions of original *Skolithos/Ophiomorpha*-like burrows that have been later modified by seismic shaking. No lower contact was observed. Upwards, the limestone grades via interbeds into shelly sandstone (S2) and mudstone (M1). Petrography ranges from packed biomicrites to poorly washed biosparites, while the sandstone interbeds are typically muddy bioclastic arenites. Cements are isopachous sparite rims and microbioclastic micrite with common siliciclasts. Carbonate contents range up to c.70% with the siliciclastic grains being of medium silt and fine sand size. The Whakapunake Limestone is likely a transgressive deposit (TST) fining upwards into shelly sandstone (TST/HST) of Wairoa Formation C, again overall tectonically driven but with possible superimposed eustatic sea level changes.

Tahaenui Limestone (L1, L3) occurs in discrete outcrops (10-30 m thick) across the full area. At Nuhaka, it unconformably overlies late Miocene mudstone (M1), while the upper contact grades into shelly sandstone (S2). At Moumoukai, it unconformably onlaps the Opoiti Limestone. It is dominated by coarse barnacle plates with interparticle isopachous sparite rims and microbioclastic micrite. Petrographically the limestone ranges from rounded biosparite to packed biomicrite. Carbonate content is up to 90%, with the siliciclastic grains being of fine-medium silt and fine sand size. The Tahaenui Limestone is overall a transgressive deposit (TST) fining upwards into shelly sandstone and mudstone (HST) of Wairoa Formation D, largely under tectonic control.

The Pliocene limestones are economically important as potential subsurface petroleum reservoirs, as a lime resource for agricultural use and as a hard stone source for aggregate. Recommendations of the immediate economic potential for development include local aggregate and fertiliser sources from the Tahaenui Limestone at Nuhaka and Mahia.

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Maree Southward

Jane Lodge

Jonathan Drinnan

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CHAPTER ONE – INTRODUCTION AND AIMS

1.1 THESIS RATIONALE

The Opoiti, Whakapunake and Tahaenui limestones crop out extensively in the vicinity of Wairoa and locally on Mahia Peninsula in northern Hawke's Bay (Figure 1.1). They are the northern equivalents of other widespread sheets of limestone extending south through eastern North Island into Wairarapa, all part of the regional Pliocene age Te Aute limestones (Beu 1995; Nelson *et al.* 2003). The structurally complex East Coast Basin (ECB) in which the limestones are contained is a result of active convergence and subduction at the Pacific - Australian plate boundary just offshore eastern North Island (Figure 1.1).

Figure 1.1 - New Zealand's North Island, showing locality of Hawke's Bay region, Wairoa and Mahia Peninsula. Red line shows convergent plate boundary, with arrows indicating subduction direction. East Coast Basin boundaries are taken from Crown Minerals (2003, p. 52).

How and why the limestones formed in such an active tectonic setting is an important aim of the research. Also important is an understanding of the compositional make up of these limestones and the diagenetic processes that converted the original unconsolidated carbonate sediments into lithified limestones.

Following detailed sedimentological descriptions of the limestone units and their associated strata, a sequence stratigraphic approach has been considered in an attempt to unravel the interplay between tectonics, sea level shifts, climate change and sediment supply rates on their formation and distribution.

The limestone units are economically important as potential subsurface petroleum reservoirs, and as a hard stone source for aggregate (Francis 1993b). The Wairoa district, being relatively remote, includes few good quality road metal resources, and would benefit from additional aggregate quarries. Additionally, the limestones are a potential source of lime for production of cement and fertiliser.

The New Zealand Geological Timescale of Cooper (2004), recently updated by Hollis *et al.* (2010), is used as the basis for the New Zealand stage names and their absolute ages in this study (Appendix I).

The wide geographical spread of the Pliocene limestones in northern Hawke's Bay necessitated their study be divided into two separate, but adjoining areas: in the western part, north of Wairoa, which is being undertaken by MSc student colleague Jared Jiang; and in the east, in the vicinity of Mahia, reported in this thesis.

1.2 THESIS OUTLINE

Chapter One (Introduction and Aims) introduces the area and topic of this project and outlines its specific aims. Chapter One also provides a tabulated summary of some of the earlier work that has been carried out within the immediate study area, within the wider Hawke's Bay region, and that relating to the Te Aute limestones in general.

Chapter Two (Methodology) discusses the various field and laboratory methods employed in the course of the study.

Chapter Three (Geological Setting) describes the larger geomorphic and tectonic framework of the geology that underpins the immediate study area. It introduces the lithostratigraphy and chronology of the main rock units and their distribution in the regional geological landscape, as well as the broadscale geological development of the region through to the present day.

Chapter Four (Pliocene Stratigraphy and Lithofacies) analyses the Pliocene lithostratigraphy and facies groups defined in the field for the northern Hawke's Bay region. This is based on detailed study at three main field sites, in the vicinity of Tahaenui/Clonkeen, Mt Moumoukai and on Mahia Peninsula (Figure 1.2). The chapter includes relevant geological maps and stratigraphic columns.

Chapter Five (Opoiti Limestone), Chapter Six (Whakapunake Limestone) and Chapter Seven (Tahaenui Limestone) describe the field and petrographic characteristics of each of the three limestone units. The chapters include their lithostratigraphy, contact relationships, fossil content and laboratory properties. An initial paleoenvironmental analysis is made for each limestone unit.

Chapter Eight (Depositional Paleoenvironments and Diagenetic Evolution) examines the depositional processes and controls for the carbonate deposits. It suggests how the limestones and surrounding lithologies accumulated, and the factors that could have influenced this. The chapter includes an interpretation of possible paleoenvironments.

Chapter Nine (Sequence Stratigraphy) uses the concept of sequence stratigraphy to develop the geological history of the wider region. Theoretical sequence stratigraphy is first described, followed by possible suggestions for a sequence stratigraphic model for the actual stratigraphy in the Nuhaka/Mahia areas.

Chapter Ten (Economic Potential) discusses the hydrocarbon potential of the wider East Coast area, followed by particular focus on the aggregate, hydrocarbon and agricultural lime potential of the study area. Current economic development is outlined with some brief economic recommendations made.

Chapter Eleven (Summary and Conclusions) recaps the main findings of this research. In particular, the chapter summarises the stratigraphy, lithofacies, petrography and depositional models for the Pliocene limestones in the Mahia/Nuhaka area.

1.3 STUDY AREA

In the vicinity of Mahia, the Opoiti, Whakapunake and Tahaenui limestones crop out mainly in three separate areas: Tahaenui/Clonkeen, Mt Moumoukai and west coast Mahia Peninsula (Figure 1.2).

The Tahaenui/Clonkeen area is primarily farm land and is approximately 16 km^2 in size. It hosts very steep to undulating hills and a central flat alluvial river plain. Two intermittently working quarries are located here - the Tahaenui Quarry at the end of Kokohu Road, and the Clonkeen Quarry further north on Mangaone Road (Figure 1.2 B). The accessibility of outcrop is mainly quite good, but is lacking in the northwest of the area.

Mt Moumoukai is a prominent topographical feature, with vertical bluffs separating it from the surrounding undulating topography (Figure 1.2 C). The total area is approximately 6 km^2, with the main summit plateau being almost 1 km across. A small natural spring is located on the summit plateau. Its maximum height is at 611 m above sea level (Land Information New Zealand 2009a). The bluffs provide good geological visibility, but impose a problem for rock sampling. Accessibility to the main summit is only by the northwestern face, where a gentle slope is the only break from bluffs. Mt Moumoukai has been recently sold to Swedish owners who currently live overseas, but is still considered tapu to the local Maori people (*pers. commun*. 2009). A Maori legend of war and taunting includes the mountain, and a supposed cave exists at its summit (Pishief 2002; Walker 2008) (included as Digital Appendix A on the accompanying CD).

The third area encompasses the west coast of Mahia Peninsula, from Long Point extending south to Hekerangi Point (Figure 1.2 D). Mahia Peninsula as a whole occupies approximately 150 km^2, with the west coast study area being about 20 km^2 (Land Information New Zealand 2009b). The field area ranges from steep inland hills to flat coastal terraces, which bluff out at the coastline. One intermittently working quarry is situated adjacent to Kinikini Road. Bare geological outcrops are scattered and numerous, but accessibility can be limited along the coast, and in the particularly steep terrain.

Table 1 identifies some key land owners and farm workers in the Nuhaka and Mahia areas.

Table 1.1 - Various land owners and farm workers in the Nuhaka/Mahia area.

Name	**Address**	**Land**	**Phone**
Tahaenui/Clonkeen			
Will and Lucy de Lautour	196 Nuhaka Opoutama Road, Nuhaka	Owns the Tahaenui Quarry/Kokohu Road area	06 8378696
Rex MacIntyre	Clonkeen Station, Mangaone Road	Owns land in the Clonkeen area, Mangaone Road	
Don Bradley	Mangarara Farm, Kokohu Road	Owns the south east of Kokohu Road	
Jeremy	Kokohu Road	Farm worker at Tahaenui	
Mt Moumoukai			
'Minty'	2803 State Highway 2	Farm worker near Mt Moumoukai	
Quentin	4279 Morere Road	Works/owns land south of Mt Moumoukai	
Swedish residents	Mangatoto Station, State Highway 2	Owns Mt Moumoukai	
Mahia Peninsula			
Dieter and Elizabeth Dallmeier	Ahimanawa Station, end of Kinikini Road	Owns land around the end of Kinikini Road	06 8375058
Poppy Ormond	Kinikini Station	Owns Long Point and Kinikini Station area	06 838 3350
Pete and Anne Haynes	Reef Station, Mahia East Coast Road	Owns west of Reef Station	027 4493 3213
Len and Sally Symes	Kinikini Road	Works land north of Long Point	06 8375659

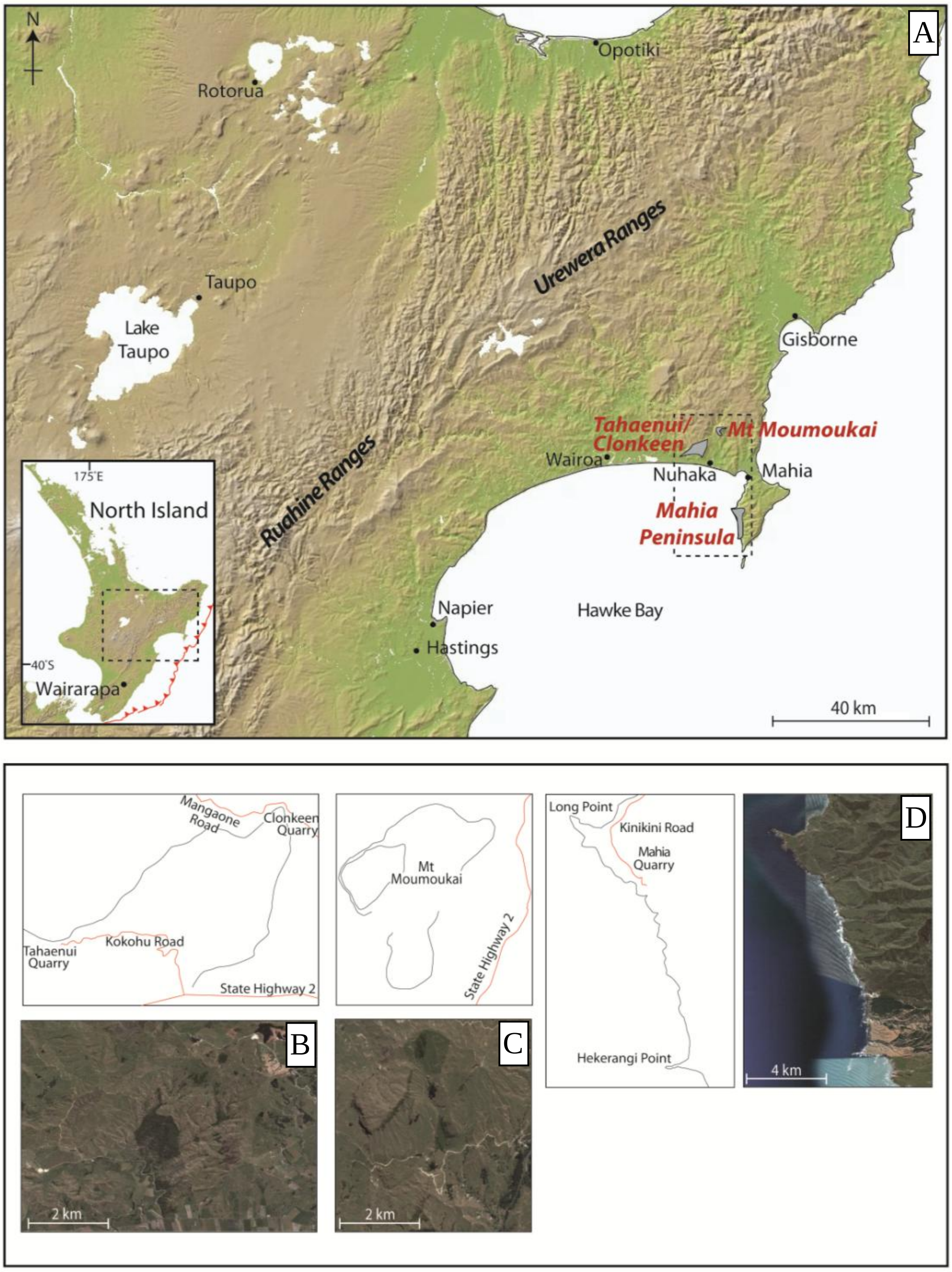


Figure 1.2 - **(A)** Locality map of the wider Hawke's Bay region and immediate field area sites outlined in grey. Inset: Dashed box shows Hawke's Bay location within the North Island and subduction zone in red. **(B)** Tahaenui/Clonkeen. **(C)** Mt Moumoukai. **(D)** Mahia Peninsula. Satellite images from Google Maps (2010).

1.4 PREVIOUS RESEARCH

Table 1.2 lists the main first authors of some selected research undertaken in the East Coast Basin of North Island. The list is partial only and is designed mainly to highlight some of the key articles particularly relevant to the immediate Mahia Peninsula area. It is certainly not a comprehensive list of all studies carried out in the area. Authors are alphabetical within the general research categories shown. Some research is truly regional while others are much more locally based with specific information on a particular area. Particular research areas of Pliocene limestones, structure, tectonism, mapping and economics are included. Note some research topics may fall under more than one category but are here divided based on the primary topic. The study areas of the entries in Table 1.2 are summarised in Figure 1.3.

Table 1.2 - First authors of a selection of geological studies in the East Coast Basin. Note that this is not a comprehensive list of all studies carried out in the area (e.g. see Field *et al*. 1997; Mazengarb & Speden 2000).

Author	***Date***	***Area***	***Topic***
Regional structure and geology			
Barnes, P.M	2004	Hikurangi Margin	Tectonic structural inversion
Begg, J.M	2002	Southern Hawke's Bay	Geology of the Wairarapa area
Bland, K.J	2007	Central Hawke's Bay	Lithostratigraphy of the Neogene succession
F. Chanier, F	1991	Hikurangi Margin	Geological processes of an accretionary prism
B.D Field, B.D	1997	East Coast region	Cretaceous - Cenozoic geology and petroleum
Kingma, J.T	1971	East Coast region	Geology of Te Aute subdivision
Lewis, K.B	1993	Hikurangi Margin	Frontal wedge of the Hikurangi Margin
Lillie, A.R	1963	Wairarapa	Geology of Dannevirke Subdivision
Mazengarb, C	2000	Raukumara	Geology of the Raukumara Area
McKay, A	1887	Northern Hawke's Bay	Geology of Auckland and northern Hawke's Bay
Smith, S.P	1876	Northern Hawke's Bay	Initial geological mapping and research
Pliocene stratigraphy			
Baggs, R.A	2004	Central Hawke's Bay	Cyclothemic Petane Group deposits
Beu, A.G	1995	East Coast region	Pliocene limestones and palaeontology
Beu, A.G	1980	Hawke's Bay region	Te Aute limestone facies

Bland, K.J	2001	Central Hawke's Bay	Pliocene forearc basin succession
Caron, V	2002	Southern Hawke's Bay	Petrogenesis of Pliocene limestones
Caron, V	2004	Central Hawke's Bay	Pliocene carbonate depositional systems
Dyer, S.D	2005	Central Hawke's Bay	Sedimentary cyclothemic deposits
Graafhuis, R.B	2001	Northern Hawke's Bay	Stratigraphy of Pliocene strata
Harmsen, F.J	1984	Southern Hawke's Bay	Sedimentology and diagenesis, Te Aute Group
Kamp, P.J.J	1988a	Hawke's Bay region	Barnacle-dominated limestone, forearc seaway
Kamp, P.J.J	1988b	East Coast region	Occurrence of active margin limestones
Nelson, C.S	2003	East Coast region	Pliocene Te Aute limestones
Ricketts, B.D	2004a	East Coast region	Diagenesis of Te Aute limestones
Local structure and geology			
Berryman, K.R	1993	Mahia Peninsula	Deformation of Holocene marine terraces
MacPherson, E.O	1927	Northern Hawke's Bay	Geology of the Morere/Mangaone areas
Ricketts, B.R	2004b	Northern Hawke's Bay	Lachlan Basin landward submarine slumping
Webb, C	1979	Mahia Peninsula	The Geology of Eastern Mahia Peninsula
Economics			
Brown, B.R	1960	Northern Hawke's Bay	Mangaone-1 well report
Francis, D.A	1993a	Mahia Peninsula	Geological report
Francis, D.A	1993b	Northern Hawke's Bay	Geological report of the Mangaone area
Ian R Brown Ass.	1998	Northern Hawke's Bay	Opoho-1 well report

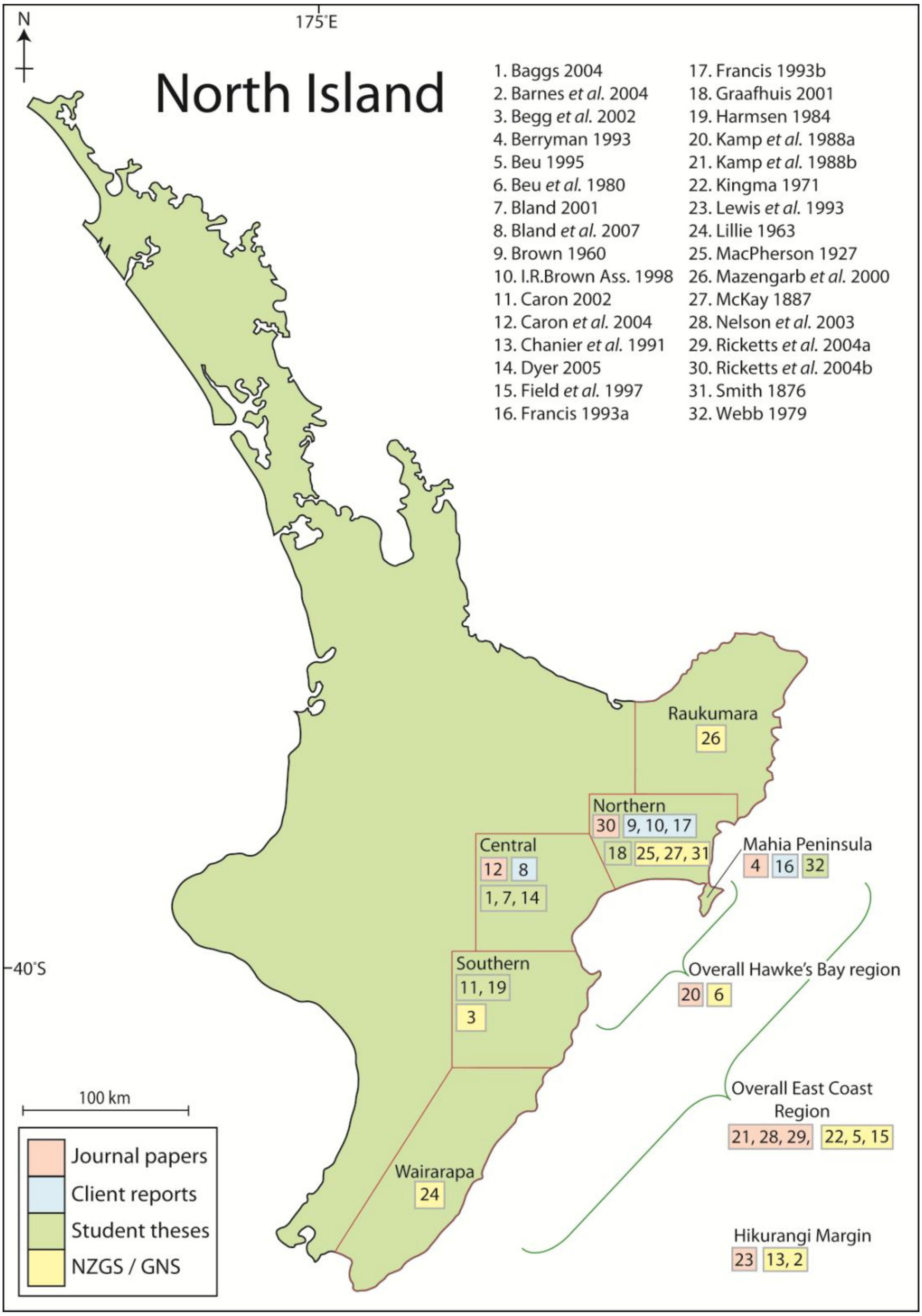


Figure 1.3 - The East Coast region of North Island, showing general research areas of the authors listed in Table 1.2. Different coloured boxes denote nature of research.

1.5 AIMS OF PROJECT

The overall aim of this MSc research project is to build a better understanding of the Pliocene limestones in the northeastern Hawke's Bay region. The study is part of an extensive sedimentary geological research programme in the onshore central East Coast Basin that has been underway for the past decade or so in the Department of Earth and Ocean Sciences at the University of Waikato (see student theses in Table 1.2).

The specific objectives of the present study are:

- To determine the distribution and stratigraphy of the Pliocene geological units in the vicinity of Mahia in northern Hawke's Bay.
- To determine a finite number of field lithofacies for these Pliocene strata, especially for the limestone deposits, and to infer their depositional conditions.
- To analyse the petrographic characteristics of the limestones, including their diagenetic properties, and suggest possible paleoenvironments of formation.
- To reference the observed field stratigraphy within a potential sequence stratigraphic framework.
- To consider the economic importance of the Pliocene limestones, as both immediate and potentially future resources.

CHAPTER TWO – METHODOLOGY

2.1 FIELD WORK

Six weeks were spent in the field over the summer 2009/2010 period during which time 232 rock samples were collected with a geological hammer or a chisel and sledge hammer combination. Samples were individually numbered according to the order of visited sites, and were separately given a New Zealand grid reference using a hand held GPS instrument (Garmin), as well as physical location, elevation and a lithological description. Twenty nine stratigraphic column locations were also labelled in this way. Field characteristics were described based primarily on Andrews (1982) and Kidwell (1991a, b). Several fossil specimens were collected from each lithological unit for later identification. Sample and stratigraphic column localities are shown in Appendix II. A descriptive sample log is held in Digital Appendix B, with extra field images in Digital Appendix C.

Accompanying maps in the field were the New Zealand 1:50,000 260 Topo Series maps X19 (Wairoa) and X/Y20 (Mahia), and the 1:250,000 scale geological map of Raukumara Peninsula (Mazengarb & Speden 2000). Localities were marked on a contoured base map created using the University of Waikato's GIS contour database. Field localities were identified using a Garmin GPS instrument set to the New Zealand 260 Series. All localities were later converted, using New Zealand Map Reference Converter computer software, to the latest New Zealand 1:50,000 Topo 50 series, so that the most recent New Zealand map grid units are used in this thesis.

Field assistance was provided on occasions by Jonathan Drinnan, Jane Lodge or Maree Southward. Accommodation was primarily in shearer's quarters and at tent-sites (Table 2.1).

Table 2.1 – Contact information for the accommodation used while undertaking geological field work in the Nuhaka/Mahia Peninsula area.

Name	**Address**	**Type**	**Phone**
Will and Lucy de Lautour	Kokohu Road	Shearers quarters	06 837 8696
Mahia Beach Motels and Holiday Park	43 Moana Drive, Mahia Beach	Camping ground	06 837 5830
Morere Tea Rooms and Camping Ground	3983 State Highway Two, Morere	Camping ground	06 837 8792

2.2 LABORATORY WORK

A flow chart summarising various sample preparation and laboratory methods is shown in here Figure 2.1.

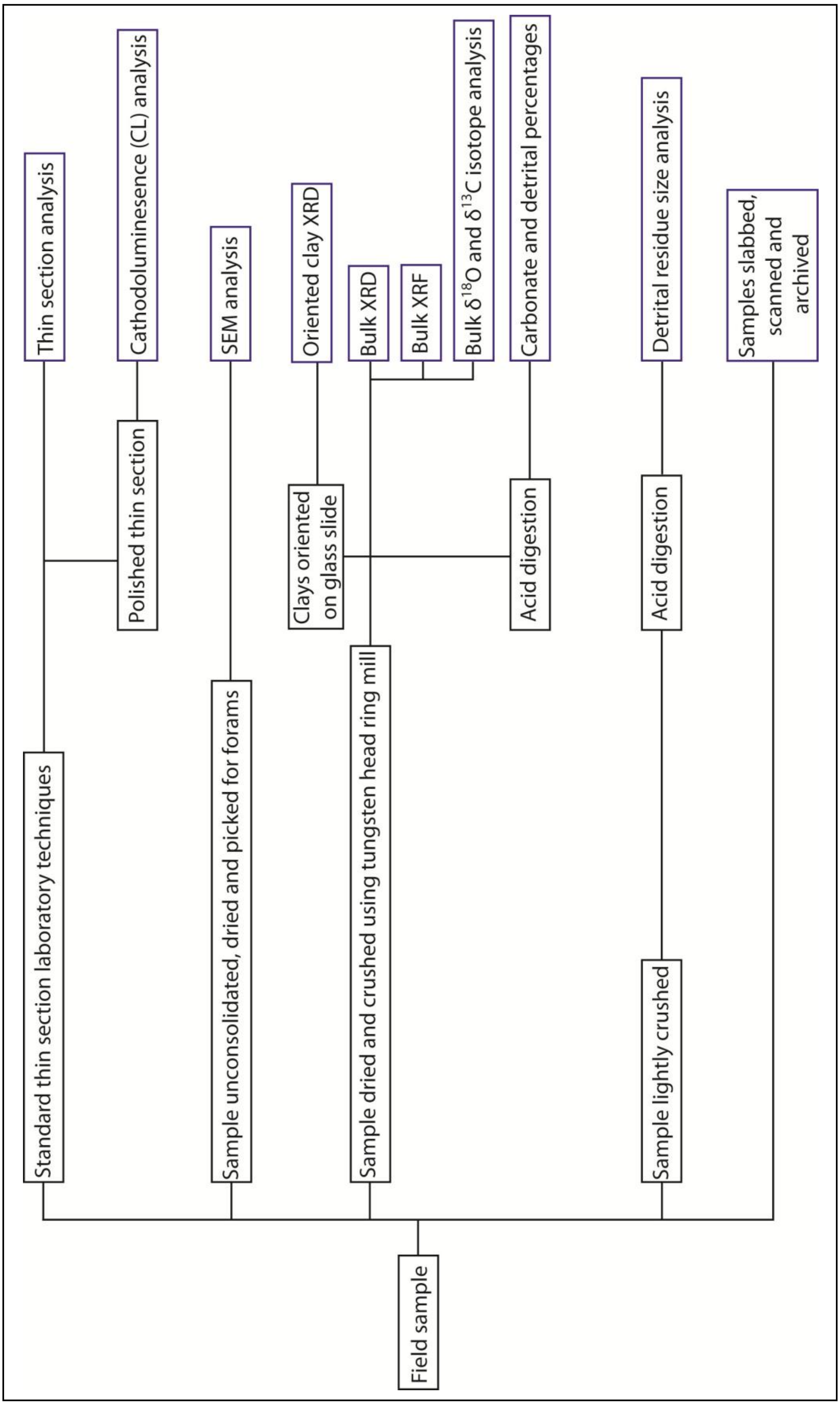


Figure 2.1 - Flow chart depicting the laboratory methods applied to samples in this study. Blue boxes denote end product.

2.2.1 Thin section preparation

A representative suite of c.200 rock samples was selected for petrographic analysis. These samples were first cut with a diamond tooth saw into approximately 5 x 2 x 2 cm blocks and numbered with a black vivid pen. After drying on a hotplate at 70^{o}C overnight, the blocks were coated with Araldite K142 resin at a ratio of 5 parts resin to 1 part hardener. This reinforced weakly cemented samples. Impregnation required the blocks to be cured on a hot palate for a further 24 hours under a fume hood. Rare unconsolidated material required a 'resin bath' to be made from aluminium foil. This produced a block of cured resin with the sample trapped inside. To ensure a flawlessly even surface, and to remove excess resin, blocks were then ground using a mix of a flat grinder and carborundum (silicon carbide) 600 powder.

Glass slides for sample mounting were prepared using a Struers diamond discoplan-TS to 'frost' one side. This afforded strong adherence of the samples to the microscopically pitted surface, as well as further leveling the glass surface. Sample blocks were mounted to the glass slide using Hillquist resin in a ratio of 7 parts resin to 3 parts hardener, followed by a further 24 hours curing time on a 40^{o}C hotplate. The Struers diamond discoplan-TS was then used to first cut away the majority of the excess rock, leaving only approximately a 1 mm thick sample on the glass slide. The slide was then held by suction to a base, and ground against the diamond discoplan to a final thickness of c.0.03 mm. During grinding, the thickness of the slide was periodically checked on a petrographic microscope, with the first order interference colour of quartz (light yellow) being compared with an Interference Colour Chart. Sample numbers were etched onto the glass slides with a diamond tipped pencil.

Depending on further analysis, finished slides were either polished with a Buehler Metaserv grinder-polisher, or given a glass cover slip as protection. Cover slips were mounted using Petropoxy resin at a ratio of 10 parts resin to 1 part hardener.

An Excel spreadsheet was prepared to track the progress of each rock sample during the thin section preparation.

2.2.2 Petrography

Standard petrography under plane polarised light (PPL) and cross polarised light (XPL) was carried out primarily on an Olympus Provis AX70 microscope. Photomicrographs were taken from each sample as it was analysed using a Nikon DXM1200 microscope camera. Computer software included Nikon ACT-1. Subsequent cathodoluminescence (CL) petrography was carried out using a CITL (Cambridge Image Technology Limited) cathodoluminescence Mk5-1 instrument, a Nikon D5-5Mc camera and Nikon NIS Elements software. Operational conditions for CL work were set with the electron gun current at 350 microamps, and a voltage of 16 kV. Petrographic data and extra images are given as Digital Appendices D and E respectively on the accompanying CD.

Petrographic data sheets (Table 2.2) were constructed to record thin section observations. These allowed for a comprehensive and systematic study of each sample, including their skeletal, siliciclastic, authigenic and cementation characteristics. Abundances of different components were recorded as N – None, 0%, R – Rare, <1%, S – Some, 1-5%, C – Common, 5-25%, VC – Very common, 25-50%, A – Abundant, 50-75%, or VA – Very abundant, >75%.

Bioclast, siliciclast, authigenic, cement and pore space percentages were visually estimated using a percentage estimation chart (based on Carpenter (1987)) as reference. In analysing the limestones, Folk's (1968) classification scheme was used (Figure 2.2). Literature aiding in petrographic identifications included Folk (1968), Carozzi (1993) and especially Scholle & Ulmer-Scholle (2003).

Petrographic terminology

The term bioclasts, or skeletal grains, refers to any particle that is the organic remains of a marine shell. The siliciclastic component includes any terrigenous or marine derived non-organic, detrital material, such as quartz and feldspar. Components classified as authigenic were glauconite and pyrite. 'Pore space' refers to any void in the original rock, creating primary porosity.

The 'cement' refers to the material that bonds the loose sediments together by authigenic precipitation. Dominant cements include coarse sparite, isopachous sprite rims, homogenous/peloidal micrite and microbioclastic micrite. Sparite is formed by the growth of precipitated calcium carbonate crystals into original pore spaces (Adams & MacKenzie 1998). Coarse sparite refers to the typically equant crystals of sparite that precipitate on the rim of a substrate (skeletal grain) and can eventually infill pore spaces in a mosaic-like pattern with crystals sizes typically upwards of 30 µm (Carozzi 1993; Scholle & Ulmer-Scholle 2003). Microspar (crystals smaller than 30 µm) is not commonly seen in the Pliocene limestones. Isopachous sparite rims can occur about the inter- and intraparticle spaces, and grow in a sharp bladed or 'scalenohedral' manner (Scholle & Ulmer-Scholle 2003). Carbonate mud (micrite) is formed by the mechanical and biological break down of skeletons and their fragments, but can also form as a precipitate (Nelson 1978; Adams & MacKenzie 1998). Micrite can appear as homogenous (smooth) or peloidal (clotted/speckled) forms, but especially as microbioclastic micrite in which abundant small fragmented chips of shell remains are indiscriminately mixed in carbonate mud. Extrinsic cement refers to the cement-filled cavities inside a skeletal grain, while intrinsic cement is the cement growth that occurs externally to the grain in interparticle spaces.

Table 2.2 – Example of a petrographic table used to methodically record data.

Sample Number	**A**	**B**	**C**	**D**	**E**	**F**	**G**
Bioclast %							
Planktic foraminifera							
Benthic foraminifera							
Bryozoans							
Echinoderms							
Bivalves							
Brachiopods							
Gastropods							
Red algae							
Barnacles							
Annelids							
Other							
Maximum size (mm)							
Modal size 1 (mm)							
Modal size 2 (mm)							
Abrasion							
Size sorting							
Siliciclastic %							
Quartz							
Feldspar							
Rock fragments							
Matrix (Clays)							
Other							
Modal size 1 (mm)							
Modal size 2 (mm)							
Shape							
Sorting							
Authigenic %							
Glauconite pellets							
Glauconite infill							
Pyrite grains							
Pyrite infill							
Cement %							
Extrinsic							
Intrinsic							
Other diagenetic features							
Empty pore %							

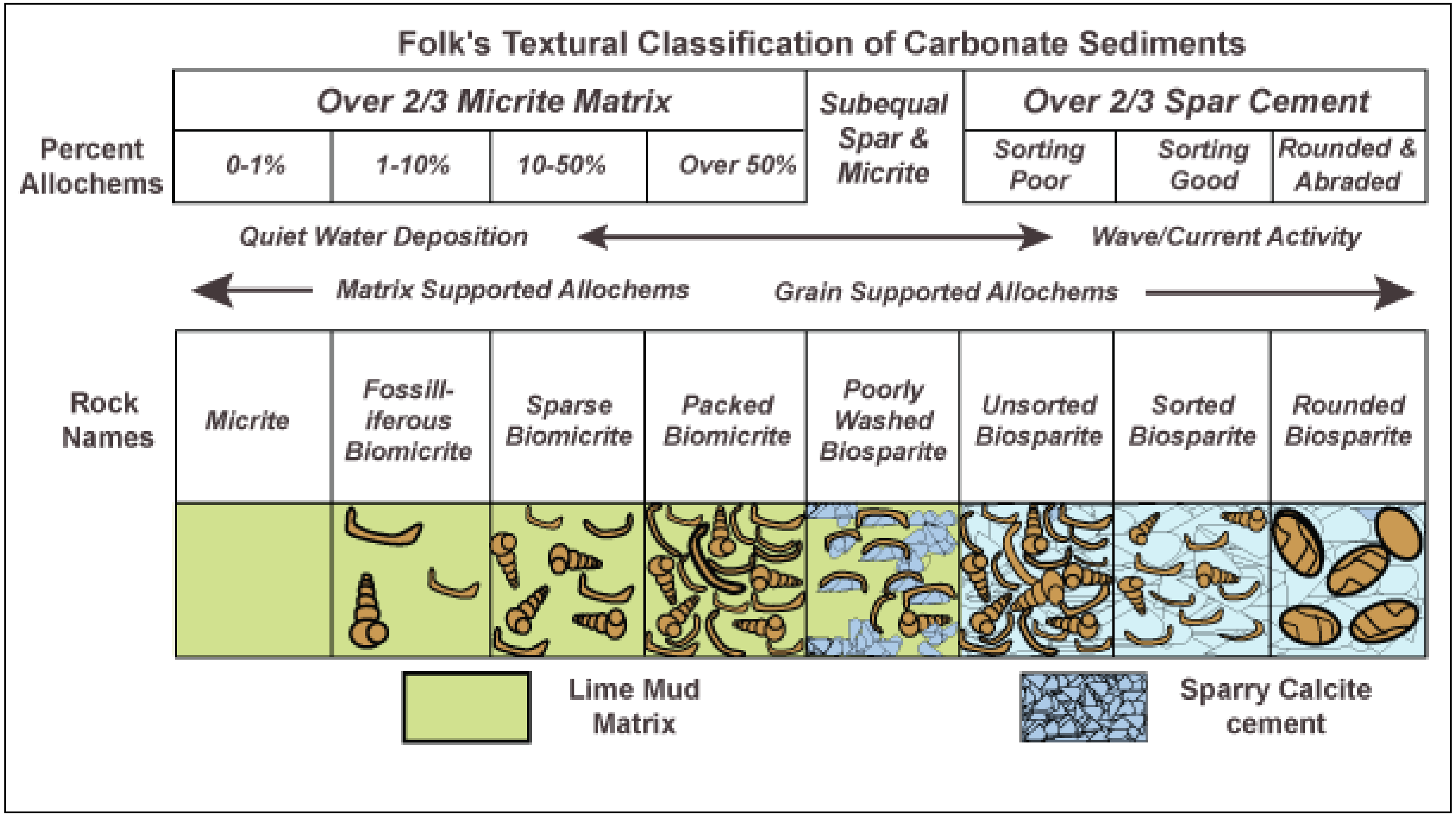


Figure 2.2 – Folk's (1968) carbonate textural spectrum used for defining petrographic characteristics of limestones in this study. Taken from C. Kendall (2011).

2.2.3 Calcium carbonate %

The content of calcium carbonate was analysed for several limestone and siliciclastic (sandstone, mudstone) lithologies. For the limestone lithofacies, this was to establish their purity. Results for the siliciclastic units allowed for a more refined understanding of their depositional paleoenvironments via insoluble grain size characteristics.

Samples were chosen that were representative of each field lithofacies. These were first powdered using a tungsten carbide ring mill so as to enable a faster acid reaction time. Approximately 10 or 5 grams of dry powder was measured into labelled 250 ml beakers and placed in a fume hood. The addition of 1 mol L^{-1} hydrochloric acid (HCl) to the powder resulted in dissolution of any calcium carbonate. Periodic stirring and small amounts of additional HCl acid acted as a catalyst to ensure all calcium carbonate was dissolved. The beakers were left to sit for an hour, after which the HCl was diluted with distilled water. The insoluble residue was then filtered through pre-dried and pre-weighed filter paper. All samples were then oven dried at 25^{o}C overnight. The calcium carbonate percentage was then calculated from the change in weight of the initial powder in relation to the weight of insoluble residue remaining. The calcium carbonate acid digestion data are given in Appendix III.

2.2.4 Insoluble grain analysis

Grain size analysis is important in aiding a more precise lithological description of units. The grain size information may also be used to help infer environments of deposition. Typically only siliciclast-rich samples are analysed in this way, however, due to the northern Hawke’s Bay limestones having a wide range of carbonate purities, the siliciclastic component of the limestones has also been analysed for its grain size distribution.

The insoluble grain size distributions were analysed using a Malvern Mastersizer-S laser particle sizer. Unlike the method for calcium carbonate percentages, samples for grain size analysis were not initially powdered as this would modify the original size of the grains. Chips from each sample were lightly crushed in a beaker, using a glass stirring rod, to gently break up the sediment. Acid digestion was then carried out to eliminate the carbonate (as in 2.2.3). Samples were left in distilled water and then transferred directly into the laser sizer. The laser sizer measures and records the percentage of the sediment that falls within certain size classes. These results can then be used to calculate the clay/silt/sand percentages, based on the Folk (1968) and Udden-Wentworth scale. Samples that had grains greater than 2 mm size (or gravel size) were first removed by sieving through a 2 mm sieve. These were later added into the clay/silt/sand/gravel calculations. Folk's (1968) grain size scale was used to interpret the grain size data (Appendix IV). Malvern Mastersizer data and graphs are held as Digital Appendix F on the accompanying CD.

2.2.5 Foraminiferal analysis

Four mudstone samples for determining foraminiferal content were immersed in a 500 ml beaker with distilled water to soften and break down. Larger pieces were lightly crushed with a glass stirring rod to encourage full disaggregation. The samples were left soaking in water overnight.

To extract the foraminifera, each sample was wet sieved through a sieve stack, generating a 150–1000 µm 'fine - coarse sand' fraction. This fraction was dried in an oven at 60˚C overnight. Once cooled to room temperature, grains were again very gently crushed with a glass stirring rod to break up any heat-derived consolidation.

Each sample was picked through using a damp fine hair brush, dividing the specimens into generalised species categories. A census slide covered in adhesive gum tragacanth was used to mount specimens, later preserved with a glass cover slip and aluminium slide. A log sheet was kept containing species and abundance (Appendix V). Foraminiferal identification was carried out with assistance from Dr. Rochelle Hansen (University of Waikato) and relevant literature (Hayward 1986; Hornibrook *et al.* 1989; Cooke 2002; Armstrong & Brasier 2005).

Images of exemplar specimens (Digital Appendix G) were then captured using Scanning Electron Microscopy (SEM) on a Hitachi S-4100 Field Emission Scanning Electron Microscope with X-ray analyser. SEM elemental analysis was carried out on three foraminiferal specimens to record their elemental composition. Data are given in relevant chapters.

2.2.6 XRD

The bulk mineralogical composition of 23 powdered samples representative of the various lithofacies was analysed on a Philips X'Pert X-Ray Diffraction machine (XRD), with X'Pert HighScore computer software. Scans were made from 2 - 42° 2θ. Subsequently, 9 special oriented slides were prepared for clay mineral analysis. Three of these samples were chosen based on the dominant clay peaks in the initial XRD run. A small amount of each of these samples was eye droppered onto three separate glass slides. One set of glass slides was air dried for 24 hours. The second set was positioned in a glass bell jar containing ethylene glycol for 24 hours, known to increase the 2θ value of smectite clays. The remaining slides were heated in a 550°C furnace for 1 hour. This was to eliminate kaolinite and decrease the 2θ value of smectite. The anticipated movement of smectite, kaolinite and chlorite peak positions under different treatments are shown Figure 2.3. XRD analysis was then carried out on all nine slides between 2 and 20° 2θ. XRD analysis used 'Configuration 2', designed for lower 2θ angles, the scan mode was continuous with a start angle at 2°, and end angle at 42° and 20°. Step size was 0.04, with time per step at 1.0 seconds. XRD peaks were identified based on tables of peak positions (Table 2.3) and 2 theta/angstrom conversion charts. XRD data are contained as Digital Appendix H on the accompanying CD.

Table 2.3 – Primary 2θ and Å peak positions of key minerals. Taken from XRD theta/angstrom charts and XRD results.

Mineral	**Degrees 2θ**	**Angstroms (Å)**
Quartz	26.62	3.35
Plagioclase	27.94	3.19
Calcite	29.42	3.03
Aragonite	26.22	3.40
Dolomite	30.9	2.89
Total clays	19.9	4.46
Illite 001	8.94	9.93
Illite 002	18.9	4.69
Chlorite 001	6.26	14.25
Chlorite 002	12.54	7.08
Kaolinite 001	12.34	7.19
Kaolinite 002	24.9	3.57
Smectite 001	5.5	16.06
Smectite 002	12.02	7.37

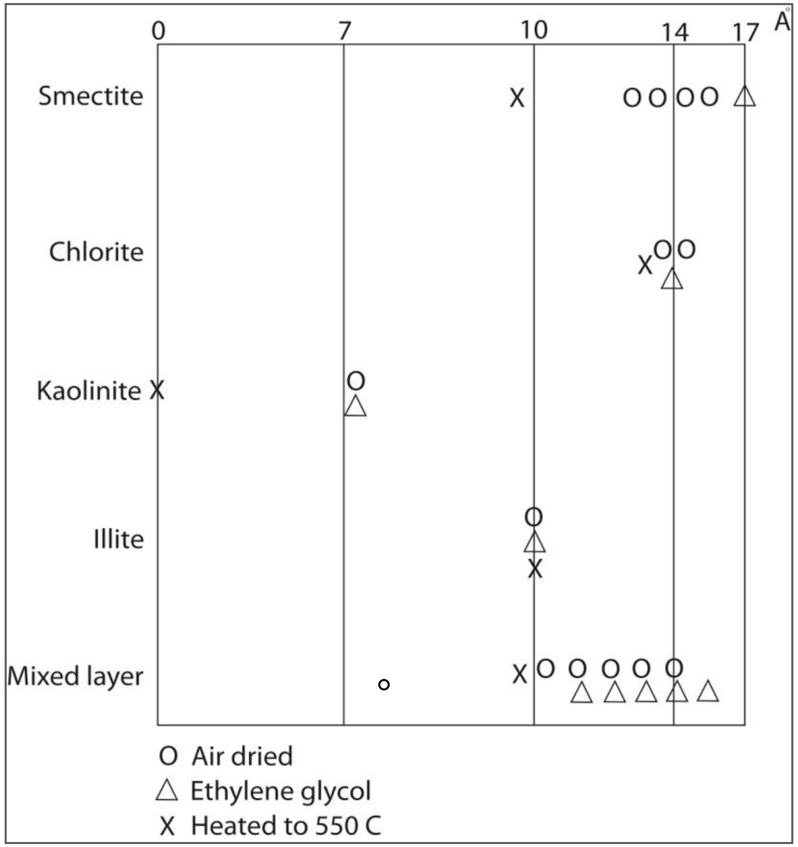


Figure 2.3 - The movement of peak positions in clay minerals when exposed to differing treatments. Adapted from University of Waikato ERTH 221 course notes.

2.2.7 XRF

The elemental composition of c.50 representative bulk samples was determined by X-Ray Fluorescence (XRF). XRF results show the elemental make up of a sample. Of particular interest in this study is the CaO content, which predominantly results from calcium carbonate. XRF results can also help identify magma type and origin of any volcanic samples by analysing SiO_2 content. This is based on Francis and Oppenheimer's (2004) classification of basalt, andesite, rhyolite and other volcanics (Figure 2.4). All XRF data are contained as Digital Appendix I on the accompanying CD.

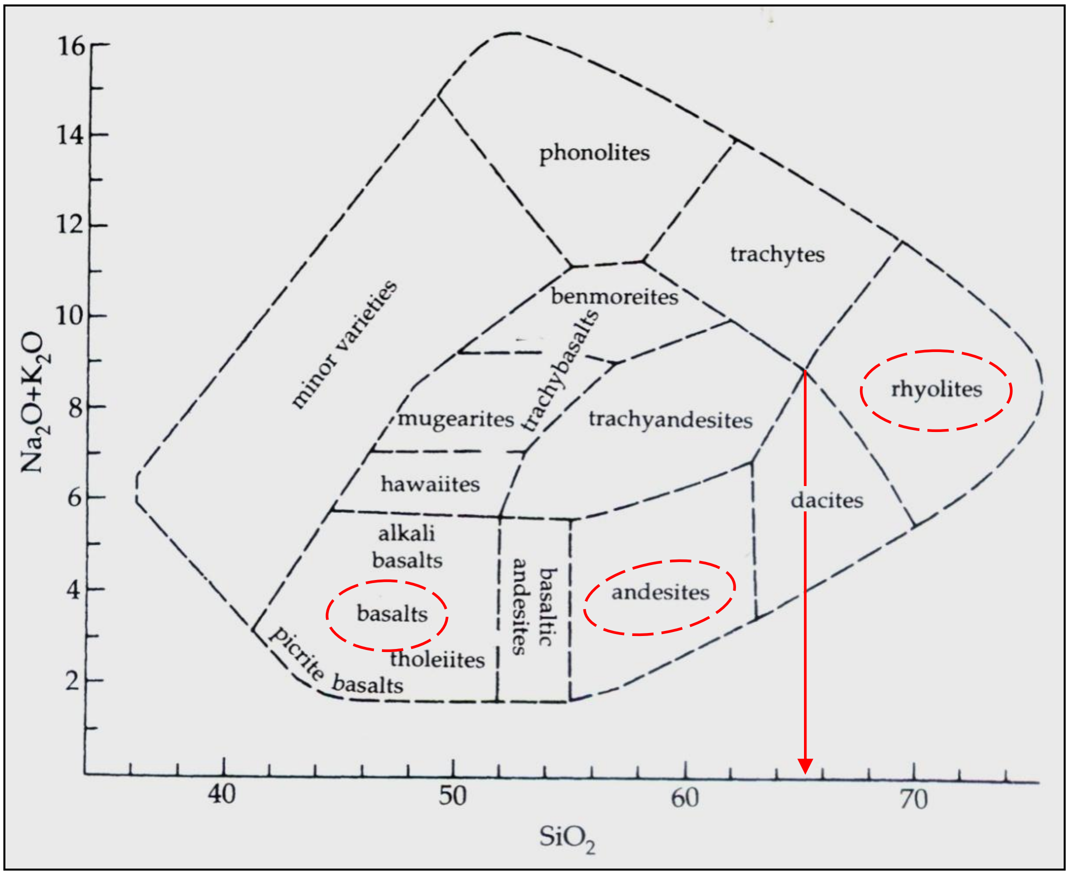


Figure 2.4 – Classification of volcanic rocks based on their SiO_2 content. Highlighted are the three primary volcanic types. Red arrow indicates the approximate rhyolitic lower limit of SiO_2 content. From Francis & Oppenheimer (2004, p. 14).

2.2.8 Stable isotope analysis

Stable isotope values are measured against the standard signature of the Cretaceous aged Pee Dee Belemnite (Vienna-PDB) that has $\delta^{18}O$ and $\delta^{13}C$ values of 0‰ (Nelson & Smith 1996). The stable isotope $\delta^{18}O$ value of carbonate can reflect the composition, salinity and temperature of the host fluid from which it arose. In addition, the stable carbon isotope of $\delta^{13}C$ can shed light on the source of carbon dioxide (CO_2) for carbonate precipitation, whether meteoric or marine water (Nelson & Smith 1996).

Stable oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotope analyses were obtained for 12 samples representative of the major lithofacies and on three skeletal samples. 0.2 mg of each of the powdered samples were secured in flat topped 0.2 ml thin walled PCR tubes, and labelled accordingly. Skeletal powders were acquired by using a Dremel Moto-tool drill with a 1 mm drill bit to directly extract powder from the skeletal component. Isotope samples were analysed at NIWA (Wellington). Here the samples were reacted with 3 drops of H_3PO_4 at 75°C in an automated individual-carbonate reaction (Kiel IV) device coupled with a Finnigan MAT253 mass spectrometer. Stable isotope data are given in Appendix VI.

CHAPTER THREE – GEOLOGICAL SETTING

3.1 REGIONAL TECTONIC SETTING OF HIKURANGI MARGIN

The Hikurangi Margin is an all embracive term for the East Coast Basin subduction system in eastern North Island. New Zealand's subaerial and submarine topography largely reflects its tectonic setting at the convergence between the Pacific Plate in the east and the Australian Plate in the west (Figure 3.1). Off eastern North Island the plate boundary exists as a convergent subduction zone, with the oceanic Pacific Plate obliquely subducting beneath the continental Australian Plate, resulting in the Hikurangi Trough (Chanier & Ferriere 1991). It is within this active tectonic setting that the present study is located. Further south, in northern South Island, tectonic deformation becomes mainly strike slip, and this merges southwards into the strike slip zone of the Alpine Fault through central South Island. Off southwestern South Island convergent subduction returns, but here the Australian Plate subducts beneath the Pacific Plate, resulting in the Puysegur Trench.

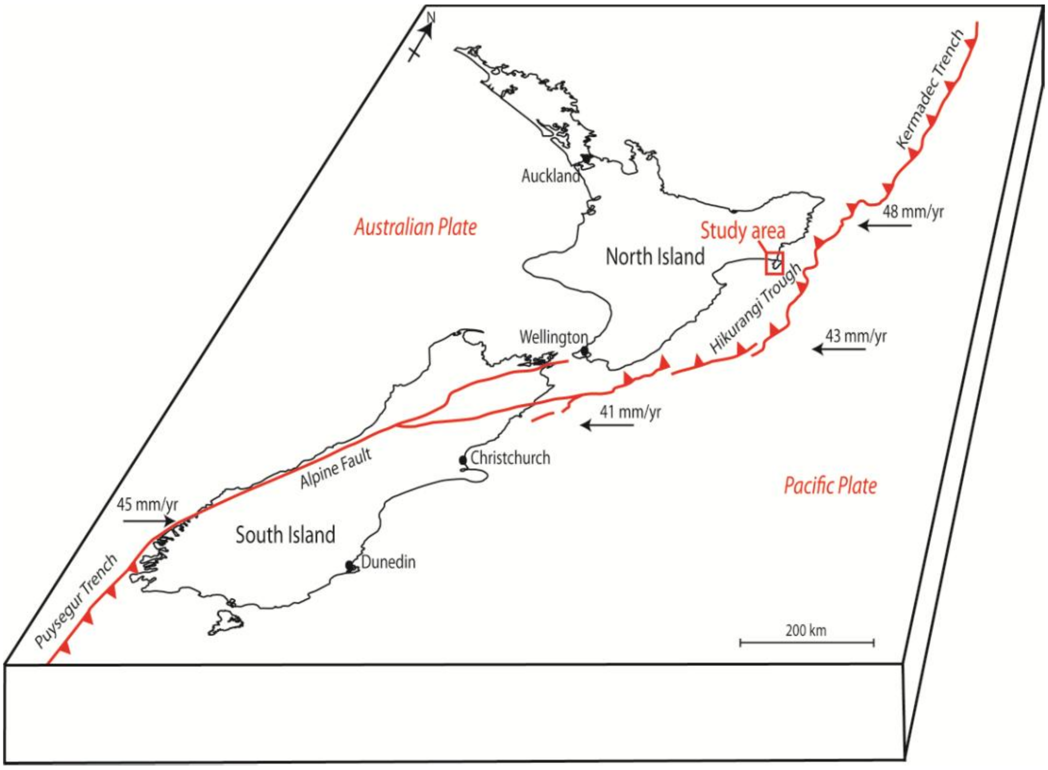


Figure 3.1 - Present plate tectonic setting of New Zealand. Red triangles indicate subduction direction. Subduction rates taken from Williams (1991) and Barnes *et al.* (2010). Modified from Kamp & Nelson (1987), Williams (1991) and Bland (2001) using University of Waikato GIS data sets.

During the Late Cretaceous and much of the Paleogene (Paleocene to Oligocene), New Zealand experienced relative tectonic quiescence with no plate boundary development (Ian R Brown Associates 1998). Off eastern North Island primary seaward imbricate thrusting has occurred since the Late Oligocene and continued throughout the Neogene to the present day (Chanier & Ferriere 1991). With the initiation of an c.45˚clockwise rotational transformation near the Oligocene-Miocene boundary (Williams 1991; Kamp & Furlong 2006), the formation of a new plate boundary and associated zone of subduction between the Australian and Pacific Plates occurred, essentially becoming the eastern margin of New Zealand (Beanland & Haines 1998; Ian R Brown Associates 1998). The Early Miocene is widely considered as marking the beginning of the present day subduction setting for several reasons, including a sudden change in sedimentation patterns, the initiation of strong tectonic deformation and the beginning of andesitic volcanism (Rait *et al.* 1991; Kamp & Furlong 2006). The lateral tectonic displacement at the plate boundary during the last c.25 Ma is c.460 km (Lewis & Pettinga 1993), and has included extension, shortening, strike-slip faulting and vertical-axis rotations (Nicol *et al.* 2007).

Off Raukumara Peninsula in the north, non-accreting subductive tectonic activity has resulted in a submarine landscape of seamounts that have acted as damming structures, with basin sediment infills up to 2 km thick (Lewis *et al.* 1998, 2004). The continental slope here has a short and steep structure. In comparison, off the Wairarapa coast to the south a typical tectonically imbricated accretionary wedge system occurs involving sediment infills up to 5 km thick (Lewis *et al.* 1998; Barnes *et al.* 2010). Lying between these sections is the central Hawke's Bay area, where the continental slope more closely reflects that off the Raukumara area, being narrow and steep (Lewis & Pettinga 1993). An illustration of the different continental margin structures is shown in Figure 3.2.

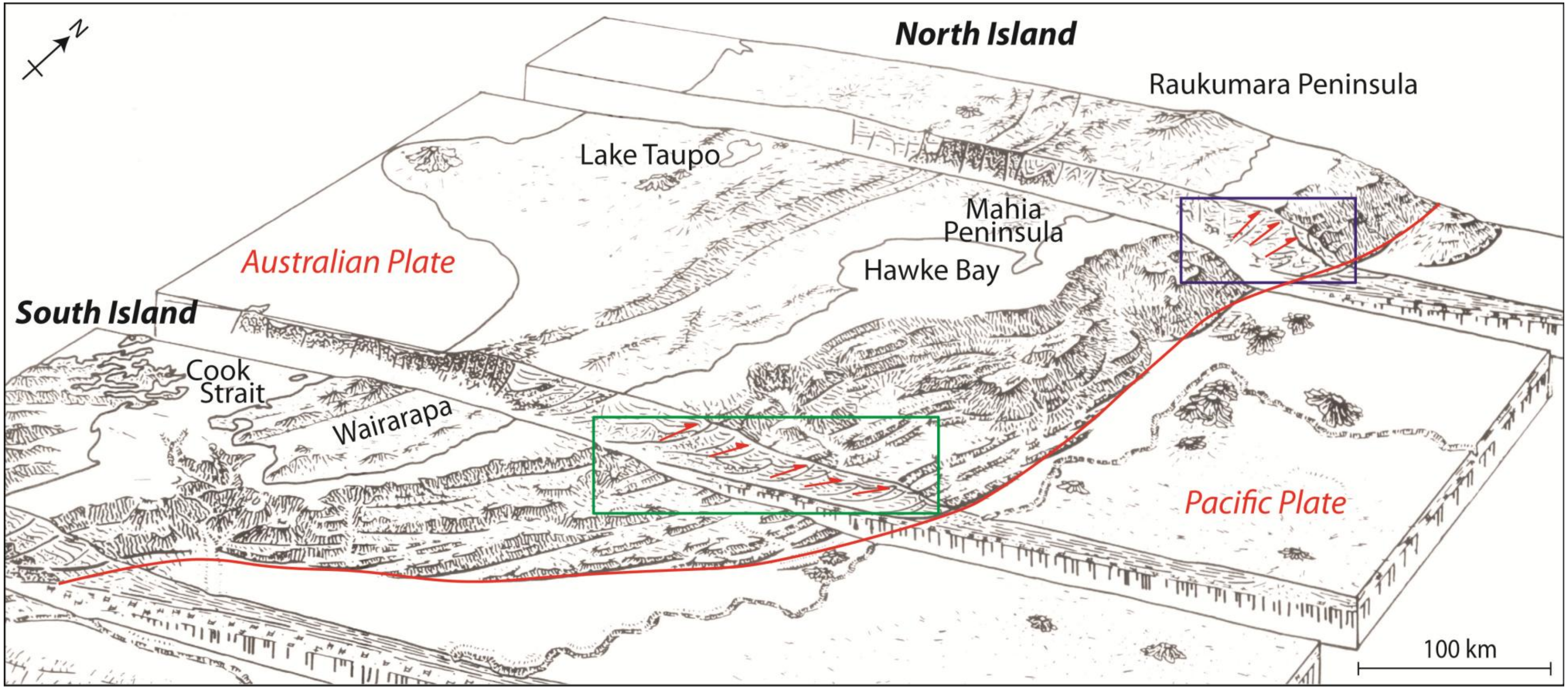


Figure 3.2 - Exploded diagram of eastern North Island illustrating the steep and narrow slope system in the north (outlined in blue), near Mahia and Raukumara Peninsulas, compared with the wide, well developed accretionary slope system (outlined in green) in the southern Hawke's Bay/Wairarapa area. Red line denotes plate boundary. From Lewis & Pettinga (1993).

The subduction zone complex was enhanced with Quaternary uplift (Cole & Lewis 1981). This continued tectonic uplift is evident at Mahia Peninsula where paleo-wave cut shorelines are exposed as land terraces. Five different aged terraces have been identified on Mahia Peninsula by Berryman (1993), mentioned later in section 3.4.1.

Tectonic subduction occurs at 43-48 mm/yr in the North Island Hikurangi Trough area (Barnes *et al.* 2010), and c.45 mm/yr in the Fiordland region (Williams 1991). Local tectonic convergence in the Hawke's Bay area is cited as c.50 mm/yr (Bland 2001). Based on seismological data, the top of the Pacific Plate is considered to be 12-25 km beneath Hawke Bay (Barnes *et al.* 2002; Barnes & Nicol 2004).

3.2 STRUCTURAL ZONES ACROSS HIKURANGI MARGIN

The subduction zone in eastern North Island has formed a tectonically complex structure comprising numerous upthrust ridges and basins. Cretaceous to Quaternary sediments make up these structures (Lewis & Pettinga 1993). The main tectonic components from east to west are the subduction trench, subduction complex, coastal highs, forearc basin, axial ranges, volcanic zone and the backarc region (Figure 3.3).

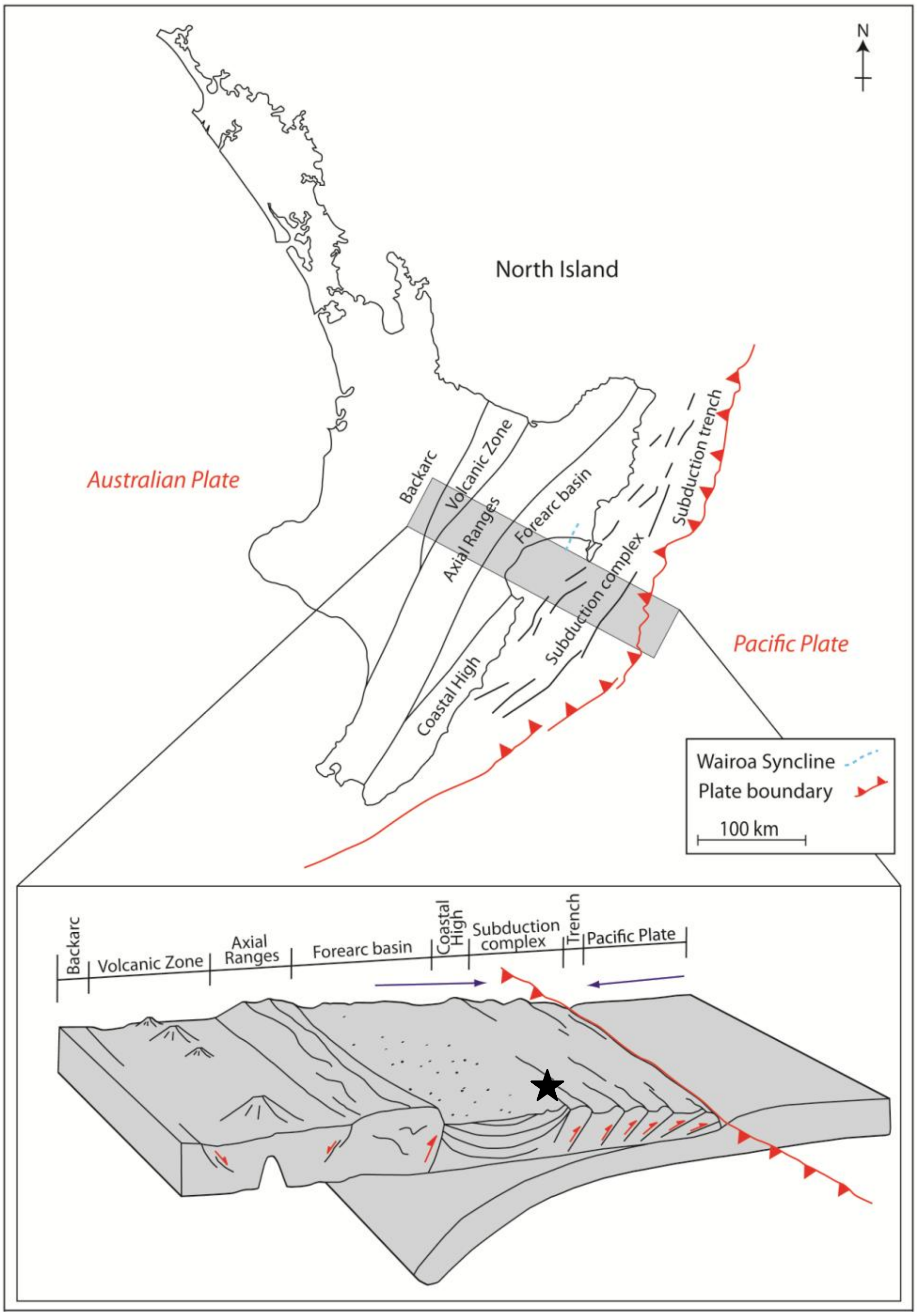


Figure 3.3 - Schematic structural zones related to the subduction boundary tectonics of the Hikurangi Margin of eastern North Island. Small red half arrows show fault systems. Red triangles indicate the area of initial subduction. Blue arrows show general direction of overall plate movement. Black star indicates the approximate tectonic location of the study area. Modified from Nelson *et al.* (2003) and Bland (2001).

3.2.1 Subduction trench

The Hikurangi Margin began forming c.25 Ma (Williams 1991; Barnes *et al.* 2010). Early Miocene compressional deformation saw tectonic subduction between the oceanic Pacific Plate and continental Australian Plate resulting in the formation of an oceanic trench, 3500 m to 2500 m deep (Chanier & Ferriere 1991; Bailleul *et al.* 2007). Partially sediment infilled (Bland 2001), the trench runs northeast-southwest, northwards of New Zealand, and is located approximately 160 km east of the present day North Island coastline (Neef 1999).

The margin has formed from westward subduction of the Pacific Plate beneath the Australian Plate at c.43-48 mm/yr (Barnes *et al.* 2010). The 10-15 km thick Pacific Plate subducts westwards at a gentle angle of c.3° for about 100 km, until it steepens beneath the North Island (Barnes & Nicol 2004; Bailleul *et al.* 2007; Barnes *et al.* 2010). Within the Hawke's Bay area, the dip of the subducting slab ranges from 6˚(offshore) to 20˚ beneath the Ruahine Ranges (Cashman *et al.* 1992). The subduction region extends as far south as Cook Strait (Ballance 1993).

3.2.2 Subduction complex

The subduction complex, otherwise named the accretionary slope, subduction wedge (Bailleul *et al.* 2007) or accretionary prism, forms an 150 km wide eastern part of the Hikurangi Margin area. It includes the western 250 km long, 10-30 km wide coastal highs of the Wairarapa region (Chanier & Ferriere 1991) and continues out to sea towards the subduction trench.

The deformed structure of this area is a prominent feature reflected in the derivation of numerous NE-SW aligned thrust faulted anticlines/antiforms/ridges. In between these upthrust antiforms are small depressions or synforms called trench-slope basins (Bailleul *et al.* 2007) or accretionary basins (Dickson & Seely 1979). These trench slope basins can be up 5-30 km wide (Cole & Lewis 1981; Bailleul *et al.* 2007), depending on the size of the upthrust antiforms. Ongoing tectonic convergence enhances the height, width and number of these anti/synforms in the developing accretionary wedge system. These thrust faults are shallow in the east and steepen toward the west.

The accretionary subduction complex is more widely developed in the Wairarapa/southern Hawke's Bay region, contrasting to the Raukumara northern section where the accretionary complex is rather steep and more difficult to recognise (Figure 3.2) (Cole & Lewis 1981; Lewis & Pettinga 1993)

During late Neogene eustatic rises and falls of sea level, superimposed upon the tectonic movements, the antiforms could eventually rise into shallow waters or even become subaerially exposed as small islets (Kamp *et al.* 1988). It was upon the more westerly of these antiforms, and into the forearc basin, that skeletal carbonate deposits could potentially accumulate. Such 'carbonate factories' experienced typically short lived periods of deposition and occurred in different places at different times (Beu *et al.* 1980; Kamp *et al.* 1988; Ballance 1993; Nelson *et al.* 2003).

3.2.3 Coastal high

The coastal high (or range) is the most westward portion of the subduction complex and is c.250 km long by 10-30 km wide, exposed by steep-angled thrust faults (Chanier & Ferriere 1991). Located mainly upon southeastern North Island, a small portion occurs also on eastern Mahia Peninsula. The peninsula area is seen as a transition zone from the southern accretionary prism structure to the northern Raukumara area margin where there is very limited accretionary structure (Figure 3.2) (Chanier *et al.* 1999).

3.2.4 Forearc basin

The forearc basin, 400-500 km long by 100-200 km wide (Bland & Kamp 2006), of the Hikurangi Margin extends throughout much of eastern North Island (Buret *et al.* 1997) and includes the Hawke's Bay and present study areas where a dominant structure is the Wairoa Syncline (Figure 3.3).

This tectonically active region is bound to the west by the axial ranges comprising Mesozoic basement rocks and to the east by the subduction complex (Barnes *et al.* 2010). The basin has undergone considerable subsidence and, as a result, has since the Early Miocene been rapidly infilled with sediment up to 5.5 km thick (Kamp 1992; Barnes & Nicol 2004; Bland *et al.* 2008). Muddy flysch dominates the infill, with occasional sandstone and limestone that becomes more common towards the stratigraphic top, illustrating a broad Miocene-Pliocene regressive sequence (Kamp *et al.* 1988). The origins of these infill sediments are both terrestrial (erosion of axial ranges and coastal hills with volcanic debris) (Cole & Lewis 1981) and marine (nearshore, shelf and slope) (Barnes *et al.* 2010).

The forearc sediment infill was deposited in a developing interior NE-SW seaway, named informally by Beu (1995) as the Ruataniwha Strait. The seaway was bound to the west by the axial ranges, and to the east by the uplifting subduction complex with its associated antiforms and possible small islets (Bland *et al.* 2008). Continued uplift of the eastern portion caused a narrowing and shallowing of the forearc basin during the Miocene, and especially in the Pliocene, which fostered the potential for shallow marine environments and carbonate deposition (Kamp *et al.* 1988). Northward-directed ocean currents brought in cold water from the subantarctic region, and some associated cold water organisms (e.g. the scallop - *Chlamys patagonica delicatula*) (Kamp *et al.* 1988). The forearc seaway was located at about 40˚S paleolatitude (Caron & Nelson 2009).

The majority of deformation of the forearc basin infill is young, occurring during the last 1-2 million years (Chanier & Ferriere 1991; Bland *et al.* 2008). A significant portion of the basin has been inverted and was subaerially exposed as land during uplift in the Plio-Pleistocene (Bland 2001). Because of tectonic structure and movement during sediment accumulation, the basin shows significant lateral differences in geology (Bland 2001), including patchy distribution of the Pliocene limestones.

3.2.5 Axial ranges

The axial ranges, otherwise named the frontal ridge, create a backstop for the forearc basin. The Rimutaka, Tararua, Ruahine, Kaweka, Kaimanawa, Urewera and the more northern Raukumara Ranges constitute the primary tectonic axial ranges, which consist predominantly of Mesozoic greywacke (Figure 3.4). The axial ranges are separated from the eastward forearc basin by strike slip displacement on the major northeast-southwest Ruahine and Mohaka Faults, along with the Wellington and Whakatane Faults. It is likely that these faults originate from older Mesozoic deformation and have been reactivated (Bland 2001). To the west, the axial ranges are bound by a transcurrent fault zone (Williams 1991). The Mesozoic greywacke basement geology developed within the active margin setting of the Gondwana supercontinent (Barnes *et al.* 2010). The greywacke has been sampled in the Ongaonga-1 exploration well in southern Hawke's Bay, within the forearc basin (Figure 3.4) (Leslie 1971).

3.2.6 Volcanic zone

Early Miocene displacement and an c.25-30° clockwise rotation in the tectonic poles have resulted in volcanism migrating from the Coromandel Volcanic Zone (CVZ) to the present day Taupo Volcanic Zone (TVZ) (Figure 3.4) (Ballance 1976; 1988; Ballance *et al.* 1982; Chanier & Ferriere 1991). Initial andesitic volcanism in the CVZ commenced at c.18 Ma, with the first rhyolitic eruptions occurring at c.10 Ma (Adams *et al.* 1994; Briggs *et al.* 2005). This continued up to c.2 Ma when the shift of volcanic zones occurred. The TVZ is a 'wedge' shaped region in which primarily calc-alkaline andesitic-rhyolitic volcanism occurs as a direct result of tectonism (Ballance 1988; Chanier *et al.* 1999). Southwards, the TVZ terminates at Mt. Ruapehu, and extends northeastwards through numerous andesite-dacite-rhyolite volcanic centres such as Lake Taupo, Rotorua and White Island. The area is dominated by volcanic structures and deposits (Williams 1991). The majority of the andesitic volcanism has been active within the last 50,000 years (Cole & Lewis 1981). Faulting adjacent to the TVZ is typically parallel, short and often in zones (Berryman & Beanland 1991). Volcaniclastic deposits found in the Nuhaka and Mahia Peninsula areas are likely derived from younger volcanic activity in the CVZ.

3.2.7 Backarc

The backarc component involves the King Country and Taranaki regions of western North Island (Figure 3.4). The backarc is an ensialic marginal basin (Cole 1984) and is characterised by NE-SW and NW-SE high angle faulting and crustal extension (Bland 2001).

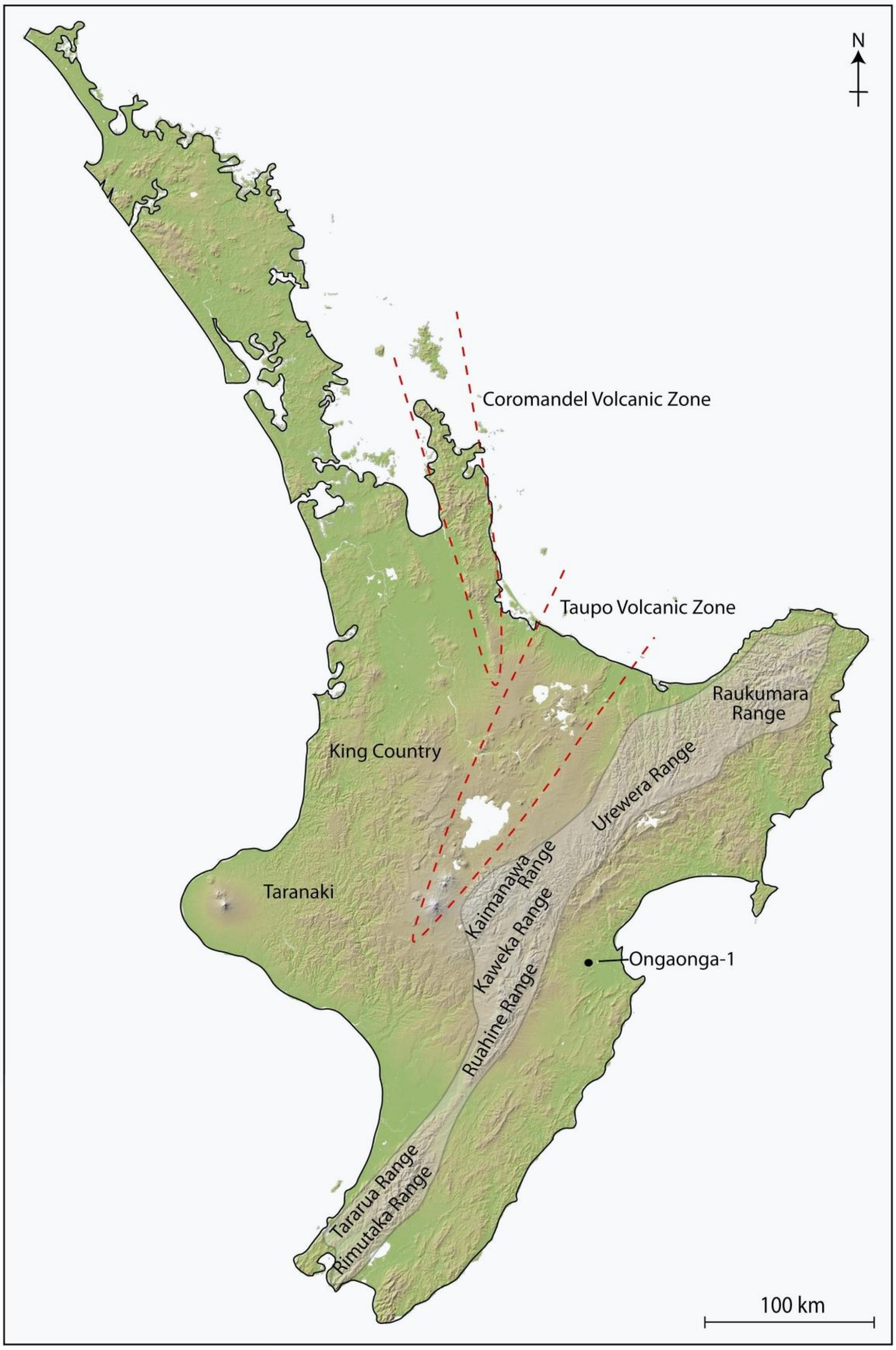


Figure 3.4 – Axial ranges, volcanic zones and back arc region of the North Island. The axial ranges are outlined in grey overlain with feature names. The Coromandel and Taupo Volcanic Zones are outlined in red dashes. Taranaki and King Country areas make up the back arc region.

3.3 FIELD AREA STRUCTURE

The northern Hawke's Bay geology occurs in a series of anticlinal and synclinal structures within the broader Wairoa Syncline (Figure 3.5). The Hawke's Bay area is controlled by compressional tectonics, which result in thrust faults and occasional strike slip deformation (Ian R Brown Associates 1998).

Specifically, the Tahaenui/Clonkeen (TC) region and Mt Moumoukai (MT) are part of the Nuhaka Syncline that extends from the Nuhaka River (near BH42/275475) southwards towards the coast. The Clonkeen Quarry (CQ) is near the basal hinge of this syncline and consequently the exposed strata show minimal dip. Mt Moumoukai is similar, being located in the middle of the Nuhaka Syncline, further north. Tahaenui Quarry (TQ) is located on the western flank of the Nuhaka Syncline, and is steeply dipping to the southeast between 52° and 17°. There are no major faults evident in these areas.

The major geological structure on Mahia Peninsula is the West Mahia Syncline, which runs inland from Mahia's northern beach (BJ43/253621) through to approximately Ahimanawa Station (BJ43/184525), after which it likely continues offshore. The west coast geology all dips towards the west/southwest at approximately 15°. Mahia Peninsula shows some N-S to NE-SW normal faulting (Chanier *et al.* 1999), the most prominent of which is observed near the Stalactite Falls Stream (Figure 3.5), where it has vertically offset the Tahaenui Limestone from the more southern exposures of Whakapunake and Opoiti Limestones.

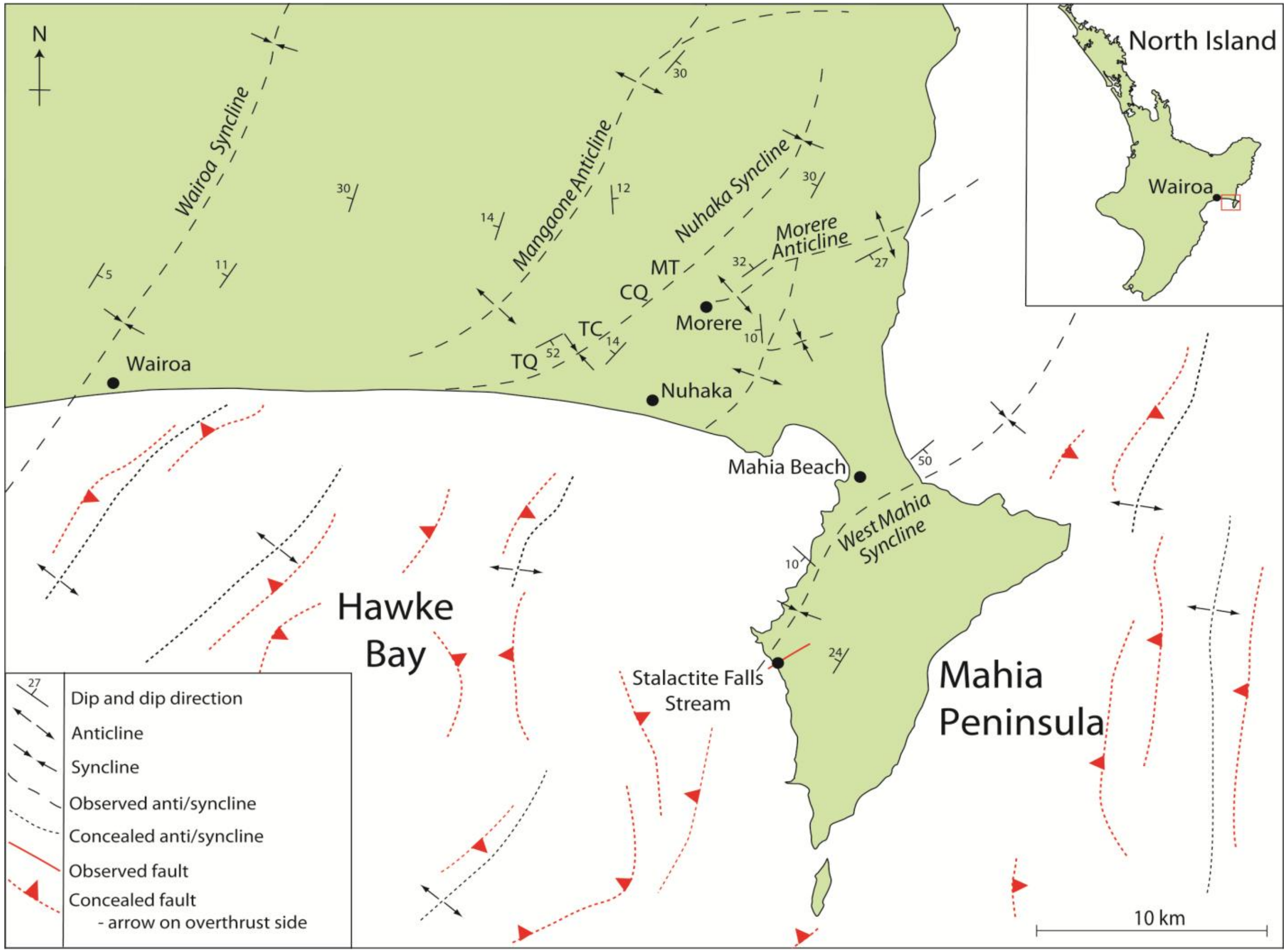


Figure 3.5 – Anticlinal and synclinal structures in the Wairoa to Mahia Peninsula region. Structural information sourced from Mazengarb & Speden (2000).

3.4 LACHLAN RIDGE, FAULT AND BASIN

The Lachlan Ridge is a present day example of an upthrust antiform. It is a submarine extension of Mahia Peninsula which runs approximately north to south, largely within the 100 m bathymetric contour (Figure 3.6) (Ricketts & Nelson 2004). Lachlan Ridge is associated with three periods of tectonic deformation since the onset of the present tectonic setting (Barnes *et al.* 2002). These periods consisted of initial thrust faulting, then extensional faulting, then the current period of structural inversion, listric thrust faulting and folding (Barnes *et al.* 2002). The Lachlan Fault, a result of compressional tectonics, runs parallel to the ridge on its eastern side, and is the main active listric fault (Barnes *et al.* 2002). It emerges on the seafloor approximately 3-8 km east of Mahia Peninsula (Barnes *et al.* 2002).

Subsidence of the inner landward Lachlan Basin has made room for more than 1500 m of Pliocene sediment infill (Ricketts & Nelson 2004). Fourteen angular unconformities have been identified through seismic reflection in the Lachlan Basin, and are interpreted as a response to major changes in sea level (Barnes & Nicol 2004). Lachlan Basin may have further extended had it not been for Late Miocene/Early Pliocene tectonic contraction which caused the growth to stop (Barnes & Nicol 2004). The Kidnappers Fault (Figure 3.6) overlaps the southern portion of the Lachlan Fault, and is the cause of the late Pleistocene – Recent rapid uplift of Mahia Peninsula (Barnes & Nicol 2004).

The Lachlan Ridge, as seen in Figure 3.7, is produced by large scale faulting, some of which have upthrust pre-Miocene aged rock now exposed at the submarine surface. The antiform shape that Lachlan Ridge produces is likely associated with the antiforms on which carbonate production has occurred.

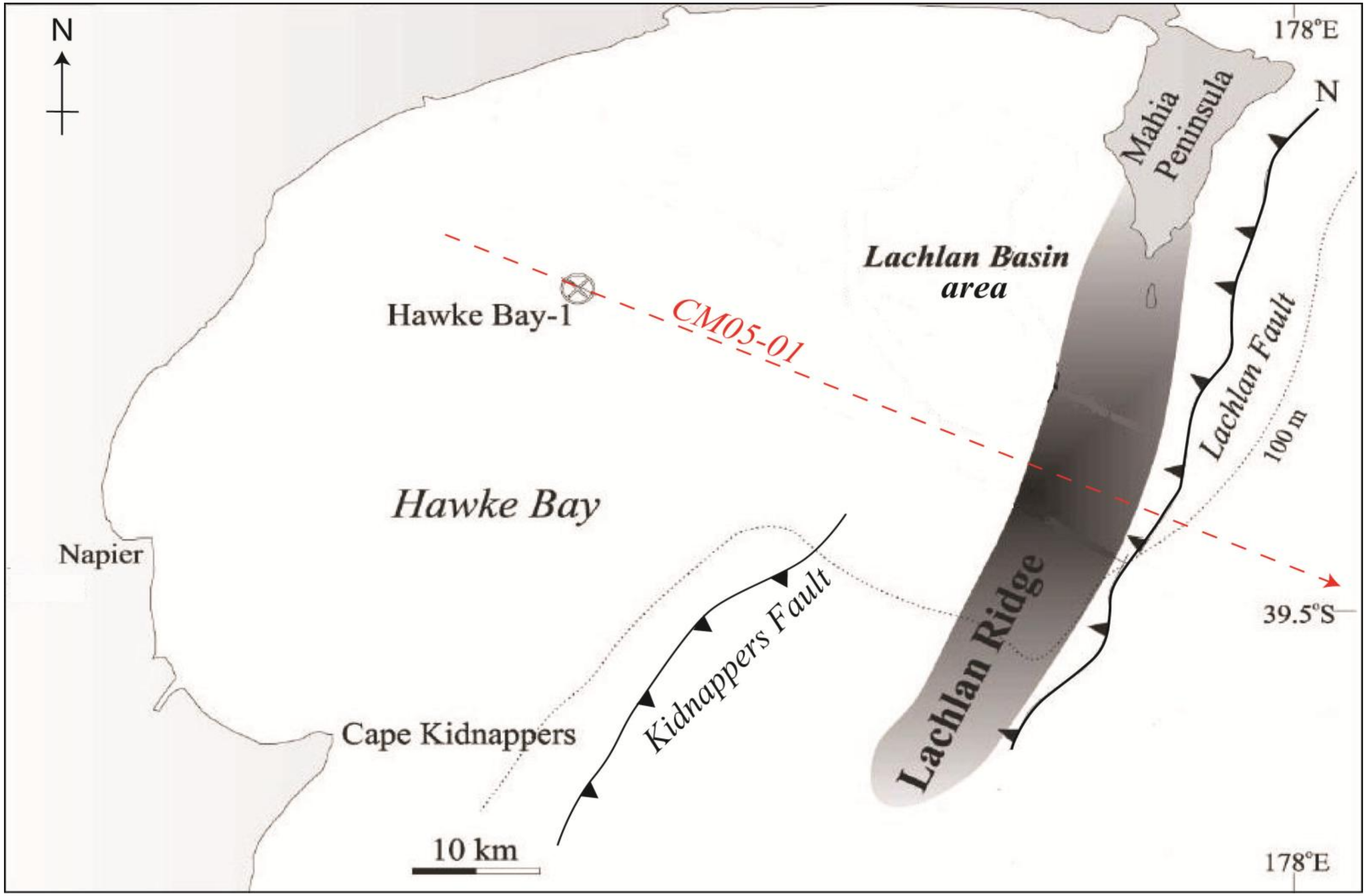


Figure 3.6 - Locality and structure of Lachlan Basin, Ridge and Fault. Red dashed arrow indicates the location of seismic line CM05-01 (Nicol *et al.* 2007) (Figure 3.7) taken by Crown Minerals, with further continuation towards the southeast. Modified from Ricketts & Nelson (2004, p. 432).

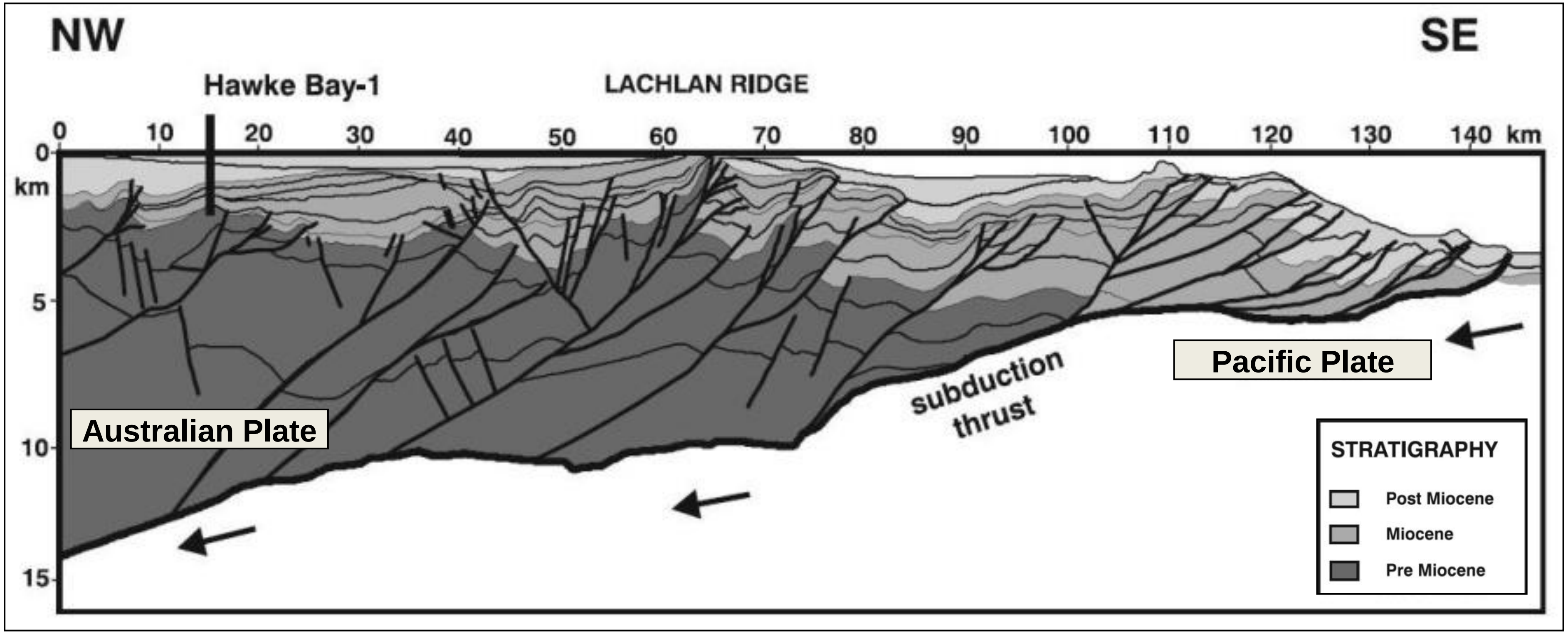


Figure 3.7 – Present day subsurface structure of the Lachlan Ridge area, showing the stratigraphy developed before, during and after the Miocene onset of subduction. Section is derived from seismic line CM05-01 (located on Figure 3.6, from Ricketts & Nelson 2004, p. 432). Vertical exaggeration is approximately 3x. Adapted from Nicol *et al.* (2007, p 12)**.**

3.4.1 Uplifted terraces

Tectonic movement, primarily involving the Lachlan and Kidnappers Faults, is responsible for the ongoing uplift of Mahia Peninsula and Lachlan Ridge, as is evident in the now exposed wave cut terraces seen on Mahia Peninsula (Figure 3.8). Specifically, five main terraces in the Mahia Peninsula area have been dated at 250, 1600, 1900, 3500 and 4500 years B.P. with uplift heights greater than 4 m (Berryman & Beanland 1991; Berryman 1993). These terraces are located mainly on the northern, eastern and southern sides of Mahia Peninsula. On the west coast of Mahia Peninsula, a prominent uplifted terrace is locally preserved up to 20 m high above sea level (Figure 3.8).

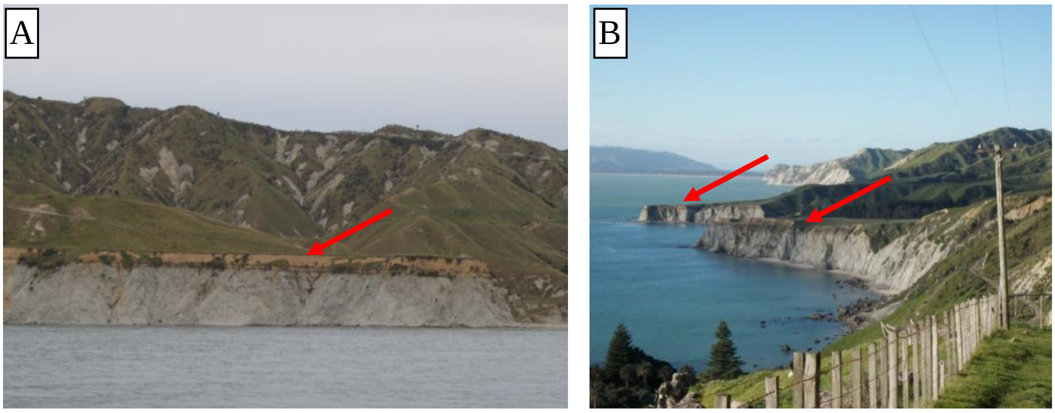


Figure 3.8 - West coast of Mahia Peninsula, showing an example of a paleowave cut terrace exposed by tectonic uplift. This terrace, located near (BJ43/184564), is approximately 20 m above sea level and has developed a brown soil horizon atop the flat paleowave cut grey mudstone. **(A)** View looking east towards Mahia Peninsula. **(B)** Same terrace looking north.

3.5 REGIONAL STRATIGRAPHY

The larger East Coast Basin consists of secondary Cretaceous to Pleistocene sedimentary basins that terminate at their western edge against the Mesozoic basement axial ranges of the North Island, and extend offshore to the Hikurangi Trough where oceanic-continental convergent subduction occurs (Ian R Brown Associates 1998). The basement of the East Coast Basin consists of Triassic-Early Cretaceous, indurated Torlesse Terrane sandstone and mudstone. Subsequent marine onlap deposited Early Cretaceous shelf sandstones and a succession of thick Late Cretaceous deep-water sandstones and mudstones (Ian R Brown Associates 1998). Successive tectonic uplift and subsidence has resulted in a Paleogene to Recent sedimentary succession ranging in thickness from 3000-6000 m (Field *et al*. 1997).

Latest Miocene to Quaternary stratigraphy across the wider Hawke’s Bay area is illustrated in Figures 3.9 and 3.10, and in Table 3.1. The rates of subsidence of the Mio-Pliocene basins are commonly from 200-900 m/m.y., but can be as high as 2000-3000 m/m.y. during short periods (Ballance 1993).

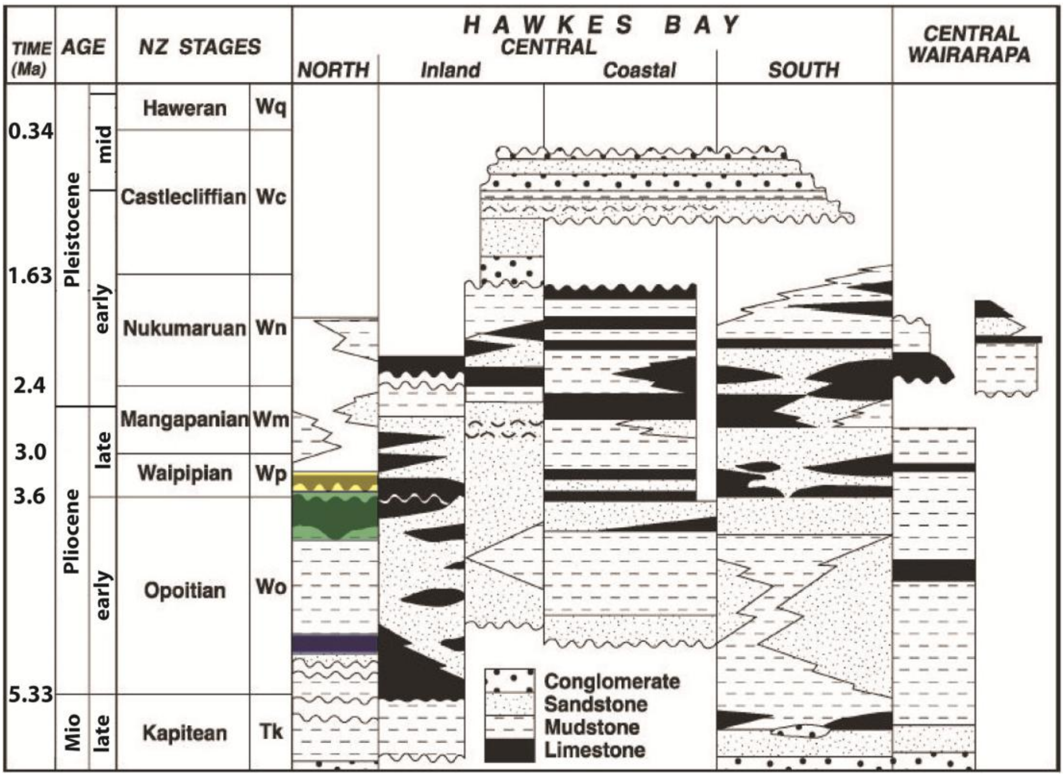


Figure 3.9 - The Opoiti (blue), Whakapunake (green) and Tahaenui (yellow) Limestones of this study in relation to other Hawke's Bay Plio-Pleistocene limestones. The three limestones have been divided primarily on the basis of their age diagnostic macrofossil taxa. Ages have been amended to correspond with the newest timescale by Hollis *et al*. (2010). Adapted from Nelson *et al.* (2003, p. 410) after Field *et al*. (1997).

Age		Group	Formation	Lithologies
Pleistocene	Haweran — 0.34			Alluvial sediment, gravel and beach deposits
Pleistocene	Castlecliffian — 1.63	Kidnappers Group		Conglomerate, mudstone and tuff
Pleistocene	Nukumaruan — 2.4	Mangaheia Group	Wairoa Formation *D* Tahaenui *C* Whakapunake *B* Opoiti *A*	Limestone, sandstone, mudstone and volcaniclastics
Pliocene	Mangapanian — 3.0			
Pliocene	Waipipian — 3.6			
Pliocene	Opoitian — 5.33			
Miocene	Kapitean — 7.2	Tolaga Group	Tunanui Formation	Flysch, undifferentiated sandstone and mudstone
Miocene	Tongaporutuan			

Table 3.1 - Summary of the stratigraphy of units in the Mahia/Nuhaka area, northern Hawke's Bay. Note that the Kidnappers Group does not outcrop in the immediate study area, and is included only for stratigraphic completeness. Taken from Francis (1993), Mazengarb & Speden (2000), Field *et al.* (1997) and Ian R Brown Associates (1998).

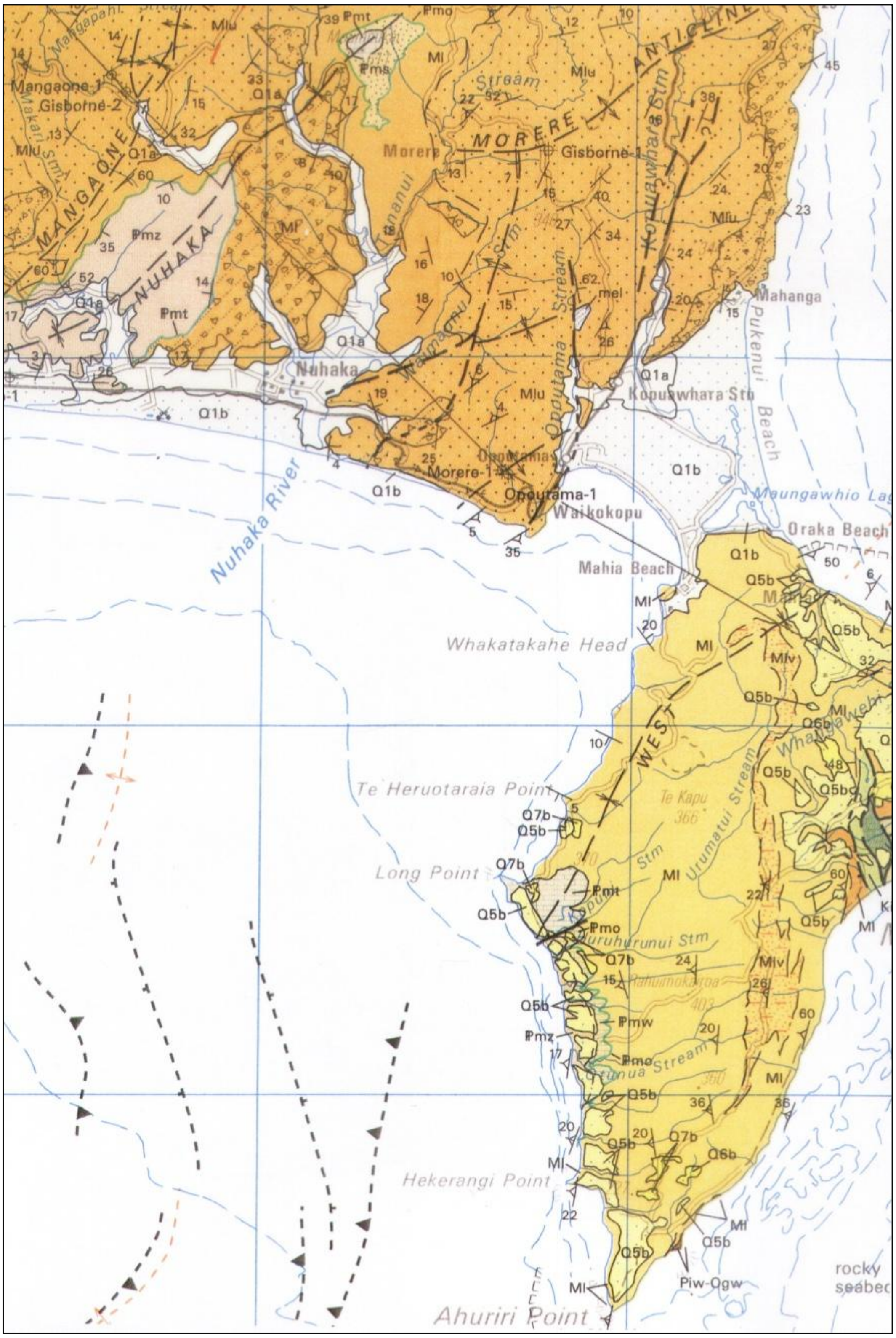


Figure 3.10 – The Nuhaka-Mahia Peninsula portion of the recent 1:250 000 QMAP geological map of Raukumara Peninsula (Mazengarb & Speden 2000) showing dominant lithologies and structure. *Pmo*-Opoiti Limestone, *Pmw*-Whakapunake Limestone, *Pmt*-Tahaenui Limestone, *Pmz*-Pliocene mudstone, *Mi/Miu*-Miocene sandstone/mudstone, *Q*-Quaternary deposits.

3.5.1 Miocene stratigraphy

The Miocene stratigraphy is contained within the broad ***Tolaga Group*** which incorporates Early Miocene (Waitakian) to Late Miocene (Kapitean) formations (Mazengarb & Speden 2000). Deposition was primarily within continental slope environments (Bland 2001), and has resulted in numerous typical Bouma-type sequences. The oldest Miocene sediments are rich in glauconite (Ian R Brown Associates 1998). During the Middle Miocene, the wider northern and eastern Wairoa area experienced rapid subsidence that resulted in very thick, lower bathyal deposits dominated by gravity-flow sandstones of the ***Tunanui Formation*** (up to 2000 m thick) (Francis 1998; Ian R Brown Associates 1998; Mazengarb & Speden 2000). Miocene stratigraphy on Mahia Peninsula is dominated by calcareous mudstones, interspersed with rhyolitic tuff and turbidite sandstones (Chanier *et al.* 1999). The Tunanui Formation gradually transitions into upper mudstones, which have different names in different places, such as the Morere/Pindari/Tangihau Mudstone members.

A low-angle angular unconformity separates the Miocene and Pliocene strata in the forearc basin (Field *et al.* 1997) and records the change between bathyal siliciclastic and shelfal (including carbonate) accumulation (Buret *et al.* 1997). This unconformity relates to an c.7 m.y. time gap near Nuhaka, and an c.2 m.y. gap on Mahia Peninsula (Buret *et al.* 1997), and is associated with the onset of uplift, driven by especially prominent compressive or transpressive tectonics.

3.5.2 Pliocene to Pleistocene stratigraphy

Pliocene to Pleistocene stratigraphy involves the ***Mangaheia Group*** (Opoitian to Nukumaruan) and the more southern ***Kidnappers Group*** (Early to mid Castlecliffian) (Field *et al.* 1997; Bland 2001). The Mangaheia Group units are dominated by shelf deposits that are unconformably overlain by the Kidnappers Group, the unconformity representing a time gap of approximately c.600,000 years (Bland 2001). The Kidnappers Group consists mainly of alluvial fan deposits (Field *et al.* 1997; Bland *et al.* 2008) and outcrops in central and southern Hawke’s Bay.

Mangaheia Group

The Mangaheia Group, Lower Opoitian to Nukumaruan in age (c.5.3-1.6 Ma) (Mazengarb & Speden 2000; Hollis *et al.* 2010), overlies the Tolaga Group with mild angular unconformity (Field *et al.* 1997) and hosts numerous formations, the majority of which crop out in southern Hawke's Bay (Bland 2001). The northern Hawke's Bay units include several informally named mudstones that envelope the Tahaenui, Whakapunake and Opoiti Limestones. The Mangaheia Group units were deposited during episodic sea-level changes in the Pliocene (Bland 2001). Overall, the Mangaheia Group involves a thick mudstone and sandstone succession with interspersed limestones associated with development of the north-south oriented paleo-seaway (Ruataniwha Strait) through the basin (Beu *et al.* 1980; Beu 1995; Bland *et al.* 2008). The Mangaheia Group also includes sparse and intermittent volcaniclastic units derived from the Coromandel Volcanic Zone.

Within the Mangaheia Group, the many East Coast limestone occurrences are commonly informally grouped as the **Te Aute limestones** (Lillie 1953; Kingma 1971; Nelson *et al.* 2003). A long standing term, the name 'Te Aute' is derived from the informal rural area in southern Hawke's Bay. These cool water Pliocene coquina units are common in eastern North Island, forming prominent outcrop ridges and peaks (Nelson *et al.* 2003). The Opoiti, Whakapunake and Tahaenui Limestones of this study are included in the 'all-encompassing' Te Aute name, and outcrop today in the Mahia-Wairoa area.

The name **Wairoa Formation** is used for the Pliocene mudstone and sandstone succession that encompasses the three Pliocene limestones (Francis 1993b; Field *et al.* 1997). Accumulating upon and about the tectonic antiforms, each limestone grades laterally into surrounding deeper water outer shelf to upper bathyal siliciclastic mudstone (and sandstone) of the Wairoa Formation (Bland *et al.* 2008). Occasional tuffaceous beds, likely derived from the CVZ, occur throughout the Wairoa Formation (Chanier *et al.* 1999). Because there has been some confusion in the literature about the name Wairoa Formation and how it relates to the three interspersed northern Hawke's Bay Pliocene limestones, the limestones here are treated as formations within the Wairoa Formation (Table 3.1; see section 4.2.1).

Kidnappers Group

The mid Pleistocene Kidnappers Group consists mainly of thick (up to c.400 m) marginal to non-marine sandstone and conglomerate as alluvial fan deposits, with estuarine mudstone and white tuff beds (Field *et al.* 1997; Bland *et al.* 2008). Outcrops of this group are limited to central and southern Hawke's Bay to the south, but the name is mentioned here for completeness.

CHAPTER FOUR – PLIOCENE STRATIGRAPHY AND LITHOFACIES

4.1 INTRODUCTION

Because the Te Aute limestones show considerable lithological variation, their fossil content has not only been used to establish age but often also to identify the different units (Beu 1995). Consequently the fossil age of a unit is typically being used to name lithological units, which strictly is not in accord with formal stratigraphic practice (Hedberg 1976; Boggs 2006). While the three Pliocene limestone units in this study do have some overall distinguishing lithological properties their separation at the large scale remains primarily age-related. Nevertheless they all involve a small number of distinctive lithological subunits, referred to in this chapter as lithofacies, irrespective of age.

Due to the adjoining nature of the western (Wairoa) and eastern (Mahia) field areas, the construction of lithofacies for the Pliocene strata has been carried out in collaboration with colleague Jared Jiang who is working the western area. Consequently, two of the defined lithofacies appearing in the western area do not occur in the eastern area studied here.

4.2 MAHIA AREA PLIOCENE LITHOSTRATIGRAPHY

The East Coast Basin Pliocene sediments are predominantly mudstones with lensoidal bodies of coquina limestone and numerous unconformities (Beu 1995). The stratigraphy in the wider Mahia area is within the upper portion of the Mangaheia Group and ranges from underlying Miocene sandstone flysch, visible at Tahaenui/Clonkeen, through a thick Pliocene mudstone dominated succession interspersed with limestones beds. Three limestone units crop out in the Mahia Peninsula and Nuhaka areas, namely Opoiti Limestone, Whakapunake Limestone and Tahaenui Limestone (Table 3.1, Figure 4.1). Detailed stratigraphic columns are given in Appendix VII. The total Pliocene thickness on Mahia Peninsula is c.500 m (Francis 1993a) where it occurs on the west coast only, while the total thickness of Pliocene strata in the Nuhaka area is likely to be similar.

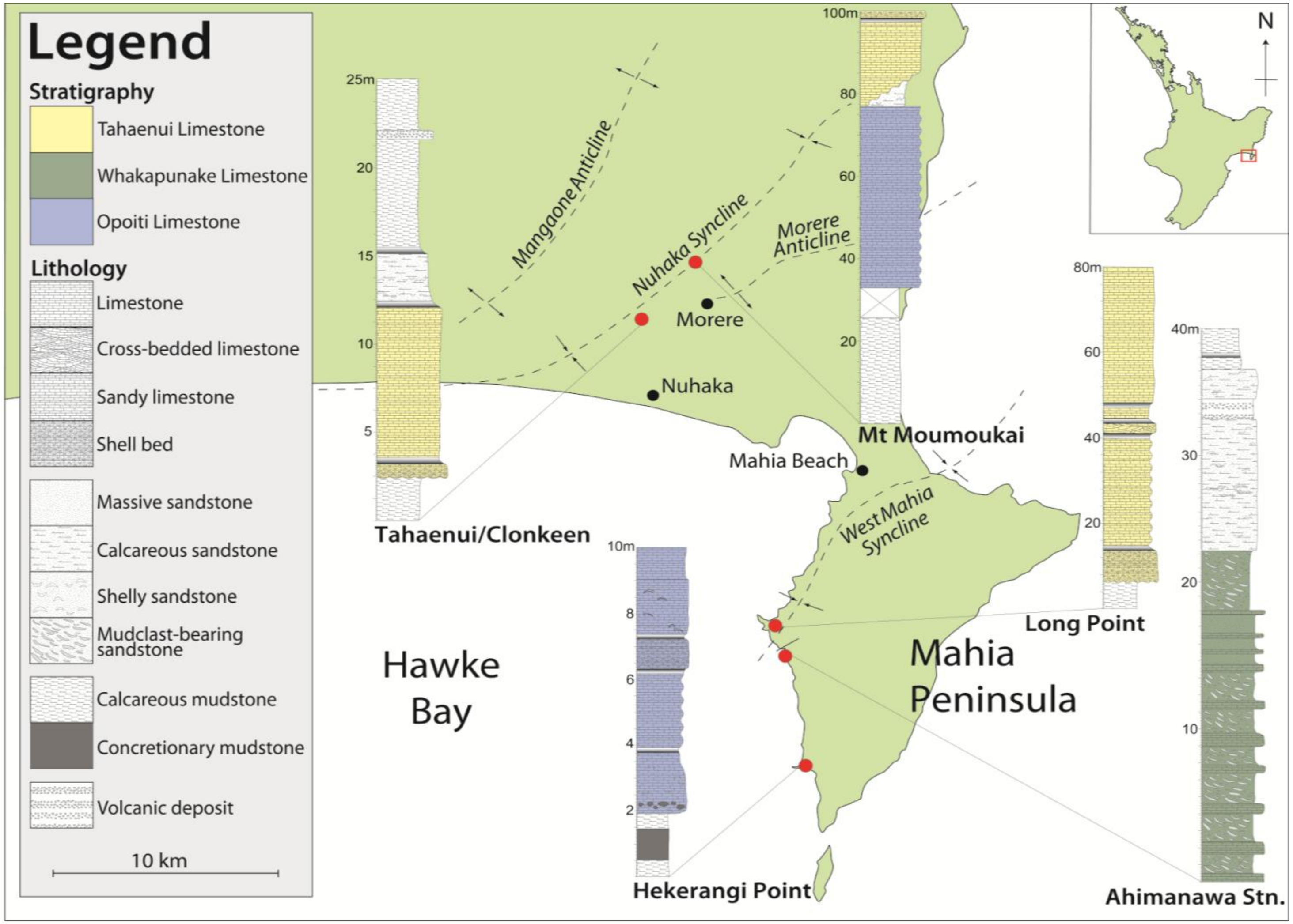


Figure 4.1 - Primary stratigraphy of the Pliocene deposits in the Mahia/Nuhaka area, illustrating specifically the Opoiti, Whakapunake and Tahaenui Limestones.

4.2.1 Lithological nomenclature

The term ‘limestone’ is used here when a lithological unit contains more than 50% calcium carbonate. While generally followed in this study, it is appreciated that in some cases the carbonate content may fluctuate within a lithology, resulting in a less strict use of the term ‘limestone’. For example, the Opoiti Limestone is known to vary greatly in siliciclastic composition (Beu 1995) and consequently in some places has less than 50% calcium carbonate, yet is still named a limestone.

The East Coast areas Pliocene lithological units have been referred to by many different formal/informal names during past research. Beu (1995) formally defined the three northern Hawke’s Bay Pliocene limestone names – Opoiti, Whakapunake and Tahaenui – which are used here.

The name Mangaheia Group was used by Mazengarb *et al.* (1991), when he redefined Steineke’s (1934) original Mangaheia Formation to incorporate an extended range of ages (Opoitian to Nukumaruan), lithologies and occurrences. The name is taken from the Mangaheia River, near Tauwhareparae, north of Gisborne.

The Pliocene portion of the Mangaheia Group is overwhelmingly dominated by siliciclastic mudstone and sandstone in which occur sporadic, typically lensoidal, limestone bodies. Given the sporadic distribution of the limestones it would seem inappropriate to assign different formal stratigraphic names to the mudstones (and sandstones) above and below the different limestone units, since away from the areas of limestone development the mudstone succession remains largely uninterrupted. In this study the term ‘Wairoa Formation’ is used to encompass the entire succession of mudstones and occasional sandstones that surround the limestone units. Where it is possible to differentiate the general stratigraphic position of the mudstones in relation to the limestones, the letters A, B, C and D can be used (Figure 4.2). For example, the mudstone/sandstone succession overlying the Opoiti Limestone is referred to as the ‘Wairoa Formation B’. Such a scheme affords a general understanding of the stratigraphic position of the all-encompassing nature of these mudstones without unduly complicating the stratigraphic nomenclature (Figure 4.2).

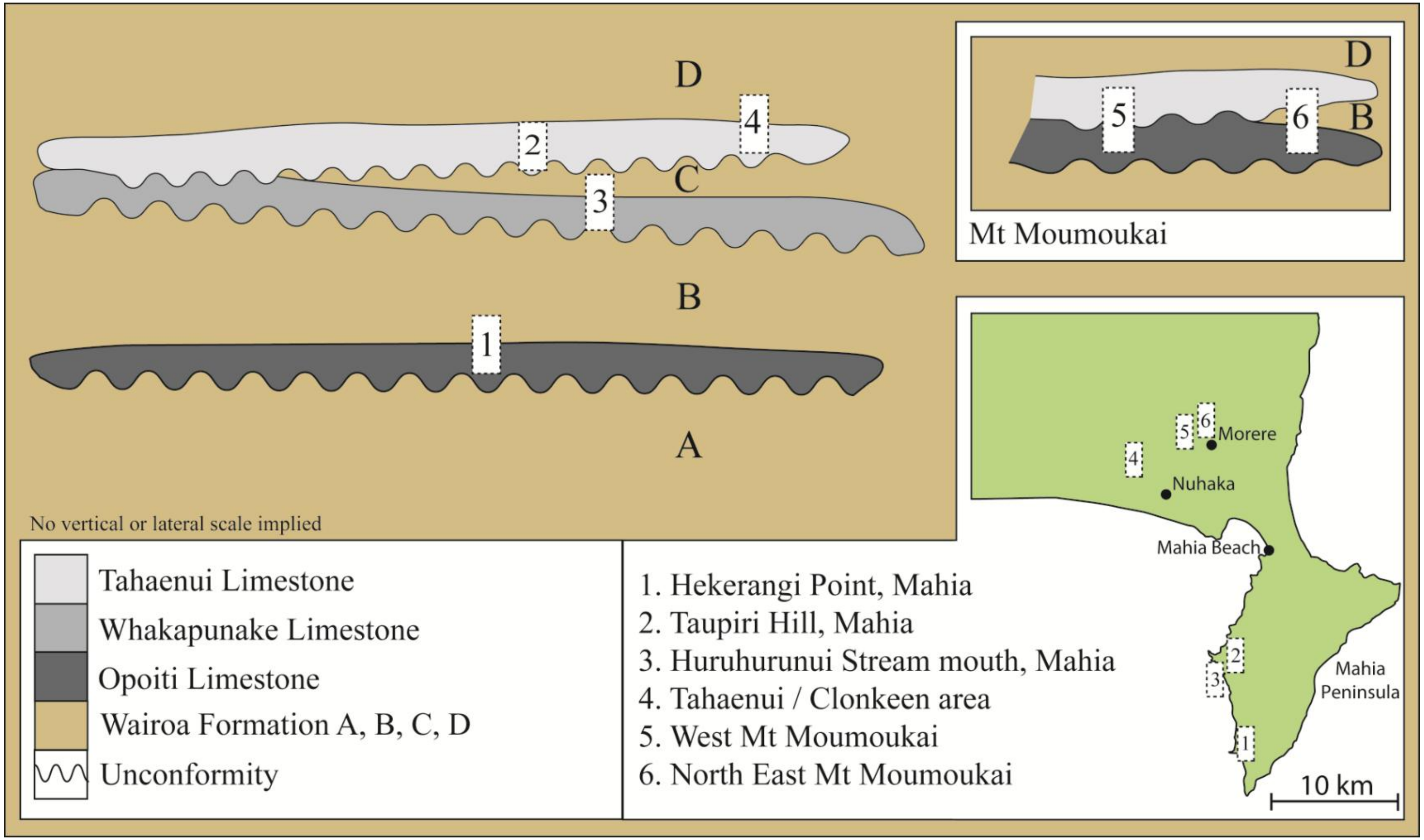


Figure 4.2 - Schematic stratigraphic placement of Pliocene limestones in an all-encompassing mudstone dominated succession. White rectangles show lithology placement at certain localities. No lateral, vertical or thickness scale implied.

The **Opoiti Limestone** has had many informal names, including Otamaharua limestone, '20 ft limestone' and Parikanapa limestone (Beu 1995). The name 'Opoiti' is derived from the informal, and now unused, Opoiti Formation (Beu *et al.* 1980) and is formally defined in Beu (1995). The southernmost outcrop of Opoiti Limestone, at Hekerangi Point on Mahia Peninsula, has been previously referred to as the Turanganui Sandstone by Francis (1993b).

The name **Whakapunake Limestone** comes from the Whakapunake Trig (BH42/993946) north of Wairoa where this limestone forms spectacular bluffs. The Whakapunake Limestone was first described in 1877 by Smith, who called it the Maungaharuru Limestone. The current name was first used by Beu *et al.* (1980) and is formally described in Beu (1995). The Whakapunake Limestone on the west coast of Mahia Peninsula at Ahimanawa Station was named the Temuka Siltstone by Francis (1993b). A more appropriate name for this Late Opoitian age equivalent (Beu 1995) unit of the true Whakapunake Limestone on Mahia Peninsula could be Whakapunake Formation since it consists of coquina units interbedded with a mudclast-bearing shelly sandstone, and is not in its entirety a pure limestone. However, because a true Whakapunake Limestone exists north of the Wairoa district (currently being studied by J. Jiang), it is deemed appropriate to retain the name on Mahia Peninsula, it being regarded as a unique lateral equivalent of the true Whakapunake Limestone.

The **Tahaenui Limestone** name originated from outcrops bordering the Tahaenui River near Nuhaka, and was first formally described by Beu (1995). Elsewhere, this limestone has been called the Kinikini Road Limestone (Francis 1993b), the Maungaharuru Limestone (Smith 1876) and the Long Point Limestone (McKay 1887) where it forms the Long Point promontory on Mahia Peninsula. The overlying Pliocene mudstone and underlying late Miocene mudstones have been previously named the Wairoa Formation (Francis 1993b; Ian R Brown Associates 1998) and the Tangihau (Francis 1993b)/Pindari (Ian R Brown Associates 1998) Mudstones, respectively. The underlying mudstone on Mahia Peninsula has been referred to as the Otunua Formation by Francis (1993b). In the present study the overlying mudstone is referred to as Wairoa Formation D (Figure 4.2).

4.3 MAHIA AREA PLIOCENE LITHOFACIES

To discriminate different field lithologies and inferred paleoenvironments, twelve lithofacies have been created from field descriptions (Table 4.1). Theoretically facies groups must be able to be compared, can act as a guide for future work and should be a basis for interpretation (Walker 1992). The lithofacies are first discriminated by primary lithology (i.e. Limestone-L vs Sandstone-S vs Mudstone-M vs Volcanic-V) and subsequently by distinctive characteristics, such as bedding, induration or skeletal components. The lateral relationships amongst lithofacies can be used to help depict coeval depositional environments (Boggs 2006). However, the paucity of continuous outcrop and lensoidal nature of the Pliocene limestones in the northern Hawke's Bay occurrences renders lateral associations difficult to determine. At best the lithofacies can depict a general shallowing or deepening trend which can be used to help infer sedimentary paleoenvironments.

Table 4.1 - Pliocene lithofacies cropping out in northeastern Hawke's Bay. ‘Other features’ may apply to any carbonate, siliciclastic or volcanic lithofacies group.

Lithofacies	Description	Additional Features
Limestone		
L1 Bioclastic limestone	Massive to poorly bedded, variably indurated, barnacle rich pure limestone	**Hb** - Horizontal bedding **Xb** - Cross bedding
L2 Coquina	Sandy, indurated, limestone coquina shell beds	**S** - Siliciclastic rich **Mc** - Mudstone clasts (<5 mm)
L3 Sandy limestone	Massive to well bedded, moderately indurated, mixed siliciclastic-bioclastic limestone	**Gl** - Glauconite laminae **Bra** - Brachiopod rich **Biv** - Bivalve rich
Sandstone		**P/O** - Pectinid/oyster rich
S1 Calcareous sandstone	Massive, moderately indurated, calcareous fine sandstone	**Bio** - Bioturbation **Bor** - Boring/burrows
S2 Bioclastic sandstone	Thickly bedded, moderately indurated, fossiliferous fine sandstone, with rare to common macrofossils 1-2 cm in size	
S3 Volcaniclastic sandstone	Non-calcareous, volcaniclastic fine sandstone	
S4 Mudclast-bearing sandstone	Variably indurated, shelly sandstone, with common and regularly spaced mudstone clasts, up to 20 cm in size	
Mudstone		
M1 Massive mudstone	Massive, weakly to moderately indurated, calcareous mudstone	
M2 Bedded mudstone	Bedded (20-30 cm thick), weakly to moderately indurated, highly calcareous mudstone	
M3 Concretionary mudstone	Massive, highly indurated, concretionary mudstone	
M4 Fossiliferous mudstone	Massive, weakly to moderately indurated, fossiliferous mudstone	
Volcanic		
V1 Volcaniclastite	Massive to incipiently laminated, pumiceous, sandy volcaniclastite, may include mudstone clasts	

4.3.1 Limestone lithofacies

Figure 4.6 illustrates some limestone lithofacies in the field.

Lithofacies L1

Description: Massive to poorly bedded, variably indurated, well sorted barnacle rich pure limestone. This lithofacies has a very high componentry of fragmented coarse barnacle plates, up to 5 mm in size, all of which lie flattened and parallel to one another. Siliciclasts are rare. Pore spaces are frequent, and result from varying degrees of compaction. Shell beds can be interspersed throughout, usually with convex upwards pectinids. Thickness of lithofacies L1 can be up to 40 m. Figure 4.3 illustrates petrographic components of lithofacies L1

Stratigraphic occurrence: Lithofacies L1 is the primary make up of the Tahaenui Limestone in all geographic localities, and also appears, slightly more sandy, within the upper Opoiti Limestone on Mahia Peninsula.

Palaeontology: The species of barnacles present are probably *Balanus (Austrobalanus) vestitus/Notobalanus vestitus*, *Balanus (Megabalanus) decorus* and the now extinct *Balanus (Megabalanus) tubulatus/(Fosterella) tubulatus* (Beu *et al.* 1980; Buckeridge 1983; Kamp *et al.* 1988). Lithofacies L1 is associated with common occurrences of the pectinid *Phialopecten marwicki*, oysters *Ostrea chilensis* and *Crassostrea ingens* and the brachiopod *Neothyris* cf. *obtusa* or *Neothyris campbellica elongata* (Neall 1972: *pers. commun*. Beu 2010).

Depositional environment: Deposition occurred within a high energy, shallow marine setting with strong nutrient input. Vague horizontal bedding suggests fluxes of carbonate deposition. The rarity of siliciclasts is anticipated, as barnacles require near sediment free environments to live in (Beu *et al.* 1980; Kamp *et al.* 1988).

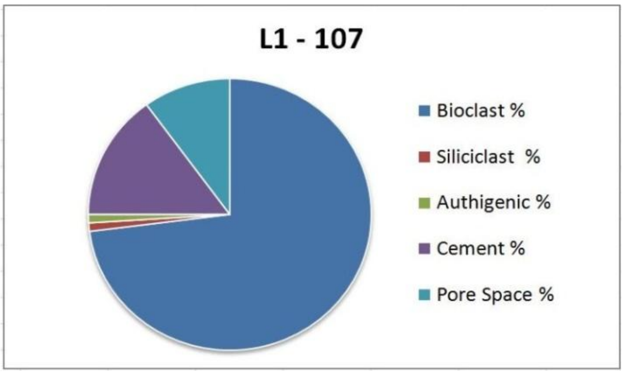


Figure 4.3 - Compositional pie graph of a representative lithofacies L1 sample. Note large proportion of bioclasts. Sample 107 (Tahaenui Limestone) is from Mahia Peninsula.

Lithofacies L2

Description: Lithofacies L2 is a very sandy, poorly sorted, indurated coquina shell bed. The coquinas host numerous complete shells (pectinids and brachiopods). The pectinids tend to show convex upwards orientations, while the brachiopods are commonly completely disorientated. Thickness can be up to 1.5 m. Figure 4.4 illustrates petrographic components of lithofacies L2.

Stratigraphic occurrence: All occurrences of the true lithofacies L2 are within the Opoiti Limestone, usually at, or near, the lower contact. Similar shell beds do occur within the Tahaenui Limestone, but are included as lithofacies L1-Bra/P/O, and not as L2 lithofacies due to their lack of siliciclasts.

Palaeontology: The brachiopod *Neothyris* dominates the Opoiti Limestone coquinas, and is up to 5 cm in size. Common pectinid (likely *Towaipecten ongleyi* (Beu 1995)) specimens are observed.

Depositional environment: Sediment texture and composition indicate deposition occurred within a high energy (disorientation of brachiopods and large input of siliciclastic material), shallow marine setting.

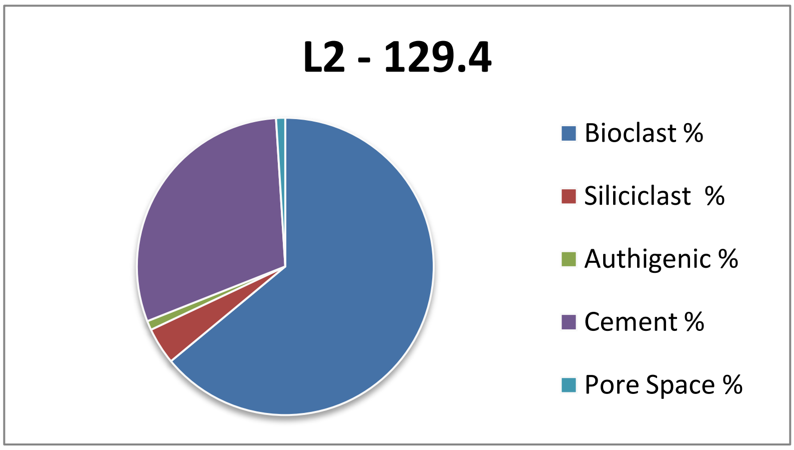


Figure 4.4 - Compositional pie graph of a representative lithofacies L2 sample. Note that pore space is less and siliciclast componentry higher than lithofacies L1. Sample 129.4 (Opoiti Limestone) from Hekerangi Point, Mahia Peninsula**.**

Lithofacies L3

Description: Massive to well bedded, moderately indurated, poorly sorted, mixed siliciclastic-bioclastic limestone, grey to red/brown in colour with occasional intact macrofossils. Thickness ranges from 30 cm beds to massive structures up to 3 m. Figure 4.5 illustrates petrographic components of lithofacies L3.

Stratigraphic occurrence: Lithofacies L3 occurs within the Whakapunake Limestone on Mahia Peninsula interbedded with lithofacies S4. Lithofacies L3 is also common in the lower Opoiti Limestone with a large proportion of siliciclastic material.

Palaeontology: Lithofacies L3 in Whakapunake Limestone hosts pectinid specimens of *Phialopecten marwicki* and *Mesopeplum waikohuense*. Opoiti Limestone on Mahia Peninsula has common intact bivalves of *Glycymeris mahiana*, up to 6 cm in size.

Depositional environment: Deposition occurred within a high energy, shallow marine setting with a dominant source of siliciclastic material in close proximity. Intact shells suggest close distance to the source of carbonate production.

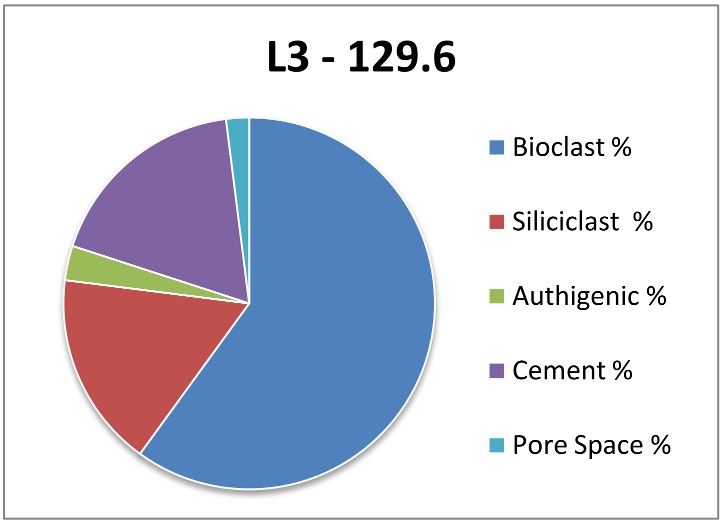


Figure 4.5 - Compositional pie graph of a representative lithofacies L3 sample. The siliciclastic portion is prominent. Sample 129.6 (Opoiti Limestone) from Hekerangi Point, Mahia Peninsula.

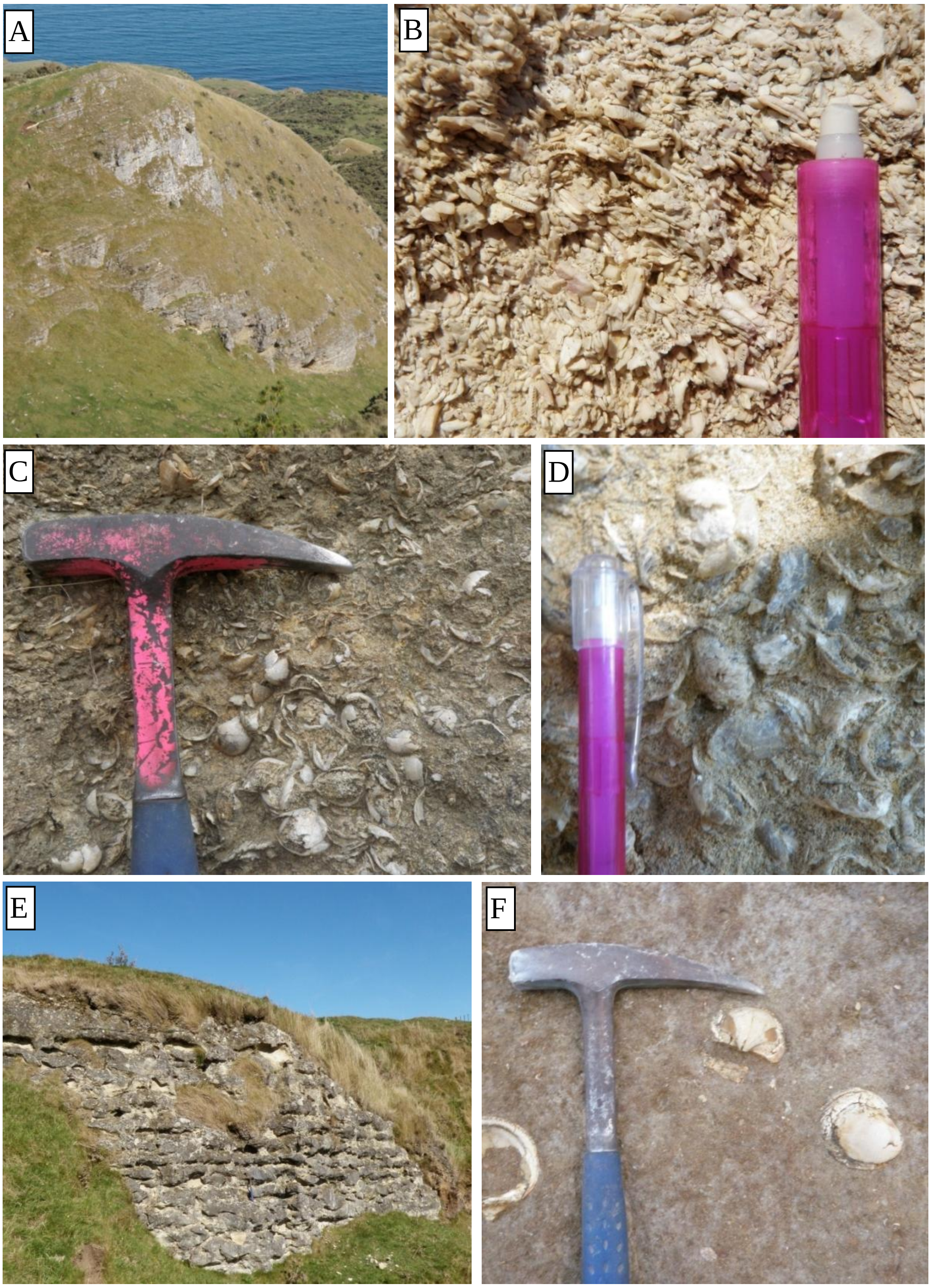


Figure 4.6 - Limestone lithofacies L1, L2 and L3. **(A)** Lithofacies L1 makes up large vertical succession of Tahaenui Limestone on Mahia Peninsula. **(B)** Close up view of Tahaenui Limestone, pictured in A, illustrating the dominance of barnacles as the primary bioclast. Barnacles are aligned parallel to one another and dip, in this case, c.20° SW. **(C)** Lithofacies L2 makes up thick brachiopod dominated coquina at the base of the Opoiti Limestone near Reef Station, Mahia Peninsula. **(D)** Close up view of lithofacies L2, Opoiti Limestone, at Ahimanawa Station, Mahia Peninsula. **(E)** Well bedded Opoiti limestone at Mt Moumoukai is commonly lithofacies L3, a sandy bioclastic mix. **(F)** Very sandy lithofacies L3, with common whole *Glycymeris* shells, forms a portion of Opoiti Limestone at Hekerangi Point, Mahia Peninsula. *Hammer - 32 cm long, pencil - 0.8 cm wide.*

4.3.2 Sandstone lithofacies

Figures 4.10 and 4.11 illustrate some sandstone lithofacies in the field.

Lithofacies S1

Description: Massive, moderately indurated, homogenous and well sorted, calcareous fine to medium grained, grey to brown coloured sandstone, can be up to c.10 m in thickness. Figure 4.7 illustrates petrographic components of lithofacies S1.

Stratigraphic occurrence: Lithofacies S1 is relatively rare, occurring only in the gradational intervals above the Tahaenui and Opoiti Limestones.

Palaeontology: No macrofossils are evident. Some occurrences of circular trace fossils occur in lithofacies S1 at Mt Moumoukai.

Depositional environment: Deposition occurred within a moderate energy, relatively shallow marine setting. The homogenous character could reflect bioturbation as evidenced by indiscriminate trace fossils.

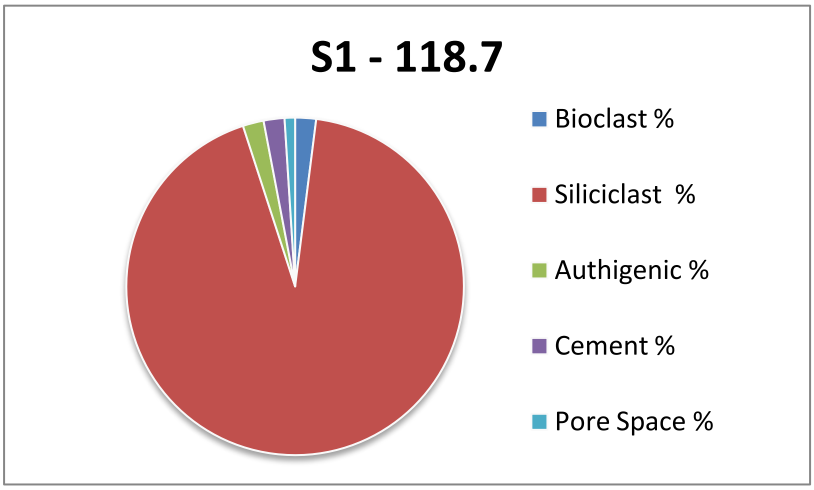


Figure 4.7 - Compositional pie graph of representative sample of lithofacies S1, which emphasises the large proportion of siliciclasts. Sample 118.7, comes from above the Whakapunake Limestone on the west coast of Mahia Peninsula.

Lithofacies S2

Description: Thickly bedded, moderately indurated, grey to brown coloured, fossiliferous sandstone, with rare to common whole macrofossils 1-2 cm in size. Figure 4.8 illustrates petrographic components of lithofacies S2.

Stratigraphic occurrence: The fossil bearing lithofacies S2 occurs in several localities in the study area. The Tahaenui Limestone in the Tahaenui/Clonkeen area transitions upwards gradually into this shelly sandstone. The Whakapunake Limestone on Mahia Peninsula's west coast grades upwards into thick (up to c.8 m) units of lithofacies S2.

Palaeontology: Abundant, small (1-2 cm) bivalves are the dominant fossil type, with rare gastropods up to 2 cm. Bioturbation is common within the S2 lithofacies on Mahia Peninsula.

Depositional environment: Lithofacies S2 was likely deposited within a moderate energy, relatively shallow marine setting. Intact small fossils indicate probable close proximity to a carbonate source.

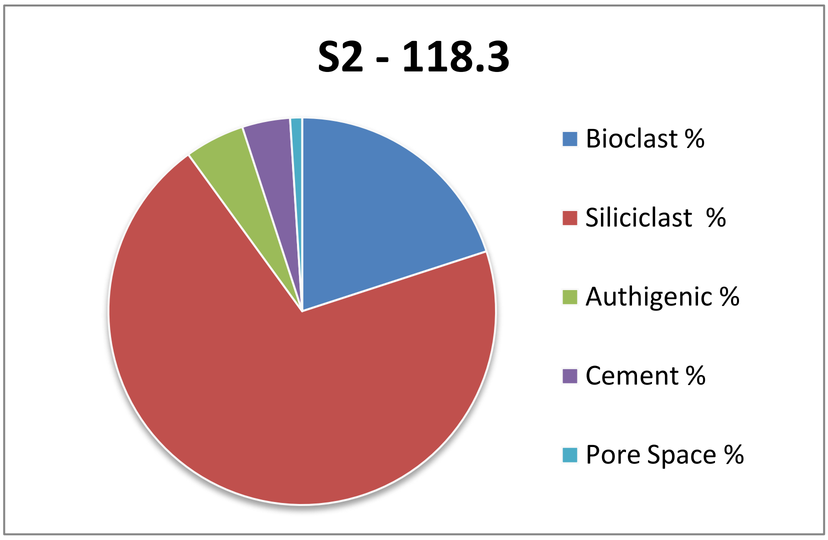


Figure 4.8 – Compositional pie graph of representative lithofacies S2 sample, which emphasises the greater bioclast portion than lithofacies S1. Samples 118.3 comes from above the Whakapunake Limestone on the west coast of Mahia Peninsula.

Lithofacies S3

Description: Non-calcareous, volcaniclastic fine sandstone, that is restricted in distribution to the western (Wairoa) region, outside the present study area.

Lithofacies S4

Description: Variably indurated, poorly sorted, shelly sandstone with common and regularly spaced mudstone clasts up to 20 cm in size. Clasts can vary in size, shape and angle between interbeds, and can have a pitted or irregular boundary. Clasts most commonly show angular orientations of c.40° westwards (BJ43/179523). Thickness of beds range from 20-100 cm. Figure 4.9 illustrates petrographic components of lithofacies S4.

Stratigraphic occurrence: Lithofacies S4 occurs interbedded with lithofacies L3 on the west coast of Mahia Peninsula where they comprise the Whakapunake Limestone.

Palaeontology: The shelly sandstone matrix surrounding the mudstone clasts hosts common small fragmented shells and numerous 2-3 mm bryozoan fragments, evident in both foraminiferal pickings and in thin section.

Depositional environment: Deposition of lithofacies S4 occurred within a moderate to high energy, relatively shallow marine setting. Sedimentary structures indicate varying environmental conditions.

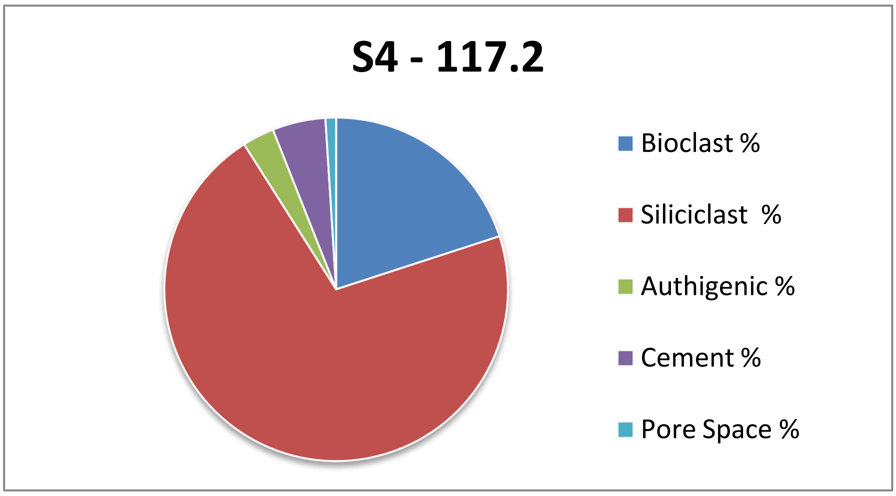


Figure 4.9 – Compositional pie graph of a representative lithofacies S4 sample. The large siliciclastic portion is derived from both the contained sand grains and the associated mud clasts. The percentage of bioclasts is derived from the shelly sandstone matrix. Sample 117.2 is within the Whakapunake Limestone on the west coast of Mahia Peninsula.

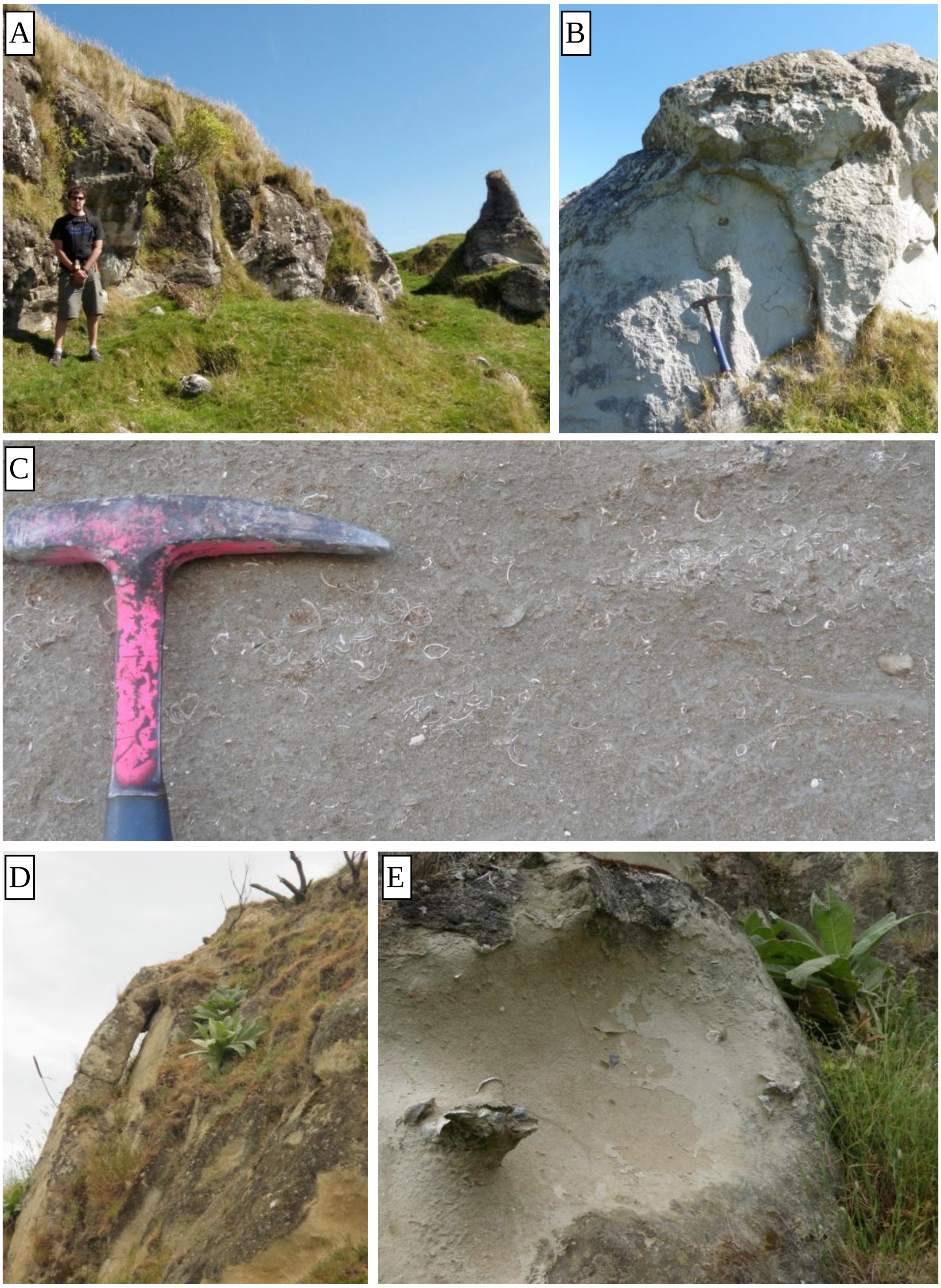


Figure 4.10 - Sandstone lithofacies S1 and S2. **(A** and **B)** Sandstone lithofacies S1 forms smooth outcrops at Mt Moumoukai as a weathering feature. **(C)** Shelly sandstone lithofacies S2 with scattered small (1-3 cm) bivalves on west coast Mahia Peninsula. **(D** and **E)** Shelly sandstone lithofacies S2 in the Tahaenui/Clonkeen area, gradationally overlying the Tahaenui Limestone. Dominant shell type is small (4-5 cm) pectinids. *Hammer - 32 cm long.*

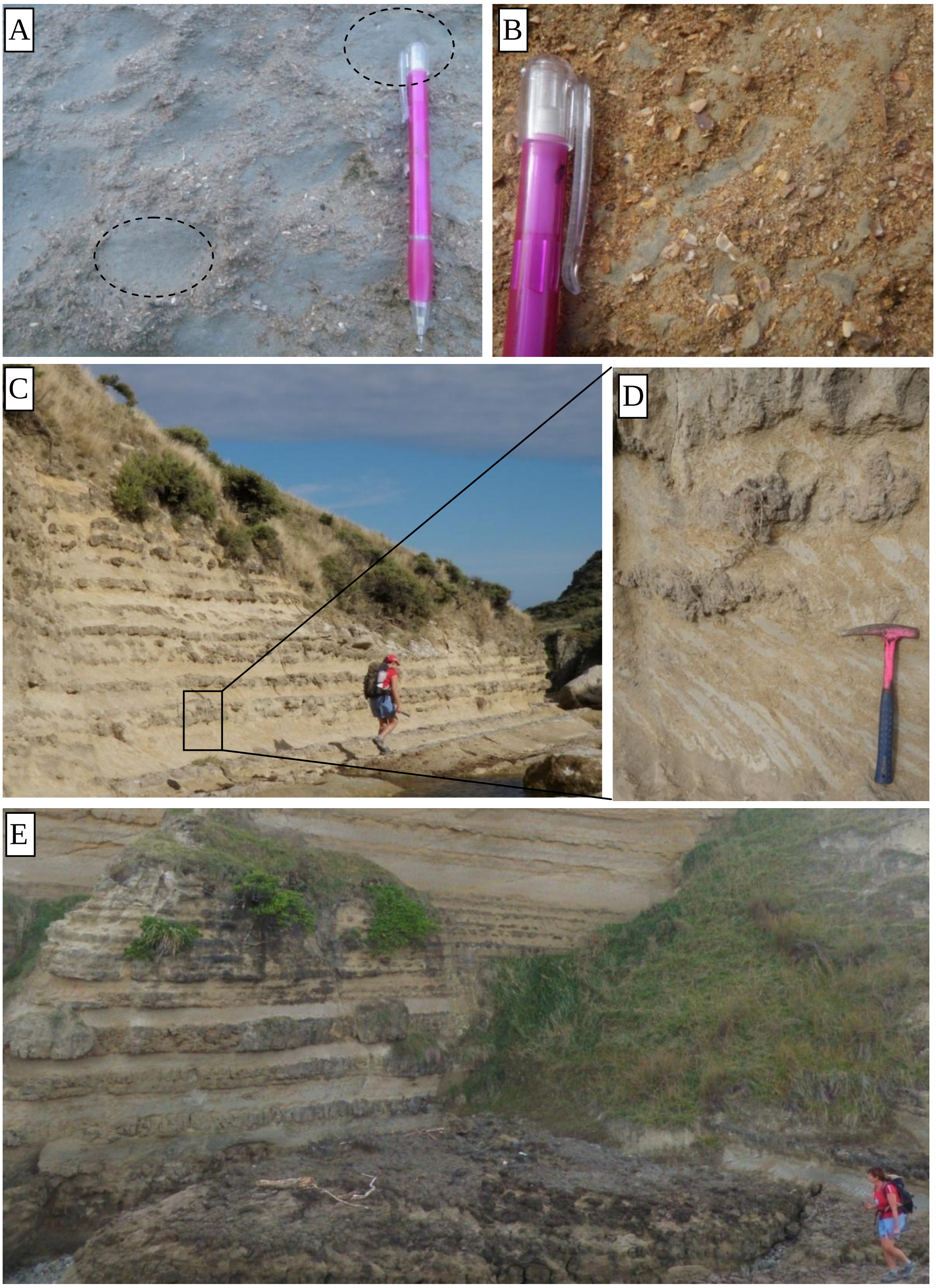


Figure 4.11-The mudclast bearing shelly sandstone, lithofacies S4, in Whakapunake Limestone at Ahimanawa Station, west coast of Mahia Peninsula. **(A)** The mudstone clasts as they appear in horizontal cross section on the flat coastal platform. In this view they appear roughly circular (dashed outline), but in vertical section they are elongated. **(B)** Stratigraphically higher in the Whakapunake succession the mudstone clasts become significantly smaller (4-5 cm) with less defined shape. The shelly sandstone matrix is clear in this image. **(C)** The Whakapunake Limestone succession includes lithofacies L3 (harder protruding beds) and S4 (softer eroded beds), Stalactite Falls Stream, west coast, Mahia Peninsula. **(D)** Close up image of the mudstone clasts within the shelly sandstone, interbedded with limestone lithofacies L3. **(E)** Whakapunake Limestone outcrops on the coast at Ahimanawa Station. Lithofacies S4 (lighter beds) are interbedded with lithofacies L3 (darker beds). *Hammer - 32 cm long, pencil - 0.8 cm wide.*

4.3.3 Mudstone lithofacies

Figure 4.15 illustrates some mudstone lithofacies in the field.

Lithofacies M1

Description: Massive, weakly to moderately indurated, calcareous mudstone. Fine grained, blue-grey in colour and ranges in thickness from c.5-100 m. Figure 4.12 illustrates basic componentry of lithofacies M1.

Stratigraphic occurrence: Occurs widely throughout entire field area, both underlying and overlying the limestone units. Specifically, lithofacies M1 underlies the Opoiti Limestone, overlies the Whakapunake Limestone, and both under and overlies the Tahaenui Limestone.

Palaeontology: Macrofossils are rarely observed, but some bioturbation is evident.

Depositional environment: Deposition occurred within a likely low energy, relatively shallow and quiet marine setting.

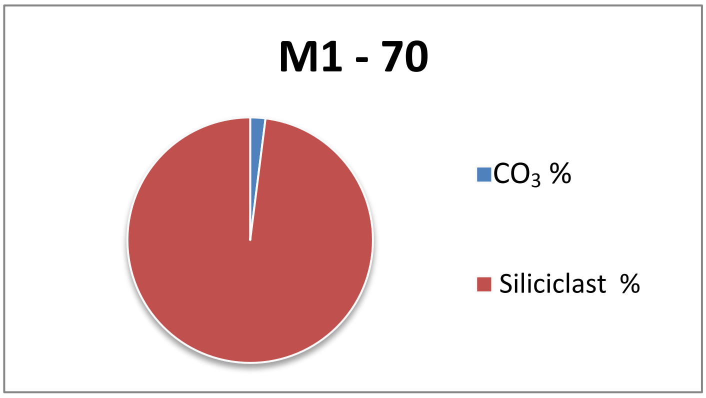


Figure 4.12 – Hypothetical compositional pie graph of lithofacies M1. The simple, yet dominant portion of siliciclastic material gives the lithofacies M1 its homogenous character. Due to difficulty in thin section preparation, results here are estimated. Sample 70 underlies the Opoiti Limestone at Mt Moumoukai.

Lithofacies M2

Description: Lithofacies M2 comprises bedded (20-30 cm thick), weakly to moderately indurated, highly calcareous mudstone, that is restricted in distribution to the western (Wairoa) region outside the present study area.

Lithofacies M3

Description: Massive, highly indurated, concretionary mudstone. Fine grained and grey-brown in colour. Lithofacies M3 can involve large subspherical concretions up to 1.5 m across, smaller concretions up to 30 cm size, or uniform concretionary beds up to 30 cm thick. Figure 4.13 illustrates petrographic components of lithofacies M3.

Stratigraphic occurrence: A bed of 30 cm subspherical concretions and a single concretionary bed are found at and near the base of the Opoiti Limestone at Hekerangi Point, Mahia Peninsula. Large concretions up to 1.5 m are evident within a thick succession of Wairoa Formation mudstone B, above the Opoiti Limestone.

Palaeontology: No macrofossils are evident although the smaller concretions at Hekerangi Point support peripheral pholad borings, 5 mm wide and up to 4 cm deep.

Depositional environment: Deposition occurred within a likely low energy, relatively shallow and quiet marine setting allowing the precipitation of carbonate into concretions near below the seafloor.

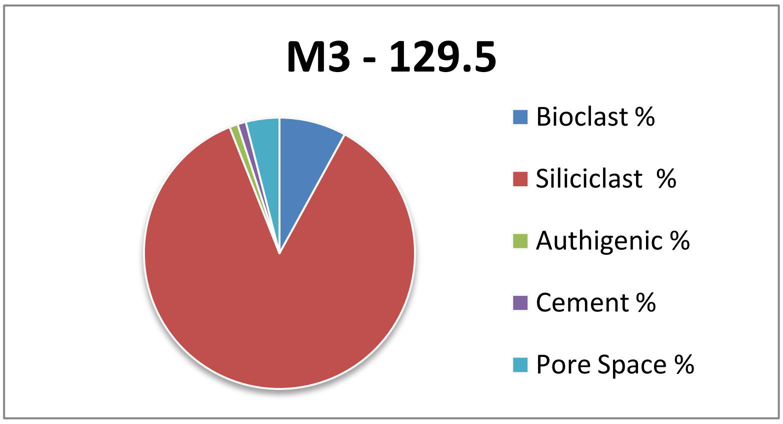


Figure 4.13 - Compositional pie graph of a representative lithofacies M3 sample. Sample 129.5 is a c.10 cm concretion near the base of the Opoiti Limestone, Hekerangi Point, Mahia Peninsula. Authigenic and bioclastic componentry are from the partial limestone infill of pholad borings. Secondary pore space is from unfilled pholad borings.

Lithofacies M4

Description: Weakly to moderately indurated, poorly to moderately sorted, fine grained fossiliferous mudstone. Units are massive and are up to 3 m thick. Figure 4.14 illustrates basic componentry of lithofacies M4.

Stratigraphic occurrence: Fossiliferous mudstone is distributed widely throughout the study area. Lithofacies M4 occurs within the intervals above the Tahaenui Limestone and Opoiti Limestone. Lithofacies M4 also underlies the Opoiti Limestone at Mt Moumoukai and occurs above the Whakapunake Limestone near Stalactite Falls Stream, Mahia Peninsula.

Palaeontology: Fossils, mainly small bivalves, are up to 3 cm size, and have a relict appearance with fractures and loss of original shell lustre.

Depositional environment: Deposition occurred within a likely low energy, relatively shallow and quiet marine setting with sufficient energy to transport common small shells.

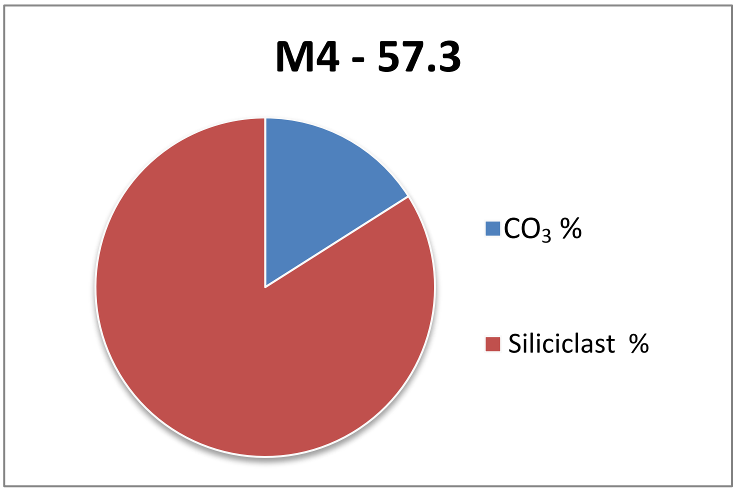


Figure 4.14 - Hypothetical compositional pie graph of lithofacies M4. Note the greater proportion of $C0_3$ caused by the higher presence of shells than in lithofacies M1. Sample 57.3 overlies the Tahaenui Limestone in the Tahaenui/Clonkeen area. Due to difficulty in thin section preparation, results here are estimated.

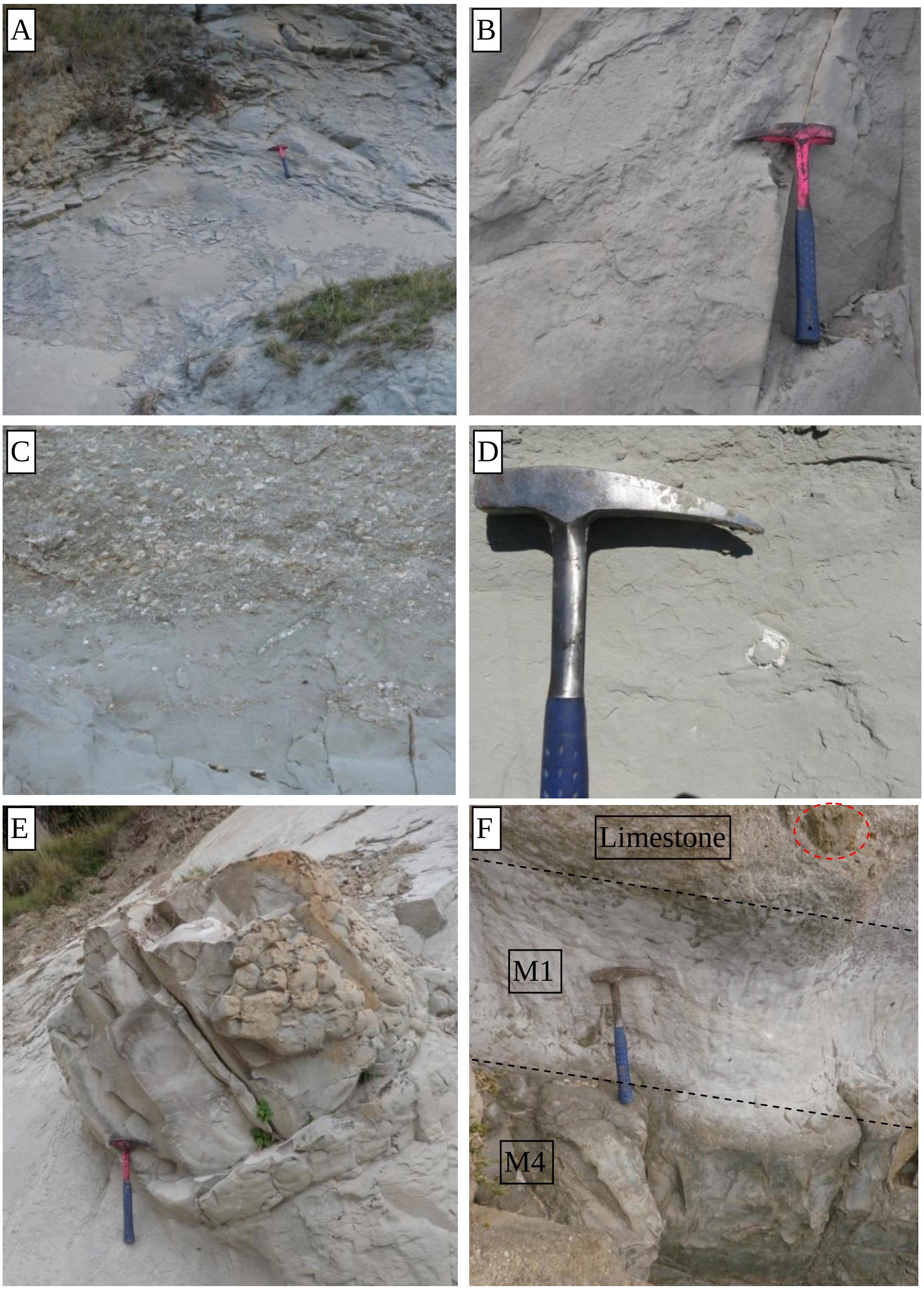


Figure 4.15 - Mudstone lithofacies M1, M3 and M4. **(A** and **B)** Homogenous mudstone lithofacies M1, underlying **(A)** and overlying **(B)** the Opoiti Limestone, cropping out at Mahia Peninsula. **(C)** Lithofacies M3, **s**helly mudstone underlying the Opoiti Limestone at Mt Moumoukai; individual bivalves are c.1 cm in size. **(D)** Rare bivalve embedded in lithofacies M3, overlying the Tahaenui Limestone in the Tahaenui/Clonkeen area. **(E)** Large concretion, lithofacies M4, in homogenous mudstone, Otunua Stream, Mahia Peninsula. **(F)** A concretionary mudstone bed, lithofacies M4, transitioning upwards into lithofacies M1, both underlying the Opoiti Limestone at Hekerangi Point, Mahia Peninsula. Small circular concretion visible in upper right corner, circled in red. *Hammer - 32 cm long.*

Mudstone clay mineralogy

XRD analysis shows that illite and chlorite minerals are the dominate clay mineral in the mudstones of the Wairoa Formation (Figure 4.16). Illite, being relatively stable, nonreactive to ethylene glycol and resistant to high temperatures (550˚C) is straightforward to identify. Chlorite has several peaks, often dominant at the 002 position and of lesser intensities at the 001 and 003 positions. All have reduced slightly in intensity upon heating. A small amount of smectite is evident in the glycolated samples as 'swollen' peaks that are destroyed when heated to 550˚C. Any kaolinite is also of minor abundance. The chlorite 002 peak coincides with the kaolinite 001 peak. The chlorite/kaolinite peak at 12.54˚ 2θ is smaller in the heated samples, suggesting the destruction a small amount of kaolinite, leaving stable chlorite behind.

The dominant illite and chlorite clay mineralogy can be compared with two nearby New Zealand areas, the Waipaoa River near Gisborne and the Te Kuiti area in the King Country. The Waipaoa River hosts a large sediment input dominated by illite clays sourced from Mesozoic basement greywacke (Lloyd 2007). The similarity of having illite as a dominant clay mineral in the Wairoa Formation suggests that the ultimate source of the Nuhaka/Mahia Peninsula clay minerals was from Mesozoic basement greywacke.

The Triassic basement greywackes in western North Island have illite and chlorite clay minerals (Nelson & Hume 1987), with the weathering of feldspars providing some kaolinite and smectite (Nelson & Hume 1987). The presence of chlorite also suggests the ultimate derivation of siliciclastic sediment from the basement rocks (Nelson 1973; Lloyd 2007).

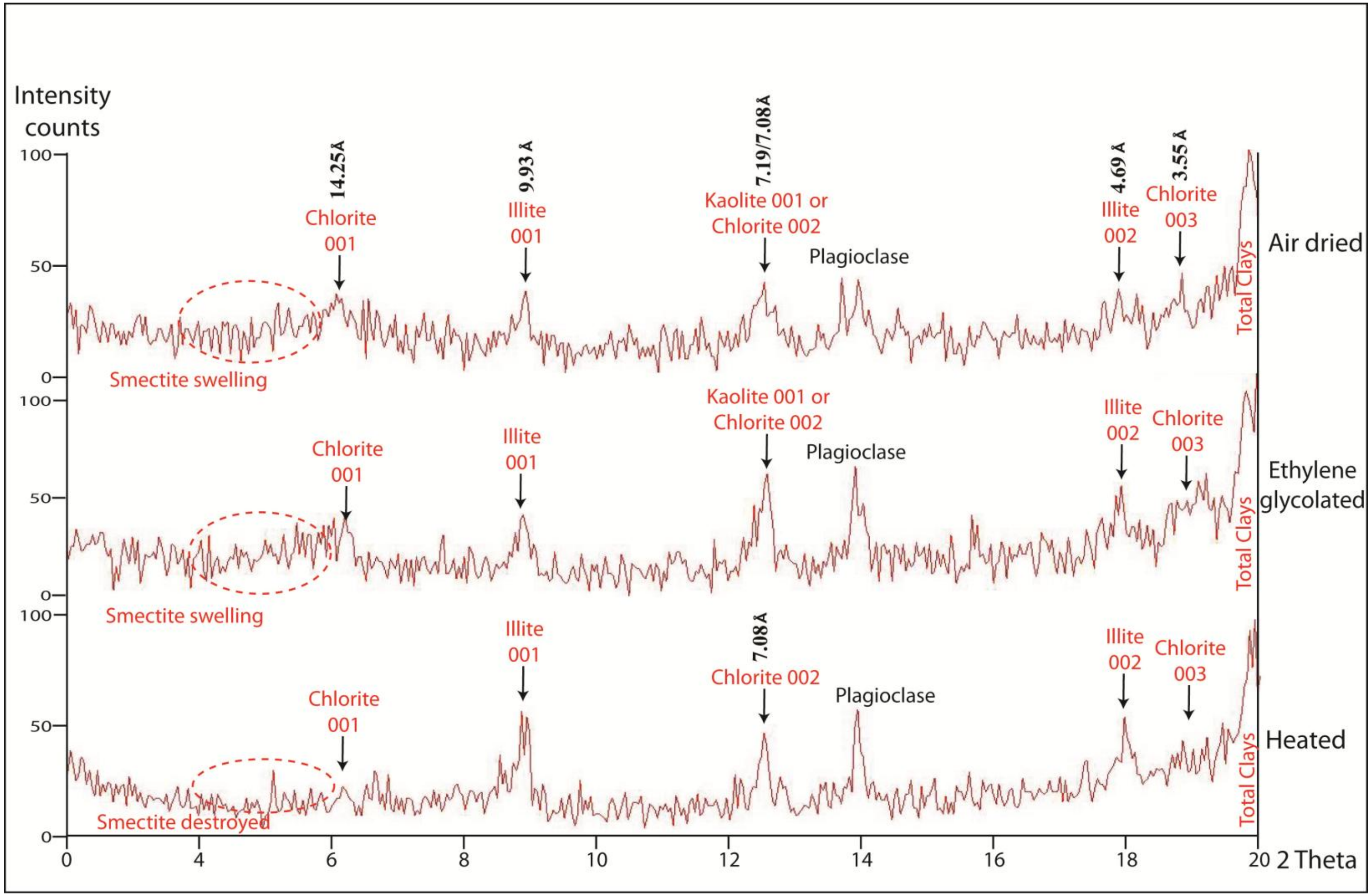


Figure 4.16 – Example of an X-ray diffraction graph illustrating air dried, ethylene glycolated and heated treatments of Wairoa Formation D mudstone, sample 57.3. Dominant clay mineral peaks are illite and chlorite.

4.3.4 Volcanic lithofacies

Figure 4.18 illustrates some features of the volcaniclastic lithologies in the field.

Lithofacies V1

Description: Massive to incipiently laminated, very soft, pumiceous, moderately sorted, medium grained volcaniclastite, which may include a number of small, rounded mudstone clasts. Microscopic 'Y shaped' glass shards are common. Thickness ranges from 30-80 cm. Figure 4.17 illustrates petrographic components of lithofacies V1.

Stratigraphic occurrence: Several volcaniclastic units are evident within the field area, both on the west coast of Mahia Peninsula and at Tahaenui/Clonkeen. The volcaniclastic units occur within the upper siliciclastic successions, closely overlying the Tahaenui and Whakapunake Limestones. A c.15 cm volcaniclastic unit lies within the thick mudstone of the Wairoa Formation B (indistinctly overlying the Opoiti Limestone on Mahia Peninsula).

Palaeontology: The internal mould of a solitary bivalve was collected from a c.15 cm volcaniclastic unit within the Wairoa Formation B, but cannot be accurately identified. It is possibly a mould of a *Glycymeris* specimen (*pers. commun.* Beu 2010).

Depositional environment: Volcaniclastites observed in the study area are likely secondary volcaniclastic deposits, reworked from original volcanic material into a sedimentary sequence. Physical characteristics (poor sorting and lack of gravity settling) imply an original volcanic subaqueous flow rather than an air fall deposit (Fisher 1984), which settled within a marine environment dominated by siliciclastic accumulation.

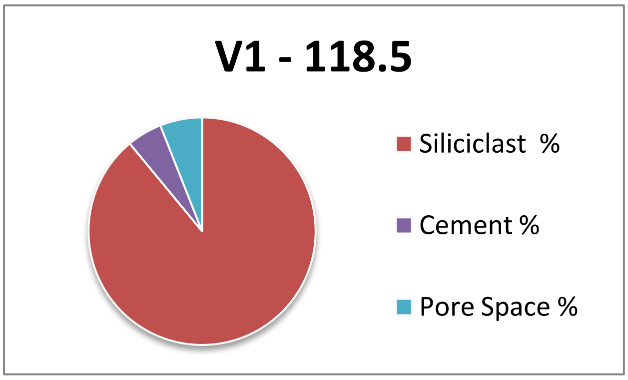


Figure 4.17- Compositional pie graph of lithofacies V1. Siliciclastic component is primary pumice clasts and small amounts of mudstone. Pore space is derived from small vesicles within pumice. Sample 118.5 occurs within the siliciclastic succession overlying the Whakapunake Limestone, west coast Mahia Peninsula.

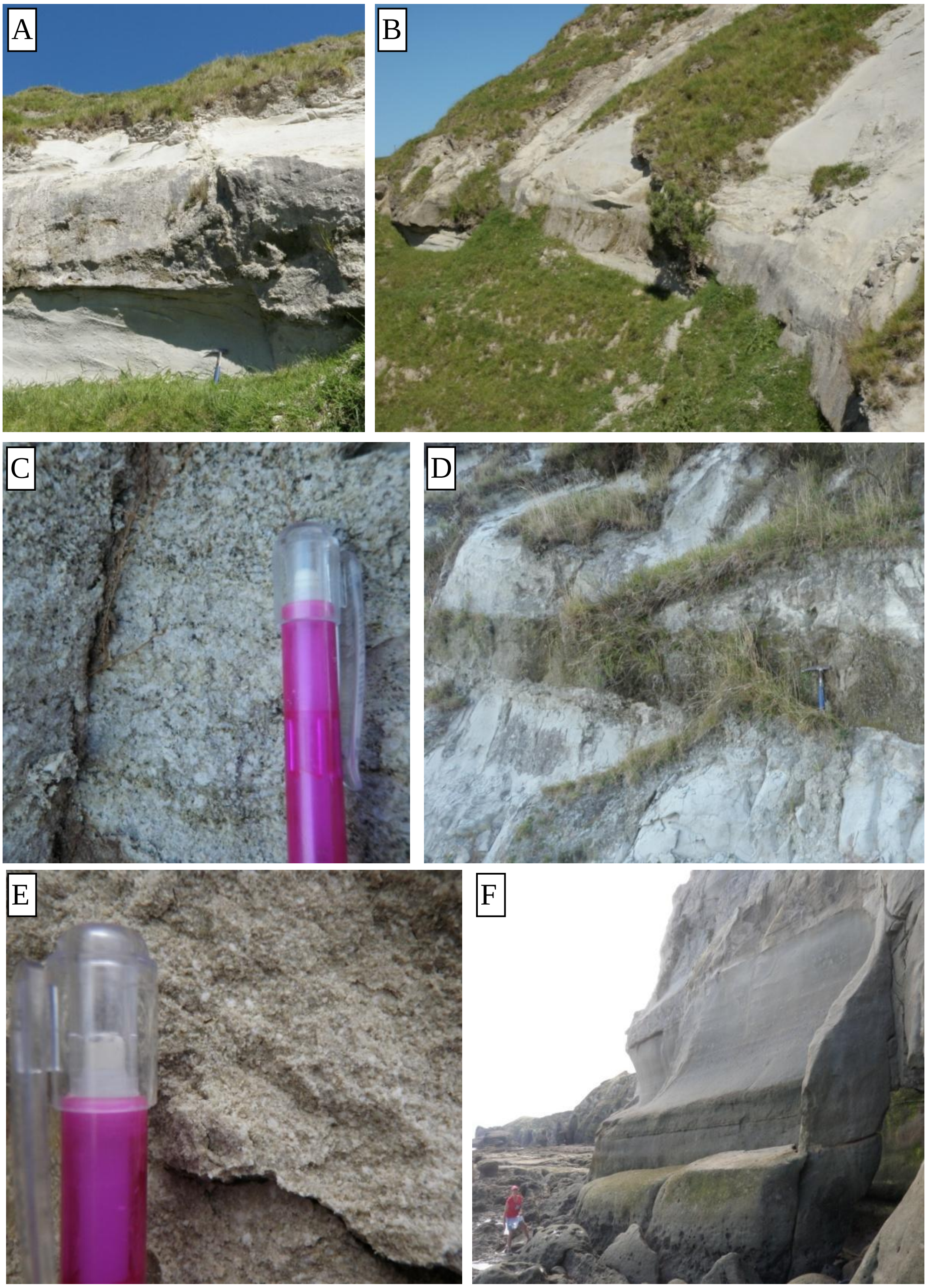


Figure 4.18 - Volcanic lithofacies V1. **(A** and **B)**. A 60 cm volcaniclastite within mudstone succession overlying the Tahaenui Limestone at Tahaenui, Kokohu Road. The same volcaniclastic unit **(C)** illustrating small laminations (perhaps derived from settling within water) and pumiceous componentry **(D)**, cropping out at Clonkeen Station, Mangaone Road. **(E** and **F)** A 50 cm thick, pumiceous, volcaniclastic unit within the mudstone succession overlying the Whakapunake Limestone, Ahimanawa Station, Mahia Peninsula. *Pencil - 0.8 cm wide.*

4.3.5 Additional features

These additional features include a range of distinctive geological characteristics that can further classify a lithofacies group, but are not substantial enough on their own to necessitate an individual lithofacies group. These can be used to add extra distinguishing features and information that might aid in inferring paleoenvironments of deposition. These features are largely paleontological based or are sedimentary structures that should enhance the interpretation of the primary lithofacies. These features can be associated with any carbonate, siliciclastic or volcanic lithofacies. Figure 4.19 illustrates some of these other features in the field.

Hb *- Horizontal bedding*
Xb *- Cross bedding*
S *- Siliciclastic rich*
Mc *- Mudstone clasts (<5 mm)*
Gl *- Glauconite laminae*

Bra *- Brachiopod rich*
Biv *- Bivalve rich*
P/O *- Pectinid/oyster rich*
Bio *- Bioturbation*
Bor *– Boring/burrows*

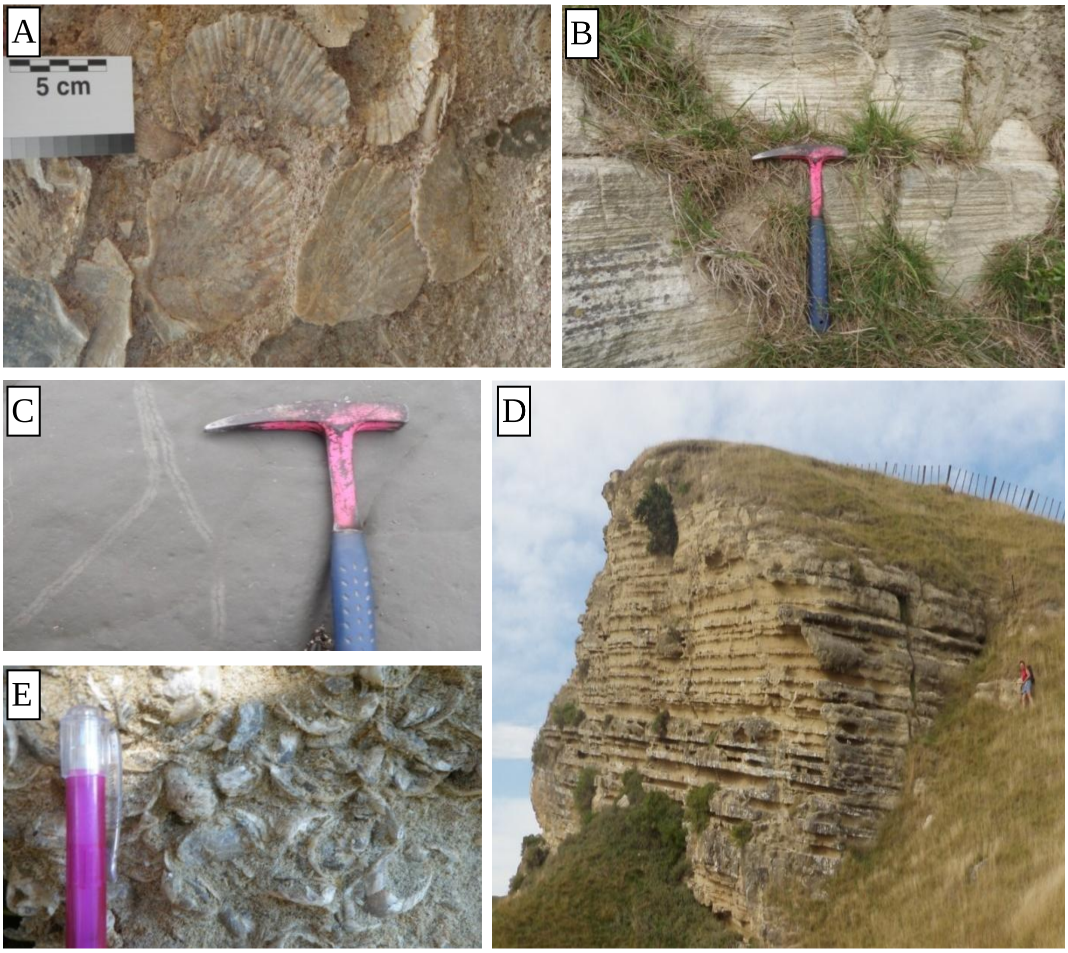


Figure 4.19 – Field characteristics of additional features able to be added to any lithofacies group. **(A)** Pectinid/oyster rich. **(B)** Glauconite laminae. **(C)** Burrows. **(D)** Horizontal bedding. **(E)** Brachiopod rich. *Hammer - 32 cm long, pencil - 0.8 cm wide.*

Chapter Five – Opoiti Limestone

Previous Page - Opoiti Limestone forming high bluffs, Ahimanawa Station, west coast of Mahia Peninsula.

CHAPTER FIVE - OPOITI LIMESTONE

5.1 LITHOSTRATIGRAPHY

The Opoiti Limestone of early Pliocene (Opoitian) age (Appendix I, Beu (1995)) is the most widely distributed of the Pliocene limestones in the northern Hawke's Bay region. Within the immediate study area, the limestone crops out at Mt Moumoukai and on the west coast of Mahia Peninsula (Figure 5.1). The type locality for the Opoiti Limestone is the outcrops on the banks of the Mangapoike River (BH41/962841), c.35 km northwest of Mahia (Appendix VIII). A nearby reference section (BH41/952802) having easier access was given by Beu (1995) in the Makaretu Stream (Appendix VIII).

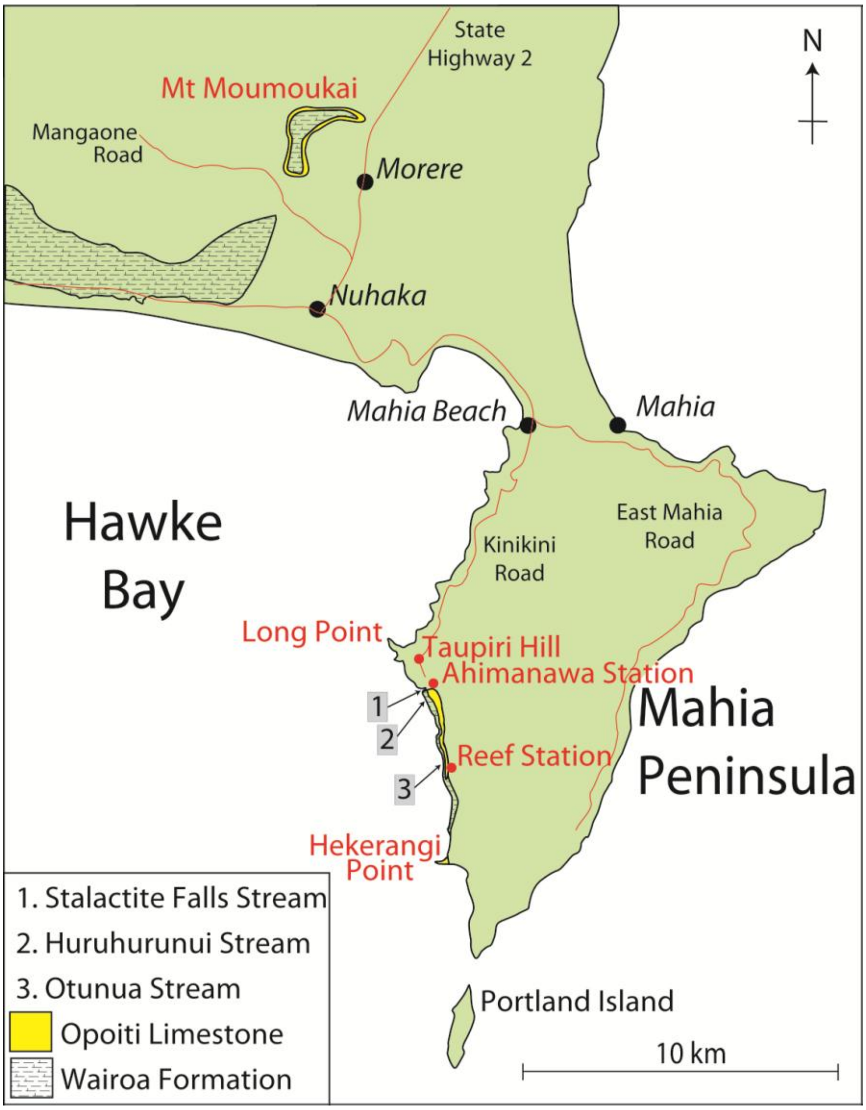


Figure 5.1 – Distribution of the Opoiti Limestone and encompassing Wairoa Formation in the immediate study area**.** Names of stations, streams and features referenced in this chapter are shown on the map.

Mt Moumoukai

Mt Moumoukai (BH42/126770) (Figure 5.2) is a dominant topographical feature, hosting a ‘cap’ of bluff forming limestone, and has peripheral northern and southern ridges. These adjacent ridges are formed from the Opoiti Limestone. The northern ridge of Opoiti Limestone reaches up to 20 m in vertical thickness (Figure 5.3) and is very indurated (primarily lithofacies L3). Alternations of horizontal ‘wavy’ hard and soft beds (20-30 cm thick) are dominant, with physical weathering increasing recessive inward erosion (Figure 5.4 A, B, E), (Stratigraphic column 9, Appendix VII). The fabric is a very dense crystalline structure with fresh fragmented shell material – most commonly bioclast supported. Angular to subangular mudstone clasts (2-5 mm, occasionally iron weathered) and a large amount of siliciclastic grains are present, with recessive beds tending to host a greater proportion. Rare, unidentifiable fragmented bivalves occur. The western flank of Mt Moumoukai exposes the Opoiti Limestone underlying the Tahaenui Limestone (Figure 5.4 C, D).

An outcrop of the Opoiti Limestone on the southern arm is up c.5 m to thick and much more weathered (Figure 5.4 F) (Stratigraphic column 28, Appendix VII). It hosts an abundant population of small bivalves (1-2 cm) (Figure 5.4 G) in the basal limestone where it overlies late Miocene mudstone. Here the Opoiti Limestone is red to brown in colour, massive to poorly bedded and very sandy with occasional mudstone clasts (up to 2 mm in size).

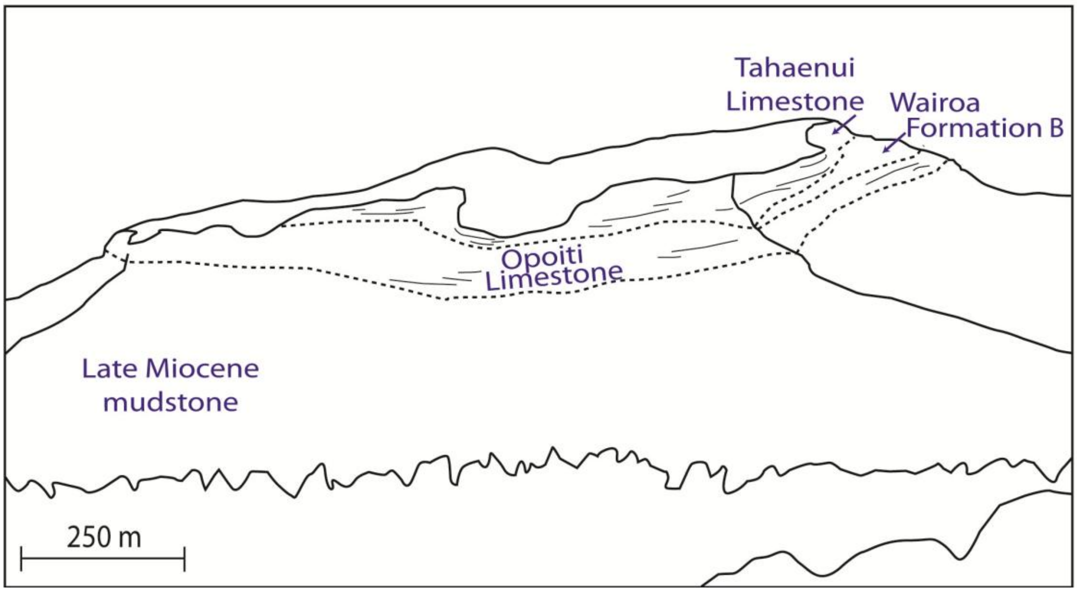


Figure 5.2 – The southwest face of Mt Moumoukai showing the Tahaenui Limestone unconformably resting directly on top of the Opoiti Limestone. Eastwards, the Wairoa Formation B is visible between the limestone units. Late Miocene mudstone underlies the Opoiti Limestone. Note scale is only approximate as the actual distance changes with perspective.

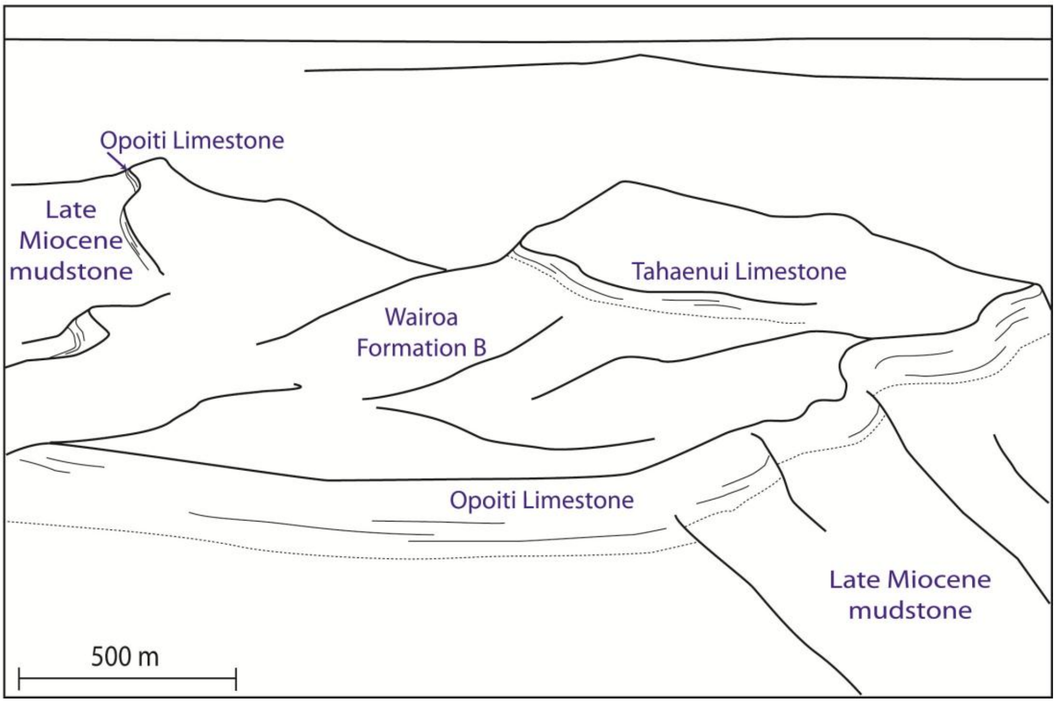


Figure 5.3 – An oblique aerial view of Mt Moumoukai, showing the northern ridge of Opoiti Limestone in foreground with Tahaenui Limestone as a cap to the west. Late Miocene mudstone underlies the Opoiti Limestone, with Wairoa Formation B forming a 'wedge' between the two limestone units. A small extension of the Opoiti Limestone is visible in the southwards distance. Photograph reproduced from Beu (1995, p. 82). Note scale is only approximate as the actual distance changes with perspective.

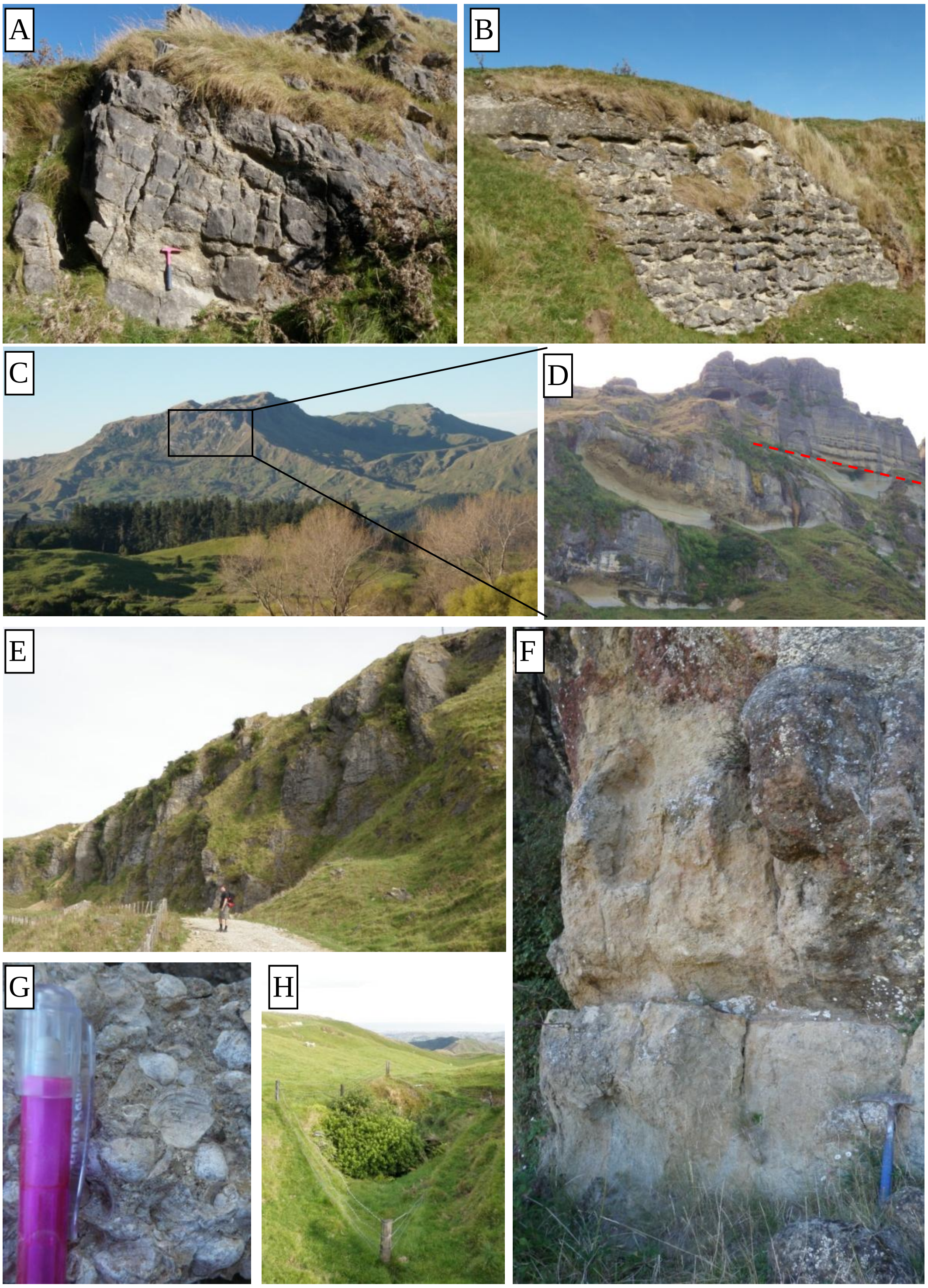


Figure 5.4 – Field photographs of the Opoiti Limestone at Mt Moumoukai. **(A** and **B)** Opoiti Limestone on the northeast side of Mt Moumoukai with horizontal 'wavy' bedding, moderately dipping (c.10˚SW). **(C)** The southwest face of Mt Moumoukai, where the Tahaenui Limestone rests unconformably atop the Opoiti Limestone. Highest point is 611 m asl**. (D)** Mt Moumoukai's southwest flank in which the unconformable contact between the lower Opoiti Limestone and overlying Tahaenui Limestone can be observed (Beu 1995), although this was not apparent during the current field work and is inferred by red dashed line. **(E)** Opoiti Limestone at its observed thickest, up to c.15 m, northeastern Mt Moumoukai**. (F)** Highly weathered, sandy and massive Opoiti Limestone, south Mt Moumoukai. **(G)** Very sandy Opoiti Limestone with densely packed small bivalve shells near its basal contact with late Miocene mudstone, south Moumoukai**. (H)** One of several sink holes on the top plateau of Mt Moumoukai, evidence of established weathering processes. *Hammer - 32 cm long, pencil - 0.8 cm wide.*

Mahia Peninsula

The Opoiti Limestone on Mahia Peninsula exhibits a range of lithological characteristics. Hekerangi Point (BJ43/185460) (Figure 5.5, Figure 5.6 A, B) is the most southern outcrop of the Opoiti Limestone, with exposures of the underlying contact and the lower c.9 m of the limestone (Figure 5.6 C). At its base the Opoiti Limestone is very sandy with a high content of shelly material, including pectinids up to 6 cm in size with typically convex upwards orientation and abundant brachiopods up to 4 cm in size (Figure 5.6 D). Here near the base is a single bed of iron weathered subspherical concretions up to 30 cm in size that support peripheral pholad borings c.3 cm in length. Lack of reaction to hydrochloric acid suggests the presence of dolomite, subsequently confirmed by XRD analysis and cathodoluminescence petrography. Upwards from here the Opoiti Limestone grades through lithified beds (c.20 cm thick) of sandy light grey limestone with very common densely packed brachiopods into a dominantly sandy red-brown limestone with a central band of 6 cm size intact *Glycymeris mahiana* bivalve fossils showing no preferred orientation (Figure 5.6 E, Figure 5.7 - Stratigraphic column 26, also held in Appendix VII).

Northwards, at Reef Station (BJ43/196498), the lower contact is again visible. Here it is dominated by a 1 m thick sandy coquina unit (lithofacies L2), rich in the brachiopod *Neothyris* (Figure 5.8 F), that grades upwards into an exceptionally sandy unit c.2-3 m thick (Figure 5.8 G, Stratigraphic column 23, Appendix VII). Further north, at Ahimanawa Station (BJ43/184525), the basal contact zone is again observed, with a very sandy, highly weathered Opoiti Limestone sharply overlying mudstone. The limestone here includes significantly less brachiopods than the two southern localities, only a few weathered specimens being evident (Stratigraphic column 19, Appendix VII). The changes in the basal character of the Opoiti Limestone across the three localities illustrate the kinds of lateral variations typical of the Pliocene limestones in this area.

Ahimanawa Station hosts a stratigraphically higher portion of the Opoiti limestone exposed in a 30-40 m high prominent bluff (Figure 5.8 C). Here the Opoiti Limestone is light cream to brown coloured and comprises a fine grained, well sorted, sandy matrix with fragmented shells, often barnacles, up to 4 mm size (lithofacies L1-L3) (Stratigraphic column 22, Appendix VII). Glauconitic laminae are present, approximately 2 mm thick (Figure 5.8 E). Beds (20-30 cm thick) are very distinctive with protruding hard bands alternating with recessed softer bands (Chapter frontispiece, Figure 5.8 D).

The most northern exposure of Opoiti Limestone on Mahia Peninsula occurs immediately south of the Stalactite Falls Stream (Figure 5.1) where it shows the same distinctive hard/soft bedding with a fragmented shelly sandy fabric (Figure 5.8 A, B).

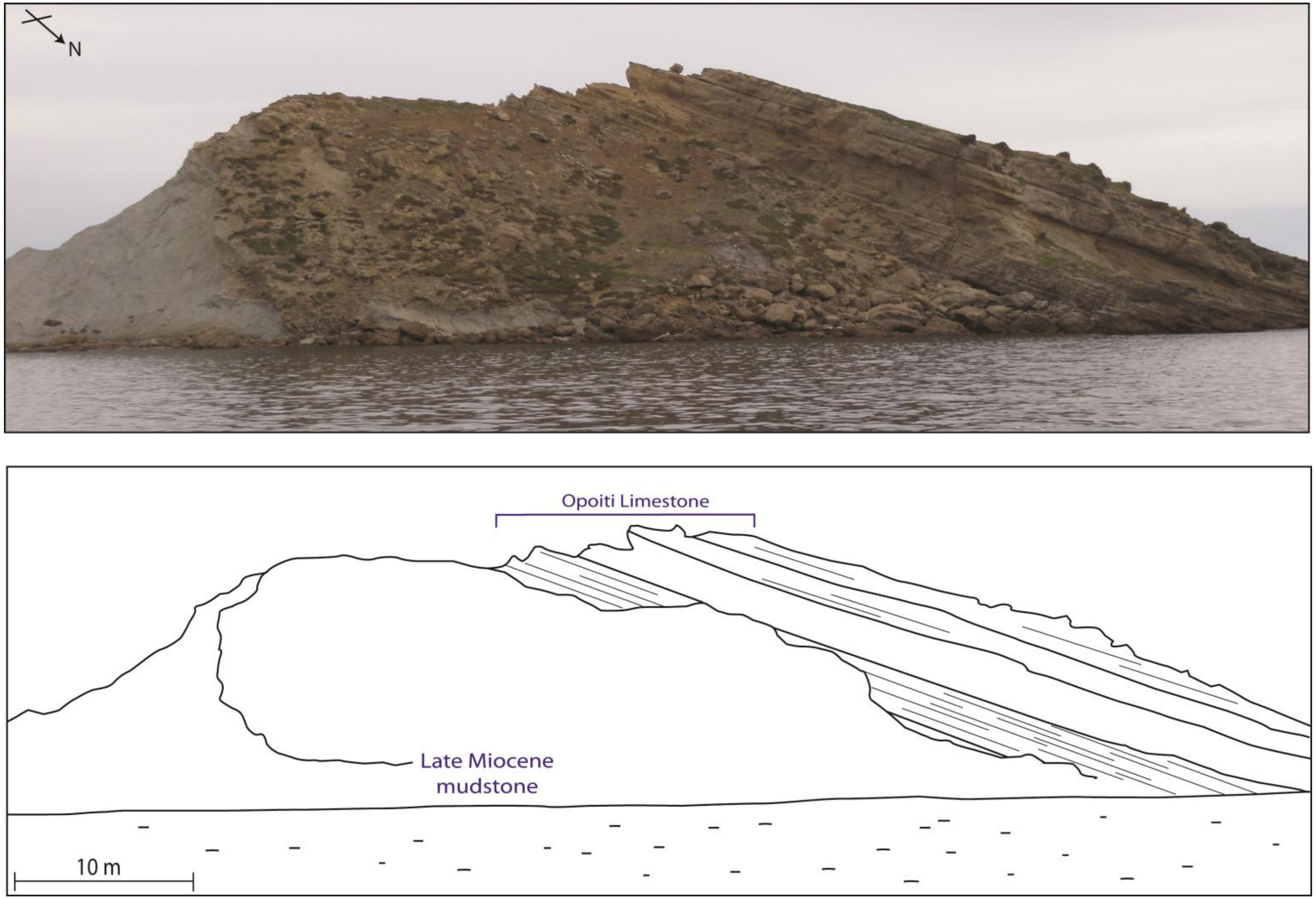


Figure 5.5 – Opoiti Limestone forms a steeply dipping (c.30˚W) cap on Hekerangi Point, west coast Mahia Peninsula, overlying late Miocene mudstone. Note scale is only approximate as the actual distance changes with perspective.

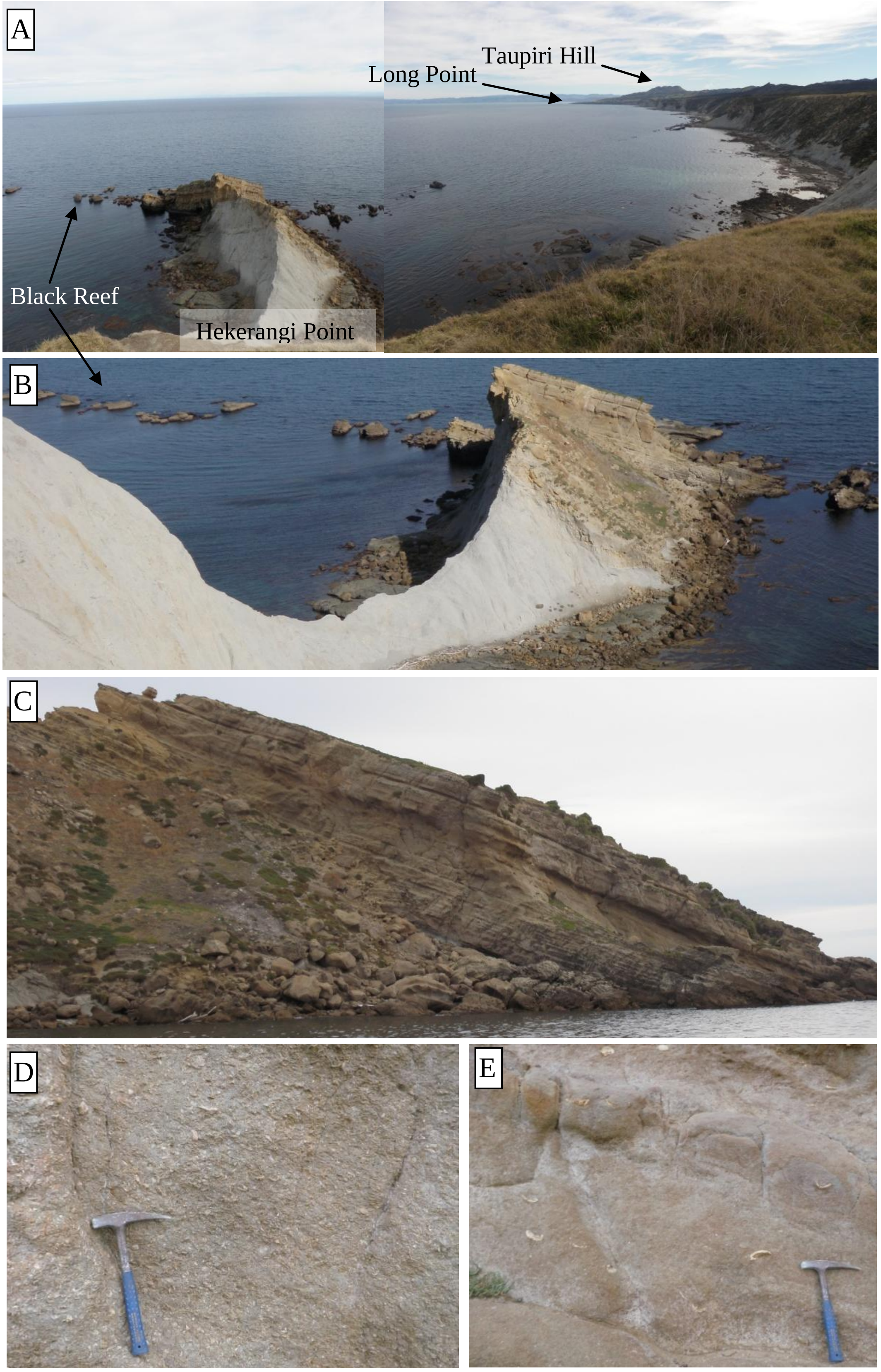


Figure 5.6 - Field photographs of the Opoiti Limestone on Hekerangi Point, Mahia Peninsula. **(A)** Stitched image looking north along the west coast of Mahia Peninsula from Hekerangi Point (left) up to Long Point and Taupiri Hill (right). Black Reef is a continuation of the Opoiti Limestone. **(B)** Southwards view of Hekerangi Point illustrating the underlying late Miocene mudstone and hard limestone beds at the end of Black Reef. **(C)** The c.9 m thick Opoiti Limestone tip that makes up Hekerangi Point (See figure 5.5). **(D)** The limestone at Hekerangi Point consists of a highly indurated, sandy brachiopod-bearing unit grading upwards to **(E)**, an especially sandy bed containing common *Glycymeris mahiana* macrofossils. *Hammer - 32 cm long.*

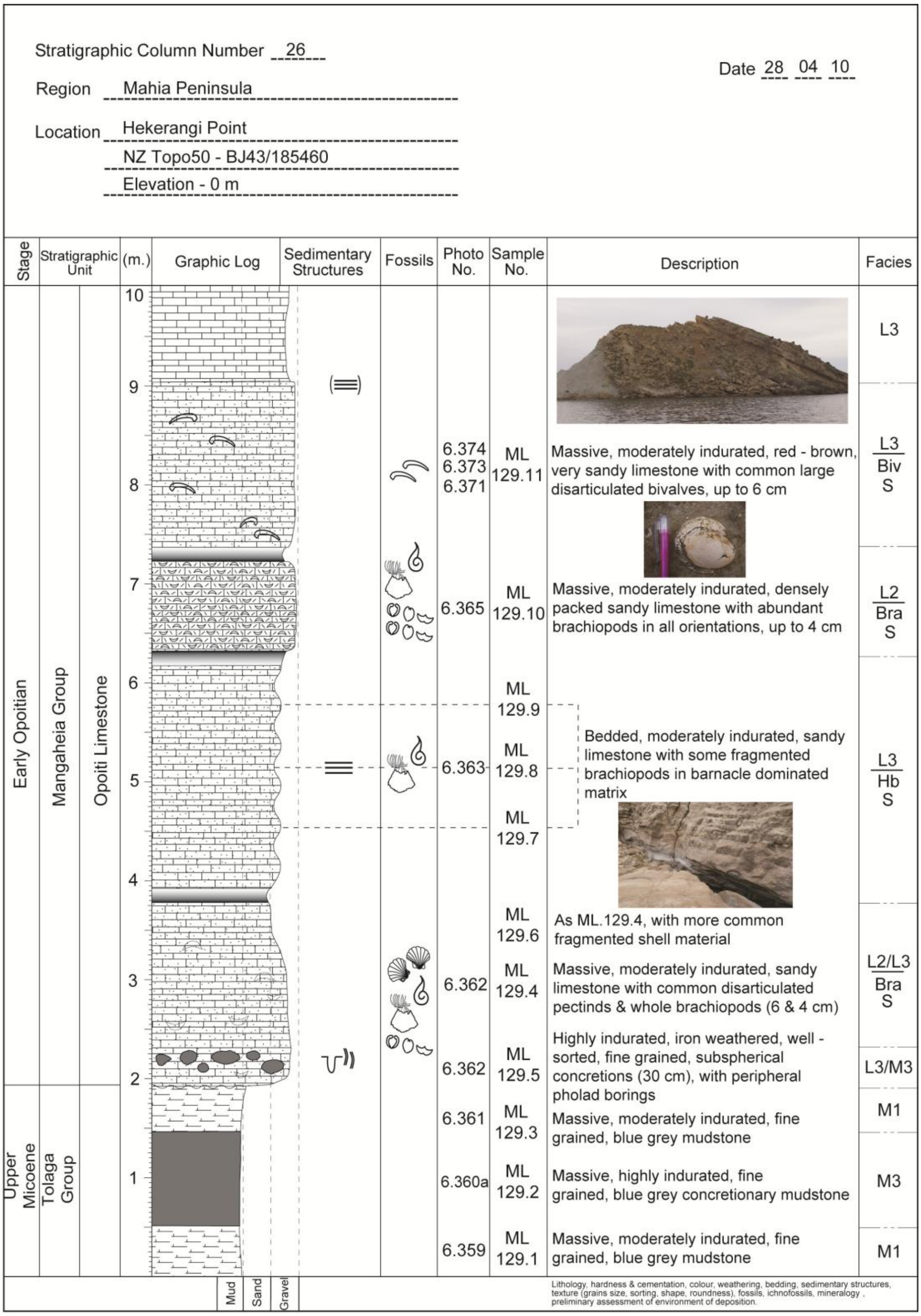


Figure 5.7 – Stratigraphic column of the Opoiti Limestone at Hekerangi Point, west coast Mahia Peninsula.

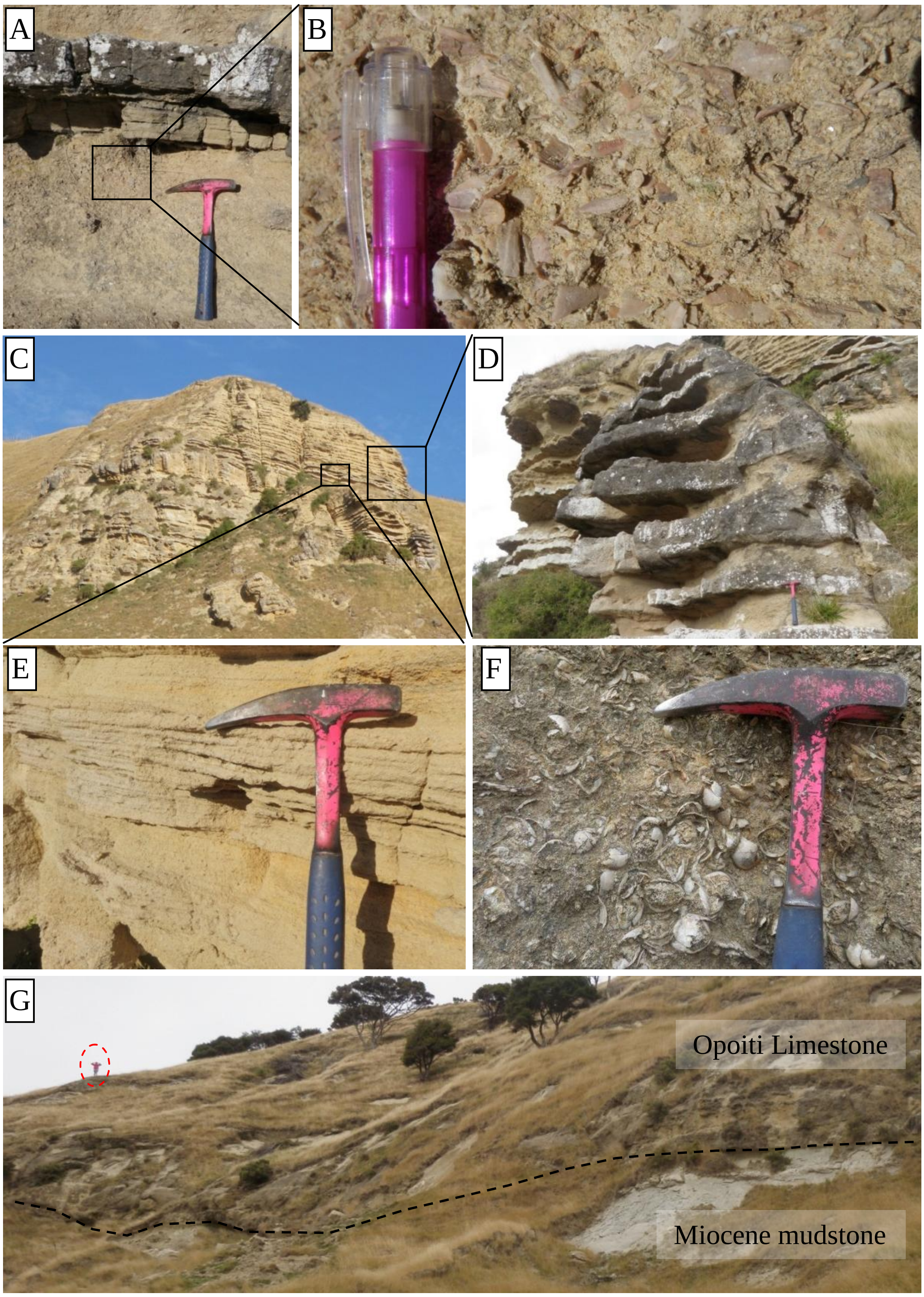


Figure 5.8 – Field photographs of the Opoiti Limestone on Mahia Peninsula. **(A** and **B)** Upper Opoiti Limestone cropping out on the south bank of the Stalactite Falls Stream area consists of massive, sandy, barnacle rich limestone with glauconite laminae. **(C** and **D)** Prominent well bedded outcrop of upper Opoiti Limestone near Ahimanawa Station. **(E)** Thin horizontal glauconite rich laminations in Opoiti Limestone. **(F)** Brachiopod dominated sandy coquina at the base of the Opoiti Limestone, at Reef Station. **(G)** Very sandy, brachiopod rich, thin Opoiti Limestone unconformably overlying late Miocene mudstone at Reef Station (Person circled for scale). *Hammer - 32 cm long, pencil - 0.8 cm wide.*

5.1.1 Contacts

At Mt Moumoukai, (BH42/144778) and (BH42/123772), the lower contact of the Opoiti Limestone is masked within a c.10 m grass covered slope. However, a small ridge immediately south of Mt Moumoukai (BH42/133759) exposes Opoiti Limestone resting sharply upon the underlying mudstone (late Miocene). Here the numerous small bivalves (1-2 cm size) that make up the dominant skeletal type in the Opoiti Limestone are also scattered throughout the upper 40 cm of mudstone (Figure 5.9 A). Some burrowing is evident (Figure 5.9 B). Francis (1993) considered the lower contact of the Opoiti Limestone at Mt Moumoukai to be an unconformity due to the sharp lithologic change and the presence of mudstone clasts within the basal limestone.

No direct upper contacts were observed in this study at Mt Moumoukai. However, past research (Beu 1995) has mentioned an observed angular unconformity formed by onlap of the Tahaenui Limestone over the Opoiti Limestone on the western flank of Mt Moumoukai. A ‘wedge’ of massive, calcareous, light grey sandstone (Wairoa Formation B) appears at Mt Moumoukai (Figure 5.9 C, D, E), overlying the Opoiti Limestone, but is truncated by the Tahaenui Limestone resting unconformably on the Opoiti Limestone (Figure 5.3). The direct upper and lower contacts of this sandstone are hidden in vegetation.

The lower contact of the Opoiti Limestone is accessible on Mahia Peninsula at three known locations: Ahimanawa Station (BJ43/184525) (Figure 5.10 C, D, E), Reef Station (BJ43/196498) and Hekerangi Point (BJ43/185460) (Figure 5.10 A, B). At all localities fine grained late Miocene mudstone is sharply overlain by the Opoiti Limestone which includes conspicuous shell material and sometimes concretions in its basal portion. No upper contacts were directly found on Mahia Peninsula, but it appears to grade upwards into sandy mudstone (Wairoa Formation B) (Figure 5.10 F-J).

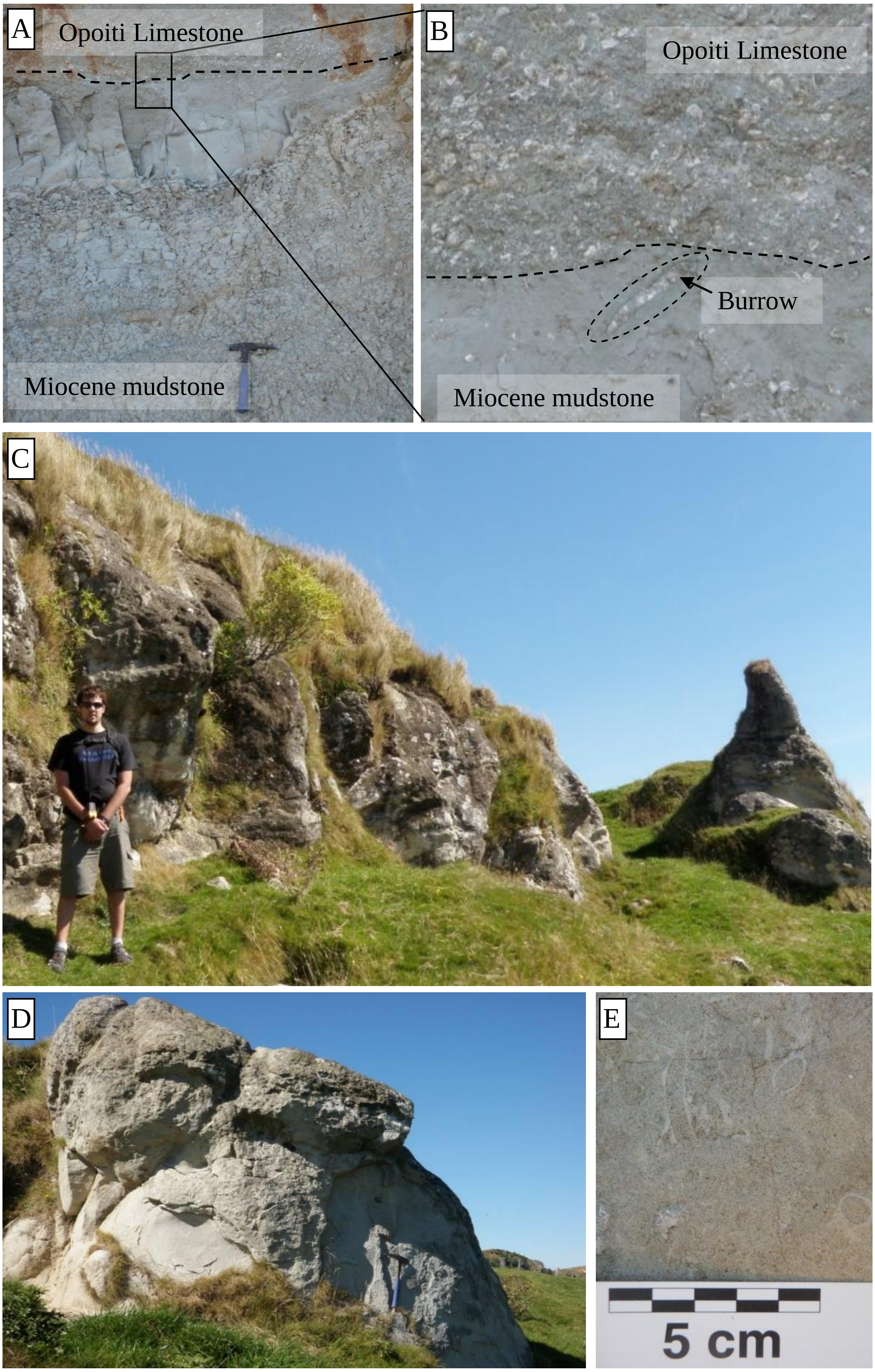


Figure 5.9 – Field photographs of the associated lithologies and contacts under- and overlying the Opoiti Limestone at Mt Moumoukai. **(A** and **B)** The underlying late Miocene mudstone passes rapidly upwards into silty limestone with abundant small bivalves. A 5 cm long infilled burrow is outlined. Southern Mt Moumoukai. **(C** and **D)** Opoitian aged massive sandstone (Wairoa Formation B) overlies the Opoiti Limestone, but the actual contact was not observed. Northeast Mt Moumoukai. **(E)** Small burrows/bioturbation within the Wairoa Formation B sandstone at Mt Moumoukai. *Hammer - 32 cm long.*

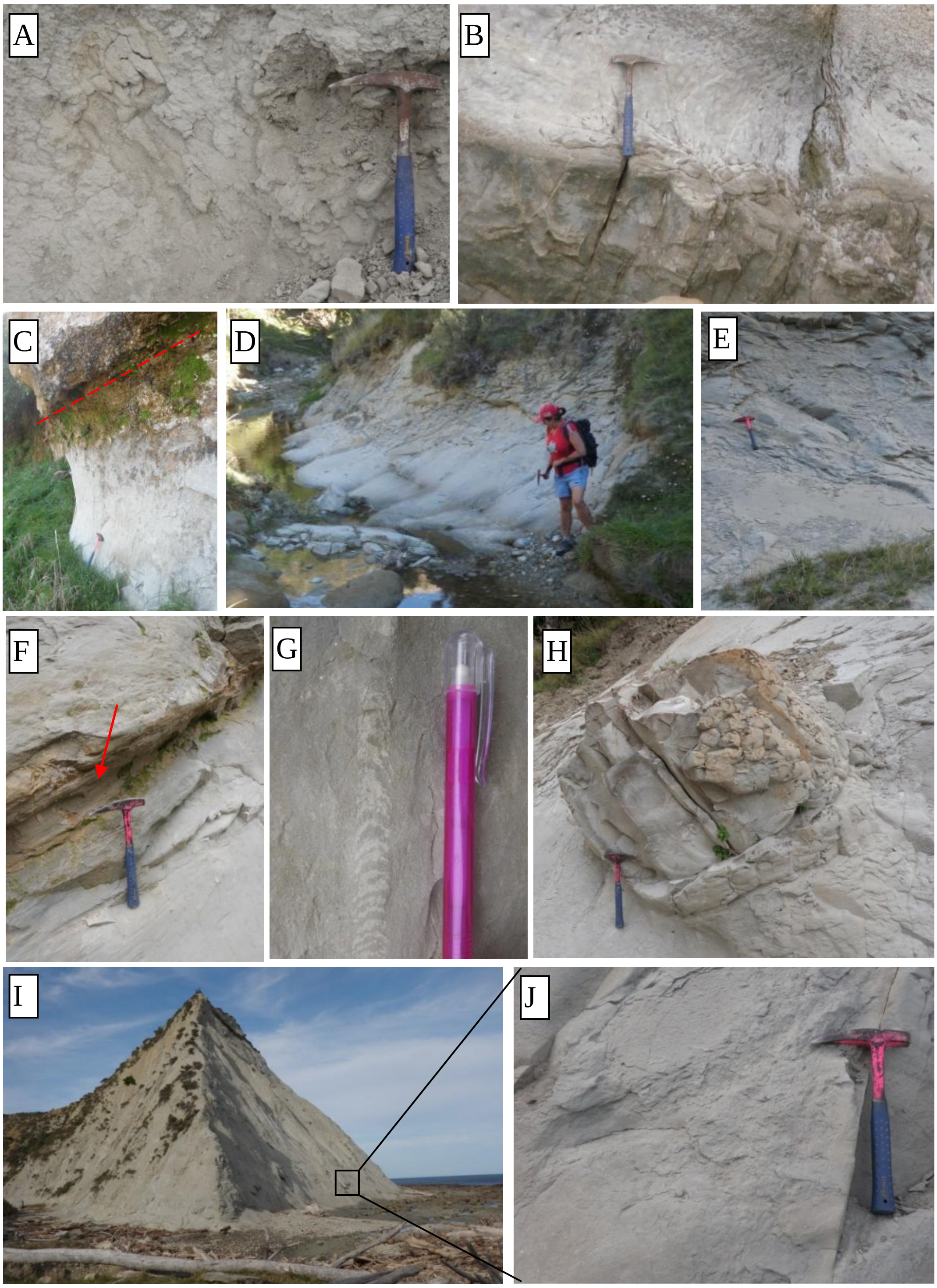


Figure 5.10 – Field photographs of the associated lithologies and contacts under- **(A-E)** and overlying **(F-J)** the Opoiti Limestone on Mahia Peninsula. The underlying late Miocene mudstone at Hekerangi Point consists of **(A)** friable mudstone and **(B)** a 1 m thick concreted mudstone unit that directly underlies the Opoiti Limestone. **(C)** Contact (red dashed line) of a very sandy and weathered Opoiti Limestone above late Miocene mudstone outcropping at Ahimanawa Station. **(D)** Smooth outcrop of late Miocene mudstone in Stalactite Falls Stream. **(E)** Friable late Miocene mudstone in the Huruhurunui Stream. **(F)** A thin volcaniclastic unit (arrow) in Wairoa Formation B in the Otunua Stream **(G)** Narrow ?*Scolicia* burrow in Wairoa Formation B, Otunua Stream. **(H)** Large concretion exposed within the Wairoa Formation B in the Otunua Stream bed. **(I** and **J)** Coastal exposure of Wairoa Formation B at the outlet of the Otunua Stream. *Hammer - 32 cm long, pencil - 0.8 cm wide.*

5.1.2 Lithofacies

Lithofacies included in the Opoiti Limestone and its under- and overlying lithologies include all limestone lithofacies (L1-L3), one sandstone lithofacies (S1), two mudstone lithofacies (M1, M3) and one volcanic lithofacies (V1) (Figure 5.11)

The barnacle dominated limestone with siliciclasts, lithofacies (L1/S), is common at Mt Moumoukai and on Mahia Peninsula, but is interspersed with the more sandy limestone lithofacies (L3). Sandy coquinas (L2) are rare except sometimes near the base of the Opoiti Limestone. These coquinas are dominated by brachiopods (*Neothyris*). A massive, calcareous, well sorted, light grey sandstone (lithofacies S1) overlies the Opoiti Limestone at Mt Moumoukai. The QMAP project (GNS) previously mapped this as "undifferentiated sandstone and shelly sandstone" (Mazengarb & Speden 2000). Massive mudstone (M1) overlies the Opoiti Limestone at Mahia Peninsula. South Mahia Peninsula hosts the only occurrences of lithofacies M3, a concretionary mudstone. A thin volcaniclastic unit (20 cm) (Figure 5.10 F) was noted within the Wairoa Formation B and is the only volcanic lithofacies (V1) associated with the Opoiti Limestone.

The lateral distribution of the underlying Miocene mudstone, Opoiti Limestone, Wairoa Formation B lithofacies is patchy but a general connection can be seen, especially with the sandy lithofacies L3 (Figure 5.12).

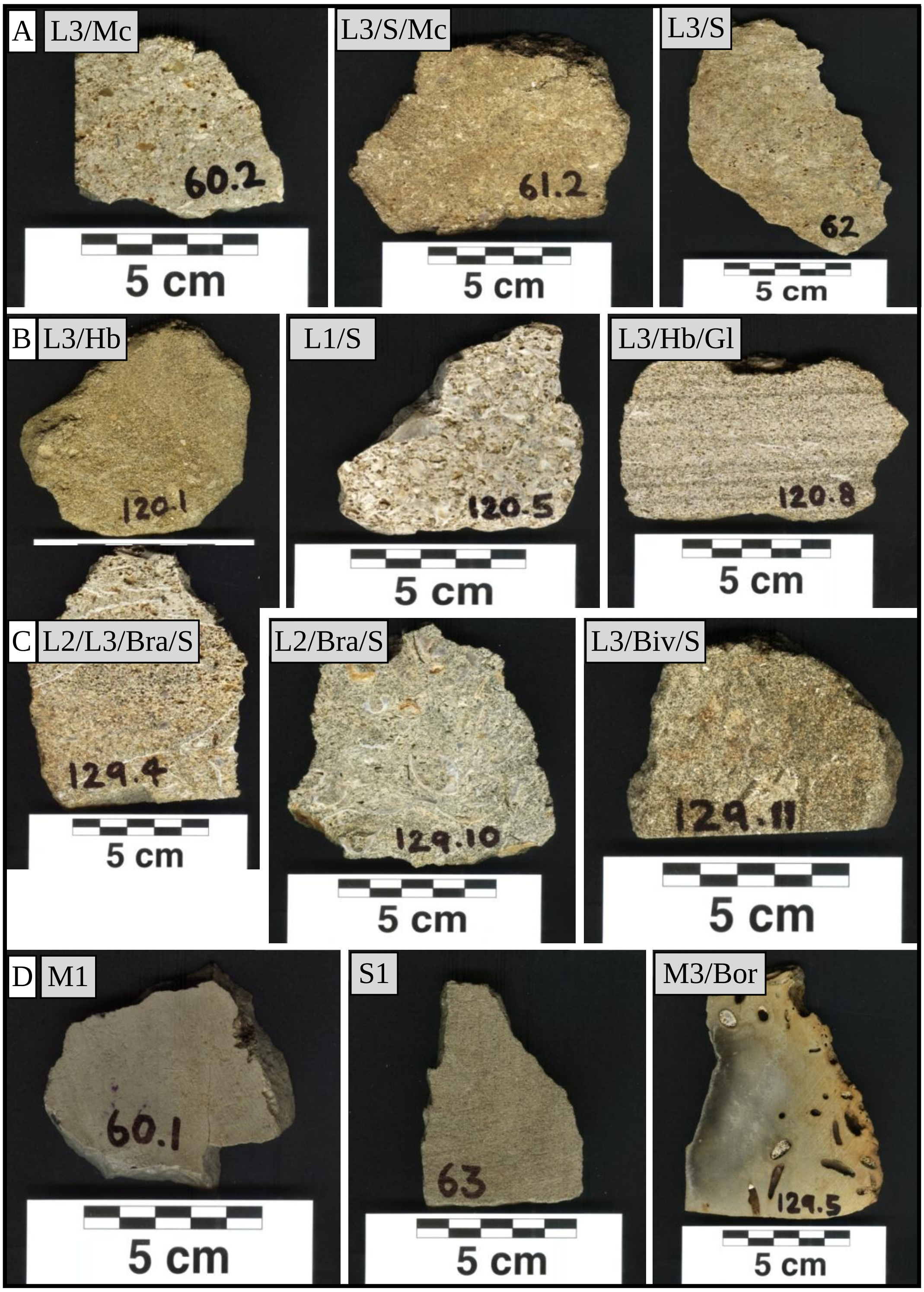


Figure 5.11 - Cut slabs of Opoiti Limestone and associated lithologies illustrating the related lithofacies. **(A)** Mt Moumoukai, **(B)** Ahimanawa Station, **(C)** Hekerangi Point, **(D**) Mt Moumoukai mudstone (60.1) and sandstone (63) (late Miocene mudstone and Wairoa Formation B) and a pholad bored spherical concretion (129.5) from Hekerangi Point. Refer to Table 4.1 for facies definition and codes.

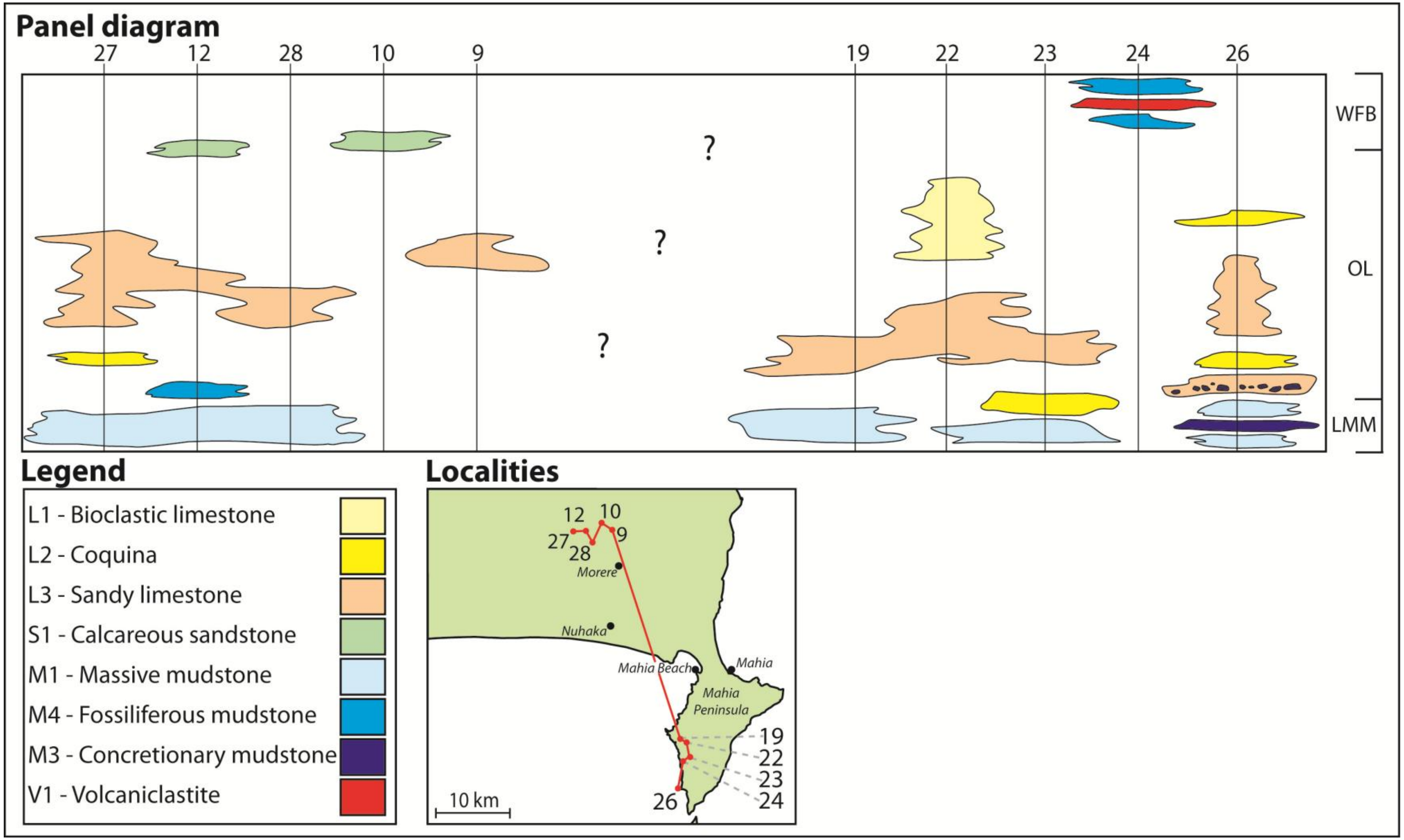


Figure 5.12 – Panel diagram showing the lateral relationship between lithofacies of underlying late Miocene mudstone (LMM), Opoiti Limestone (OL), and overlying Wairoa Formation B (WFB). Numbers relate to stratigraphic columns (refer to Appendix VII). No vertical scale implied.

5.2 FOSSIL CONTENT

The Opoiti Limestone typically hosts common brachiopods, pectinids, barnacles and some oysters and foraminifera. The Opoiti Limestone at Mt Moumoukai hosts common specimens of the pectinid *Towaipecten ongleyi* (Beu 1992, 1995). Because the limestone is usually highly indurated it is difficult to extract good specimens. Specimens of *Towaipecten ongleyi* also occur in Opoiti Limestone at Hekerangi Point, Mahia Peninsula. The brachiopod *Neothyris (?obtusa)* (Beu 1995) is common here, forming an c.3 m thick coquina at the base of the limestone. Hekerangi Point is also the type section for the infaunal bivalve *Glycymeris mahiana* (*pers. commun.* Beu 2010), which also occurs commonly throughout a sandy matrix. Figure 5.13 illustrates some of the macrofossils observed in the Opoiti Limestone.

Based on foraminiferal laboratory work and subsequent scanning electron microscopy (SEM) imaging, the mudstone underlying Opoiti Limestone at Mt Moumoukai has common *Orbulina universa* specimens (Figure 5.14 C) – often with smooth surfaces from secondary calcite - common fragmented echinoid spines (Figure 5.14 A), and occasional *Globigerina* (Figure 5.14 B) and *Nodosaria longiscata. Orbulina universa* specimens can be slightly 'squashed' into an oval shape, a physical result of burial and compaction. The infill of the planktic *Orbulina universa* specimens shows perfect rhombohedral crystal shapes, assumed to have been calcite crystals (Figure 5.14 D). After elemental mapping with EDAX attachment on the SEM, a strong silicon (Si) peak was present, giving a reading of c.7.5% silicon (Si) (Table 5.1). This may be due to clay impurities. Table 5.2 shows the elemental composition of the *Orbulina universa* wall for comparison.

Table 5.1 - SEM elemental table displaying the existing elements of the supposed calcite crystal on the interior of an *Orbulina universa*.

Element	**Wt.%**
Carbon	34.94%
Oxygen	49.29%
Silicon	7.49%
Calcium	8.27%

Table 5.2 – Elemental composition of the *Orbulina universa* wall.

Element	**Wt.%**
Carbon	13.78%
Oxygen	35.84%
Silicon	4.71%
Calcium	39.11%
Aluminium	1.37%
Selenium	5.19%

Figure 5.13 – Opoiti Limestone macrofossils. **(A, B** and **C)** All are specimens of *Glycymeris* found *in situ* at Hekerangi Point. **(D)** A likely *Glycymeris* internal mould found within a 20 cm volcaniclastic bed in the Otunua Stream bed (Figure 5.1). *Glycymeris* is typically found within warm (subtropical) to temperate waters (Beu & Maxwell 1990).

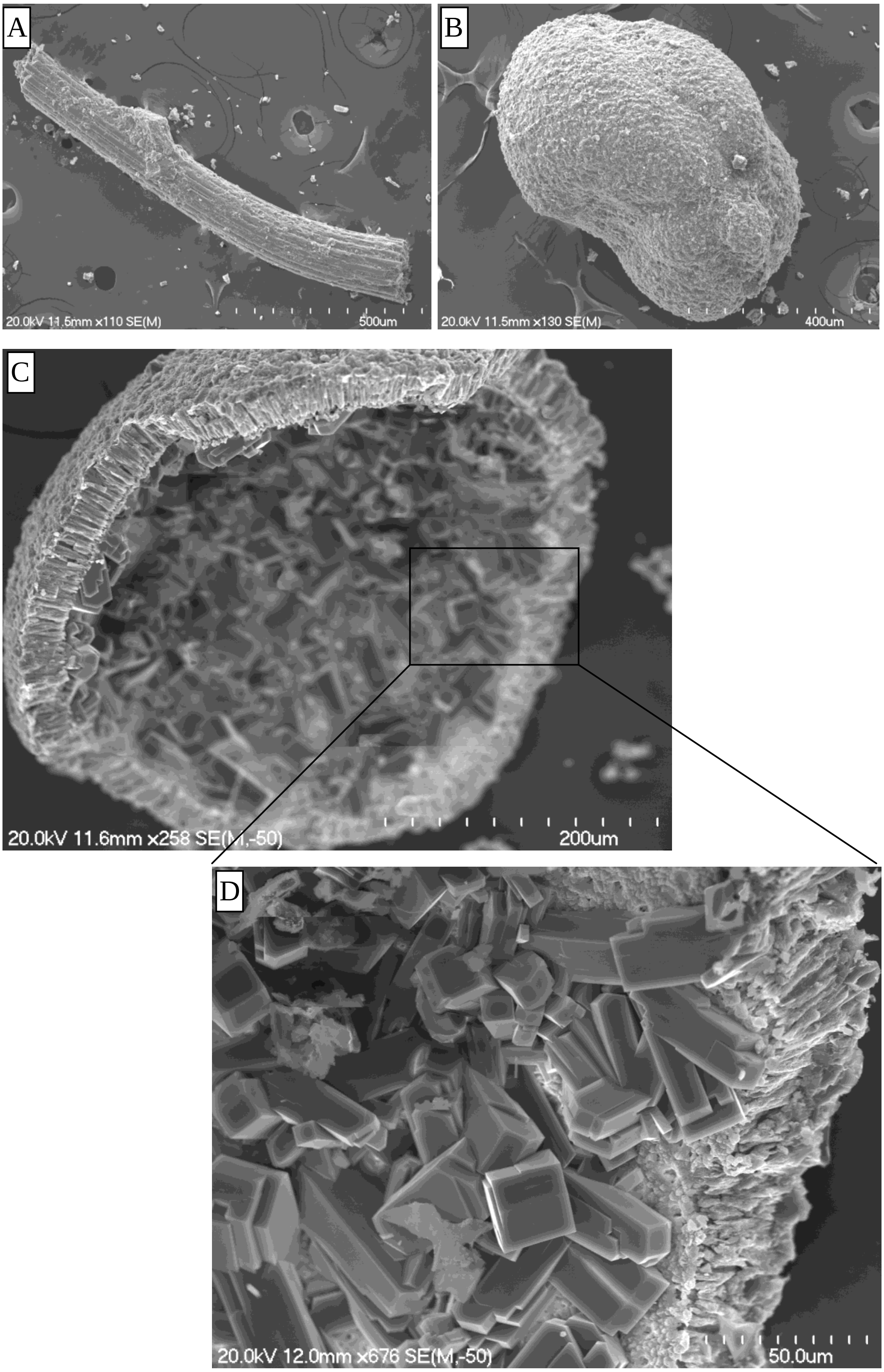


Figure 5.14 – Scanning electron images of microfossils in the late Miocene mudstone (sample 130.1) underlying the Opoiti Limestone. **(A)** Broken echinoid spine. **(B)** *Globigerina.* **(C** and **D)** Broken *Orbulina universa* test infilled with likely calcite crystals.

5.3 LABORATORY PROPERTIES

5.3.1 Calcium carbonate %

Calcium carbonate data are given in Appendix III. Figure 5.15 plots the calcium carbonate and siliciclastic values of the Opoiti Limestone and Wairoa Formation B. The Opoiti Limestone has a typically low to moderate carbonate content, ranging from c.55-75% (Table 5.3). The Opoiti Limestone at Mt Moumoukai has a slightly lower content than outcrops on Mahia Peninsula. At Mt Moumoukai the Opoiti Limestone has an associated overlying sandstone lithofacies S1 (Wairoa Formation B) with a carbonate content ranging from 17-30%. Lithofacies S2, fossiliferous sandstone, has an expectedly slightly higher carbonate content of approximately 33%. Two concretionary mudstones (lithofacies M3) have much higher carbonate contents of 51-53%, which XRD analysis shows is due to the presence of dolomite.

Table 5.3 - Carbonate and siliciclastic percentages in the mudstone (lithofacies M3), Opoiti Limestone (lithofacies L2, L3), and overlying Wairoa Formation B (lithofacies S1).

Sample Number	Facies	Carbonate %	Sand %	Mud %
129.4	L2	76.0	12.6	11.3
112.1	L2	66.9	18.4	15.5
129.6	L3	56.8	18.6	24.6
131.2	L3	32.4	53.2	15.5
62	L3	56.7	24.2	19.7
63	S1	17.9	62.2	20.5
64	S1	29.1	57.3	14.2
129.5	M3	53.8	8.0	38.9
129.2	M3	51.3	5.4	43.5

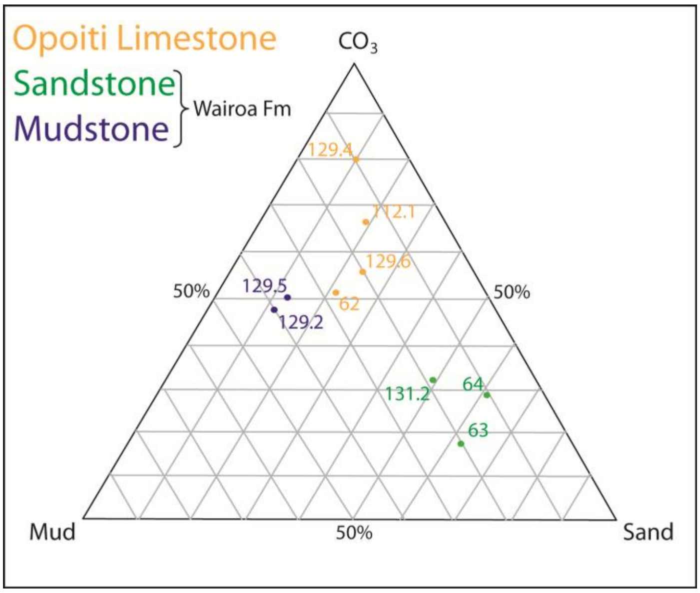


Figure 5.15 – Ternary plot depicting the carbonate-siliciclastic sand-siliciclastic mud composition for samples from the Opoiti Limestone and overlying Wairoa Formation B. The Opoiti Limestone has some of the lowest carbonate values of the three limestones. The high CO_3 content of samples 129.2 and129.5 are due to the presence of dolomite.

5.3.2 Insoluble grain analysis

Malvern Mastersizer data and graphs are contained as Digital Appendix F on the accompanying CD. Figure 5.16 shows the sand-clay-silt grain sizes of the Opoiti Limestone and overlying Wairoa Formation B, with percentages in Table 5.4. The Opoiti Limestone has a modal acid insoluble grain size of 123-177 µm i.e. very fine sand upper to fine sand lower. Associated sandstones have a smaller range of modal sizes from 123-137 µm. The modal size in mudstones is coarse silt, ranging from 30-37 µm. The similar sizes of the siliciclastic grains suggest that the terrigenous material in the limestones and sandstones had similar sources and origins. Lithofacies L3 has an expected higher amount of sand than the coquina lithofacies L2.

Table 5.4 - Siliciclastic percentages in the mudstone (lithofacies M3), Opoiti Limestone (lithofacies L2, L3), and overlying Wairoa Formation B (lithofacies S1).

Sample Number	Facies	Sand %	Silt %	Clay %
129.4	L2	50.6	46.3	3.0
112.1	L2	55.48	42.0	2.5
129.6	L3	46.6	51.5	1.7
131.2	L3	73.2	25.2	1.5
62	L3	53.2	44.4	2.2
63	S1	72.2	26.7	0.9
64	S1	75.3	23.7	0.9
129.5	M3	15.0	80.4	4.4
129.2	M3	10.4	85.4	4.0

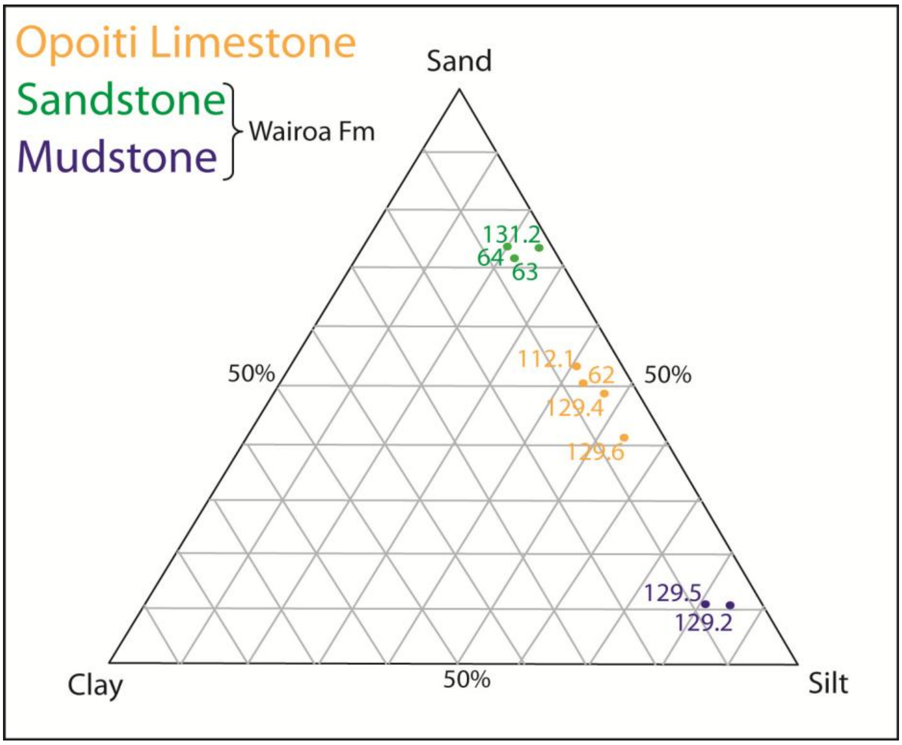


Figure 5.16 – Ternary plot depicting the acid insoluble sand-silt-clay grain sizes for the Opoiti Limestone and overlying Wairoa Formation B. The siliciclastic component within the Opoiti Limestone shows very similar sizes. The same occurs for the sandstone and mudstone groupings.

5.3.3 XRD

Table 5.5 presents XRD data from the Opoiti Limestone, underlying late Miocene mudstone and overlying Wairoa Formation B. Complete XRD data and graphs are contained as Digital Appendix H on the accompanying CD. Samples from the Opoiti Limestone show calcite peaks up to 686 counts and quartz peaks up to 333 counts. The amounts of plagioclase vary within the Opoiti Limestone with low counts of c.20 and higher counts up to c.90. Only a small amount of aragonite might be hinted at within the Opoiti Limestone, within sample 131.2 (L3) showing a peak of 33 counts. This sample hosts abundant small (1-2 cm size) bivalves which would be the source of aragonite. The only significant occurrences of dolomite are (1) within the concreted mudstone bed located at the contact of the Opoiti Limestone with late Miocene mudstone and (2) within the subspherical mudstone concretions that lie within the basal Opoiti Limestone, which display peaks up to 546 and 509 respectively. In cathodoluminescent petrography, this dolomite shows up as bright yellow matrix specks.

Table 5.5 – XRD count values for the Opoiti Limestone and overlying Wairoa Formation B. Count values < c.20 may well be part of the background spectra and do not necessarily mean the mineral name indicated is present.

Sample	Quartz	Plagioclase	Calcite	Aragonite	Dolomite	Total Clays
2˚θ	**26.62**	**27.94**	**29.42**	**26.22**	**30.9**	**19.9**
L2-129.4	69	25	686	7	12	5
L2 - 112.1	333	21	631	8	12	13
L3 - 129.6	143	13	658	9	5	9
L3 - 62	96	28	628	6	11	7
L3 - 131.2	384	94	234	33	22	24
S1 - 63	462	83	246	22	12	21
S1 - 64	419	87	327	17	10	26
M3 - 129.5	498	68	28	14	509	11
M3 - 129.2	216	84	13	8	546	12

5.3.4 Petrography

Comprehensive petrographic analyses (PPL, XPL, and CL) of 30 thin sections from the Opoiti Limestone and associated lithologies are given in Digital Appendix D. Total petrographic componentry is shown in Figure 5.17.

Skeletal componentry

Total petrographic componentry is given in Figure 5.17. Sand size skeletal components within the Opoiti Limestone include common planktic and benthic foraminifers, rare (Mahia Peninsula) to very common (Mt Moumoukai) bryozoans, varying amounts of brachiopod and barnacle fragments (Figure 5.18 and 19 A, B) and rare echinoderm and bivalve material. Skeletal components show typically moderate abrasion and sorting, with typically bimodal physical sizes in the c.0.2-0.5 mm (fine to medium sand) and c.2-25 mm (gravel) sizes. Some microborings and pitting of bioclast edges occurs, most commonly in brachiopods.

Cements

Petrographically, the cements in the Opoiti Limestone typically consist of primary microbioclastic micrite and rare homogenous micrite with some ‘secondary’ isopachous sparite (refer to section 2.2.2 for definitions). Microbioclastic micrite is the dominant cement type and occurs widely throughout the Opoiti Limestone (Figure 5.18 A, B). Microbioclastic micrite tends to ‘trap’ skeletal grains in haphazard orientation. While it occurs most commonly as an inter particle filler, microbioclastic micrite does also infill larger skeletal pore spaces (Figure 5.18 A). Patches of pyrite infill are common within the microbioclastic micrite. Stratigraphically higher, sparite becomes more common. Clear isopachous sparite rims tend to be host-specific, favouring barnacles (Figure 5.19 A, B), where micritic material is lacking. These ‘dog toothed/scalenohedral’ rims are typically extrinsic features which line the internal cavities of grains with individual crystals up to c.0.05 mm long (Figure 5.19 B). Pressure dissolution is commonly observed and has likely occurred prior to any sparite precipitation (Figure 5.19 A).

Porosity

In microbioclastic micrite dominated samples (Figure 5.19 A, B) original interskeletal space (excludes cement) can be quite high (c.50%) with only sparse shell fragments. Since being infilled with microbioclastic micrite the modern porosity, represented by the open uncemented interparticle pore space, is low at 1-2%. In contrast, in sparite dominated samples (Figure 5.19 A, B) original interskeletal space (excludes cement) can be quite low (c.15%) due to the shells (typically barnacles) being in close contact.

Cathodoluminescence

Under CL, the skeletal components show rare dark purple (aragonitic) gastropods (Figure 5.21 B) and moderate to dull orange barnacles and pectinids. Abundant small bivalves in the Opoiti Limestone at Mt Moumoukai show bright purple luminescence under CL light (Digital Appendix E, sample 131.2), suggesting an aragonitic mineralogy. This was confirmed by XRD analysis (Table 5.5).

Concretions in mudstone beneath the limestone and within the basal limestone are dolomitic, evident from bright yellow speckled cathodoluminescence petrography, (Figure 5.22 A, B) and confirmed by XRD analysis. These are the only identified occurrences of dolomite in this study area.

Classification

Using the limestone classification from Folk's carbonate textural spectrum (Folk 1968) (section 2.2.2, p. 18) the Opoiti Limestone ranges from a sandy sparse-packed biomicrite to a variably sandy, poorly washed/rounded biosparite. Bioclastic arenite is more appropriate in some places where siliciclastic grains dominate.

Siliciclastic and authigenic componentry

Siliciclastic grain sizes range from 0.1-0.2 mm, or very fine sand to fine sand. Siliciclastic grains, mainly quartz and feldspar, are typically subrounded to subangular and moderately to well sorted (Figure 5.20 B). Terrigenous sand quantities are higher at Mahia Peninsula than at Mt Moumoukai. Some subrounded mudstone fragments (0.5-2 mm size) occur in samples from Mt Moumoukai. The authigenic minerals glauconite and pyrite are ubiquitous but generally sparse, the glauconite being most common in pelletal form (Figure 5.20 B). Pyrite is often observed infilling the punctae holes in brachiopod shells (Figure 5.20 A).

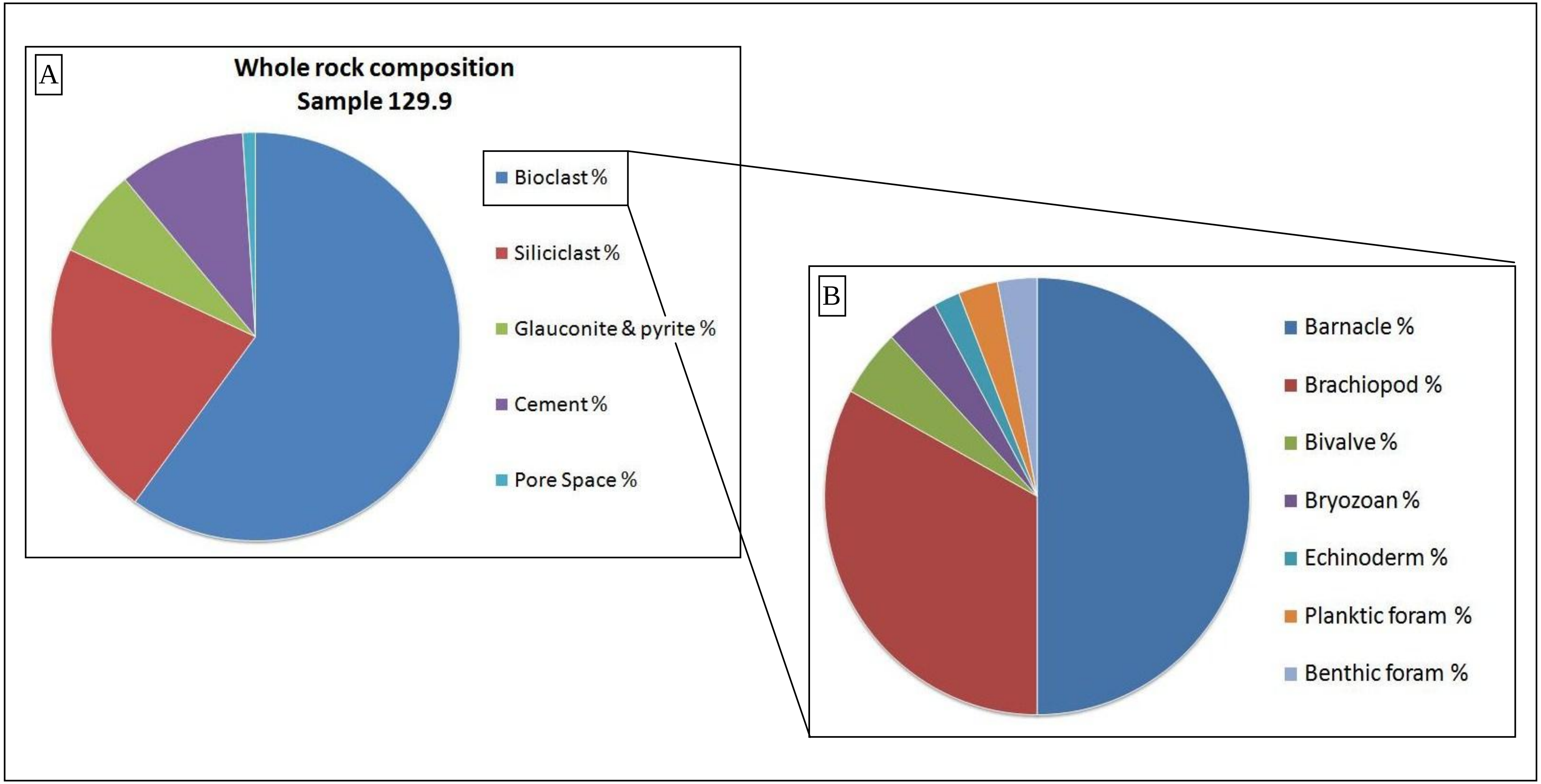


Figure 5.17 – Pie graphs showing the total petrographic componentry **(A)** and the primary skeletal componentry **(B)** of a representative sample from the Opoiti Limestone. Sample 129.9 (lithofacies L) crops out at Hekerangi Point, west coast of Mahia Peninsula.

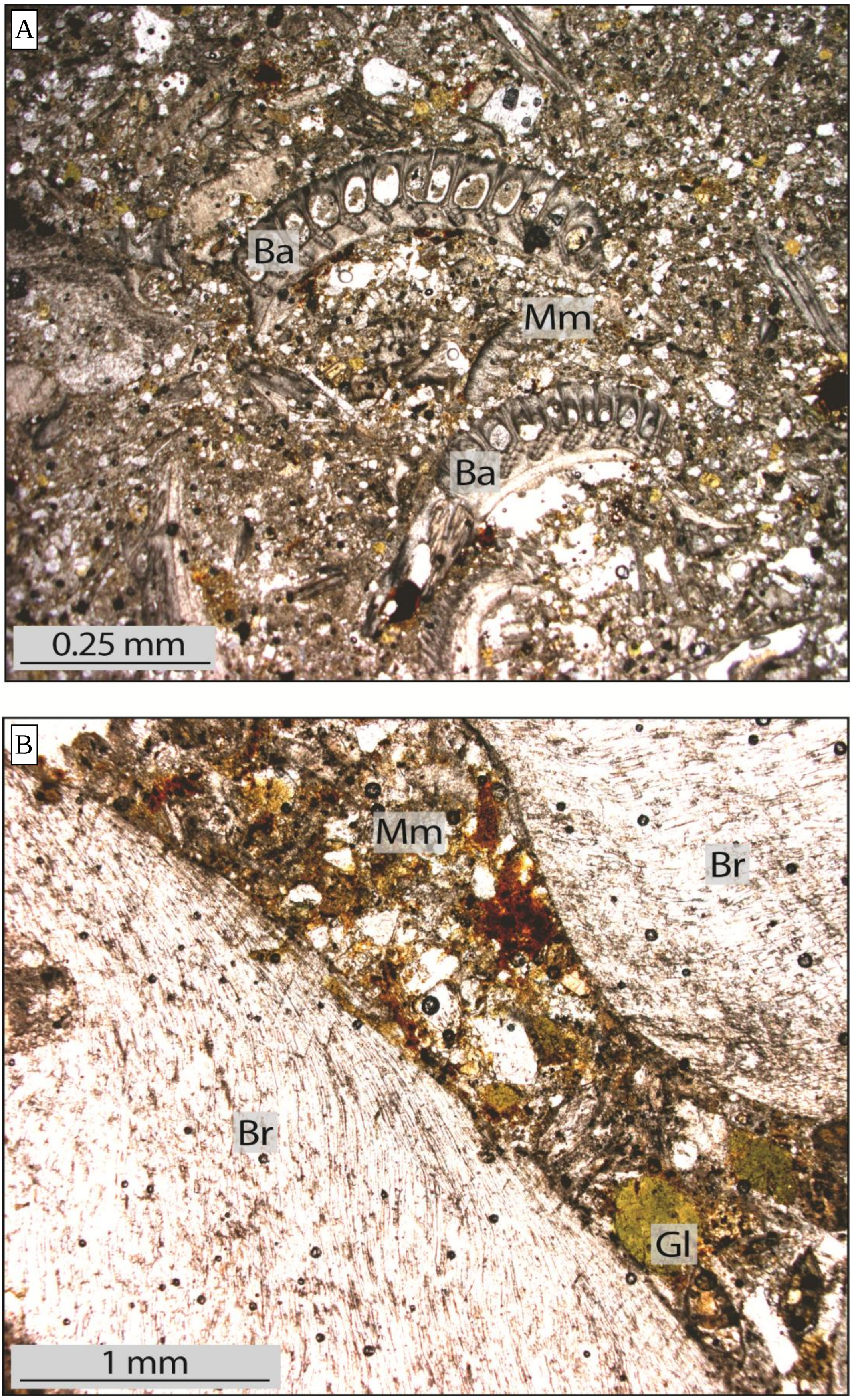


Figure 5.18 – Petrographic images from the Opoiti Limestone on Mahia Peninsula. **(A)** Sample 120.4, a packed biomicrite, illustrating scattered barnacle fragments (Ba) in a microbioclastic micrite (Mm) matrix. A small amount of microbioclastic micrite infills barnacle pores. Plane polarised light (PPL). **(B)** Sample 112.1, also a packed biomicrite, showing large brachiopod grains (Br) separated by microbioclastic micrite (Mm) matrix. Glauconite (Gl) is relatively common in the matrix. PPL.

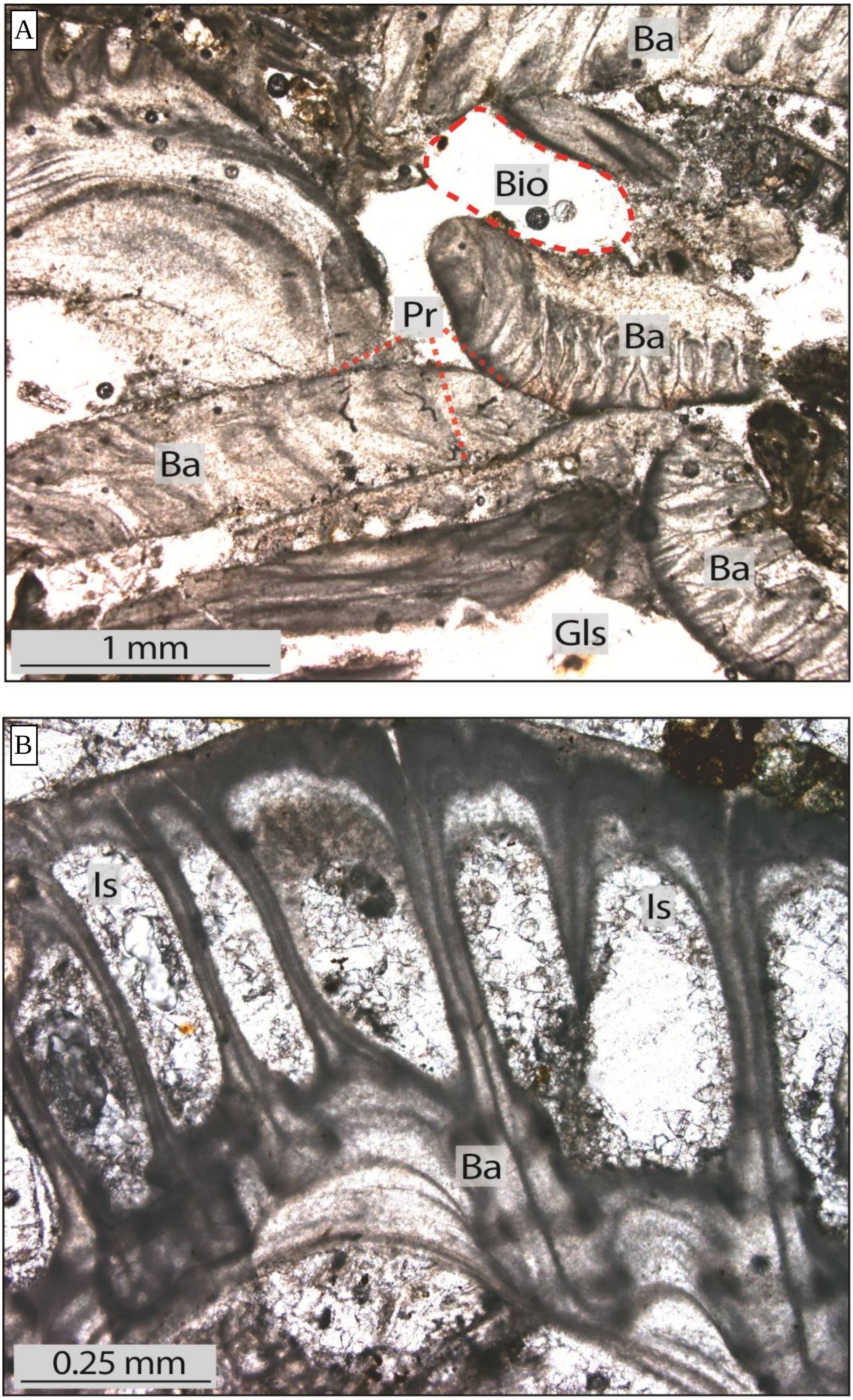


Figure 5.19 – Petrographic images from the Opoiti Limestone at Mahia Peninsula. **(A)** Sample 120.3, a rounded biosparite, illustrating rounded barnacle (Ba) fragments in pressure dissolution (Pr) contact. Rare biomoulds (Bio) indicate the original presence of likely aragonitic infaunal bivalve skeletal grains that have dissolved. Gls – glass slide indicating pore space. (PPL). **(B)** Sample 120.8, a sorted biosparite, showing isopachous sparite (Is) rims lining the cavities of a barnacle plate (Ba). PPL.

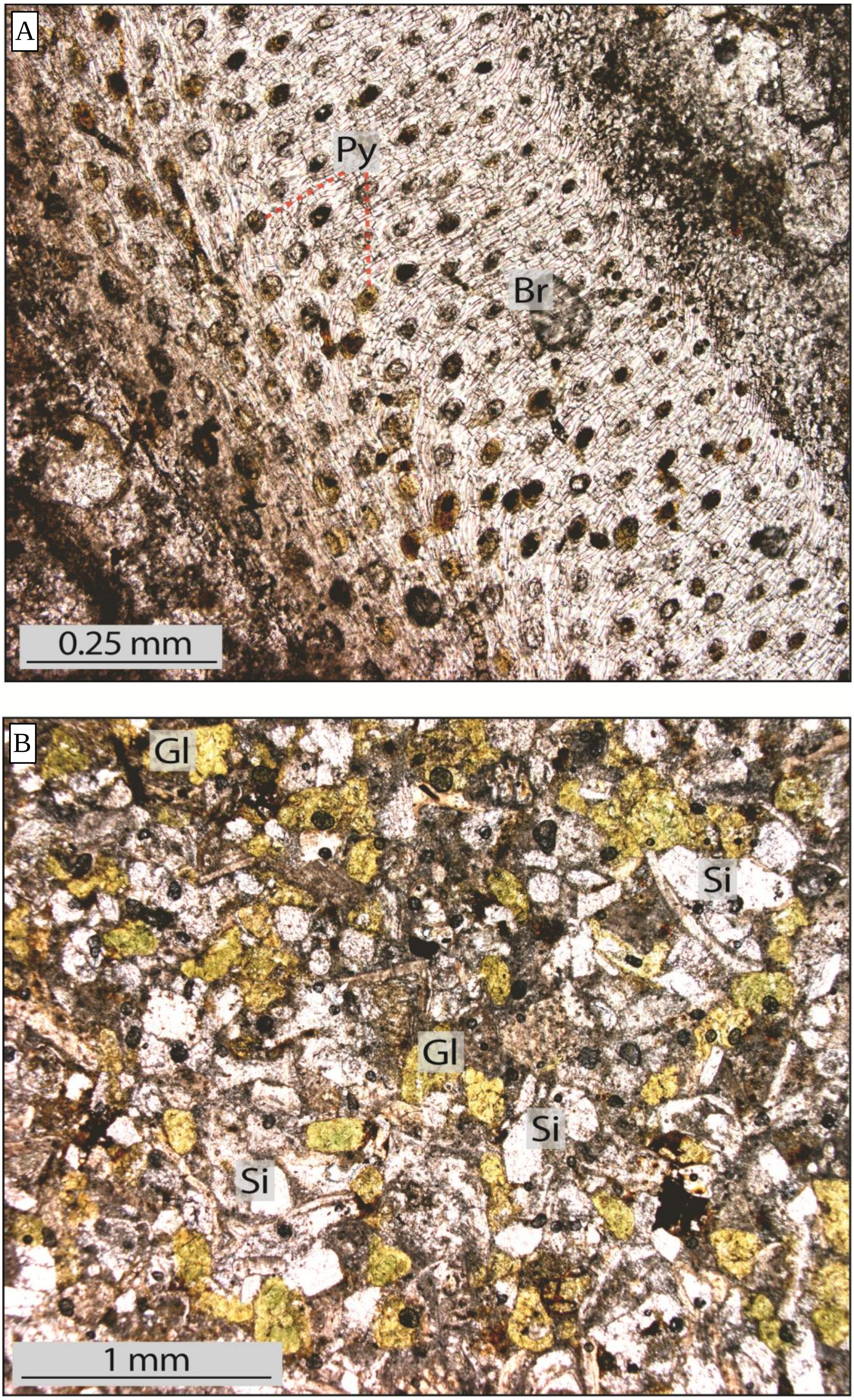


Figure 5.20 – Petrographic images from the Opoiti Limestone at Mt Moumoukai (A) and Mahia Peninsula (B). **(A**) Sample 61.1 showing punctae holes on the surface of a brachiopod (Br) fragment, infilled with pyrite (Py). PPL. **(B)** Sample 129.11, a fossiliferous biomicrite, demonstrating a very high proportion of sand grains (Si) within a localised part of the Opoiti Limestone, Hekerangi Point. Pelleted glauconite (Gl) is common here. PPL.

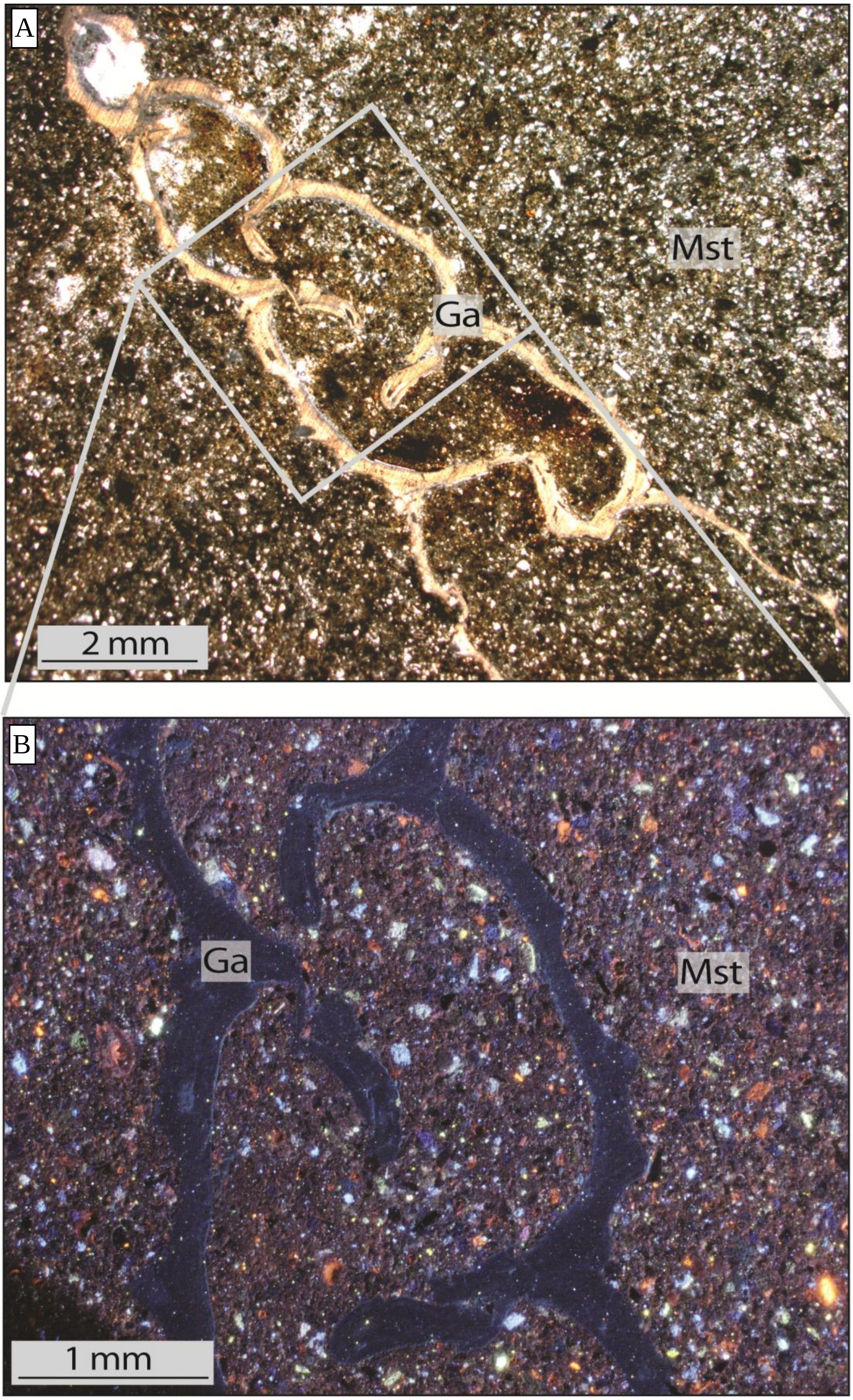


Figure 5.21 – Pair of petrographic images from Wairoa Formation B at Mahia Peninsula. Sample 124.1. **(A)** Sole gastropod (Ga) within the mudstone (Mst). PPL. **(B)** Enlarged view under cathodoluminescent light (CL) illustrating the dark purple colour of the gastropod, indicative of an aragonitic mineralogy.

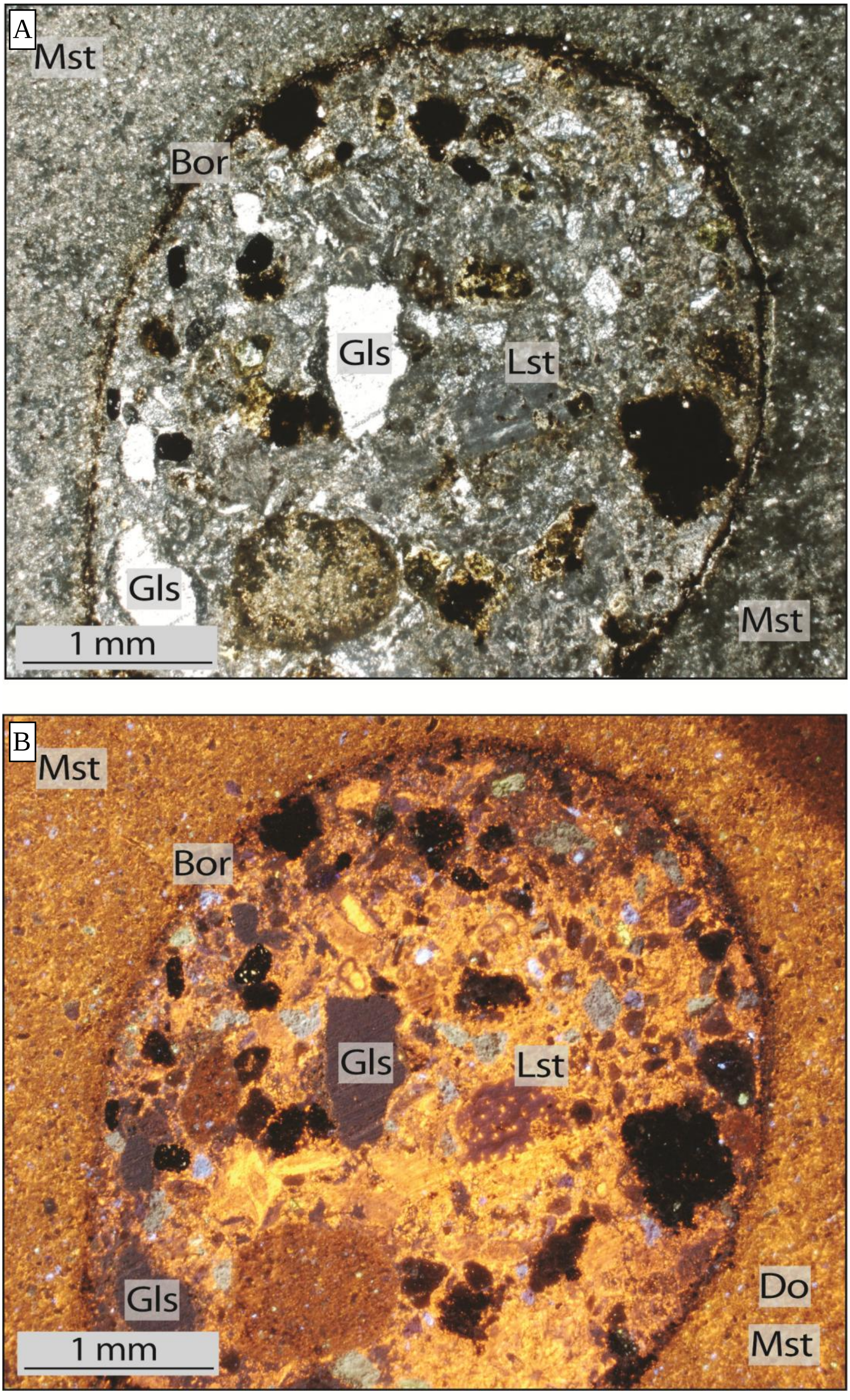


Figure 5.22 – Pair of images under plane and cathodoluminescence light from the spherical concretion within the Opoiti Limestone at Hekerangi Point. Sample 129.5. **(A)** Circular pholad boring (Bor), infilled with limestone sediment (Lst) in lithified mudstone (Mst). Gls – glass slide. **(B)** Identical image under cathodoluminescent light illustrating a bright yellow to orange luminescence associated with the presence of dolomite (Do) in the mudstone.

5.3.5 Stable isotope analyses

Table 5.6 presents stable isotope data for the Opoiti Limestone. Some samples were run twice and thus have two sets of data. Figure 5.23 plots the data in a $\delta^{18}O$-$\delta^{13}C$ cross-plot.

Table 5.6 – Stable isotope data for samples from the Opoiti Limestone. Although bulk rock samples were analysed, the primary cement types are also recorded here.

Bulk sample	Facies	Locality	$\delta^{13}C$	$\delta^{18}O$
120.3	L1	Ahimanawa Station	1.16	0.26
129.4	L2	Hekerangi Point	-2.15	-0.21
			-1.98	-0.14
112.1	L2	Ahimanawa Station	0.63	-0.33
			0.47	-0.62
129.10	L2	Hekerangi Point	0.30	-1.31
123.2	L2	Reef Station	1.89	-0.17
			1.80	-0.22
129.6	L3	Hekerangi Point	-0.11	-0.04
			-0.05	0.06
61.2	L3	Mt Moumoukai	1.91	-0.14

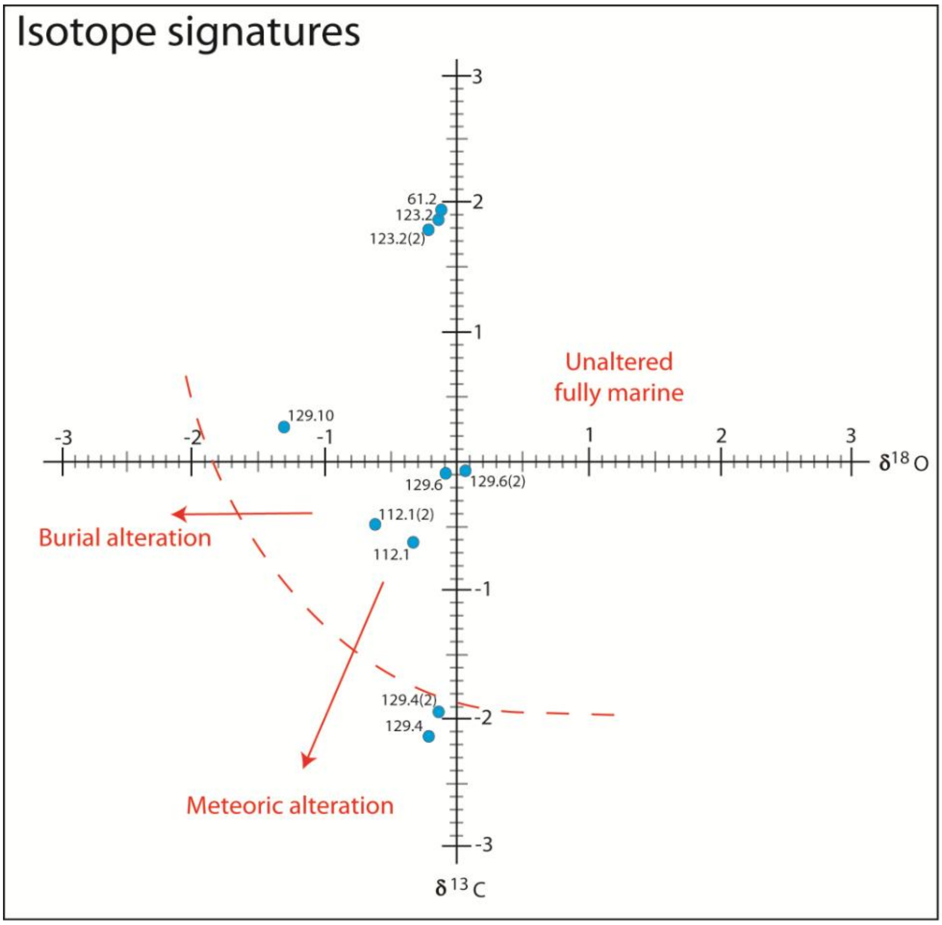


Figure 5.23 –Stable isotope results for the Opoiti Limestone. Minimal amounts of alteration are evident by the mainly positive isotope values, but with a slight trend toward meteoric alteration. Boundaries of alteration taken from Nelson & Smith (1996).

Because of the limitation on the number of samples sent for analysis, no skeletal powders from the Opoiti Limestone were analysed. Seven bulk samples from the Opoiti Limestone were analysed and came from different L1/L2/L3 lithofacies. The Opoiti Limestone isotope signatures show a range of oxygen and carbon values (-2.15 to +1.89 $\delta^{13}C$ and -1.31 to +0.26 $\delta^{18}O$) (Table 5.6), and plot widely over the cross-plot. The small negative values in all $\delta^{18}O$ and some $\delta^{13}C$ analyses illustrate a slight directional movement toward meteoric alteration (Figure 5.23).

Cement in the Opoiti Limestone is dominated by microbioclastic micrite and isopachous sparite fringes. Unfortunately it was not possible to drill separate powders for these cement types. Samples dominated by microbioclastic micrite plots with a negative trend, possibly showing a burial alteration influence.

Samples 129.6, 112.1 and 129.4 all have negative $\delta^{13}C$ values, and show a linear decrease in values (Figure 5.23). When compared with calcium carbonate values the opposite pattern occurs, with the highest CO_3 values in sample 129.4 (lowest $\delta^{13}C$ value) and the lowest CO_3 values in sample 129.6 (highest $\delta^{13}C$ value) (Refer to section 5.3.1 for CO_3 values).This suggests that meteoric alteration is perhaps slightly more advanced in samples with high CO_3 (dominant skeletal grains), possibly due to their higher permeability allowing meteoric fluids to penetrate more easily.

5.4 INITIAL PALEOENVIRONMENTAL ANALYSIS

The Opoiti Limestone in the study area was deposited by the shedding and reworking of carbonate sediment adjacent to upthrust anticlines in the vicinity of the northeastern margin of the Pliocene Ruataniwha Strait (Kamp *et al.* 1988; Beu 1995). Figure 5.24 illustrates the possible depositional setting for the Opoiti Limestone about an upthrust antiform.

The moderately to well abraded nature of the skeletal grains, and the moderately well sorted nature of the typically subrounded siliciclastic sand fraction, suggest formation in a relatively high energy setting or reworking and emplacement away from such a setting. The conspicuous content of siliciclastic sandy sediment throughout much of the Opoiti Limestone attests to either local derivation from erosion of older sediment exposed at the contiguous sea floor by uplift from thrust faulting, or a more distant source about the margins of the tidal current-dominated Ruataniwha Strait in the west and north into the Mahia district, perhaps via longshore drift associated with a shore-connected wedge of siliciclastic sand.

The basal coquina bed, rich in whole but disorientated brachiopods, is a shallow-marine, high energy deposit having many of the characteristics of a transgressive shell bed (Kidwell 1986). A high influx of siliciclastic sand terminates this shell bed formation, possibly the result of storm emplacement (Figure 5.24). Thereafter barnacles dominate the skeletal component of the sandy limestones, characteristic of much of the Opoiti Limestone in the study area. Their presence attests to a high nutrient supply within the tidal current swept seaway (Beu 1995).

The bedded nature of the Opoiti limestone, evident in most outcrops in the study area, may well reflect event beds resulting from storm emplacement shedding (Figure 5.24). From each event the coarse sediment settles first followed by the finer grained sediment. Hence the lower part of these couplets are slightly more dominated by skeletal grains with the upper portions having a higher amount of finer grained siliciclasts (Figure 5.24). This produces a relative skeletal enrichment in the lower portions of sedimentation units and a relative siliciclastic enrichment in upper portions. Because carbonate and siliciclastic grains attract different cementation processes, with the local areas of carbonate grains becoming more cemented and siliciclastic areas less so (a result of available CO_3), the resulting weathered outcrop appearance differs showing recessive and protruding beds.

The concretionary bed, directly underlying the Opoiti Limestone, is likely to have been caused by an increase in calcium carbonate precipitation just prior to the beginning of carbonate deposition. XRD analyses shows dolomite to be the primary form of calcium carbonate. Uncompacted muds typically show c.50% original pore space and during compaction this pore space can be infilled with high amounts of calcium carbonate, in this case dolomite, indicating very early diagenesis.

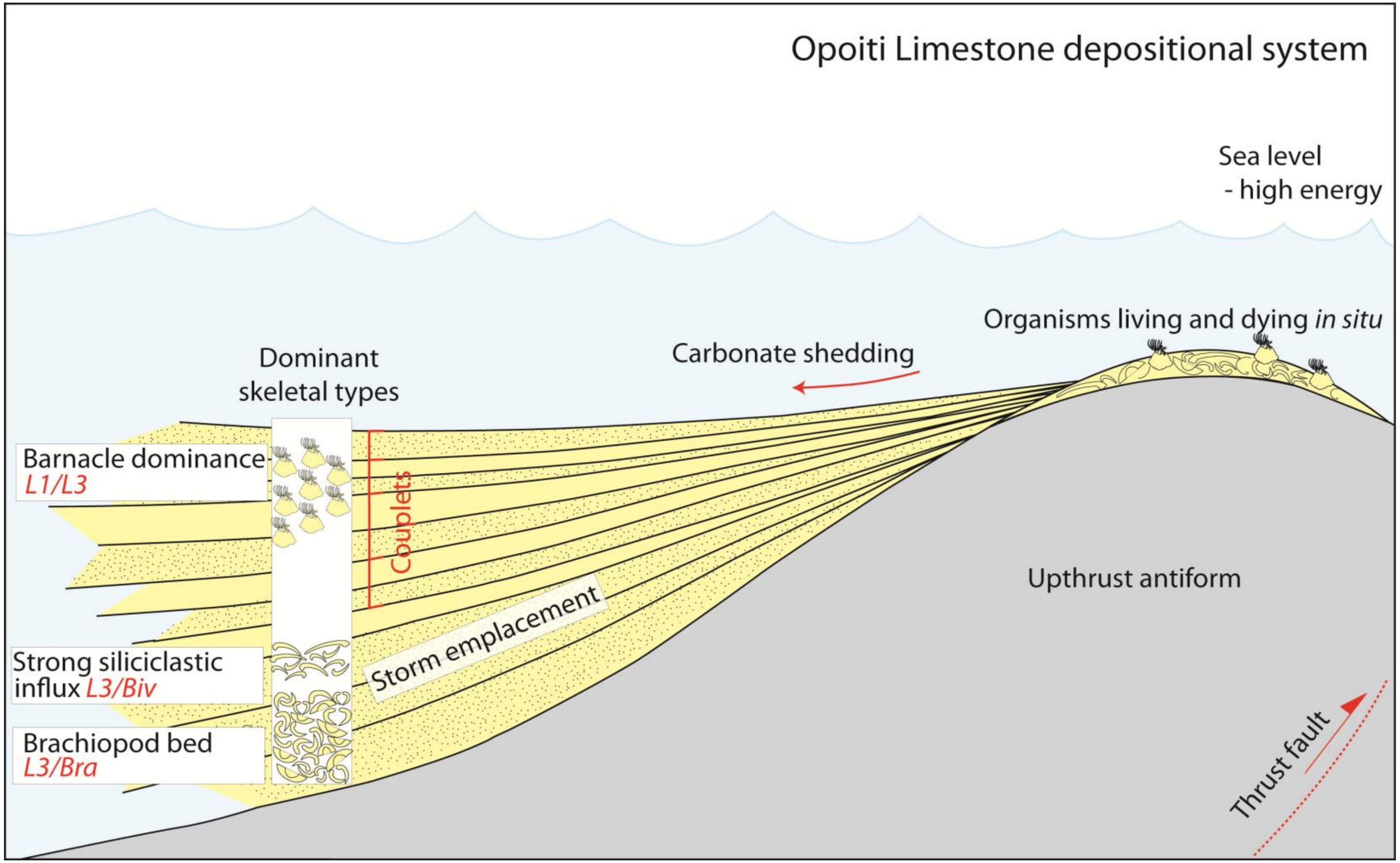


Figure 5.24 - Depositional system for the Opoiti Limestone. Limestone accumulation is first dominated by brachiopod shells in a sandy matrix, followed by a strong influx of siliciclastic sediment. The barnacle rich-siliciclastic rich couplets in the upper portion accumulated when the siliciclastic influx lessened, allowing growth of a barnacle community, and were shed from the antiforms, likely in storm deposits. While the entire Opoiti Limestone is typically sandy, here the stipple represents areas with higher siliciclastic contents. Lithofacies are highlighted in red. Vertically exaggerated for clarity.

Chapter Six – Whakapunake Limestone

Previous Page - Whakapunake Limestone forming coastal bluffs at the Huruhurunui Stream mouth, Ahimanawa Station, west coast of Mahia Peninsula.

CHAPTER SIX – WHAKAPUNAKE LIMESTONE

6.1 LITHOSTRATIGRAPHY

Within the immediate study area the Whakapunake Limestone of late early Pliocene (late Opoitian) age (Appendix I, Beu (1995)), crops out only on the west coast of Mahia Peninsula (Figures 6.1, 6.2). At its type locality (BH41/942853), near the Mangapoike River c.35 km to the northwest, the limestone has been recorded as being up to 460 m thick (Beu 1995), although Kamp *et al.* (1988) suggested the maximum thickness was nearer c.300 m. The type section is within the Haupatanga Gorge (Appendix VIII) and is mainly inaccessible, and so a reasonably complete reference section has been established nearby (c.BH41/946854) (Beu 1995). Further information about these sections is available in Jiang (in prep.).

Occurring in only limited exposures on the west coast of Mahia Peninsula, the Whakapunake Limestone is unique in that it is a prominently bedded unit comprising limestone-sandstone couplets, the sandstone portions including unusual ‘mudclasts’ (see below) (Figure 6.3) (Stratigraphic column 20, Appendix VII). Beu (1995, p. 86) suggested the Whakapunake Limestone on Mahia Peninsula was an ‘offshore equivalent of the Whakapunake Limestone’, as it differs from the ‘true’ Whakapunake Limestone at the type locality in the Haupatanga Gorge. The exposed thickness is up to c.40 m, but with no lower contact visible the true thickness is unknown. Travelling south on Mahia Peninsula, the Whakapunake Limestone is first exposed on Kinikini Road (c.BJ43/179528), after which the unit extends along the coast for approximately 600 m until it passes upwards into coastal mudstone bluffs.

The distinctively bedded nature of the Whakapunake Limestone on Mahia Peninsula could have been represented in the uppermost stratigraphy of the ‘true’ Whakapunake Limestone, at Haupatanga Gorge (BH41/942853). This is because here the upper beds are missing due to truncation by the Tahaenui Limestone in a mild angular unconformity (Beu 1995).

The interbeds of more resistant true limestone (lithofacies L3) within the Whakapunake Limestone on Mahia Peninsula are 10-100 cm thick and have sharp contacts with the sandstone beds either side (Figure 6.4 A, B, C). Siliciclastic material is common in the limestones which are brown - red coloured, well indurated, and comprise densely packed skeletal material reaching up to 40 mm size (Figure 6.4 D). The limestone can have a crystalline appearance in which smaller individual bioclasts are indeterminable. External case hardening of outcrop surfaces is common. Exposures on the coastal platforms reveal a variety of pectinids and occasional oysters up to 5 cm size.

The sandstone interbeds (lithofacies S4) in the Whakapunake Limestone on Mahia Peninsula are typically recessive, leaving the harder limestone beds as protruding units. These variably indurated, brown/red/grey sandstone beds are 20-100 cm thick and host unique mudstone clasts surrounded by a shelly sandstone matrix. This matrix contains densely packed fragmented shell material up to 3 mm in size. The siliciclastic material is coarse grained (c.0.5 mm) and reasonably well sorted. Rare intact brachiopods up to 5 cm size are observed. The distinctive mudstone clasts can be as small as 6 cm, but are more commonly 15-30 cm long, with a 'stretched' elongated shape (Figure 6.5 A). Their boundaries are generally irregular and jagged. In 'horizontal' cross profile the mudstone clasts are roughly rounded in shape (Figure 6.5 B). Many are therefore crudely tubular in morphology, standing up in steep angles of c.40°W.

The Whakapunake Limestone grades upwards via the above limestone-sandstone interbeds into friable, dark grey, shelly bioturbated sandstone including burrow structures up to 10 cm long (Figure 6.2). Interrupting this capping Wairoa Formation C sequence is a 1 m thick, very soft and friable, white, pumiceous volcaniclastite deposit (Figures 6.2, 6.6 D).

Figure 6.1 – Distribution of the Whakapunake Limestone and surrounding Pliocene Wairoa Formation siliciclastic deposits in the study area. Names of stations, streams and features referenced in this chapter are located on the map.

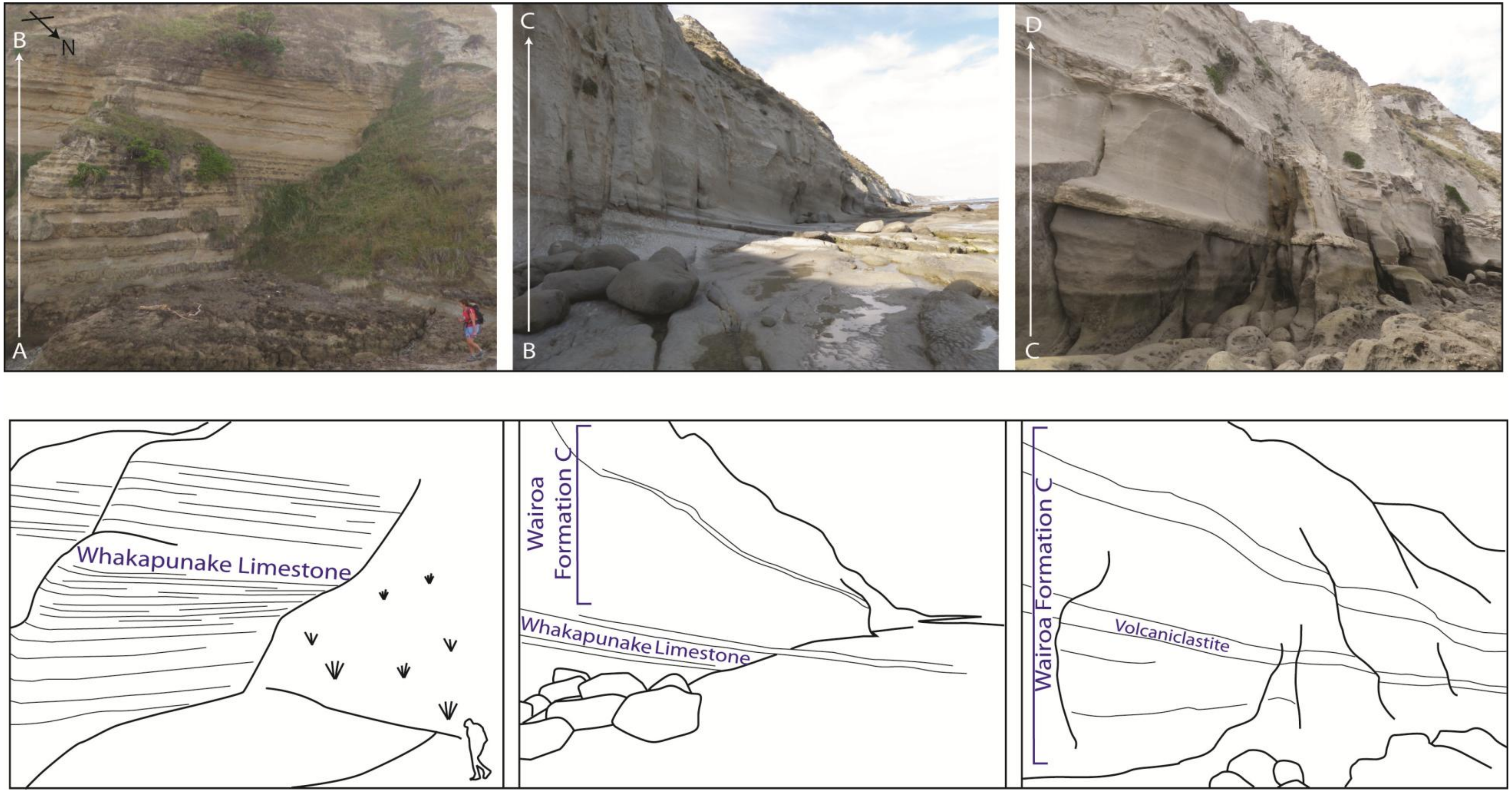


Figure 6.2 – The Whakapunake Limestone as it outcrops on the coast at Ahimanawa Station, Mahia Peninsula. The limestone grades upwards via sharp interbeds into shelly sandstone and fossiliferous mudstones of the Wairoa Formation C. Note that A-B-C-D is in stratigraphic order. Note scale is only approximate as the actual distance changes with perspective.

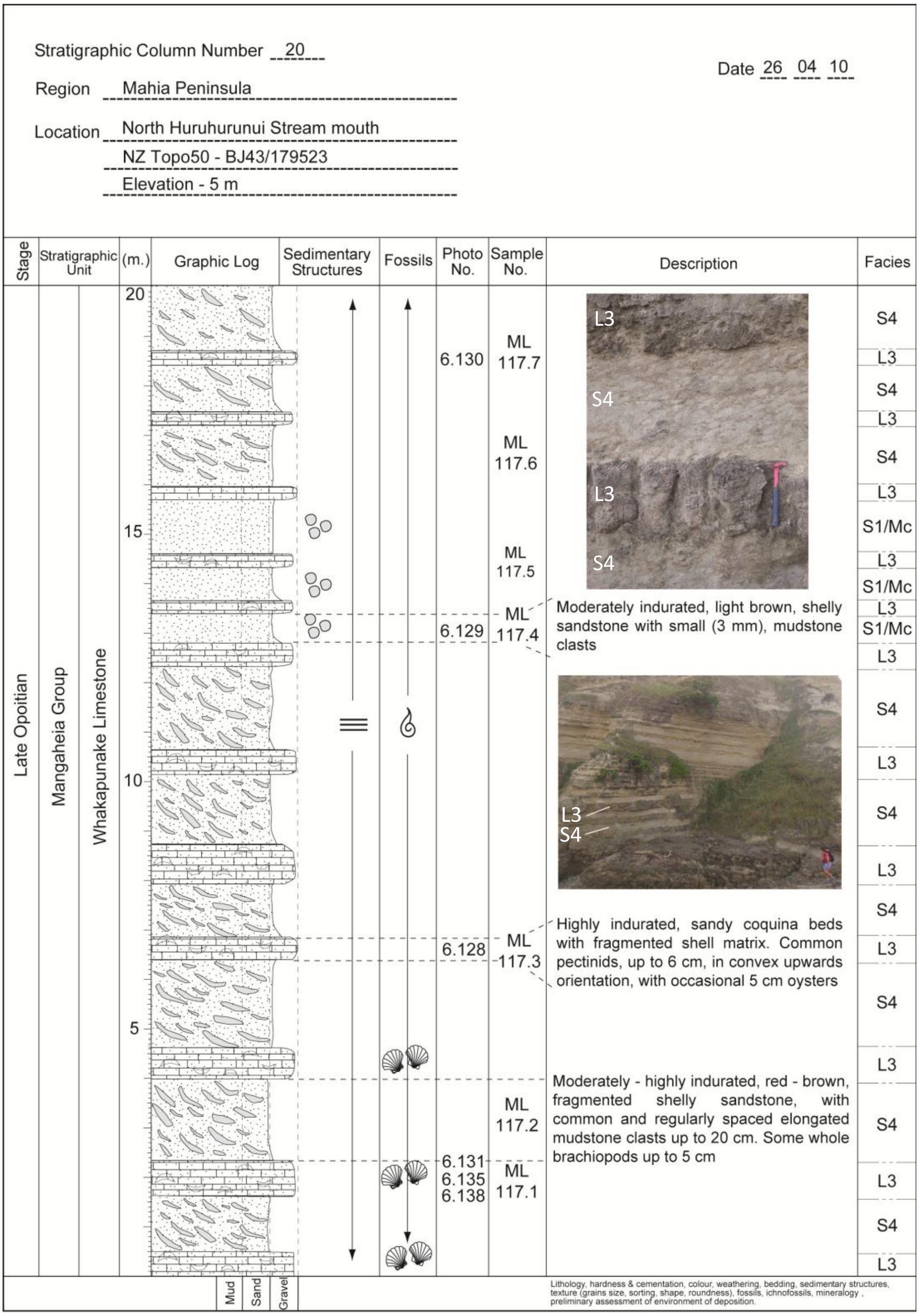


Figure 6.3 –Stratigraphic column of the Whakapunake Limestone at the Huruhurunui Stream mouth, near Ahimanawa Station on the west coast of Mahia Peninsula.

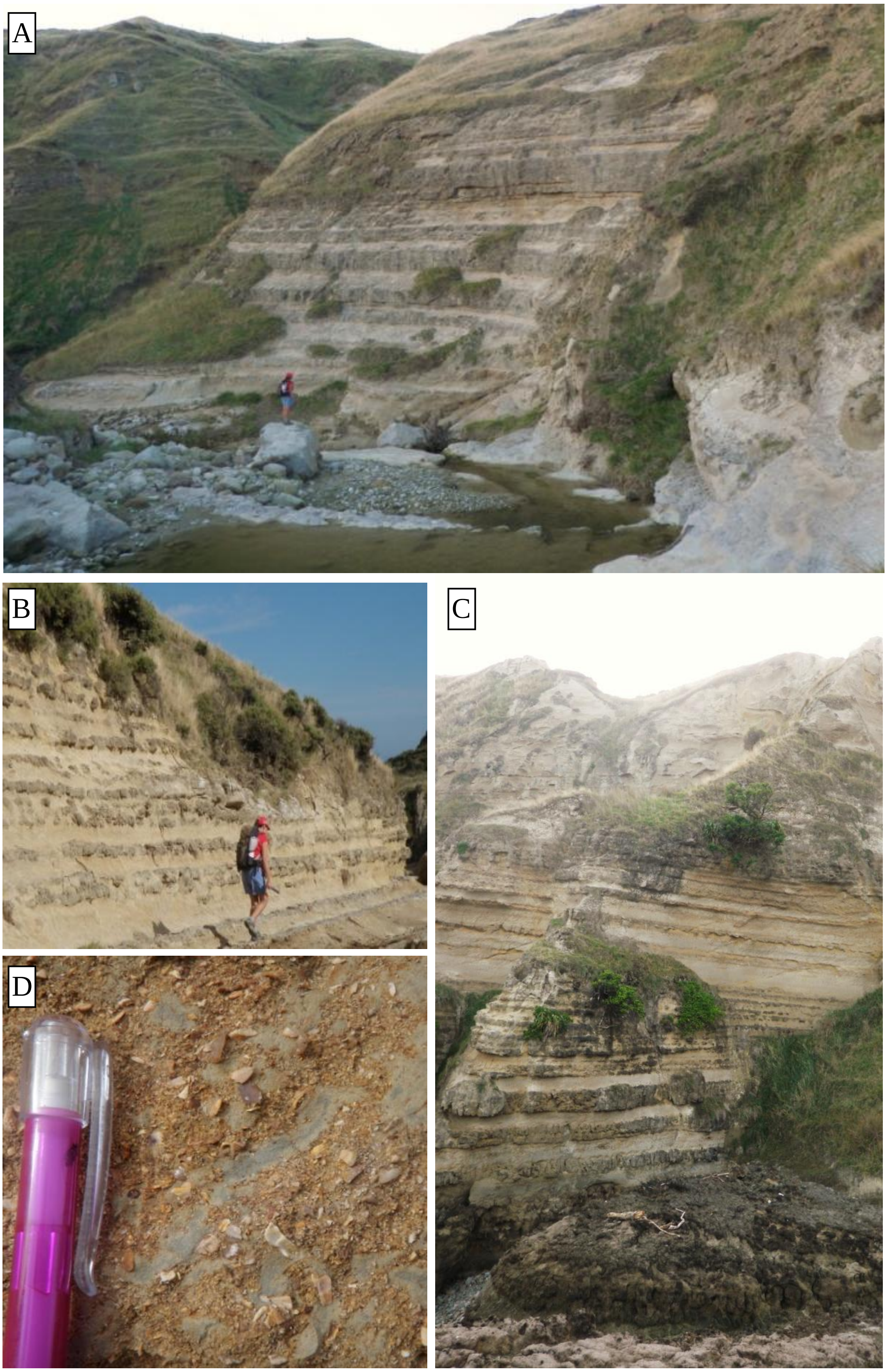


Figure 6.4 - Field photographs of the Whakapunake Limestone on the west coast, Mahia Peninsula. **(A** and **B)** The Whakapunake Limestone at Huruhurunui Stream comprising limestone beds up to 1 m thick interbedded with mudclast-bearing shelly sandstone. **(C)** The Whakapunake Limestone forming high cliffs on the coast at Ahimanawa Station. Here the thickness of the limestone beds decrease upwards at the expense of the thickening sand dominated beds. **(D)** Small irregular mudstone clasts within a coarse shelly sandstone matrix from the higher portions of the Whakapunake Limestone at Kinikini Road. *Pencil - 0.8 cm wide.*

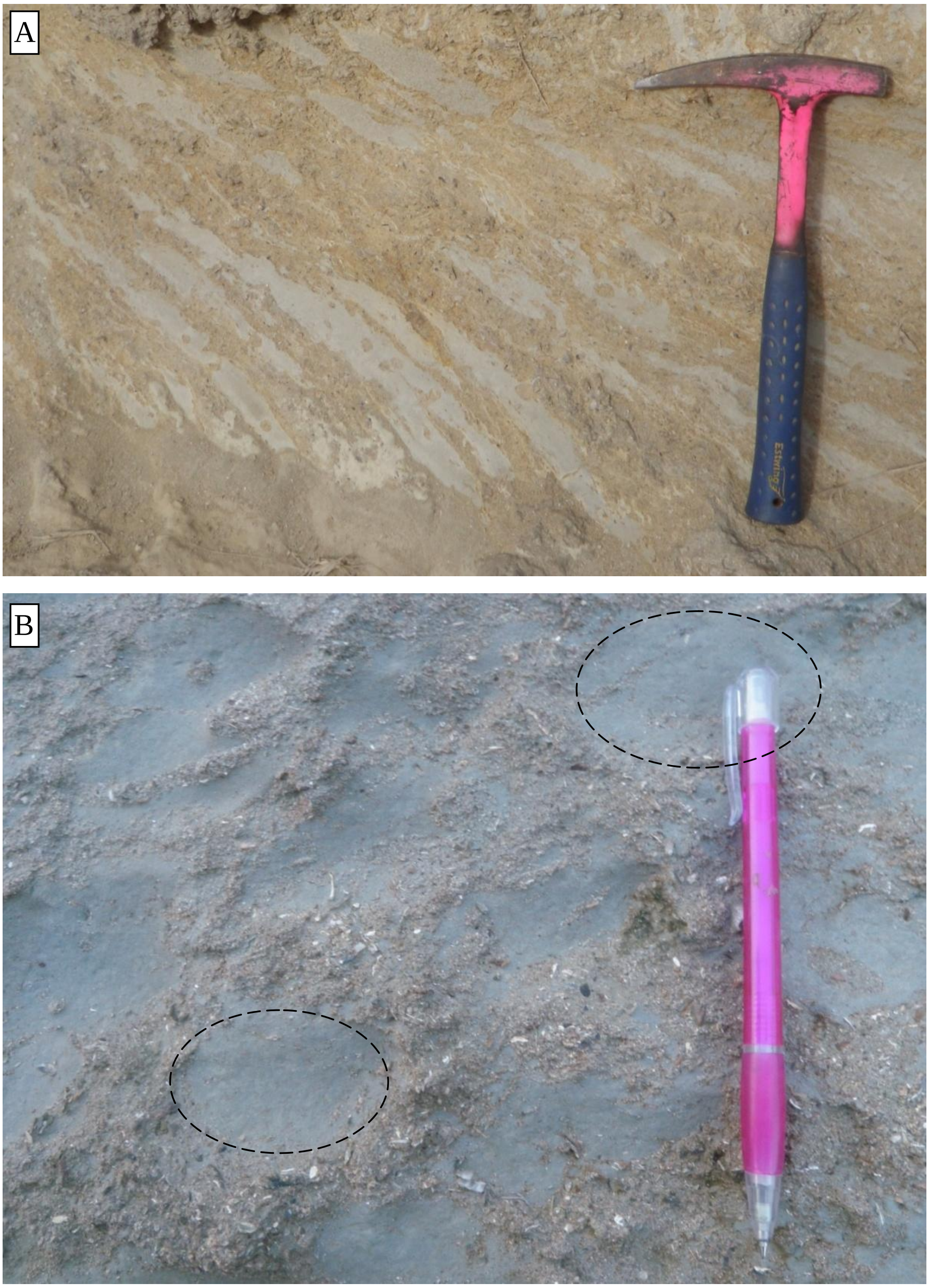


Figure 6.5 – Mudclast-bearing shelly sandstone near the coast at Ahimanawa Station, west Mahia Peninsula. **(A)** Vertical section showing elongated mudstone lenses in the coarse shelly sandstone matrix of the sandstone interbeds in the Whakapunake Limestone. **(B)** Cross section view of the mudclasts shows they have a roughly pitted elliptical shape. *Hammer - 32 cm long, Pencil - 14 cm long.*

6.1.1 Contacts

The Whakapunake Limestone on Mahia Peninsula (BH43/179522) grades upwards via thinning limestone and thickening mudclast-bearing sandstone beds which ultimately gives way to shelly sandstones and sandy mudstones (Wairoa Formation C) (Figures 6.6 and 6.7 A) (Stratigraphic column 21, Appendix VII). The shelly sandstones are blue grey, moderately sorted and coarse grained (c.0.5 mm) with bivalve and rare gastropod skeletons up to 2 cm size (Figure 6.7 B, C). A 1 m thick light coloured, pumiceous volcaniclastite is included within this sandstone succession (Figure 6.7 D). The uppermost mudstone (Figure 6.7 E) is accessible from the inland side of the coastal bluffs. No lower contacts of the Whakapunake Limestone are visible on Mahia Peninsula.

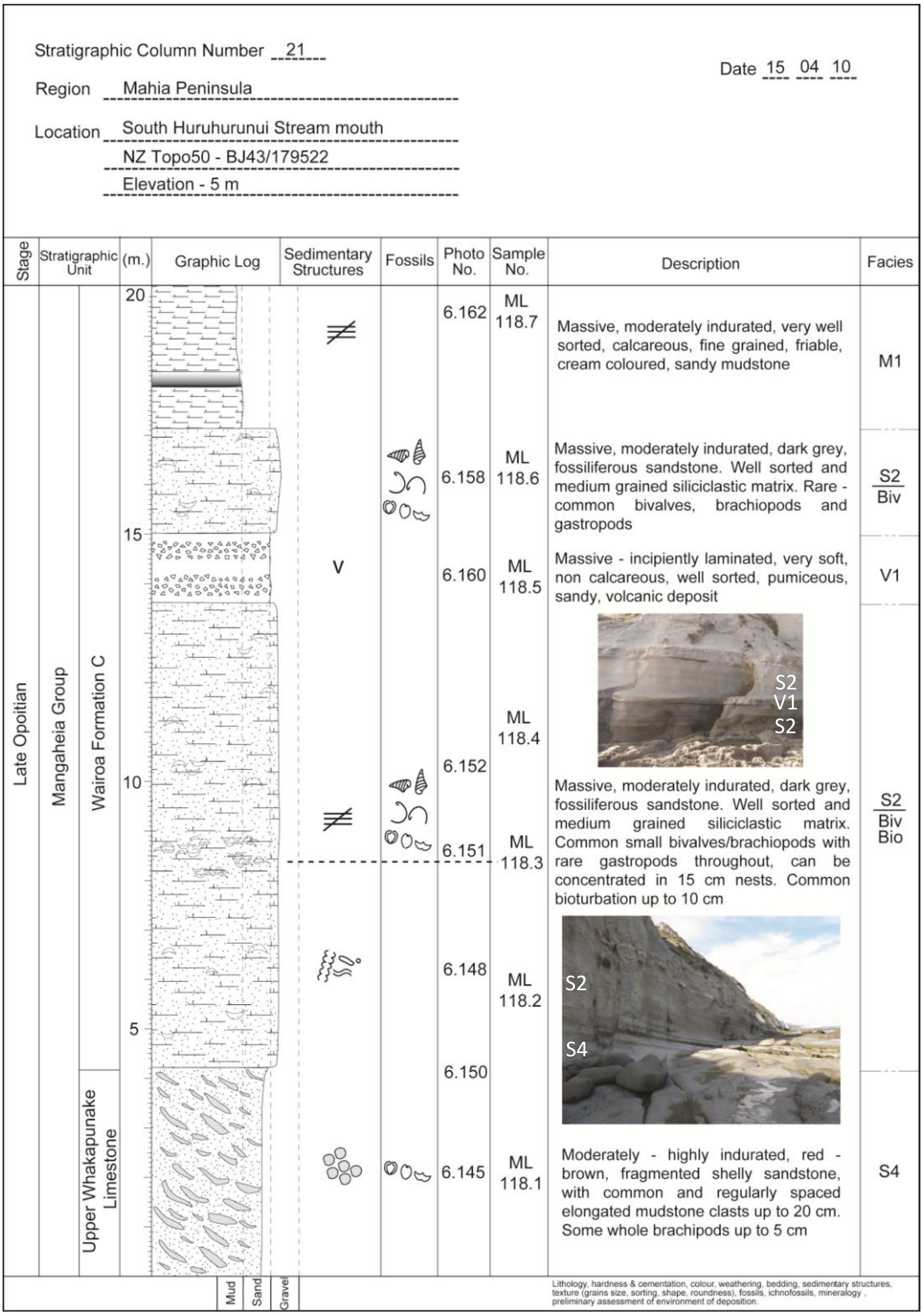


Figure 6.6 – –Stratigraphic column of the mudstone and sandstone succession (Wairoa Formation C) overlying the Whakapunake Limestone at the Huruhurunui Stream mouth, near Ahimanawa Station on the west coast of Mahia Peninsula.

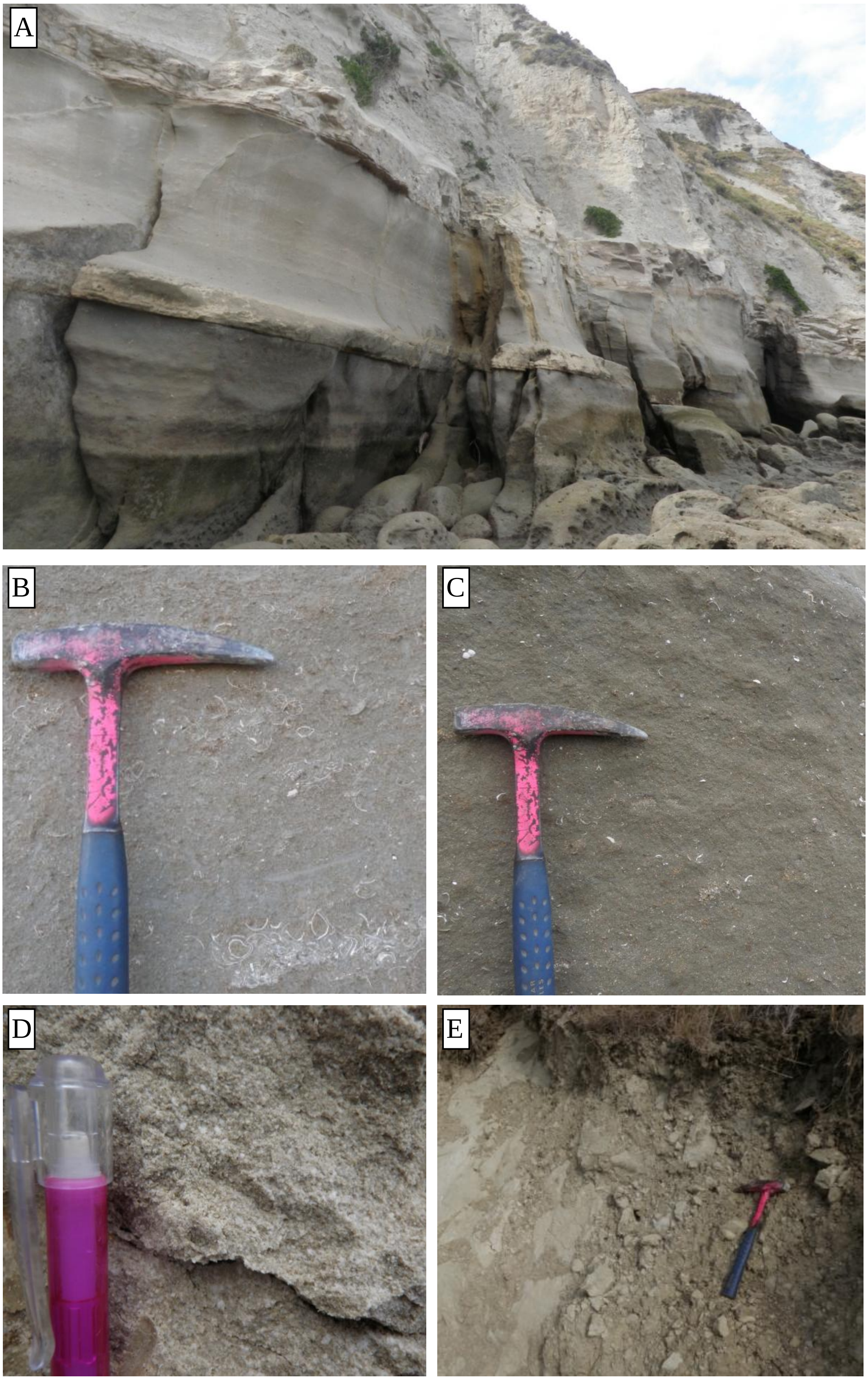


Figure 6.7 – Field photographs of the associated lithologies and contacts overlying the Whakapunake Limestone at Mahia Peninsula. **(A)** The Wairoa Formation C at Ahimanawa Station. The lower lithology here is shelly sandstone overlain by a pumiceous volcaniclastite unit. A homogeneous mudstone follows that grades into inaccessible sandstone, overlain by further mudstone. **(B** and **C)** Close view of the shelly sandstone in (A). Shells can be in clustered 'nests' (B) or scattered (C). **(D)** Pumice grains are the dominant component in the volcaniclastite unit in (A). **(E)** Friable mudstone at the stratigraphic top of the Ahimanawa Station section within Wairoa Formation C. Whakapunake succession. *Hammer - 32 cm long, pencil - 0.8 cm wide.*

6.1.2 Lithofacies

Lithofacies in the Whakapunake Limestone and the overlying Wairoa Formation C include one limestone (L3), three sandstone (S1, S2, S4), one mudstone (M1) and one volcanic (V1) type (Figure 6.8).

The distinctive nature of the Whakapunake Limestone on Mahia Peninsula requires establishment of a unique sandstone lithofacies (S4) which is interbedded with 'more typical' sandy mixed bioclastic-siliciclastic (L3) lithofacies. Small occurrences of lithofacies S1 occur higher in the Whakapunake Limestone interbeds. Within the Wairoa Formation C thick bioclastic sandstone (S2) occurs. This then grades above into mudstone lithofacies (M1), also in Wairoa Formation C. The volcaniclastic lithofacies V1 occurs within this upper siliciclastic succession, above the Whakapunake Limestone proper.

The lateral distribution of the Whakapunake Limestone and Wairoa Formation C lithofacies is clearly shown on a panel diagram (Figure 6.9). Because such a limited amount of Whakapunake Limestone and Wairoa Formation C occurs in the field area the panel diagram is quite simple, with lithofacies linking easily.

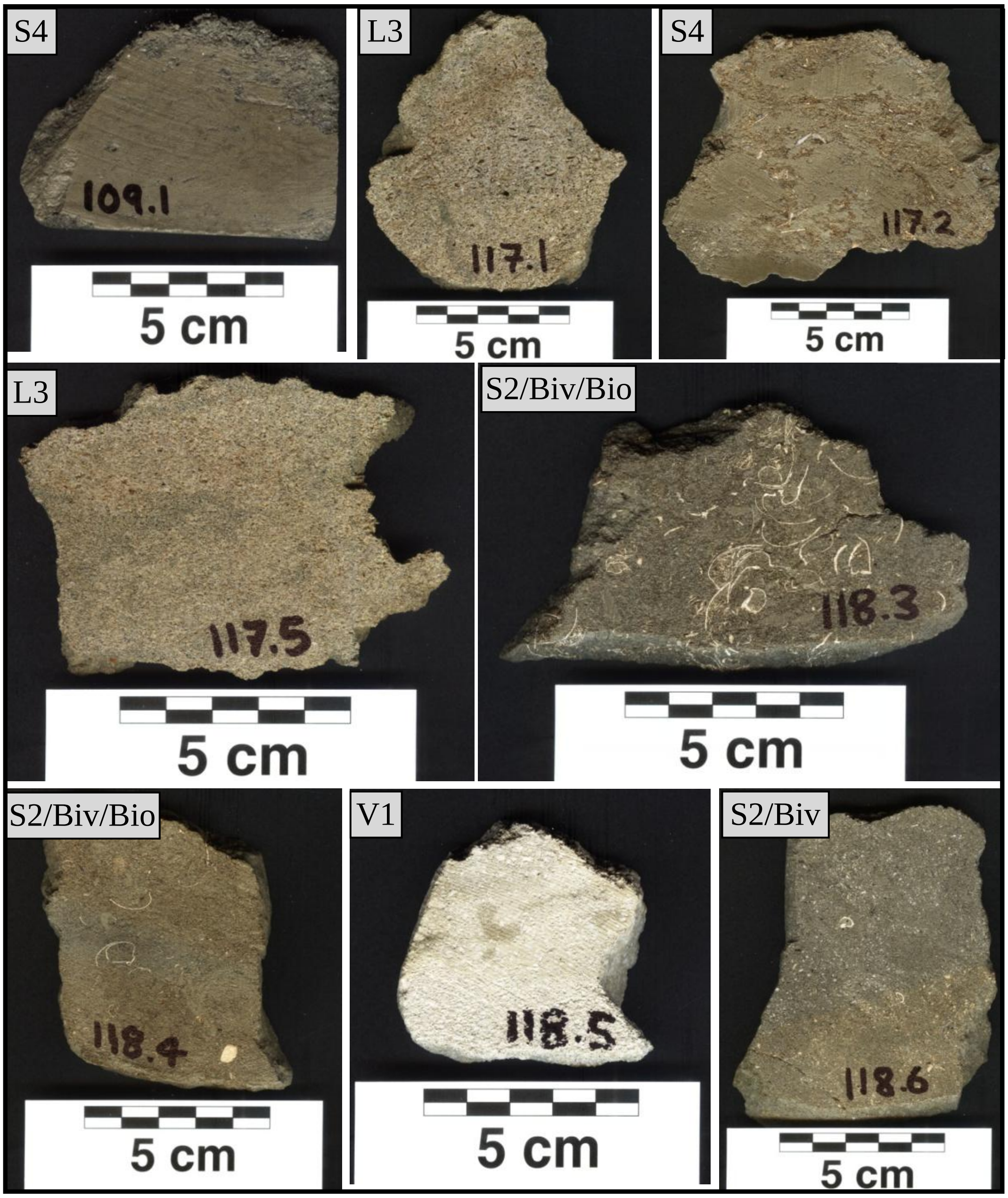


Figure 6.8 - Cut slabs showing lithofacies in the Whakapunake Limestone and overlying Wairoa Formation C in vertical stratigraphic order from the coastal section (Figure 6.2) at Ahimanawa Station, west Mahia Peninsula. Refer to Table 4.1 for facies definition and codes.

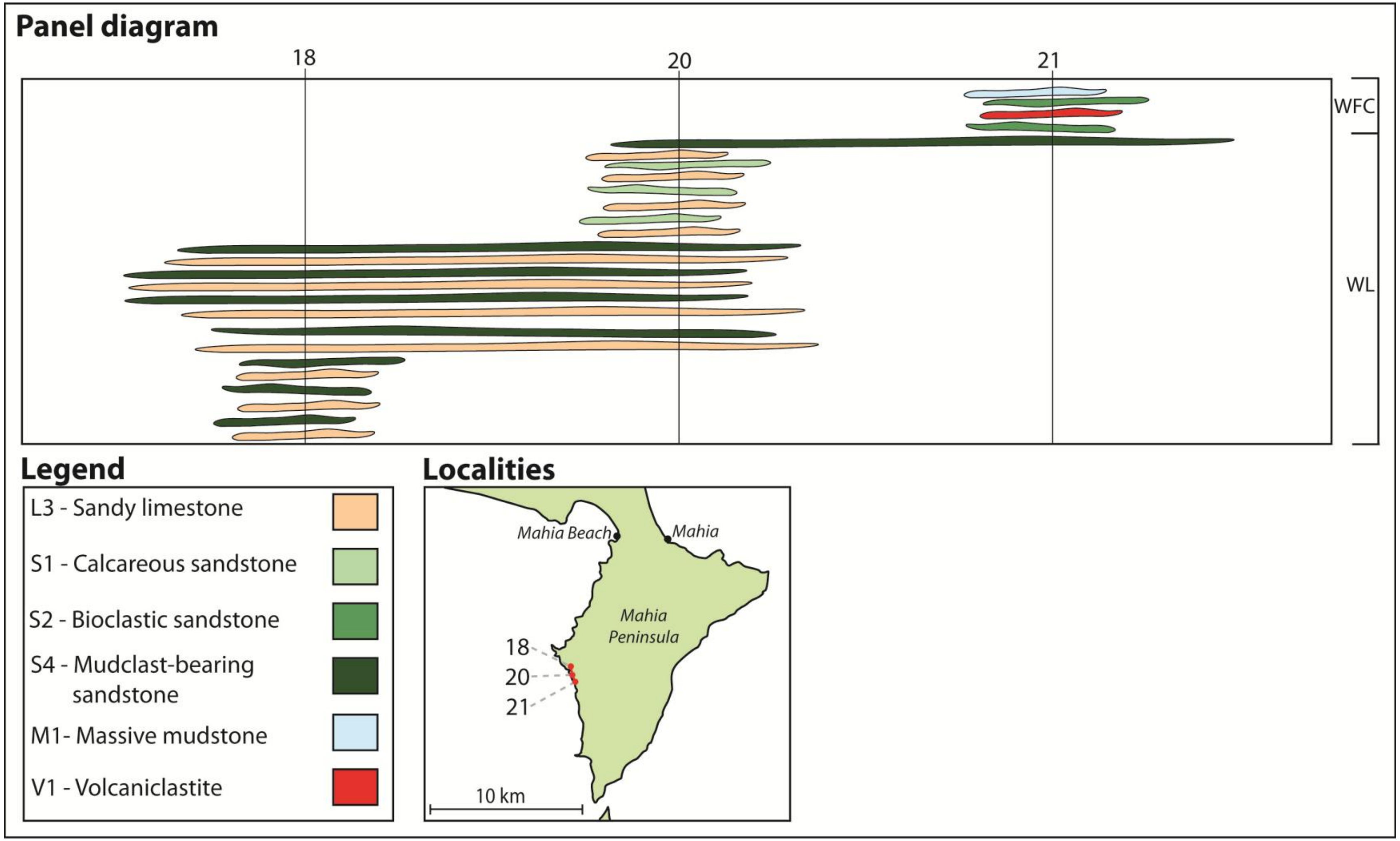


Figure 6.9 – Stylised panel diagram showing the lateral relationship between lithofacies of the Whakapunake Limestone (WL) and Wairoa Formation C (WRC). Numbers relate to stratigraphic columns (refer to Appendix VII). No vertical scale implied.

6.2 FOSSIL CONTENT

The Whakapunake Limestone typically hosts common pectinids, barnacles and oysters. The limestone lithofacies (L3) in the Whakapunake Limestone hosts common small to medium sized pectinids in convex upwards orientation. These are 3-4 cm *Mesopeplum waikohuense* (Marwick) (Figure 6.10 D, E) and occasional 5-6 cm *Phialopecten marwicki* (Figure 6.10 A). Beu (1995) has also recorded rare occurrences of *Mesopeplum crawfordi* and abundant populations of *Mesopeplum syagrus.* The brachiopod *Neothyris* (Figure 6.10 B) and small (4-5 cm size) oysters (Figure 6.10 C) also occur occasionally. The sandy mudclast bearing S4 interbeds contain no obvious macrofossils, and only small unidentifiable shell fragments.

From foraminiferal laboratory work and scanning electron microscopy (SEM) imaging, the mudstone lenses and surrounding shelly sandstone within the Whakapunake Limestone include common bryozoan material, some spiralled *Lenticulina*, some fragmented echinoid spines and rare specimens of spiralled *Notorotalia* and the agglutinating foraminifera *Textularia aff. barnwelli* (Figure 6.11). These particular foraminifera are not age defining, however a fossiliferous mudstone within the Wairoa Formation C has the index foraminifera *Globorotalia margaritae*, which is Opoitian aged (Beu 1995). The bryozoan fragments are up to 3 mm long with well preserved exterior structures, perhaps reflecting rapid deposition and burial associated with storm events.

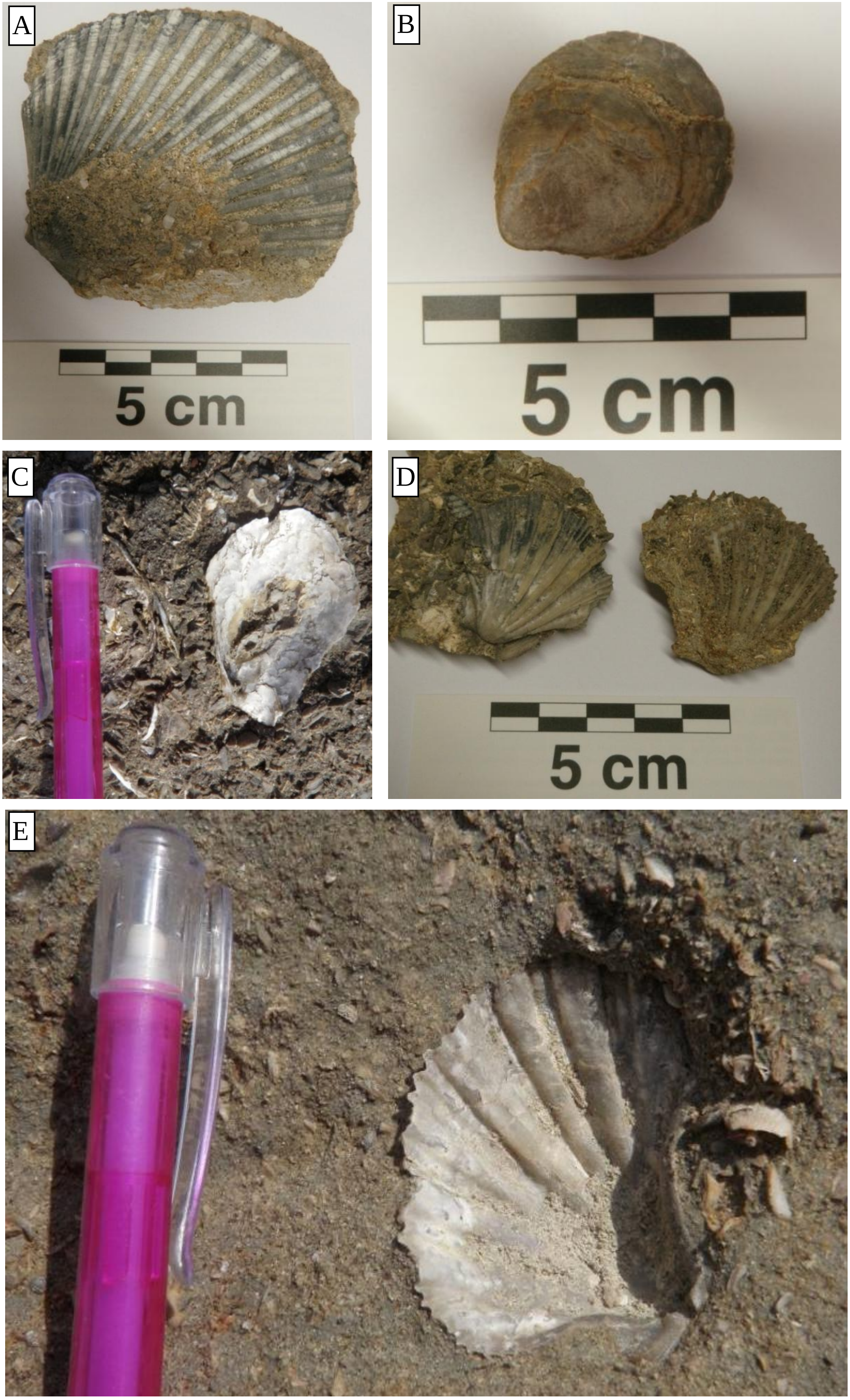


Figure 6.10 - Macrofossils in the harder Whakapunake Limestone beds, west coast, Mahia Peninsula. **(A)** *Phialopecten marwicki*; the three riblets on each costa not beginning until near the outer edge of the disc suggest a quite immature specimen. **(B)** Brachiopod *Neothyris.* **(C)** Oyster valve of uncertain affinity. **(D** and **E)** *Mesopeplum waikohuense* (Marwick). *Pencil - 0.8 cm wide.*

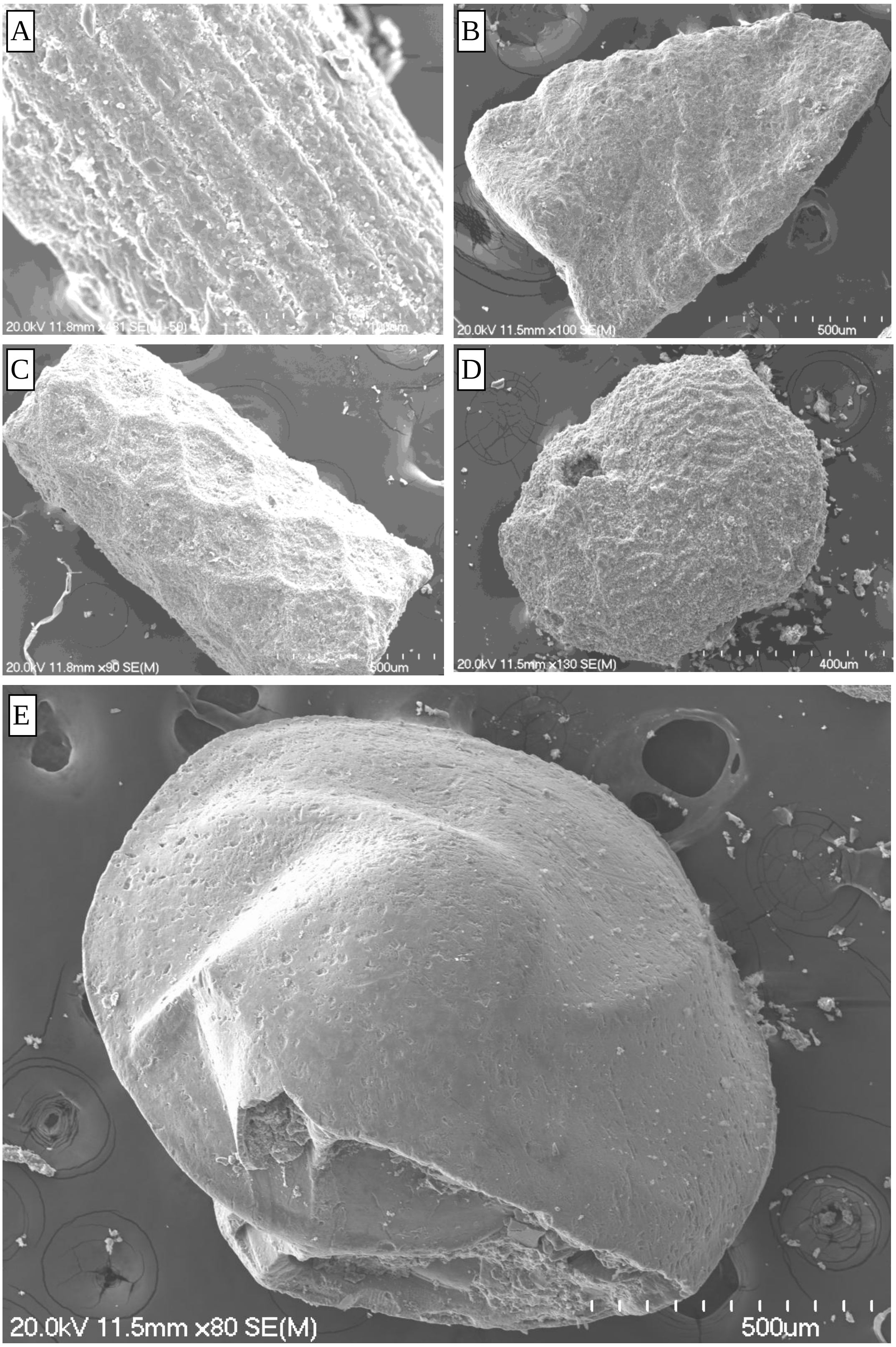


Figure 6.11 - Scanning electron images of microfossils from mudstone sample 109.1 within the sandstone interbeds of the Whakapunake Limestone. Obtained. **(A)** Broken echinoid spine. **(B)** *Textularia* aff. *barnwelli.* **(C)** Bryozoan fragment. **(D)** *Notorotalia*. **(E)** *Lenticulina.*

6.3 LABORATORY PROPERTIES

6.3.1 Calcium carbonate %

Figure 6.12 plots the calcium carbonate and siliciclastic values of the Whakapunake Limestone and the overlying Wairoa Formation C, with calcium carbonate data given in Appendix III. Whakapunake Limestone comprises mainly indurated sandy limestone (lithofacies L3) interbedded with a distinctive mudclast-bearing shelly sandstone (lithofacies S4). Lithofacies L3 has carbonate percentages near 70%, while lithofacies S4 has values nearer 40% (Table 6.1). The relatively high carbonate content of this sandstone derives mainly from the shelly matrix that surrounds the mudstone clasts. The calcareous sandstone (lithofacies S1) has a CO_3 content of c.8%, which rises to c.25% where it becomes a fossiliferous sandstone (lithofacies S2). The single volcaniclastic unit has a CO_3 content of c.7%. Depending on the origin of the volcaniclastic unit, the carbonate input has likely originated from the above and underlying calcareous mud/sandstone units when the volcanic flow entered the marine environment. The sandy limestone (lithofacies L3) hosts c.18% sand with variable mud values.

Table 6.1 - Carbonate and siliciclastic percentages in the Whakapunake Limestone (lithofacies L3, S4) and overlying Wairoa Formation C (lithofacies S1, S2, V1).

Sample Number	Facies	Carbonate %	Sand %	Mud %
106.2	L3	78.9	17.7	3.3
108.2	L3	63.9	20.8	16.1
118.7	S1	7.6	57.5	35.3
118.3	S2	27.7	56.8	16.1
117.2	S4	31.9	34.4	34.0
105.1	S4	47.7	32.6	19.7
118.5	V1	7.2	46.6	34.3

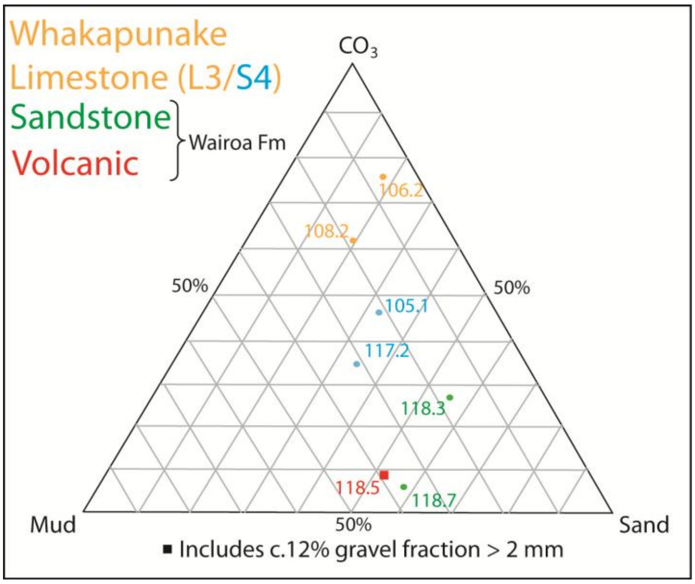


Figure 6.12 – Ternary plot depicting the carbonate-siliciclastic sand-siliciclastic mud composition for samples from the Whakapunake Limestone and overlying Wairoa Formation C. Carbonate values in lithofacies L3 ranges from c.60-70%, with interbedded lithofacies S4 showing c.40%.

6.3.2 Insoluble grain analysis

Malvern Mastersizer data and graphs are contained as Digital Appendix F on the accompanying CD. Table 6.2 presents size percentages of the siliciclastic sediment within the Whakapunake Limestone and overlying Wairoa Formation C, which are plotted on Figure 6.13. The acid insoluble material in the limestone lithofacies of the Whakapunake Limestone has two modal size ranges, 15-29 µm and 199-213 µm (medium silt and fine sand). The sandstone interbeds in the Whakapunake Limestone also show two modal ranges, 183-779 µm and 42-87 µm (fine to coarse sand and coarse silt to very fine sand) that can be related to the sandy matrix and the elongated mudstone clasts respectively. The volcaniclastic unit in the Wairoa Formation C deposits overlying the Whakapunake Limestone has modal sizes of 546 µm (pumice clasts) and 43 µm, with c.12% of the grains over 2 mm in size. Sandstone units in Wairoa Formation C have c.70% sand.

Table 6.2 - Siliciclastic percentages in the Whakapunake Limestone (lithofacies L3, S4) and overlying Wairoa Formation C (lithofacies S1, S2, V1).

Sample Number	Facies	Gravel %	Sand %	Silt %	Clay %
106.2	L3	0.0	72.7	26.4	0.8
108.2	L3	0.0	66.8	31.0	2.0
118.7	S1	0.0	61.5	37.5	0.9
118.3	S2	0.0	76.8	22.2	0.8
117.2	S4	0.0	49.4	49.0	1.5
105.1	S4	0.0	55.6	42.5	1.7
118.5	V1	12.0	52.6	34.3	1.8

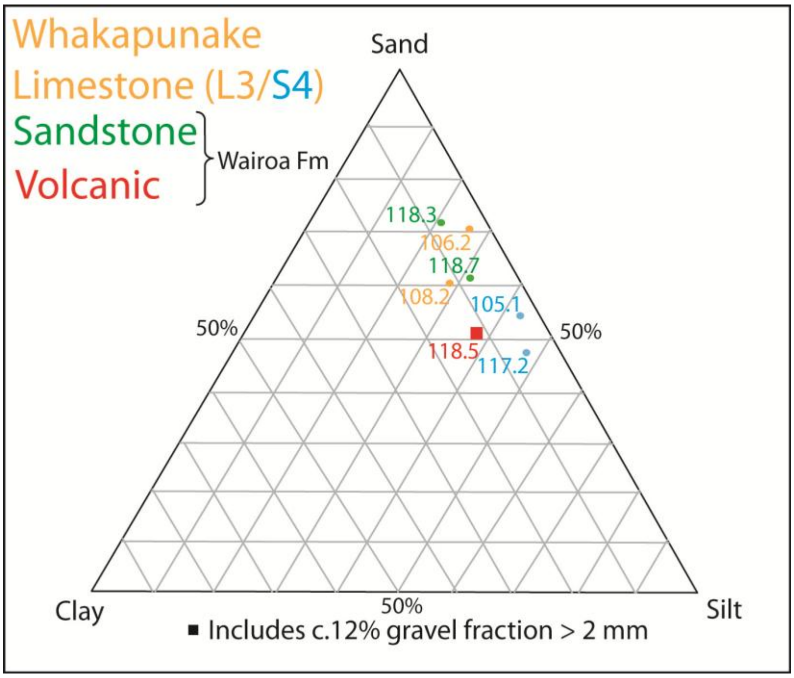


Figure 6.13 – Ternary plot depicting the acid insoluble sand-silt-clay grain sizes for the Whakapunake Limestone and overlying Wairoa Formation C. These lithologies are dominated by sand sized siliciclasts, with some silt and little clay.

6.3.3 XRD

Table 6.3 presents XRD data for the Whakapunake Limestone and overlying Wairoa Formation C. Complete XRD data and graphs are contained as Digital Appendix H on the accompanying CD. The Whakapunake Limestone lithofacies L3 shows calcite peaks up to 634 counts. Lithofacies S4 shows calcite counts up to 472, with quartz peaks up to 374, suggestive of roughly similar amounts of calcite and quartz. Plagioclase counts can be up to 117 in the Whakapunake Limestone, the greatest amount observed in any limestone sample in the field area. Aragonite is present in small quantities in the shelly sandstone sample 118.3, (lithofacies S2) with a count of 93, likely due to the presence of small infaunal bivalves, and is the highest count for aragonite of all the study area samples analysed.

Table 6.3 – XRD count values for the Whakapunake Limestone and overlying Wairoa Formation C. Count values < c.20 may well be part of the background spectra and do not necessarily mean the mineral name indicated is present.

Sample	Quartz	Plagioclase	Calcite	Aragonite	Dolomite	Total Clays
2 ˚θ	**26.62**	**27.94**	**29.42**	**26.22**	**30.9**	**19.9**
L3 - 106.2	23	15	440	8	5	9
L3 - 108.2	191	117	634	15	8	6
S1 - 118.7	507	137	100	33	24	33
S2 - 118.3	487	108	203	93	30	21
S4 - 117.2	374	86	335	30	22	20
S4 - 105.1	310	59	472	14	16	8
V1 - 118.5	90	69	39	33	43	43

6.3.4 Petrography

Comprehensive petrographic analyses (PPL, XPL, and CL) of 15 thin sections from the Whakapunake Limestone and overlying Wairoa Formation C are given in Digital Appendix D. Total petrographic componentry is shown in Figure 6.14.

Skeletal componentry

Total petrographic componentry is given in Figure 6.14. Skeletal components within the Whakapunake Limestone include common barnacles, occasional brachiopods, rare planktic and benthic foraminifera and rare bryozoans and echinoderms (Figure 6.14). The overall fabric of the Whakapunake Limestone shows a densely packed and often 'dirty' appearance (Figure 6.15 A, B) with disordered skeletal grains. Under CL barnacles appear non-luminescent with internal structure highlighted with dull orange (Figure 6.16 B). The skeletal components are typically moderately abraded with some fracturing, and show poor to moderate sorting. Skeletal sizes range from approximately 0.5-3 mm. Common bryozoan fragments occur in the sandy interbeds (Figure 6.17 B).

Cements

The Whakapunake Limestone cements are predominantly isopachous sparite rims (Figure 6.16 B) and microbioclastic micrite (Figure 6.15 A), with some coarse sparite (Figure 6.17 A) (refer to section 2.2.2 for definitions). The microbioclastic micrite appears quite coarse grained and hosts common siliciclasts (Figure 6.15 B). Isopachous sparite rims are typically clear, thin (0.01 mm) and 'wispy' (Figure 6.16 B) and favour barnacles as a substrate. Some pressure dissolution between skeletal grains is evident, and by the hint of isopachous fringe cement growth at pressure contacts (Figure 6.16 B) the cement seems to have been growing simultaneously to pressure dissolution. Interparticle porosity is low, typically only a few percent.

Porosity

Original interskeletal space (excludes cement) in microbioclastic micrite dominated samples can be up to c.40% (Figure 6.15 B), whereas in isopachous sparite dominated samples the original interskeletal space is up to c.15% (Figure 6.16 B).

Classification

Petrographically, the limestones in the Whakapunake Limestone succession are mainly packed biomicrites to poorly washed biosparites (Folk 1968) (section 2.2.2, p. 18) while the sandstones are typically muddy bioclastic arenites.

Siliciclastic and authigenic componentry

Very common quartz and plagioclase grains occur (Figure 6.15 B) and range from 0.2-0.3 mm, fine to medium sand. The grains vary from subangular to subrounded texture and are well sorted. The authigenic minerals glauconite and pyrite are common within the limestone beds, mainly as grains and pellets (Figure 6.17 A) rather than skeletal infill. The shelly sandstone interbeds of the Whakapunake Limestone host common smooth, dark green pellets of glauconite that were identified through petrography (Figure 6.17 B) and foraminiferal picking. These can be up to 2 mm in size. The boundary of the mudclasts within the shelly sandstone interbeds are shown quite clearly in Figure 6.17 B.

Cathodoluminescence

Small bivalves (up to 2 cm) in the shelly sandstone of Wairoa Formation C illuminate under CL in purple hues suggesting an aragonitic mineralogy (Figure 6.18 A, B). Interestingly, pumice clasts appear purple under CL and contrast against a speckled blue/orange background (Figure 6.19 A, B).

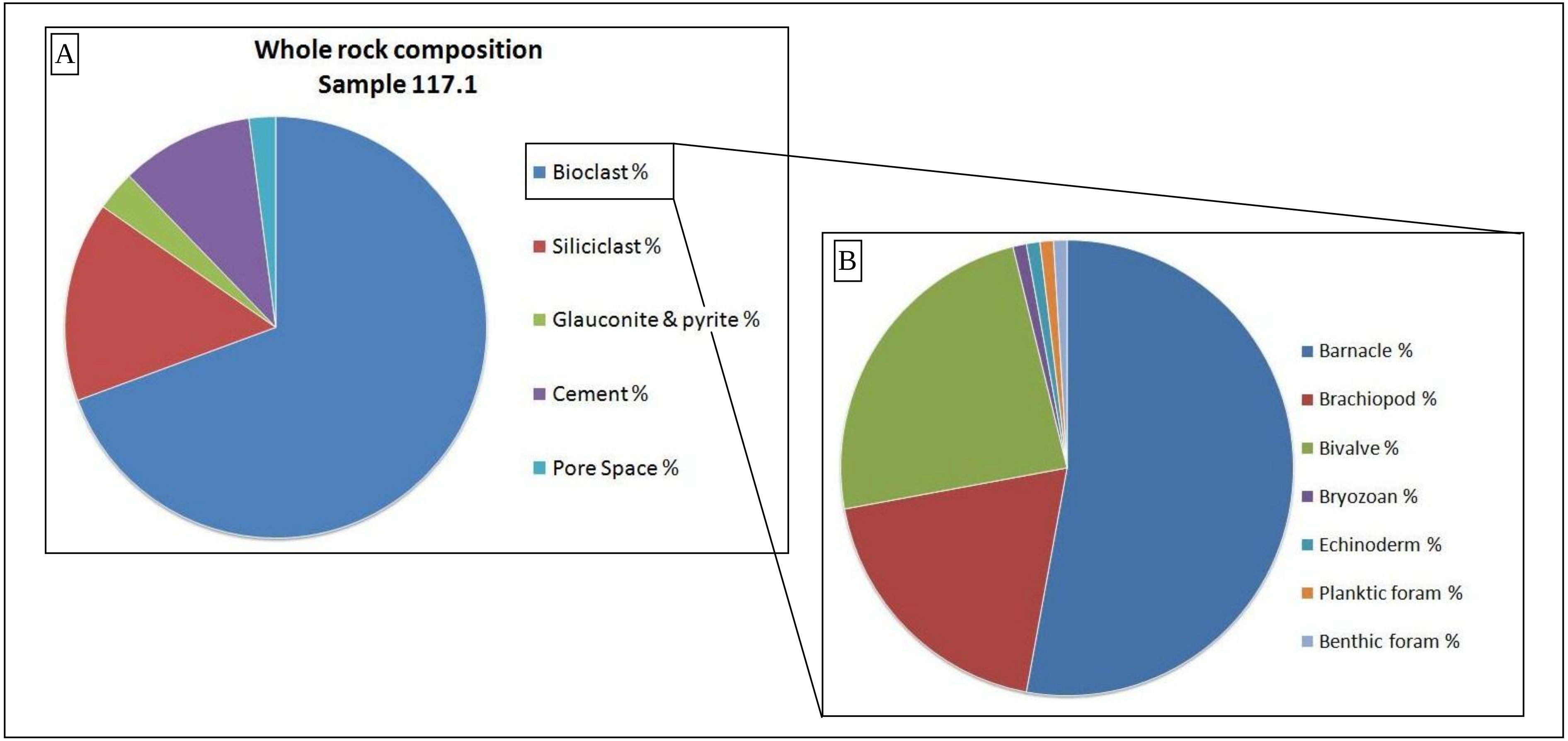


Figure 6.14 – Pie graphs showing the total petrographic componentry **(A)** and the primary skeletal componentry **(B)** of a representative sample from the Whakapunake Limestone. Sample 117.1 (lithofacies L3) crops out at the Huruhurunui Stream mouth, Ahimanawa Station, west coast Mahia Peninsula.

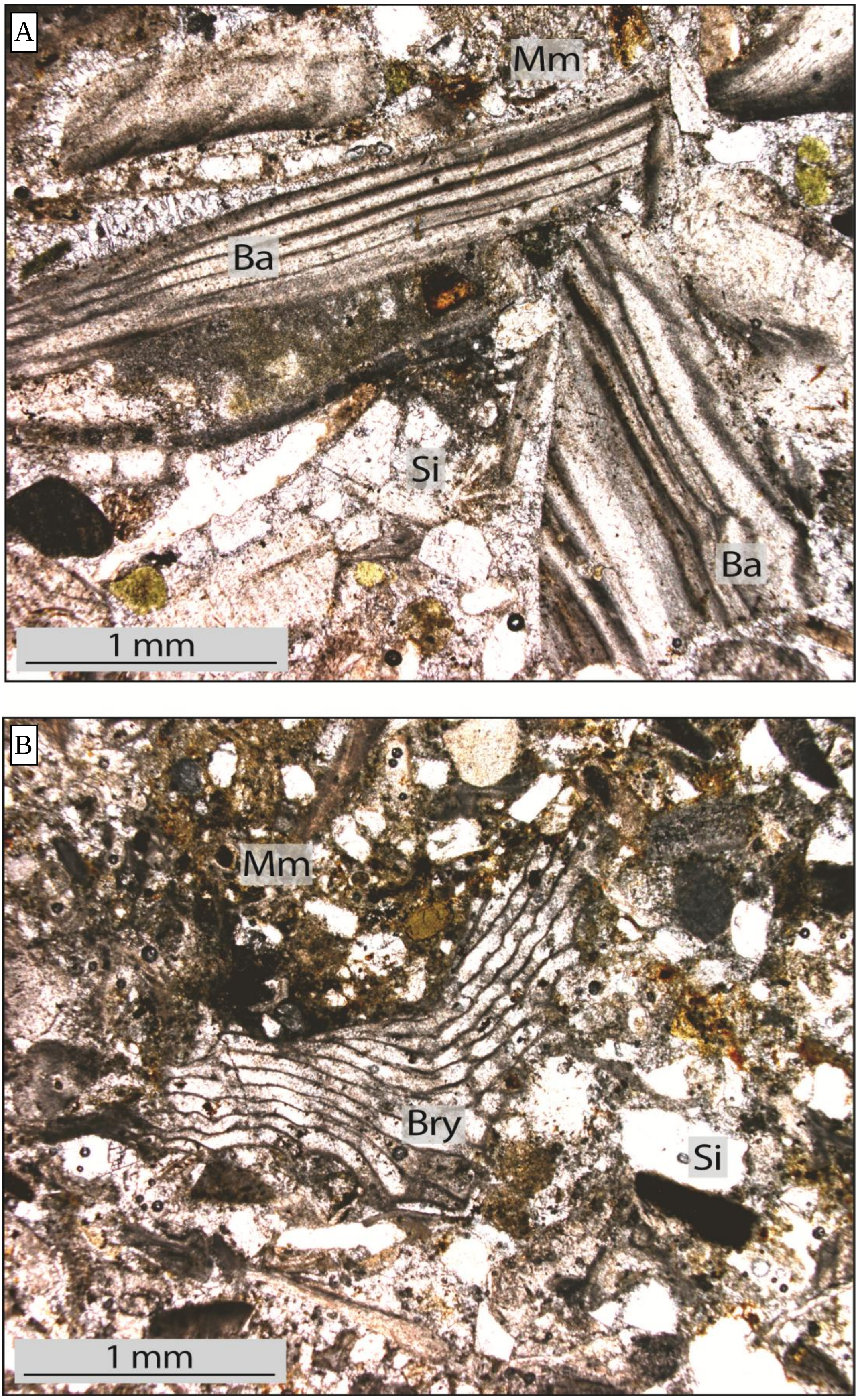


Figure 6.15 – Petrographic images from the hard Whakapunake Limestone beds at Ahimanawa Station, west coast, Mahia Peninsula **(A)** Sample 117.7, a sandy, densely packed biomicrite, showing subrounded barnacles (Bn) in a 'dirty' microbioclastic micrite (Mm) with siliciclasts (Si) and some glauconite pellets. PPL. **(B)** Sample 105.2, also a sandy, densely packed biomicrite, showing common siliciclasts (Si) in microbioclastic micrite (Mm) with bryozoan (Bry) fragment cut longitudinally. PPL.

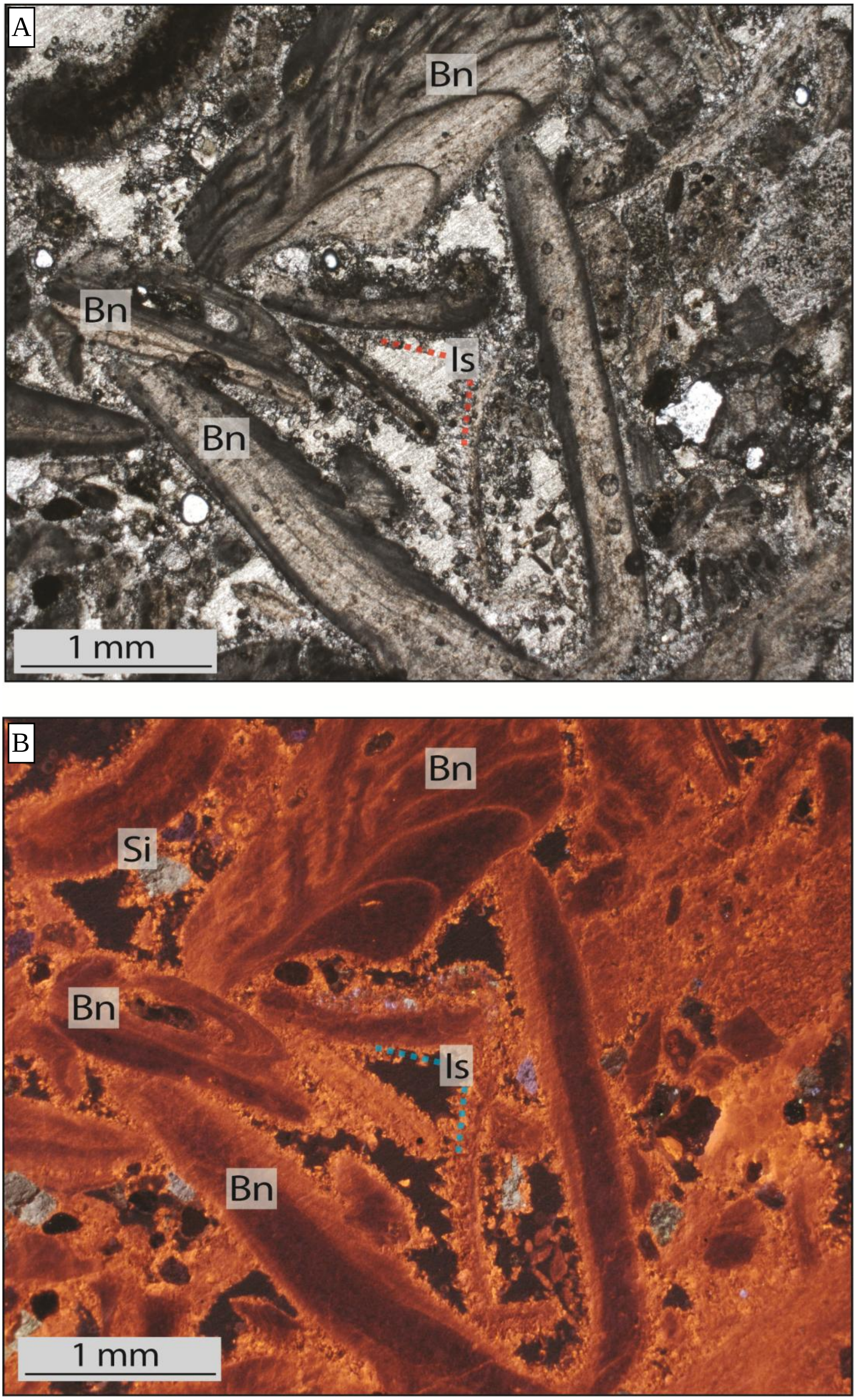


Figure 6.16 – Petrographic image pair from the hard Whakapunake Limestone beds at Ahimanawa Station, west coast, Mahia Peninsula. **(A)** Sample 109.2, a sorted biosparite, showing subrounded barnacle (Bn) fragments with thin isopachous sparite fringes (Is). PPL. **(B)** Identical image under CL highlighting the isopachous sparite fringes in dull orange. Barnacle fragments illuminated as dull orange to non luminescent. Rare siliciclasts (Si) illuminate as silver to purple.

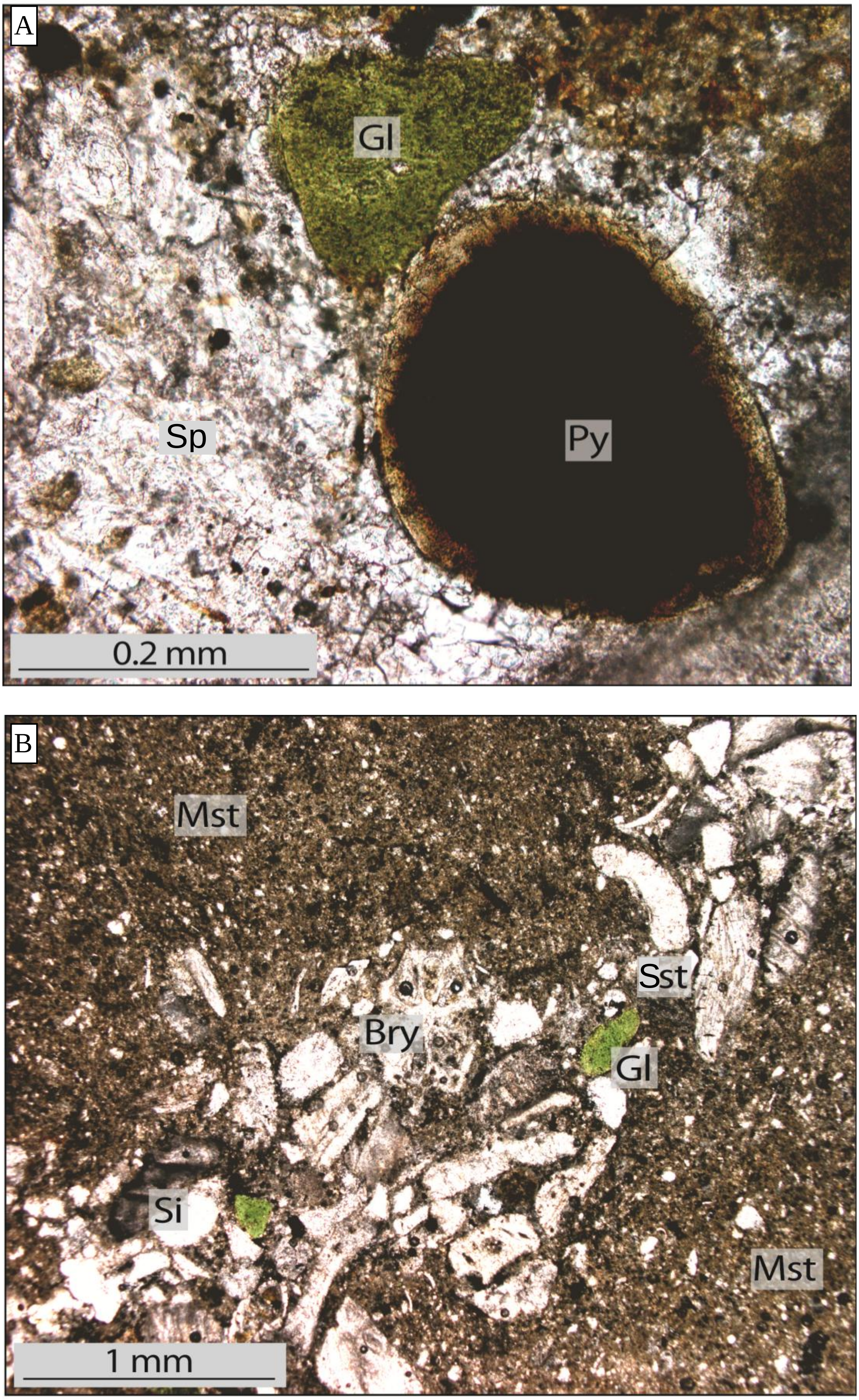


Figure 6.17 – Petrographic images from the hard (A) and sandy (B) Whakapunake Limestone beds at Ahimanawa Station, west coast, Mahia Peninsula. **(A)** Sample 117.1, a sorted biosparite, illustrating rounded glauconite (Gl) and pyrite (Py) pellets set in coarse sparite (Sp). PPL. **(B)** Sample 109.1, a muddy bioclastic arenite, showing clear separation between the mudstone clasts (Mst) and surrounding shelly sandstone (Sst). Bryozoan material (Bry), siliciclasts (Si) and glauconite pellets (Gl) are all common. PPL.

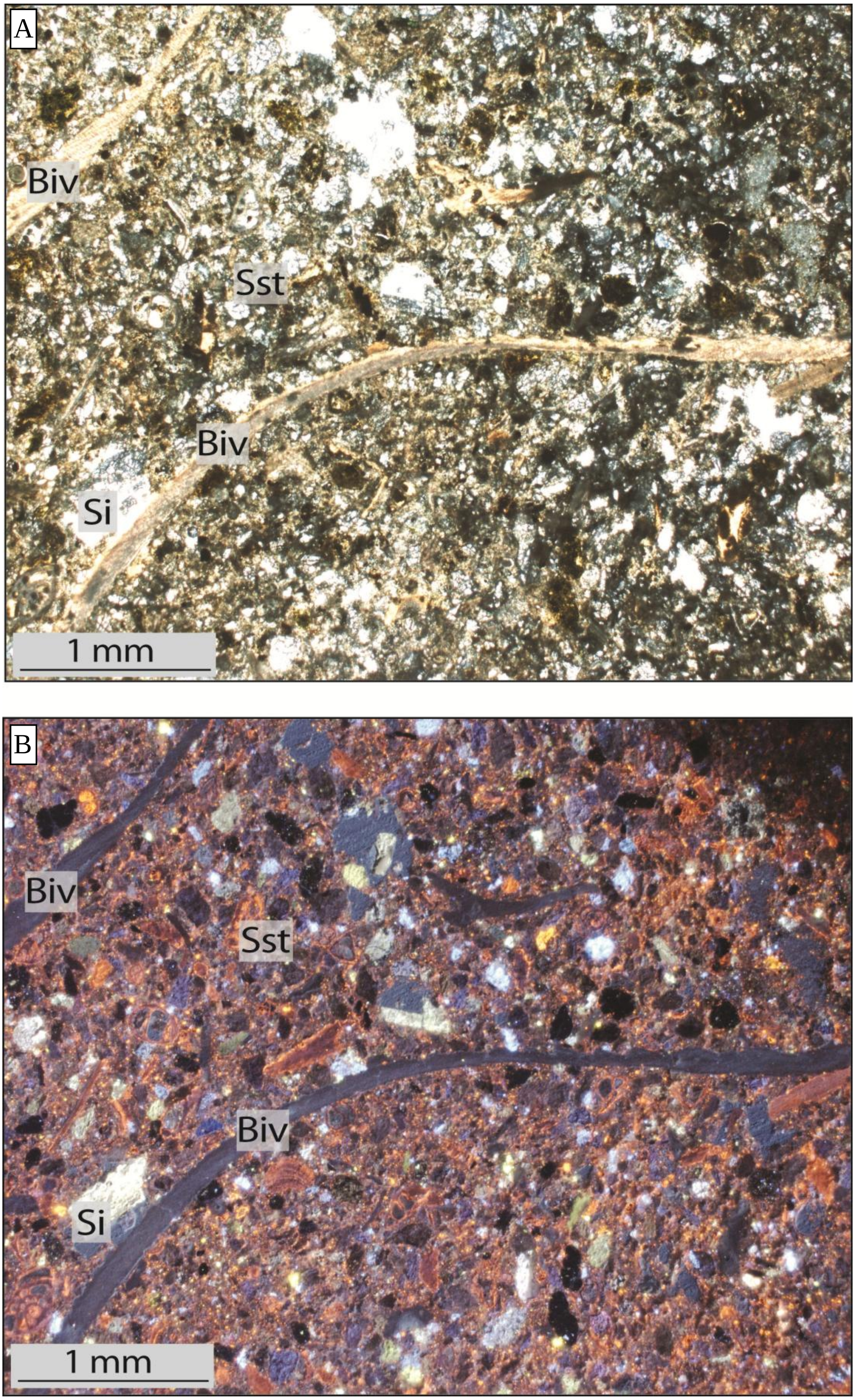


Figure 6.18 – Petrographic image pair from the shelly sandstone in Wairoa Formation C, Ahimanawa Station, west coast, Mahia Peninsula. **(A)** Sample 118.4, a bioclastic arenite, showing a 'dirty' sandstone (Sst) matrix with thin walled bivalve skeletons (Biv). Large siliciclastic grains (Si) are common. PPL. **(B)** Identical image under CL highlighting the bright purple colour of the aragonitic bivalves.

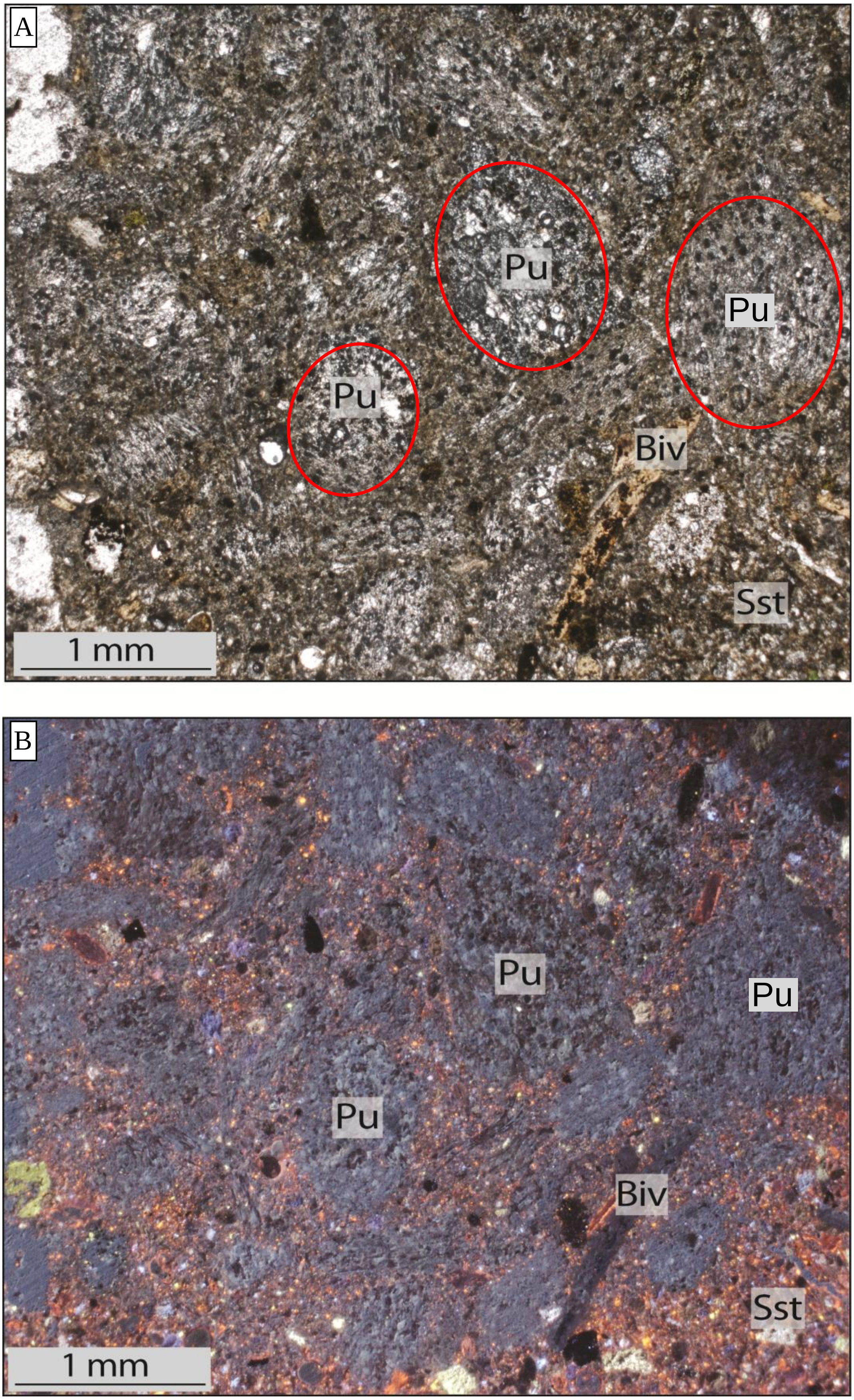


Figure 6.19 – Petrographic image pair from the volcaniclastite unit within the Wairoa Formation C, Ahimanawa Station, west coast, Mahia Peninsula. **(A)** Sample 118.4 showing dominant rounded vesicular pumice (Pu) fragments (some outlined here in red) with rare bivalve fragments (Biv). A hint of the upper contact into sandstone (Sst) is seen. PPL. **(B)** Identical image under CL highlighting the blue to purple colour of the pumice (Pu) and purple colour of the aragonitic bivalve (Biv).

6.3.5 Stable isotope analyses

Table 6.4 presents stable isotope data for the Whakapunake Limestone. Some samples were run twice and thus have two sets of data. Figure 6.20 plots the stable isotope data against its $\delta^{18}O$ and $\delta^{13}C$ values.

Table 6.4 – Stable isotope data of the Whakapunake Limestone.

Bulk sample	Facies	Locality	$\delta^{13}C$	$\delta^{18}O$
106.2	L3	Ahimanawa Station	1.13	0.19
108.2	L3	Ahimanawa Station	1.10	0.27
			1.04	0.27

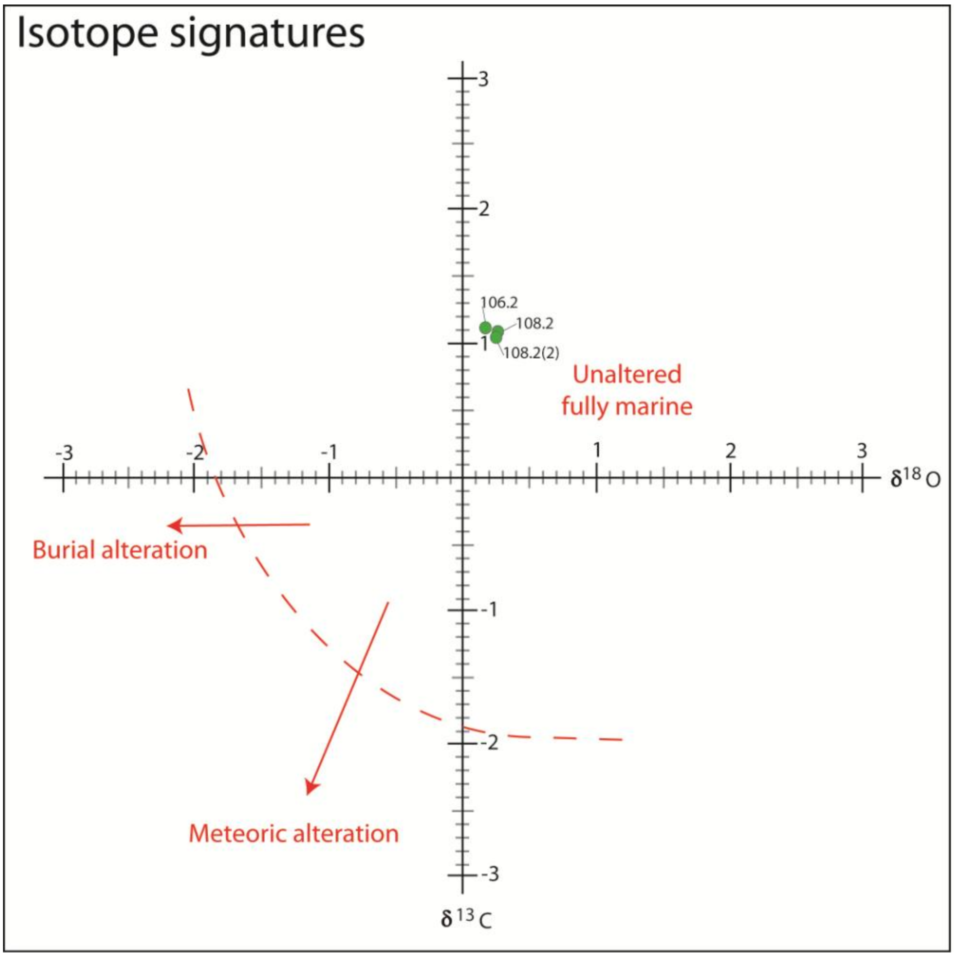


Figure 6.20 –Stable isotope results of the Whakapunake Limestone. Limited sample analysis from the Whakapunake Limestone shows both positive $\delta^{18}O$ and $\delta^{13}C$ values. Boundaries of alteration taken from Nelson & Smith (1996).

Because of the small number of samples sent for analysis, no skeletal powders from the Whakapunake Limestone were analysed. Two samples from Whakapunake Limestone were analysed and came from different beds of lithofacies L3. The Whakapunake Limestone isotope signatures show positive oxygen and carbon values (1.04-1.13 $\delta^{13}C$ and 0.19-0.27 $\delta^{18}O$) (Table 6.4) and plot close together (Figure 6.18).

6.4 INITIAL PALEOENVIRONMENTAL ANALYSIS

The Whakapunake Limestone on Mahia Peninsula results from rhythmic carbonate/siliciclastic shedding from an upthrust antiform system in the vicinity of the northeastern margin of the Pliocene Ruataniwha Strait (Kamp *et al.* 1988; Beu 1995). This is suggested by the carbonate beds having the characteristics of reworked sediment (fractured shells, poor to moderate sorting). Figure 6.19 illustrates the possible depositional setting for the Whakapunake Limestone about an upthrust antiform.

Compared to the Whakapunake Limestone in the Haupatanga Gorge, away to the northwest (Appendix VIII), Mahia Peninsula was influenced by a more significant siliciclastic material input. This also continues into overlying mudstone/sandstone deposits of the Wairoa Formation C on Mahia Peninsula which are otherwise absent in the Haupatanga Gorge, where the Tahaenui Limestone rests unconformably on an eroded surface across the Whakapunake Limestone.

The Whakapunake Limestone hosts common pectinids and barnacles, both of which require nutrient rich waters to survive (Beu 1995; Bland 2001). The carbonate organisms typically show moderate abrasion with some fracturing, and poor to moderate sorting, perhaps as a result of a high energy environment. As a result of high rates of accumulation and deposition during storms, most storm-event beds have characteristic well-preserved skeletons (Brett & Baird 1986). Conversely, because of a higher energy environment, storm emplacements can also have fractured skeletal fragments. The Whakapunake Limestone has some occurrences of intact fossils, usually pectinids, but commonly hosts broken shell material. The disorientation of small bivalves and other shells in the overlying Wairoa Formation C supports the suggestion of a high energy paleoenvironment.

The Whakapunake Limestone hosts siliciclastic grains that vary from subangular to subrounded and are well sorted. Good sorting can indicate a period of sediment working and/or an extended period of settling. Due to the resistance of quartz to physical weathering, the subangular to subrounded shape of the siliciclastic grains shows these sediments have been reworked for an extended period of time.

Sediment sourcing could be from the distant greywacke basement rock, from the northern Wairoa area where shore connected shoaling was occurring or perhaps more likely from shoaling occurring in the small 'Mahia Seaway' in the position of what is now the small isthmus connecting Mahia Peninsula to the mainland (see Figure 8.5 A).

Limestone interbedded with sandstone units can identify cyclic storm emplacements, or repeated sea level ups and downs, increasing the accumulation of siliciclastic material or carbonates. The elongated lenses/clasts of mudstone within the Whakapunake Limestone succession do illustrate periodic changes in the sedimentation patterns. These mudstone clasts are an oddity and their origin is problematic. Listed and discussed below are some possible options for the deposition of the mudclasts and the alternating limestone-sandstone beds. Despite these suggestions, none are concluded upon here.

Explanations for rhythmic bedding

- Tempestite storm deposits – with the mudclast-bearing shelly sandstone facies being the 'normal' sedimentation pattern in the environment, interrupted with pulses of carbonate shed from atop a neighbouring antiform during storm emplacement. During a storm event carbonate sediment can be shed, to a greater extent, from the antiforms to reach laterally into the otherwise siliciclastic dominated environments.
- Sea level fluctuations – Tectonic or glacial derived sea level fluctuations would affect the pattern of sedimentation between siliciclastic dominated and bioclastic dominated. The rhythmic units would imply a regular pattern of change, perhaps influenced by Milankovitch cycles (discussed further in section 9.3.1.3).
- Spring/neap tide deposits (Longhitano 2010) - During a spring tide when water levels are particularly high, the siliciclastic bed is deposited. When the sun and moon positions change, and a neap tide is caused, the sea level lowers, allowing dominant carbonate deposition. This process has resulted in alternating bioclastic-

siliciclastic deposits each up to 10 cm thick in Italy (Longhitano 2010). If this was also the case on Mahia Peninsula it would indicate an extremely rapid deposition rate of up to c.100 cm per 7 days (given that a spring/neap tide cycle occurs twice a month and deposits are up to 100 cm thick). Such high deposition rates are considered unlikely.

Explanations for mudclast origin

- Rip-up and redeposited clasts – unlikely as such a regularly oriented tubular nature would not be expected in rip-up clasts
- Rhythmic influxes of muddy material during storm events.
- Burrowing activity – The deep vertical burrowing activity of most likely shrimp-like organisms (e.g. *Skolithos/Ophiomorpha* traces) which prefer sandy to semi-consolidated substrates with high energy conditions and are associated with intertidal to subtidal environments (Collinson & Thompson 1982; Boggs 2006). *Skolithos/Ophiomorpha* typically burrow vertically downward, but can veer on an angle. A problem with this theory is that the mudclasts are highly irregular, can have ‘shredded’ geometries and some can be very small (1-2 cm) (Figure 6.4 D).
- Rhythmic slack/active currents like dune foresets. This however poses two problems. The first is that the sandy beds (lithofacies S4) are divorced from the carbonate beds (lithofacies L3), and does not explain any relationship with the carbonate beds. The second is that there is no lateral continuity that would be expected in dune geometry. If original dune structures with lateral continuity were present, their continuity may have been destroyed by seismic shaking, causing water to percolate and result in the muds grouping together.
- Seismic shaking and liquefaction could have had an effect on the clasts and ‘blur’ their boundaries (Demicco & Hardie 1994).

A further explanation for the alternating siliciclastic-bioclastic beds and the presence of mudclasts includes the carbonate beds resulting from a high energy environment, deposited with broken and whole shells with a considerable amount of siliciclastic material. The shelly sandstone that follows would also be deposited as a result of this high energy environment, with partial lithification occurring before intensive burrowing. After a period of quiescence with settling muds infilling the burrows, the high energy conditions return, starting the deposition of a mixed bioclastic-siliciclastic carbonate again.

Whatever the cause, catastrophic and tectonic-influenced sedimentation is clearly evident, with a complex depositional history.

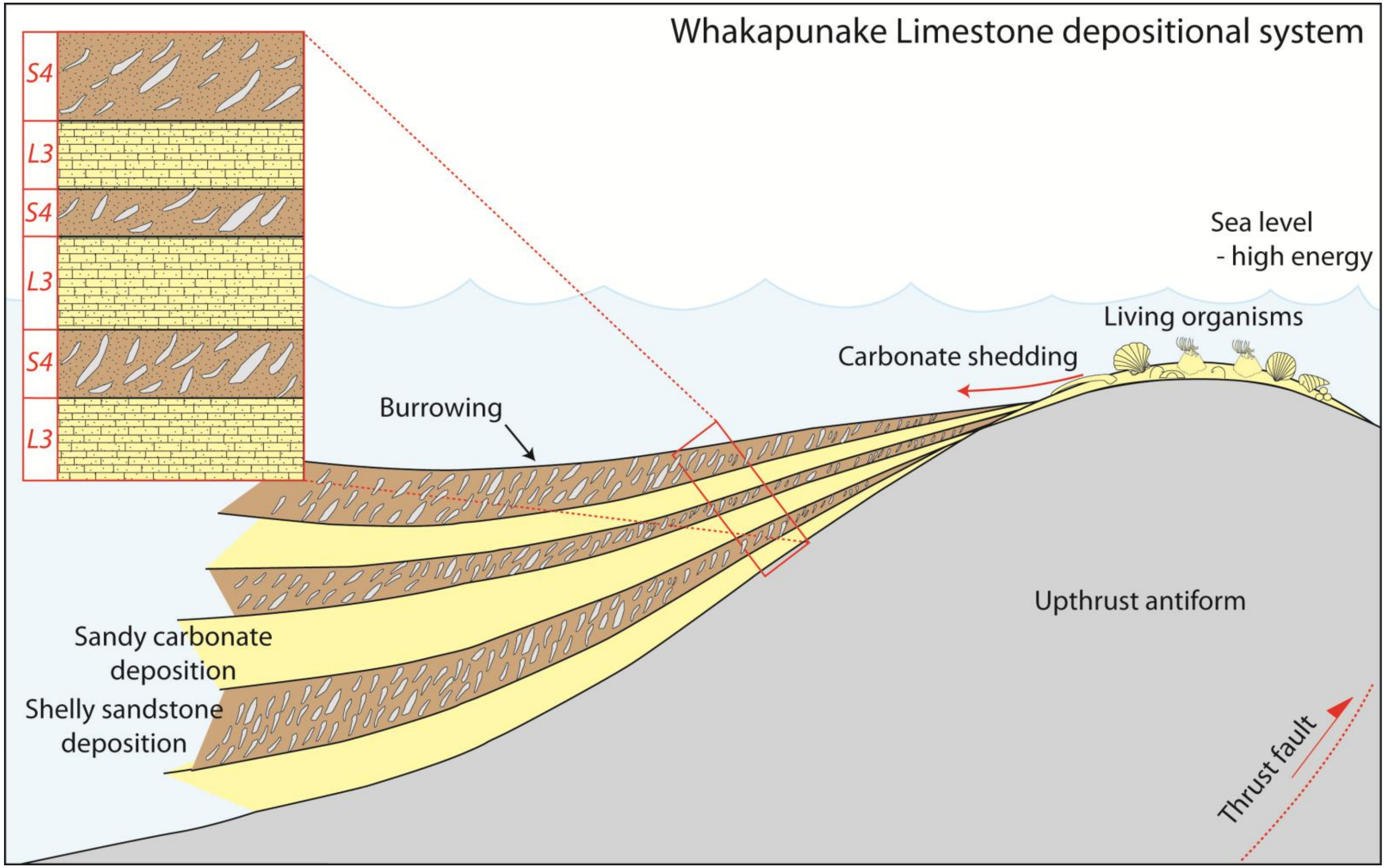


Figure 6.21 – Depositional system for the Whakapunake Limestone. Limestone beds are dominated by carbonate shedding from the tops of the antiform onto the flanks. The sandy beds are likely a result of storm emplacement, followed by partial lithification and subsequent burrowing. Lithofacies are highlighted in red. Vertically exaggerated for clarity, with no scale implied.

Chapter Seven – Tahaenui Limestone

Previous Page – The Tahaenui Limestone at Clonkeen Quarry, Mangaone Road, Nuhaka area.

7.1 LITHOSTRATIGRAPHY

The Tahaenui Limestone, of late Pliocene (Waipipian) age (Appendix I, Beu (1995)) crops out widely throughout the study area, within the Nuhaka Syncline, at Mt Moumoukai and on Mahia Peninsula (Figure 7.1). The type locality for the Tahaenui Limestone is at the Tahaenui Quarry (BH42/036700), Kokohu Road, 6 km west of Nuhaka, where the limestone is up to c.40 m thick. A reference section (BH41/942852) is designated further north, near the end of Kotare Road, approximately 7 km east of Marumaru (Appendix VIII) (Beu 1995).

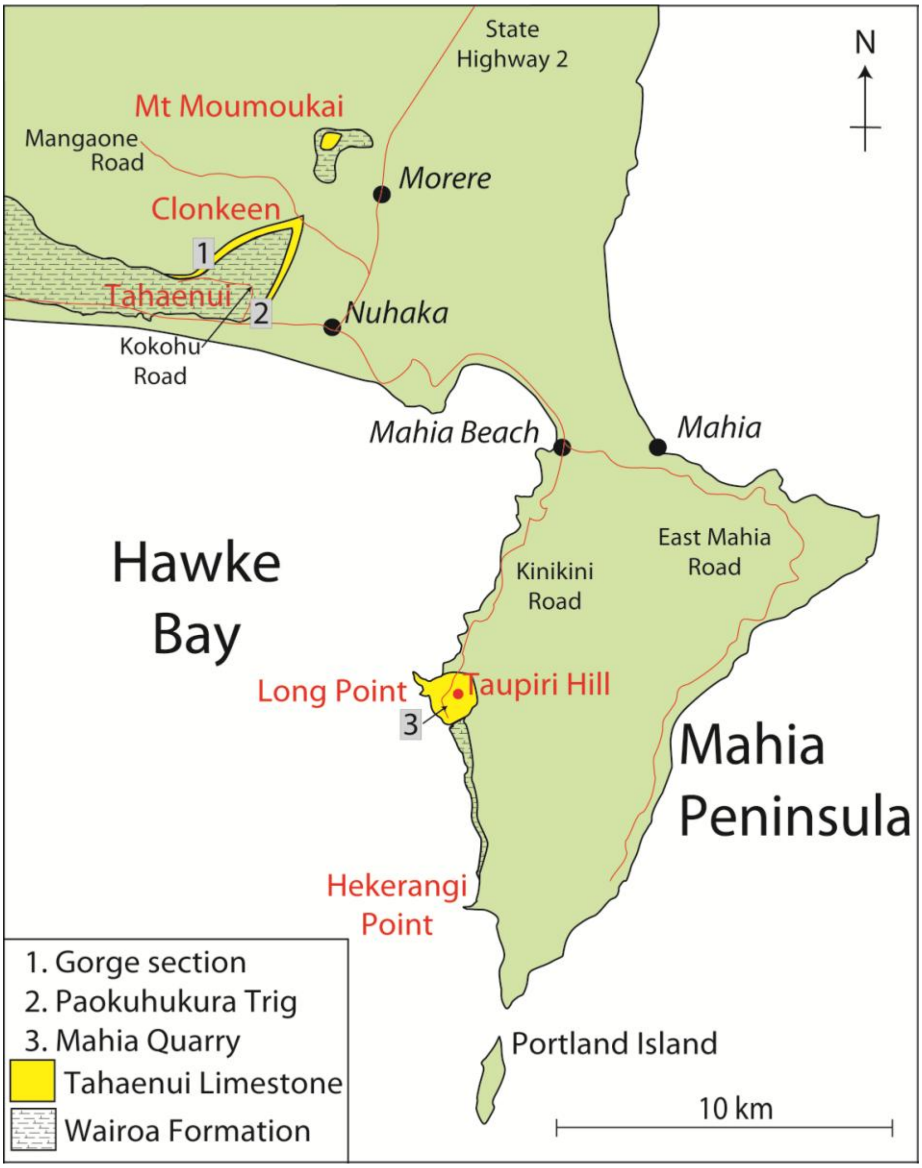


Figure 7.1 – Distribution of the Tahaenui Limestone and Wairoa Formation in the study area. Names of stations, streams and features referred to in this chapter are located on the map.

Tahaenui/Clonkeen

The Tahaenui Limestone in the Tahaenui/Clonkeen area occurs within the Nuhaka Syncline (Figure 7.2, 7.4, 7.5). It shows variable thickness, ranging from c.40 m at Tahaenui Quarry to c.10 m on the southeastern limb of the syncline. The limestone is moderately indurated, vaguely planar or horizontally bedded, cream coloured and hosts a barnacle dominated skeletal matrix. Within the lower part of the unit, the limestone can appear quite crystalline and very indurated, with individual bioclasts indeterminate. Very common pectinids (7-10 cm) (Figure 7.4 B) and brachiopods (3-4 cm), and occasional oysters, form shell beds, exposed well in a gorge cutting through the limestone at Tahaenui (Figure 7.4 C, D, E), (Figure 7.3, Stratigraphic column 2, Appendix VII). These shells are typically convex upward in orientation. Siliciclastic material is generally rare. Weathering can produce lapiez fluting on exposed top surfaces (Figure 7.5 C). The syncline is asymmetrical, with the western limb dipping at c.10-50˚southeast (Figure 7.4 A) and the eastern limb at c.10-30˚northwest. Three cores taken from Clonkeen Quarry (Figure 7.5 A) show a continuous cream coloured limestone. Drilling and limestone reached a below ground depth of at least 37.5 m (Francis 2005).

A large 30 cm spleleothem was found in quarry workings at the Clonkeen Quarry (BH42/091738), which demonstrates the existence of an established or former cave system. The Mangaone Caves Scenic Reserve occur c.500 m from the Clonkeen Quarry, and consists of one dry cave and numerous sinkholes (Figure 7.5 B, D).

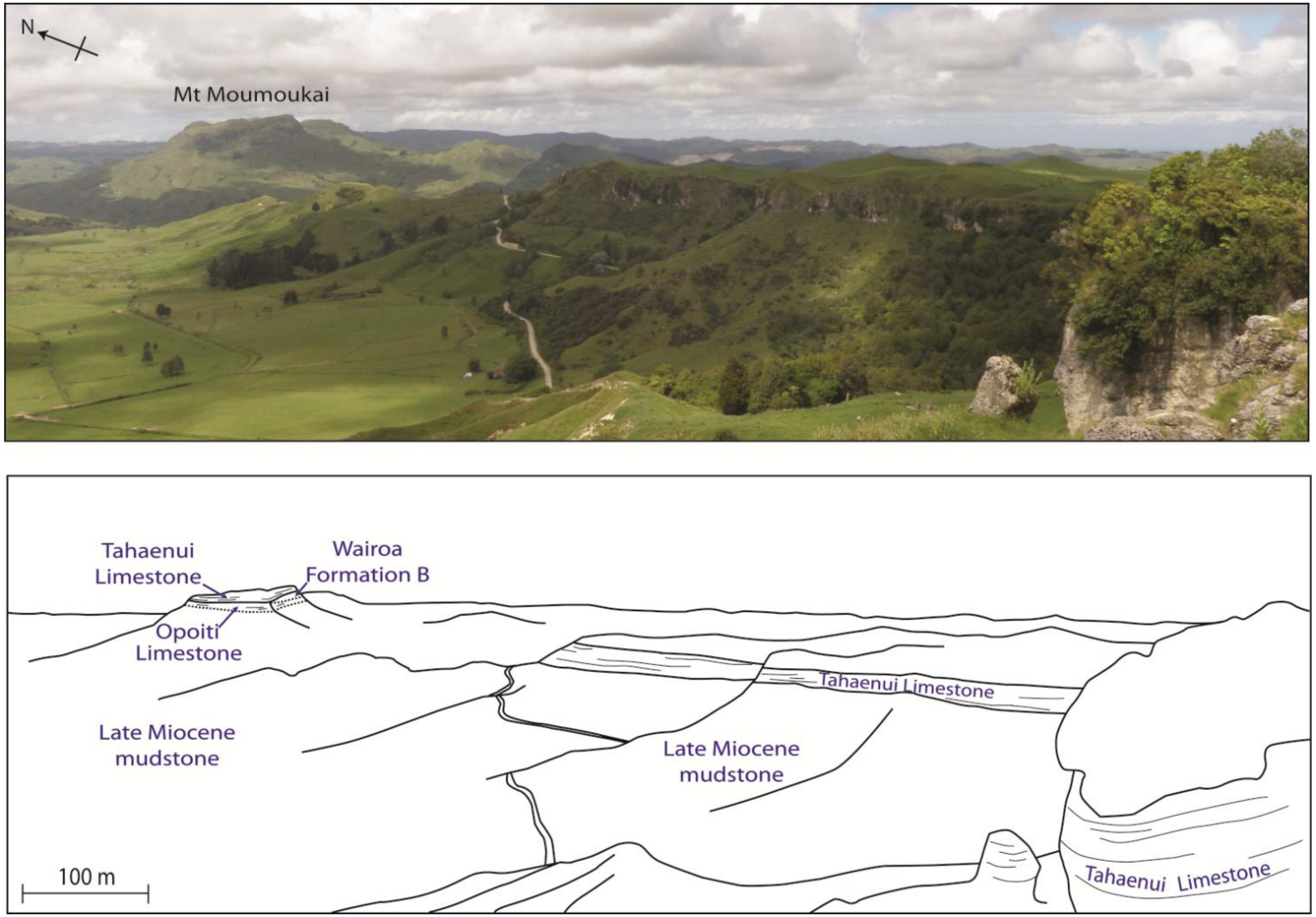


Figure 7.2 – The Tahaenui Limestone forming the western flank of the Nuhaka Syncline and as a cap on Mt Moumoukai in the distance. Note scale is only approximate as the actual distance changes with perspective.

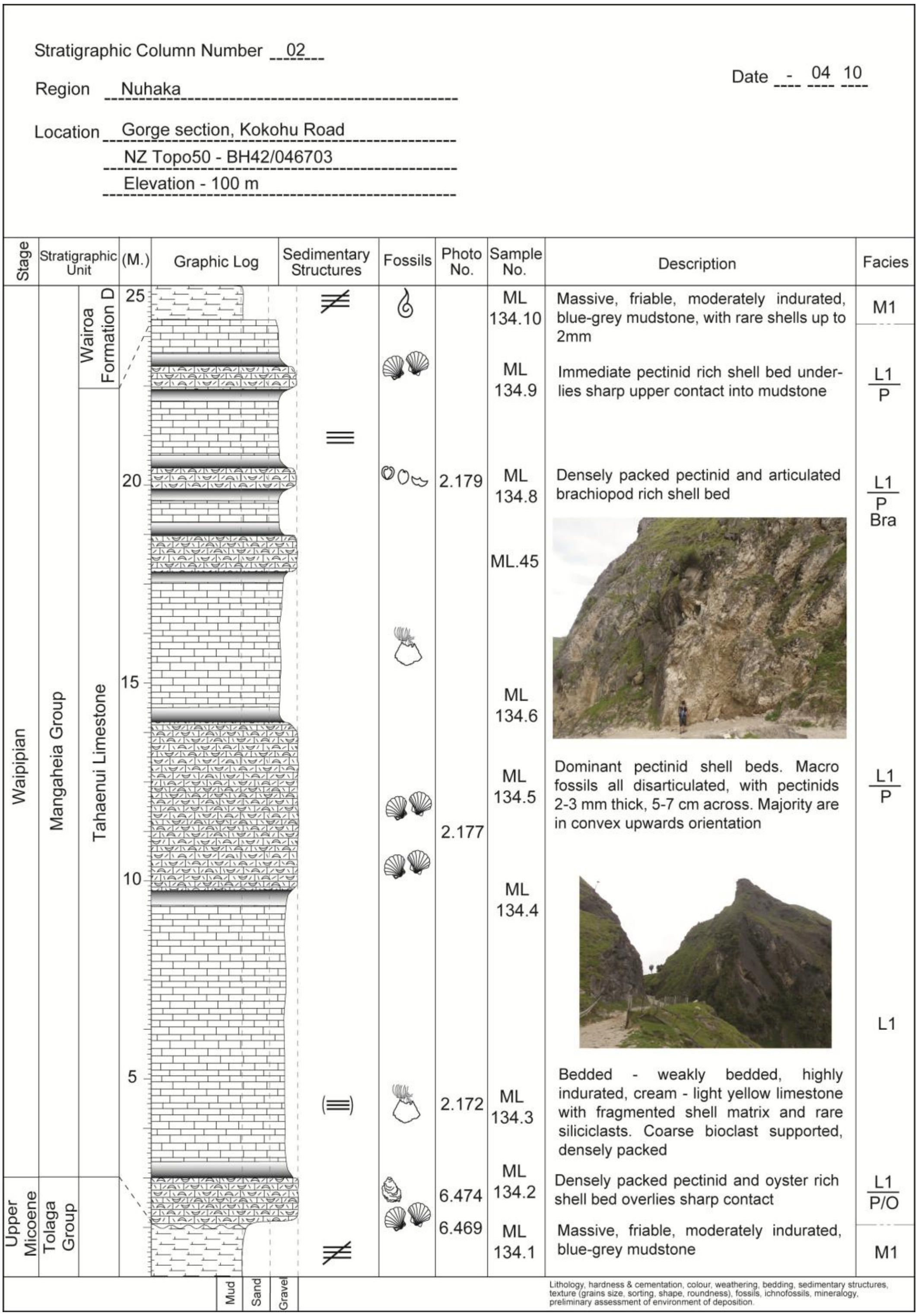


Figure 7.3 –Stratigraphic column of the Tahaenui Limestone at the Gorge section, Kokohu Road, Tahaenui/Clonkeen.

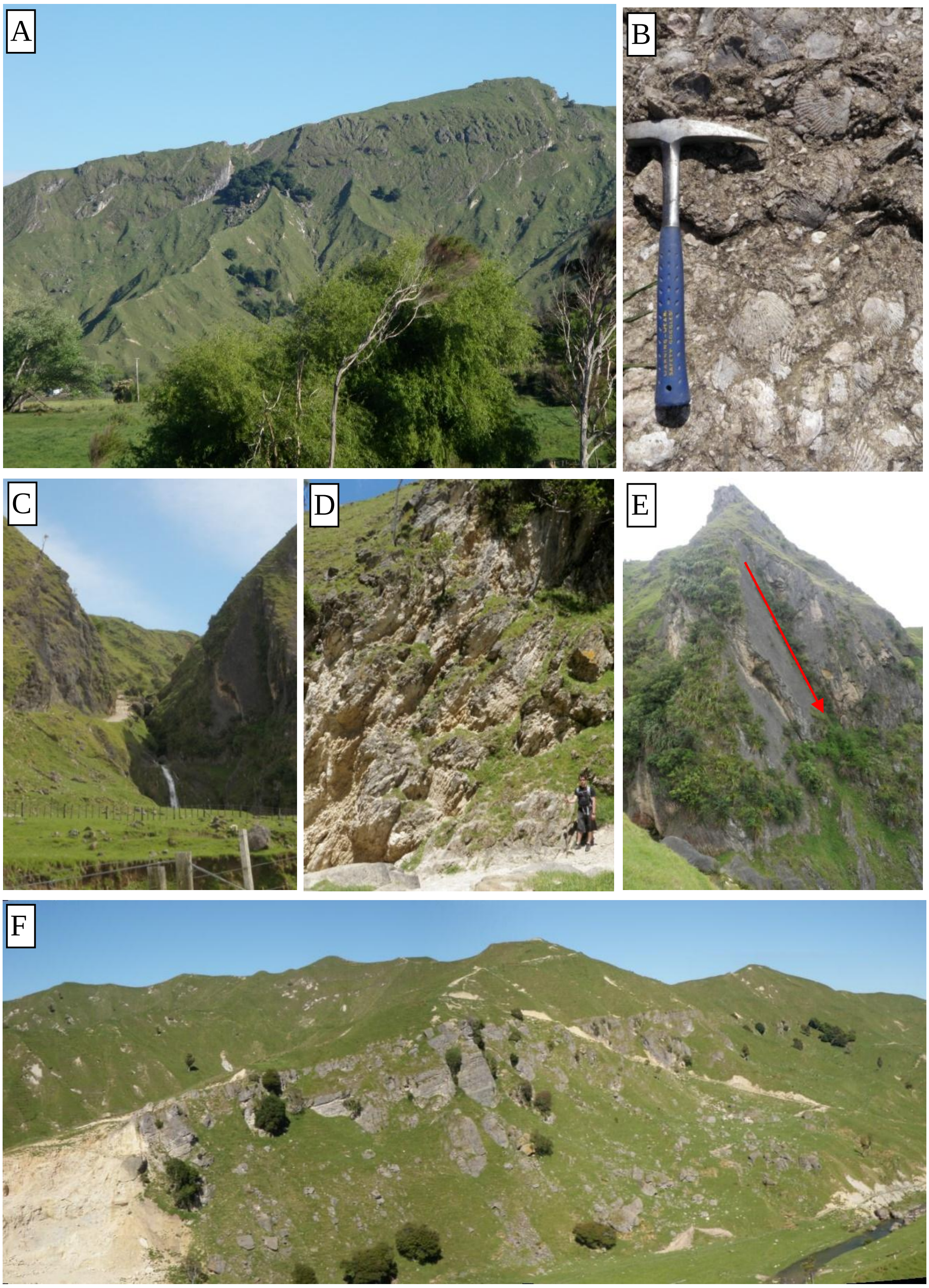


Figure 7.4- Field photographs of the Tahaenui Limestone in the Tahaenui area, Kokohu Road. **(A)** The Tahaenui Limestone dips steeply (c.50˚S) as evident in the steep topography of these hills. Sharp ridged frontal hills are the overlying mudstone (Wairoa Formation D). **(B)** The limestone here is heavily populated with broken pectinid specimens up to 12 cm in size. **(C)** A gorge cutting through the Tahaenui Limestone, that exposes an excellent cross section throughout the limestone as well as the underlying (Wairoa Formation C) and overlying (Wairoa Formation D) mudstones. Kokohu Road. **(D)** The west side of the gorge cutting, which exposes numerous shell beds of pectinids and brachiopods. **(E)** A flat surface (shown by red arrow) of the Tahaenui Limestone on the east side of the gorge cutting, illustrating the exceptionally steep dip. **(F)** The Tahaenui Limestone forms a bluff near the Tahaenui Quarry (bottom left). Here the limestone dips c.30˚S, is up to 40 m thick and is vaguely bedded. The Tahaenui River (origin of name for the limestone) is visible at bottom right. *Hammer - 32 cm long,*

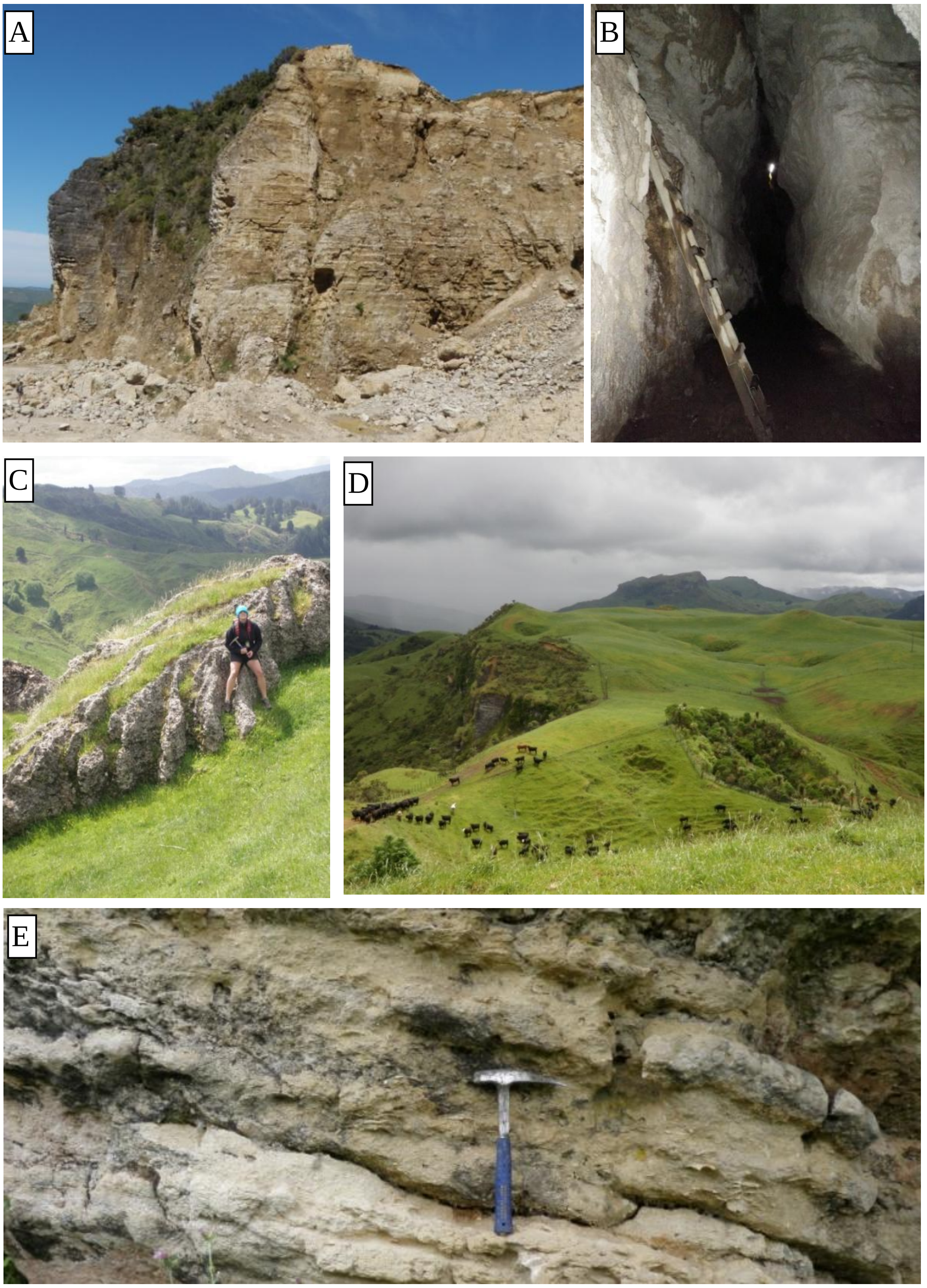


Figure 7.5 – Field photographs of the Tahaenui Limestone in the Clonkeen area, Mangaone Road. **(A)** The intermittently worked Clonkeen Quarry, Mangaone Road, exposes c.20 m of vaguely bedded Tahaenui Limestone. **(B)** Formed dry cave at the Mangaone Caves Scenic Reserve, Mangaone Road, within the Tahaenui Limestone. **(C)** Lapiez weathering within the Tahaenui Limestone, west of Clonkeen Quarry. **(D)** View towards the north from a plateau formed by the Tahaenui Limestone (grassed area). Numerous sinkholes and associated hummocky surface indicate an established cave system in the subsurface. Mt Moumoukai is visible in the northern distance. **(E)** Close up view of the Tahaenui Limestone as it outcrops west of Clonkeen Quarry. Here the limestone is well bedded with several thin shell beds. *Hammer - 32 cm long,*

Mt Moumoukai

The Tahaenui Limestone at Mt Moumoukai, in the Nuhaka Syncline, unconformably onlaps the Opoiti Limestone and associated sandstone (Wairoa Formation B) (Figure 7.6). The Tahaenui Limestone here consists of a c.10 m thick, massive to vaguely bedded (Figure 7.7, 7.8 E), indurated, very sandy limestone with a skeletal matrix (Figure 7.8 F) and scattered populations of pectinids up to 5 cm size. Rare rounded mudstone clasts (c.5 mm size) are visible in the upper stratigraphy. The limestone forms vertical bluffs around the majority of Mt Moumoukai (Figure 7.8 A) which also form valleys on the summit plateau (Figure 7.8 C). Weathering has resulted in a hummocky topography with numerous sinkholes and common vertical lapiez fluting of outcrops (Figure 7.8 B, D).

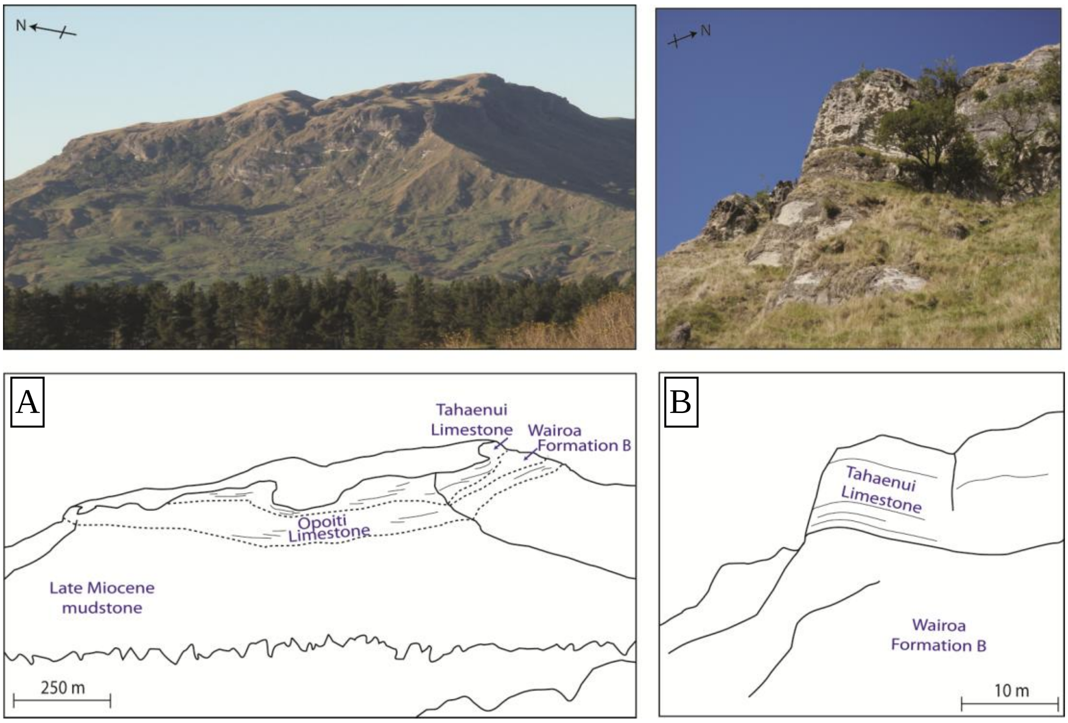


Figure 7.6 – The Tahaenui Limestone as it crops out at Mt Moumoukai. **(A)** The southwest flank of Mt Moumoukai showing both the Opoiti Limestone and the overlying Tahaenui Limestone. **(B)** The northeast side of Mt Moumoukai showing the contact zone between the Tahaenui Limestone and underlying Wairoa Formation B. Note scale is only approximate as the actual distance changes with perspective.

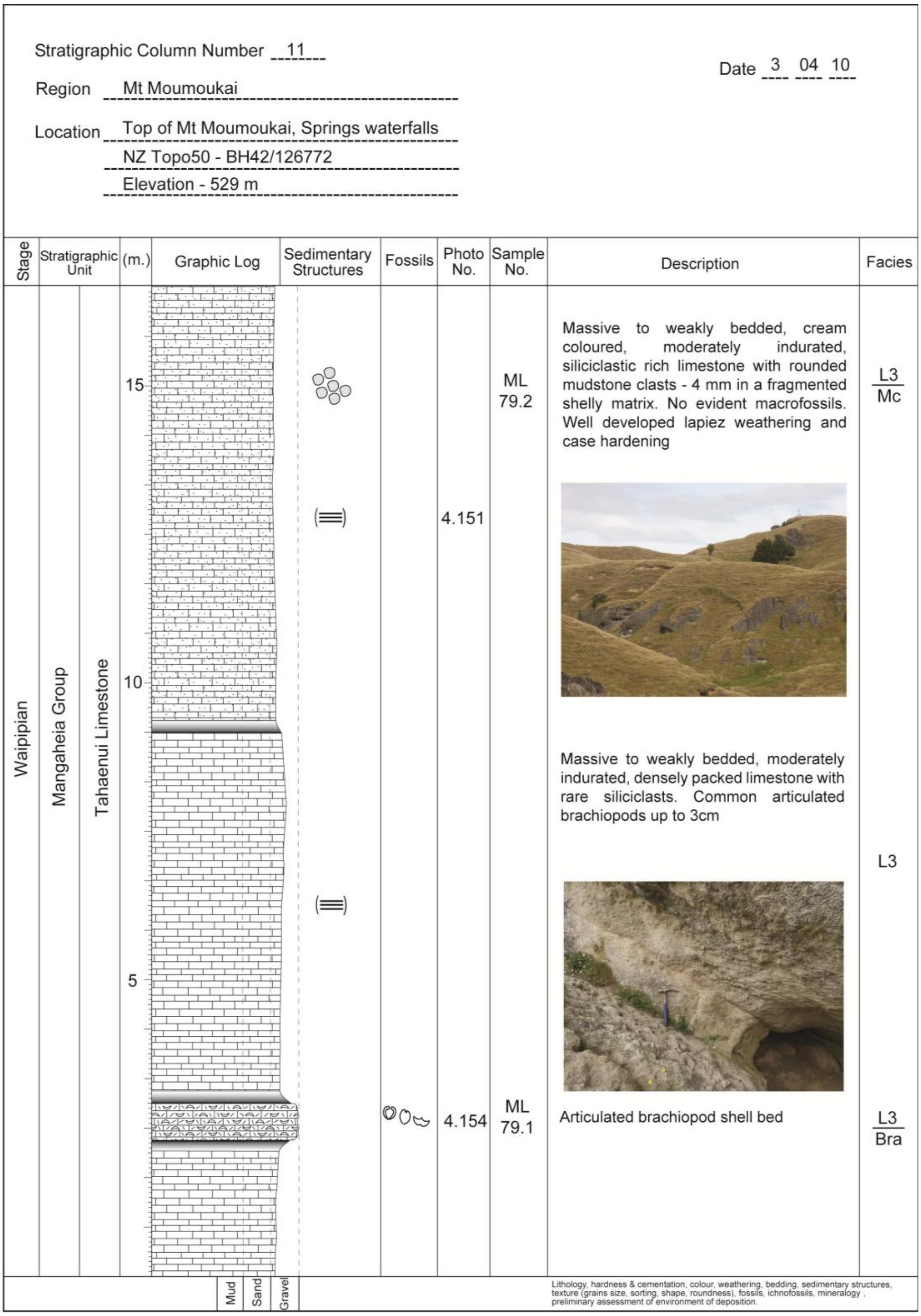


Figure 7.7 – Stratigraphic column of the Tahaenui Limestone, Mt Moumoukai plateau.

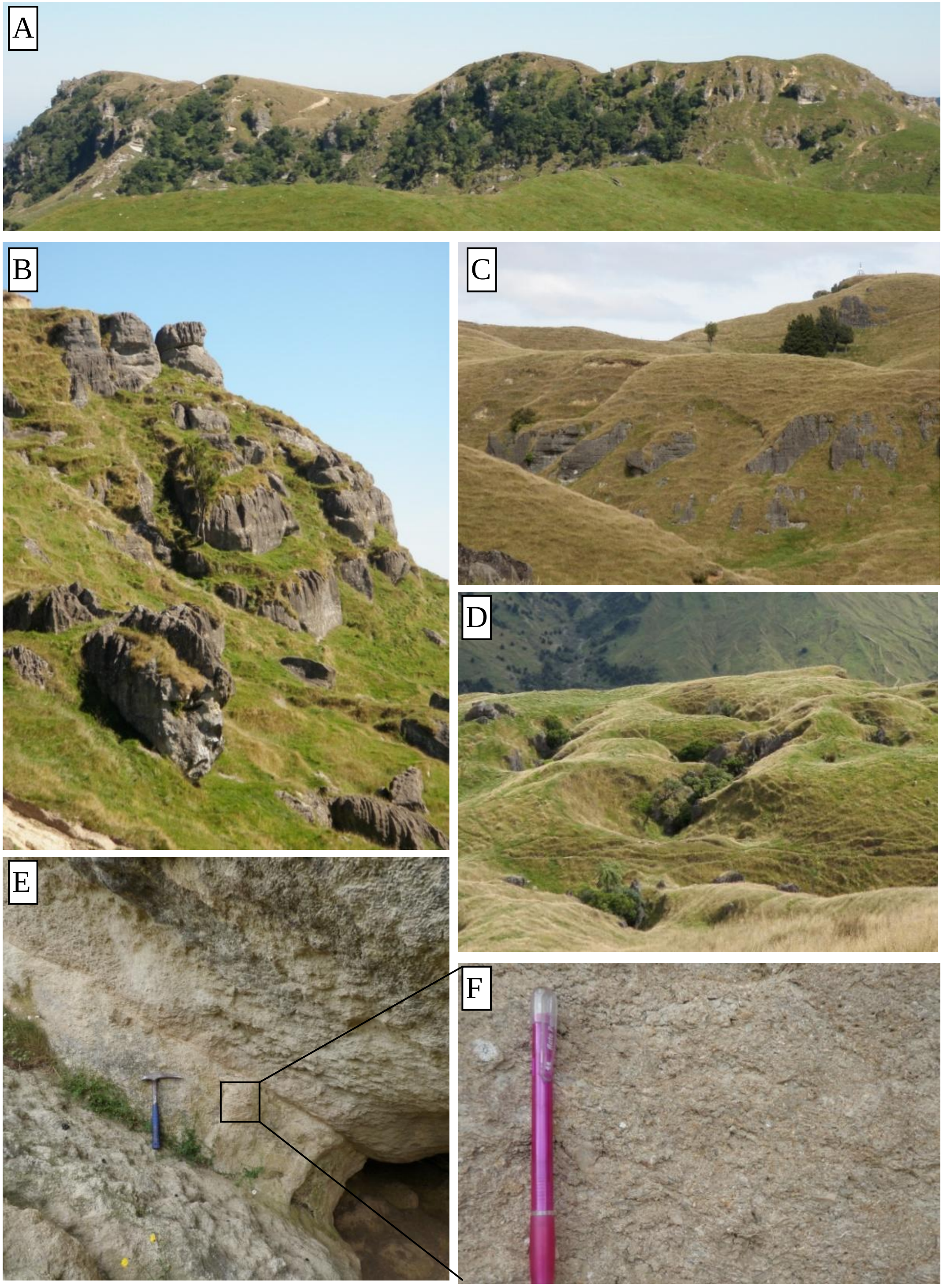


Figure 7.8 – Field photographs of the Tahaenui Limestone at Mt Moumoukai. **(A)** View towards the southwest showing the northern face of Mt Moumoukai where the Tahaenui Limestone forms the top plateau. Highest point is 611 m asl. **(B)** Lapiez weathering within the Tahaenui Limestone on the northern face of Mt Moumoukai. **(C)** The top plateau area of Mt Moumoukai exposing Tahaenui Limestone as a thick unit. **(D)** The eastern area of Mt Moumoukai's top plateau with surface topography significantly affected by numerous sinkholes and hummocky terrain, indicative of an established cave system in the subsurface. **(E** and **F)** Massive, highly indurated Tahaenui Limestone atop Mt Moumoukai. *Hammer - 32 cm long, pencil - 0.8 cm wide.*

Mahia Peninsula

The Tahaenui Limestone is well exposed at Taupiri Hill (BJ43/186544) and on Long Point (BJ43/166543), Mahia Peninsula (Figure 7.9, 7.10 - Stratigraphic column 17, also in Appendix VII). At Taupiri Hill, the c.60 m thick limestone is cream coloured and very soft, with some case hardening of external limestone surfaces (Figure 7.11 A, B). The componentry consists mainly of densely packed barnacle plates (4-5 mm size), aligned parallel to one another and to the dip of the unit. Porosity seems high from the visibly evident pore space. The limestone is massive to vaguely horizontal bedded, dipping to the west at approximately 15°. Siliciclasts are usually rare. The Mahia Quarry (Figure 7.11 D) on Kinikini Road (BJ43/178538) (Figure 7.1) gives excellent exposure of fresh Tahaenui Limestone, where it is massive, very soft and white coloured. Tahaenui Limestone continues from Taupiri Hill out to the east to form the Long Point promontory (Figure 7.11 E). This is a stratigraphically lower portion of the limestone, where the underlying late Miocene mudstone can be seen in cliff outcrop. A thickness of c.10 m of Tahaenui Limestone occurs here and it includes very common macrofossils, including brachiopods up to 3 cm and pectinids up to 7 cm in size. The matrix hosts abundant barnacle plates and some siliciclastic material. In some places on Long Point the limestone shows case hardening due to the exposed nature of the outcrop and susceptibility to meteoric weathering (Figure 7.11 C). South of Long Point, the limestone thickens to 30-40 m and contains more siliciclasts and fewer macrofossils, the largest found being 4 cm in size.

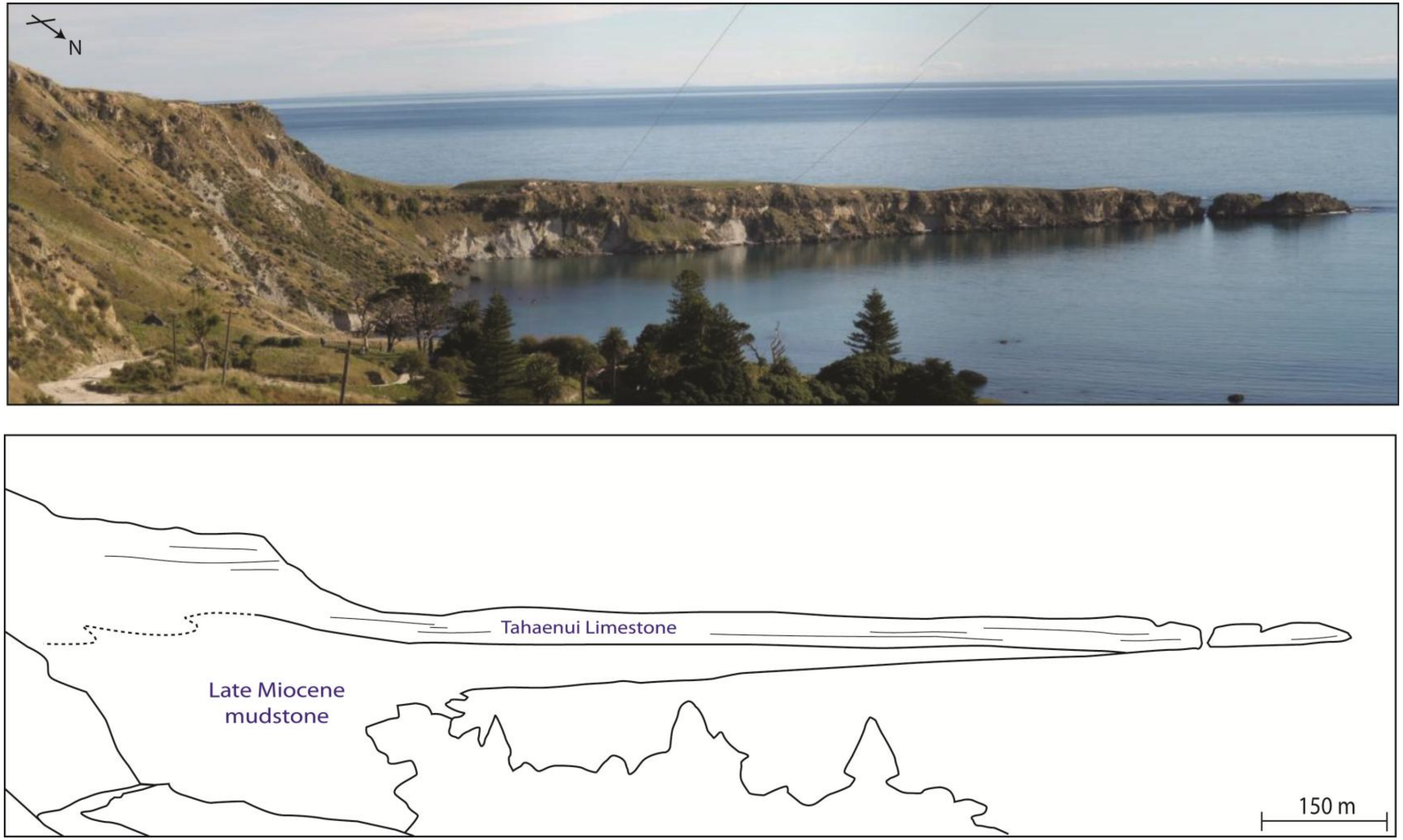


Figure 7.9 – The Tahaenui Limestone, and underlying late Miocene mudstone, form the Long Point promontory, west coast, Mahia Peninsula. To the left (east) are the lower slopes of Taupiri Hill. Note scale is only approximate as the actual distance changes with perspective.

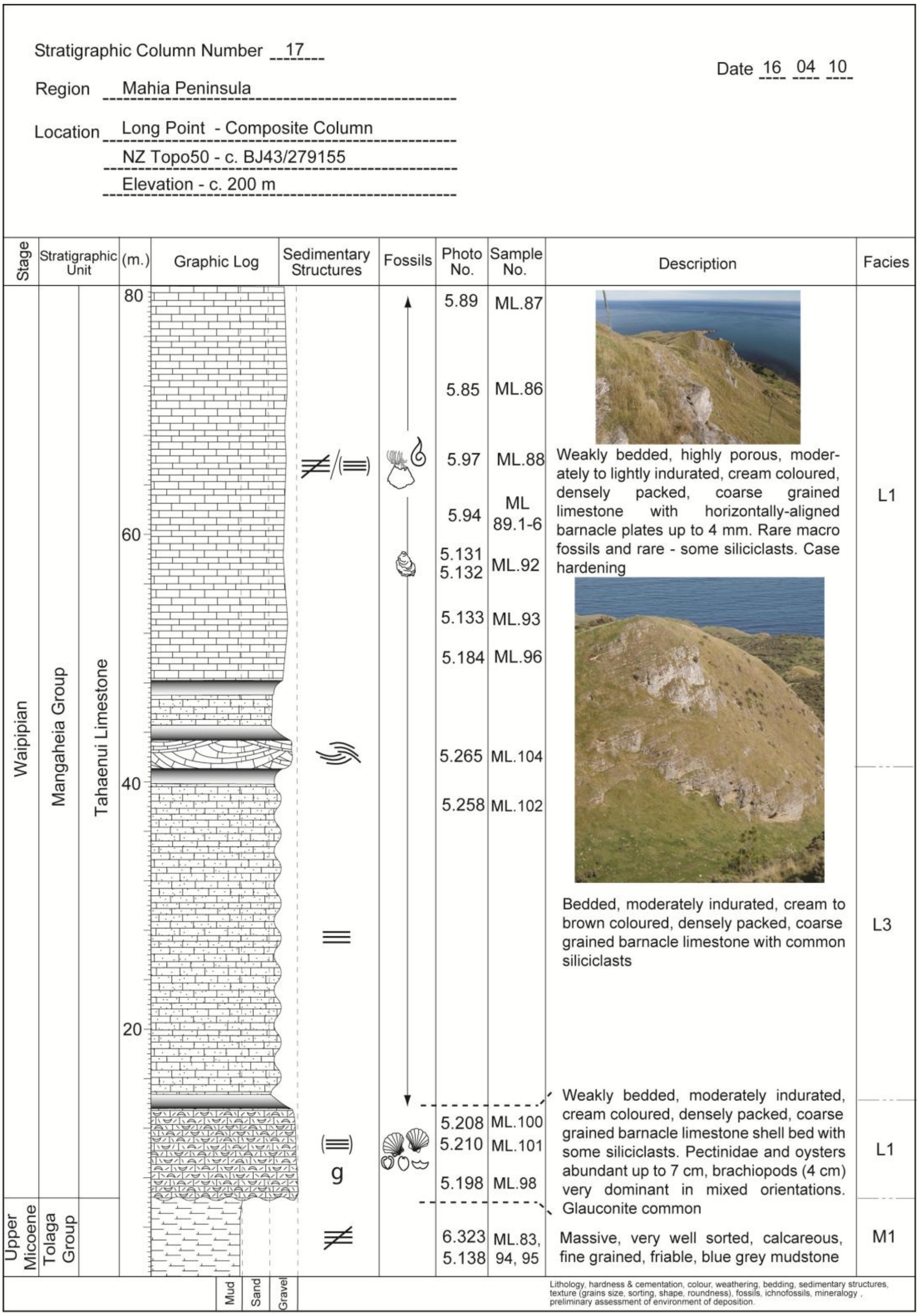


Figure 7.10 – Stratigraphic column of the Tahaenui Limestone, Long Point, west Mahia Peninsula.

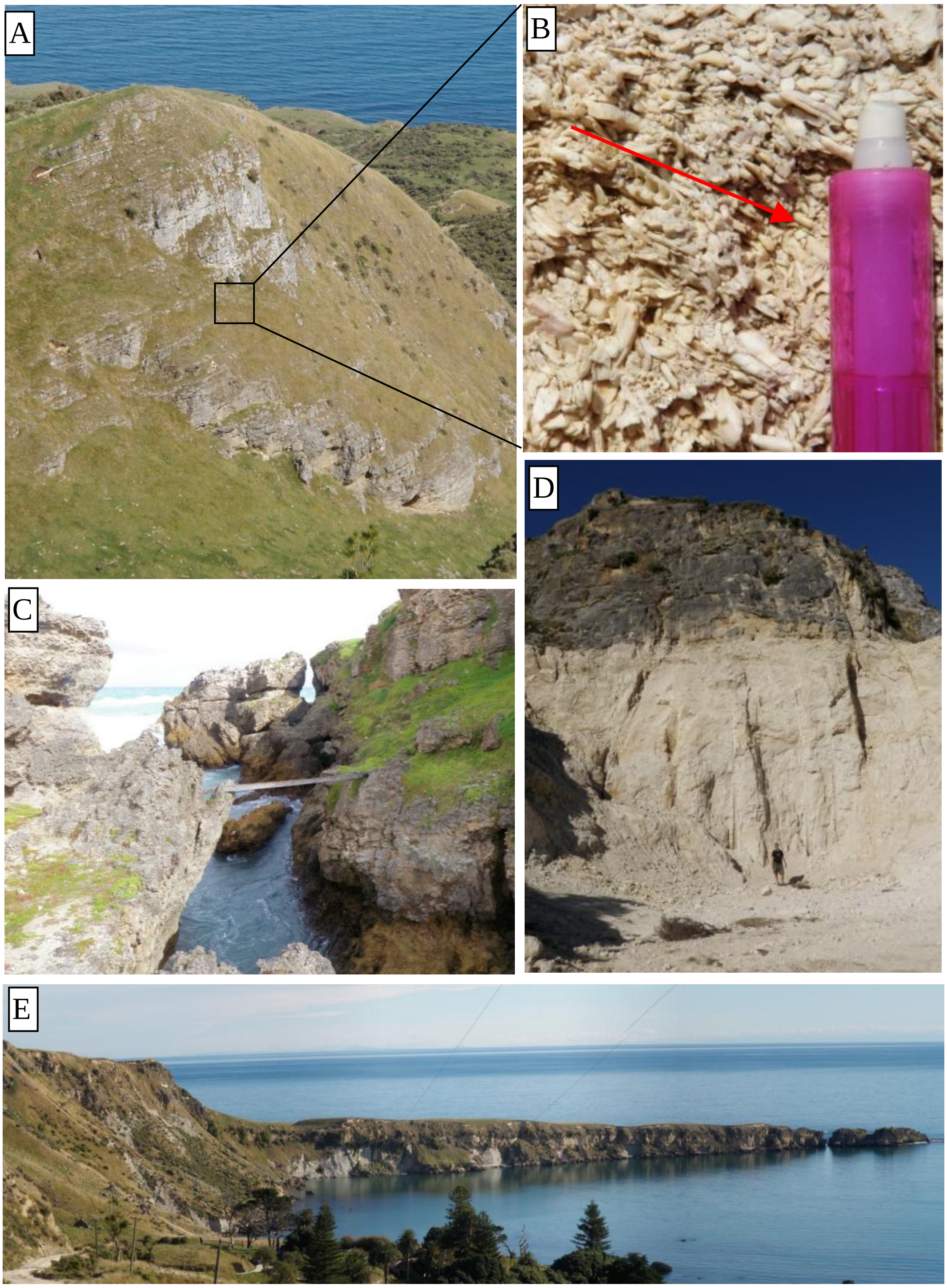


Figure 7.11 – Field photographs of the Tahaenui Limestone on the west coast, Mahia Peninsula. **(A)** Westwards view of a thick section of Tahaenui Limestone outcrop inland from Long Point (c.10˚SW). The barnacle composition here is very high. **(B)** Close up view of barnacle rich pure Tahaenui Limestone. Note how the barnacle fragments are generally aligned parallel with one another, in the direction of the geological dip (c.10°SW) (highlighted by red arrow). **(C)** The end tip of Long Point exposing rugged weathered outcrops of the Tahaenui Limestone. **(D)** A c.20 m thick outcrop of very pure, barnacle dominated Tahaenui Limestone is intermittently quarried here, Kinikini Road. The change from case hardened (dark grey) limestone at the top to freshly exposed (white) limestone at the bottom is striking. **(E)** The Tahaenui Limestone forms the Long Point promontory and continues towards the east (left) upwards into Taupiri Hill. *Pencil - 0.8 cm wide.*

7.1.1 Contacts

In the Tahaenui/Clonkeen area, the Tahaenui Limestone unconformably overlies late Miocene mudstone (Beu *et al.* 1980; Francis 1993b; Mazengarb & Speden 2000), which is seen at several locations (e.g. BH42/045706, BH42/052712, BH42/075692, BH42/046704, BH42/093731, BH42/086735 (Figure 7.12 A) and BH42/079729). Older Miocene flysch is visible underlying the mudstone at Tahaenui. The overlying Pliocene mudstone (Wairoa Formation D) is common in the southern portion of the Nuhaka Syncline (Figure 7.12 B), with the upper contact of the Tahaenui Limestone directly visible only in one location on Clonkeen Station (BH42/093730). Here the limestone sharply to gradually transitions into shelly sandstone (over an interval of c.1 m). This in turn grades to a shelly mudstone (Figure 7.12D) and eventually a pure mudstone. A pumiceous volcaniclastic unit (1 m thick) occurs within this last mudstone, with sharp lower and upper contacts. Continuations of this volcaniclastic unit are seen in several places near State Highway 2 (Figure 7.12 C). At Paokuhukura Trig (Figure 7.1) a massive, shelly sandstone crops out (Figure 7.12 E), and is likely a southern extent of the shelly sandstone at Clonkeen. This entire succession above the Tahaenui Limestone is referred to the Wairoa Formation D, and it is conformable with the underlying limestone (Figure 7.10) (Ian R Brown Associates 1998).

Another upper contact of the Tahaenui Limestone is observed c.1 km northwest of Tahaenui Quarry (BH42/031701). However, here the upper contact into mudstone is hidden by a 3 m interval of grassy slope. The top surface of the Tahaenui Limestone here has been weathered sufficiently to produce a vertical cave, suggesting that meteoric waters have managed to seep in through the boundary zone between the mudstone and the limestone.

The northeast flank of Mt Moumoukai (BH42/131774) exposes the Tahaenui Limestone resting sharply on underlying sandstone (Wairoa Formation B) (Figure 7.13). However, the western flank (BH42/124769) shows the lower contact of the Tahaenui Limestone to be unconformably onlapping the Opoiti Limestone at a shallow angle (Beu 1995). No upper contacts are present at Mt Moumoukai because the Tahaenui Limestone alone caps the hill.

On Mahia Peninsula, the lower contact of the Tahaenui Limestone upon late Miocene mudstone is visible along the north side of Long Point (BJ43/169537) (Figure 7.14 A), but it is not accessible. Near Kinikini Road (BJ43/179547) the same underlying mudstone occurs, but no direct contact is seen (Figure 7.14 B).

Upper contacts of the Tahaenui Limestone with overlying Pliocene deposits are absent on Mahia Peninsula. However, at Long Point an erosional surface atop the Tahaenui Limestone is now covered by Pleistocene sands and gravels (Figure 7.14 C, D).

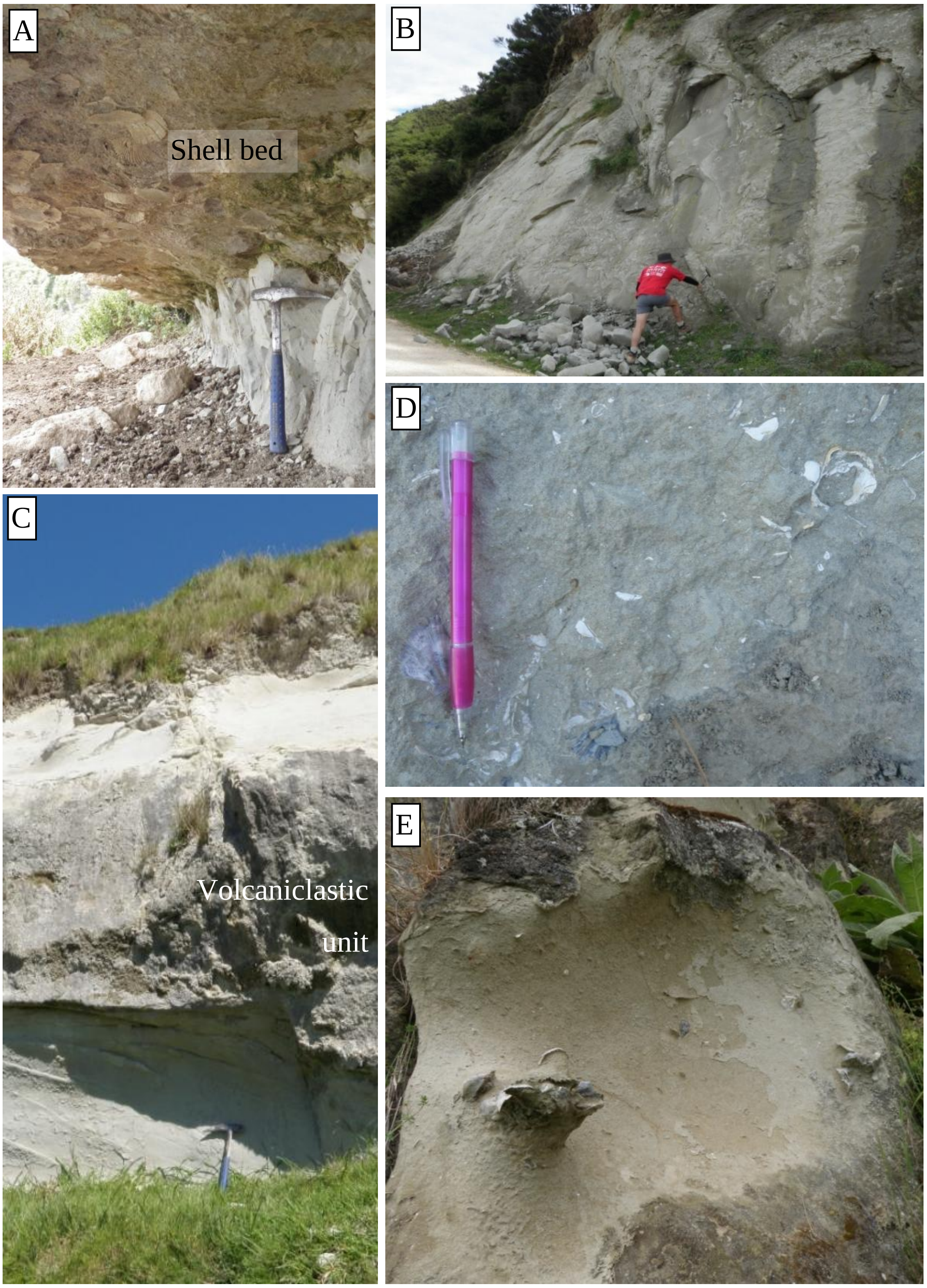


Figure 7.12 – Field photographs of the associated lithologies and contacts underlying (A and B) and overlying (C, D and E) the Tahaenui Limestone in the Tahaenui area. **(A)** The direct unconformable contact of the Tahaenui Limestone and underlying late Miocene mudstone with a densely populated pectinid shell bed at the base of the Tahaenui Limestone. **(B)** Overlying massive mudstone exposures (Wairoa Formation D) along Kokohu Road. **(C)** A 1 m thick pumiceous volcaniclastite unit within the siliciclastic succession (Wairoa Formation D) overlying the Tahaenui Limestone. A small near vertical fault offsets the volcanic unit by c.30 cm. Kokohu Road. **(D)** Shelly sandstone overlies the Tahaenui Limestone with a gradational contact, Mangaone Road. The main macrofossils here are bivalves up to 4 cm in size. **(E)** Brown shelly sandstone outcrops at Paokuhukura Trig, near Nuhaka. Although no contact zone is observed here, this sandstone overlies the Tahaenui Limestone. *Hammer - 32 cm long, pencil - 14 cm long.*

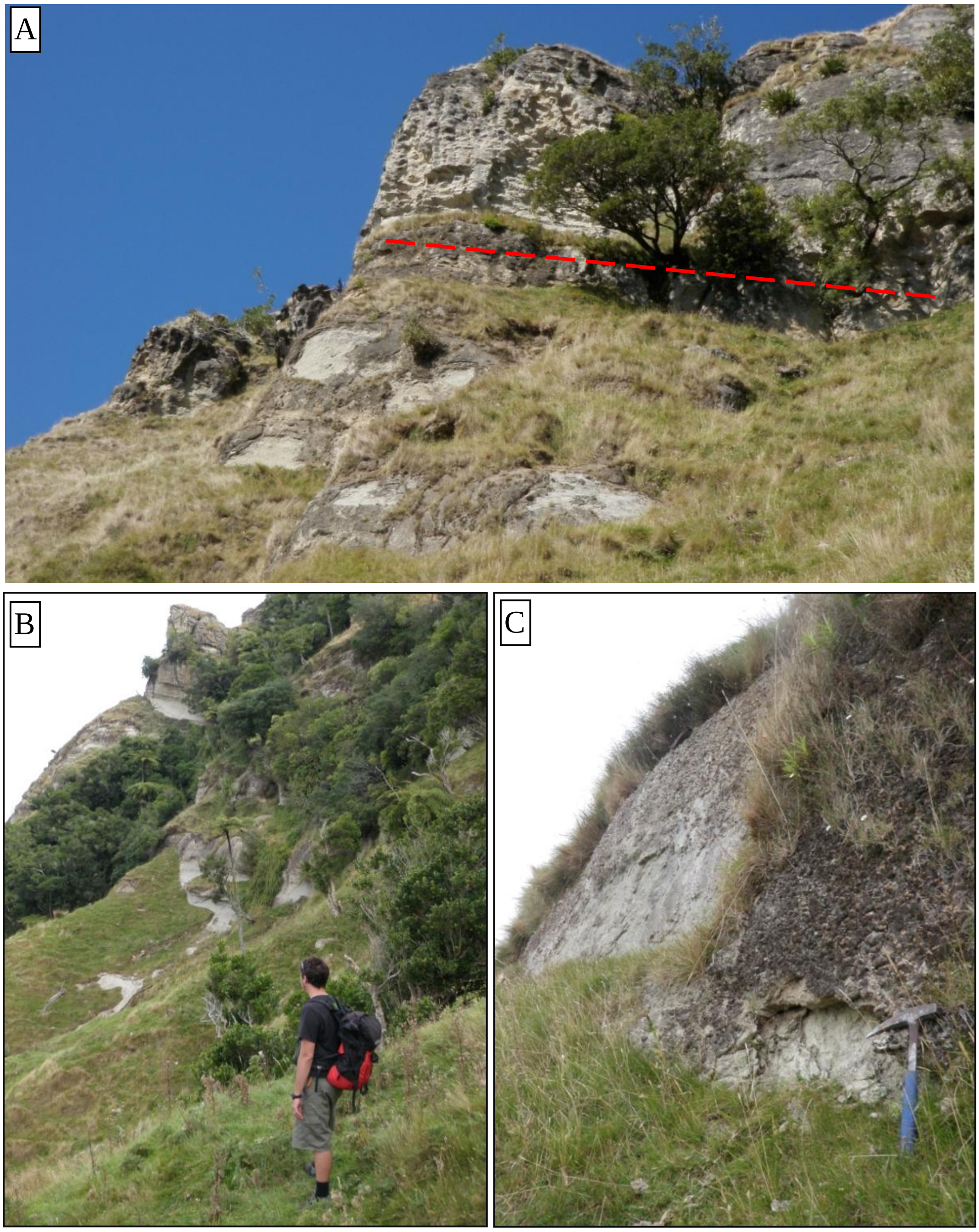


Figure 7.13- Field photographs of the associated lithologies and contacts underlying the Tahaenui Limestone at Mt Moumoukai. **(A)** The unconformable contact zone (highlighted in red) of the Opoitian aged sandy Wairoa Formation B and the overlying Waipipian aged Tahaenui limestone. **(B)** The underlying sandy Wairoa Formation B forms grassy slopes overlain by cliffs of Tahaenui Limestone. **(C)** Close up view of the underlying Wairoa Formation B, here a friable soft sandstone. *Hammer - 32 cm long.*

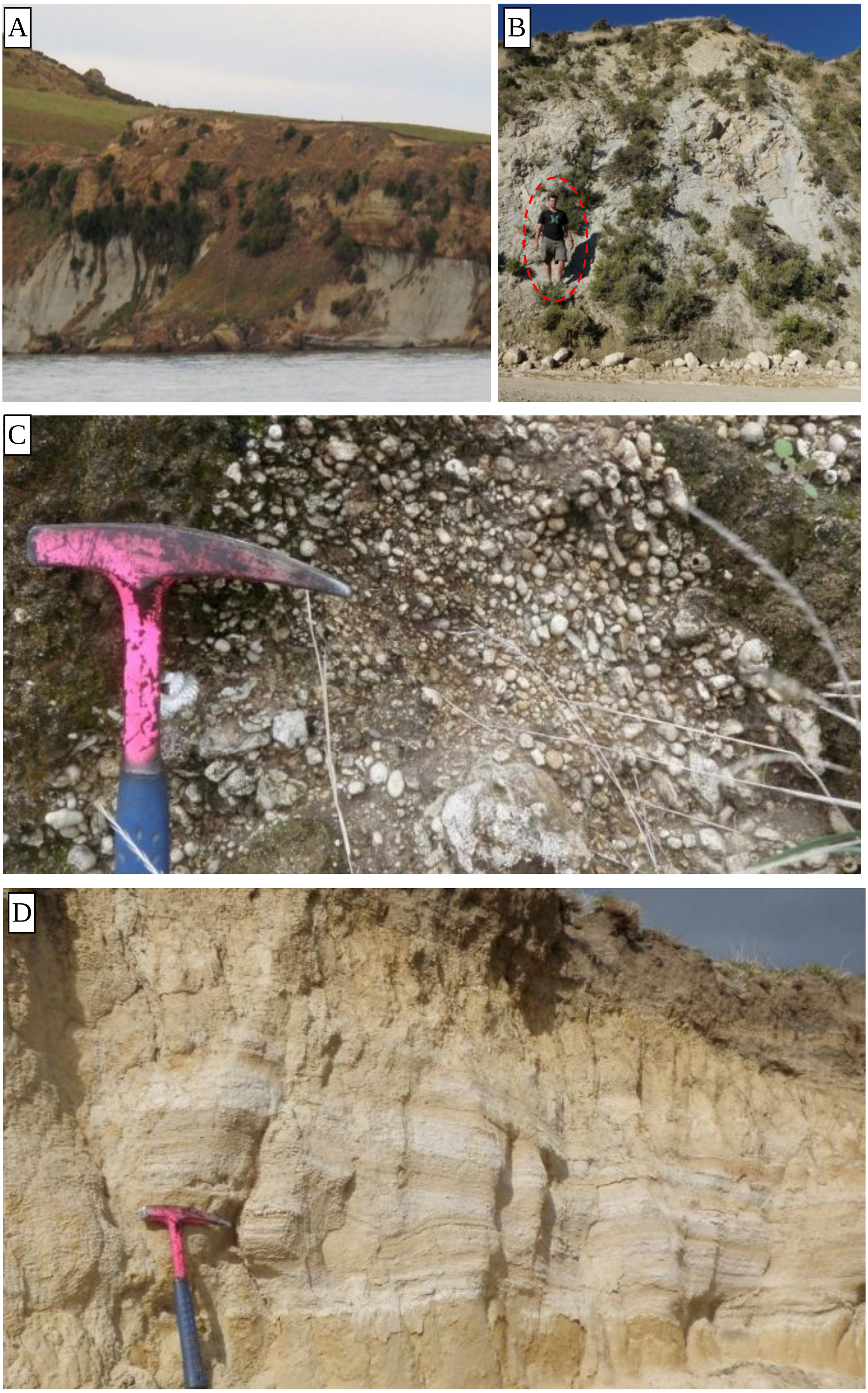


Figure 7.14 - Field photographs of the associated lithologies and contacts underlying and overlying the Tahaenui Limestone at Mahia Peninsula. **(A)** Massive late Miocene mudstone underlying the Tahaenui Limestone, Kinikini Road (Person for scale). **(B)** The only directly observed underlying sharp contact of the Tahaenui Limestone is on Long Point where accessibility is limited. **(C** and **D)** Although not stratigraphically overlying the Tahaenui Limestone, these Quaternary deposits geographically cover the limestone on Long Point. These laminated sands and gravels (pumice with rare gastropods) are Pleistocene beach deposits accumulated non uplifted paleowave cut platforms. *Hammer - 32 cm long.*

7.1.2 Lithofacies

Lithofacies included in the Tahaenui Limestone succession include two limestone lithofacies (L1, L3), one sandstone lithofacies (S2), two mudstone lithofacies (M1, M4) and the volcanic lithofacies (V1) (Figure 7.15).

The barnacle dominated limestone lithofacies (L1) is abundant throughout all outcrops of Tahaenui Limestone at all study localities. Shell beds (L1/P/O/Biv) are very common in the Tahaenui/Clonkeen syncline, but infrequent at Mt Moumoukai and Mahia Peninsula. The sandy limestone lithofacies L3 is quite common at Mt Moumoukai, but rare in the Tahaenui/Clonkeen syncline and on Mahia Peninsula.

Bioclastic sandstone (lithofacies S2) is present in Wairoa Formation D on the east flank of the Tahaenui/Clonkeen syncline, where it consists of well sorted, blue grey sandstone with occasional bivalve fragments.

Mudstone lithofacies associated with the Tahaenui Limestone are either massive (M1) or fossiliferous (M4). M1 is very common, and underlies the limestone in the Tahaenui/Clonkeen syncline and at Mahia (late Miocene mudstone). Fossiliferous (M4) and massive (M1) mudstone occurs above the Tahaenui Limestone on the east flank of the Tahaenui/Clonkeen syncline (Wairoa Formation D). A volcaniclastic (lithofacies V1) bed, up to 1 m thick, lies between these two mudstones. The volcaniclastite unit has abundant pumice clasts up to 2 mm size, with some mudstone clasts interspersed throughout. Incipient laminations are present.

The lateral relationship of lithofacies in the Tahaenui Limestone and overlying Wairoa Formation D lithofacies is stylised in Figure 7.16. The dominance of lithofacies L1 is clear, with patches of lithofacies L3. Columns 8, 3 and 4 show lateral continuity of Wairoa Formation D. The underlying late Miocene mudstone is evident across the study area.

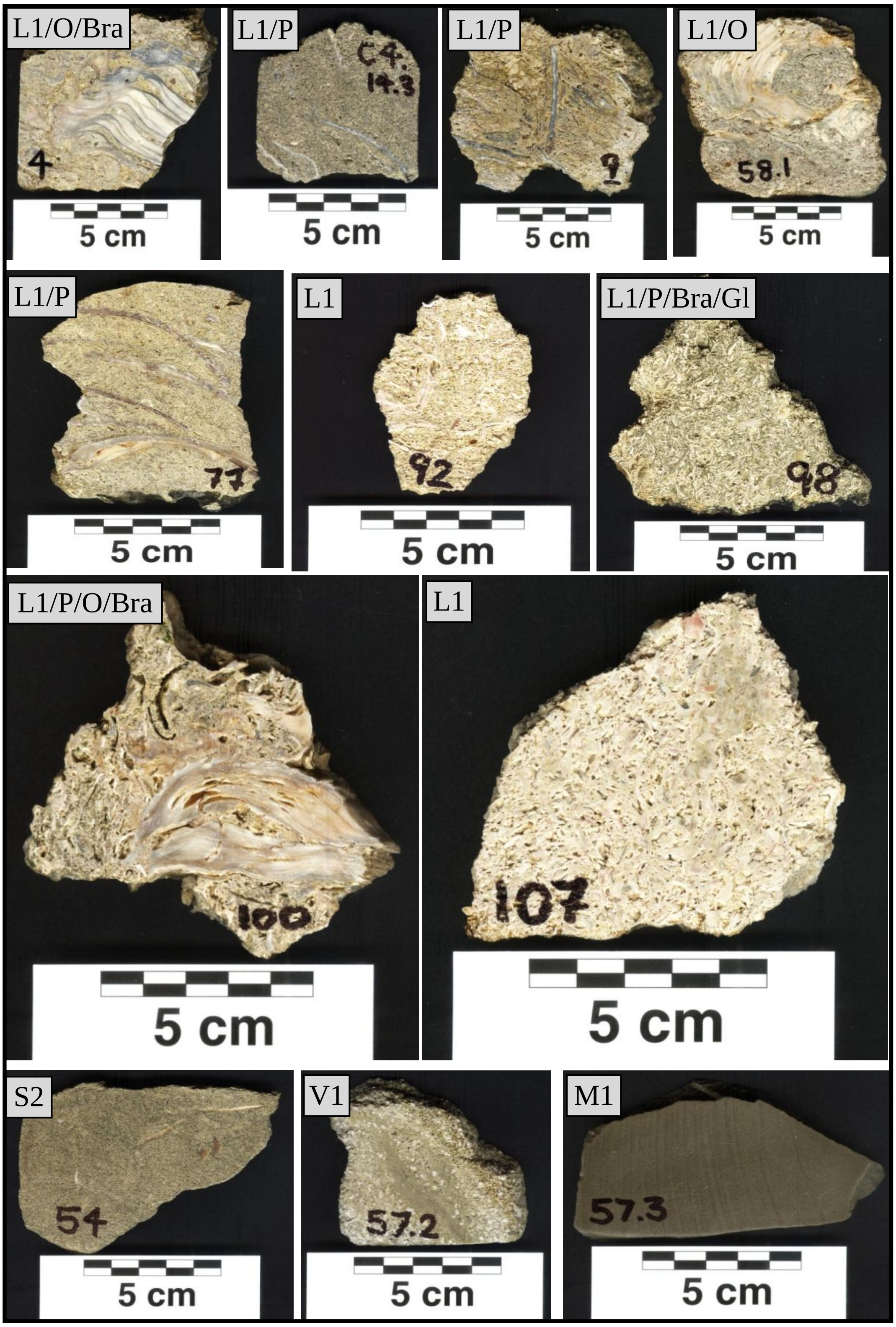


Figure 7.15 - Cut slabs of Tahaenui Limestone and associated lithologies illustrating the various lithofacies present. Samples 4, C4.14.3, 9 and 58.1 are from the Tahaenui/Clonkeen area. Sample 77 is from Mt Moumoukai. Samples 92, 98, 100 and 107 are from Mahia Peninsula. Samples 54, 57.2 and 57.3 (Wairoa Formation D) are from the Tahaenui/Clonkeen area. Refer to Table 4.1 for facies definition and codes.

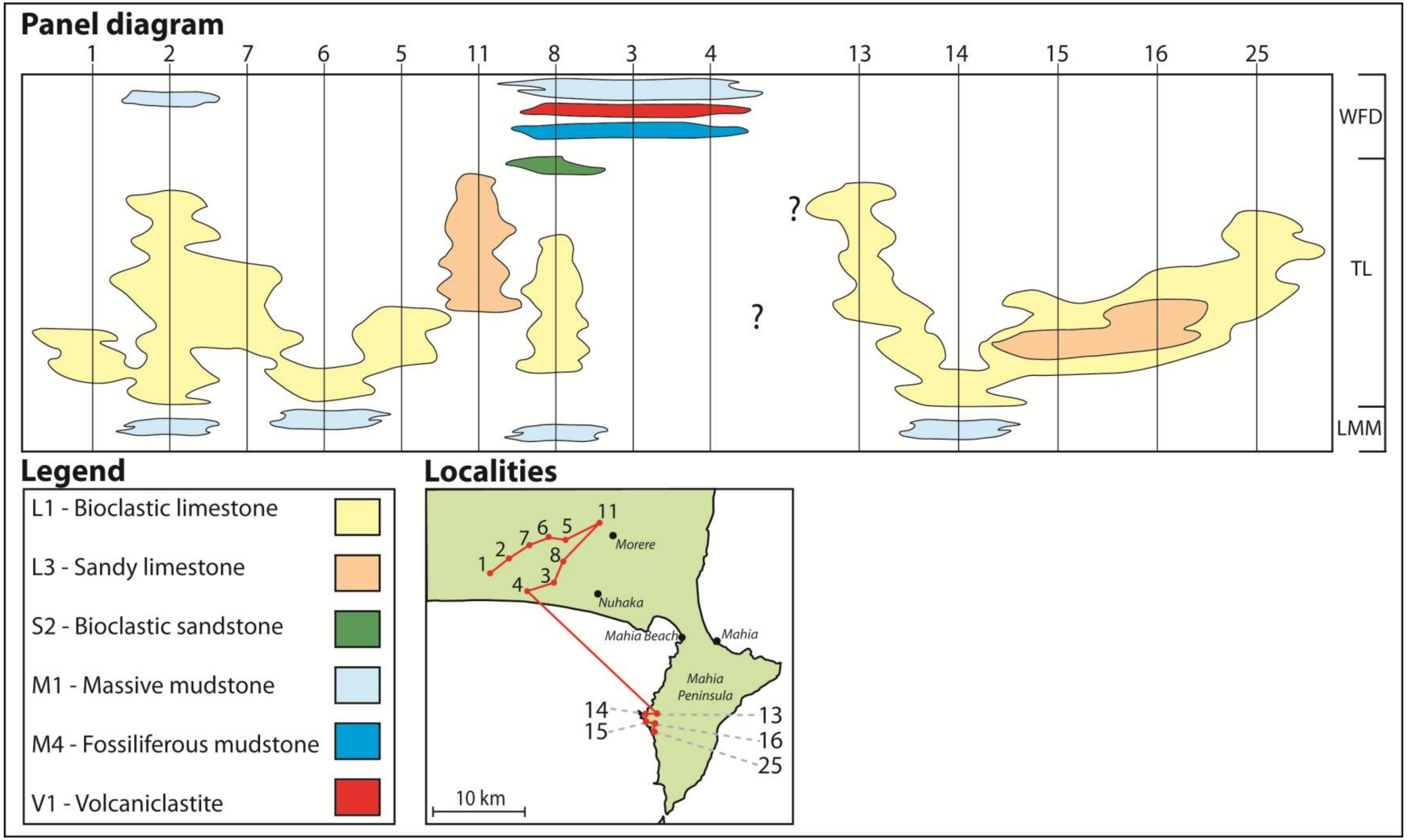


Figure 7.16 – Panel diagram showing the lateral relationship between lithofacies of the underlying late Miocene mudstone (LMM), Tahaenui Limestone (TL) and overlying Wairoa Formation D (WFD). Numbers relate to stratigraphic columns (refer to Appendix VII). No vertical scale implied.

7.2 FOSSIL CONTENT

The Tahaenui Limestone typically hosts abundant barnacles, common brachiopods, pectinids and oysters, and rare foraminifera. At all localities the Tahaenui Limestone hosts common, disarticulated, age diagnostic (Waipipian, Appendix I) *Phialopecten marwicki* pectinids (Beu 1978; 1995) (Figure 7.17 A, C). These can be up to 2-3 mm thick, 12 cm across, and are almost always in convex upwards orientation. Disarticulated oysters, *Ostrea chilensis* and *Crassostrea ingens*, are common in the Tahaenui Limestone, and are up to 4 cm thick and up to 10 cm in size (Figure 7.17 B). Very common brachiopods are identified as *Neothyris* cf. *obtusa* or *Neothyris campbellica elongata* (Figure 7.17 D). (Neall 1972; *pers. commun*. Beu 2010). The Tahaenui Limestone on Mt Moumoukai is quite highly weathered, making the macrofossils difficult to extract and of rather poor quality.

At Tahaenui Quarry, an intact barnacle specimen was observed attached to a 7 cm float pectinid (Figure 7.17 A). The barnacle was approximately 1.3 cm in diameter and 0.7 cm high. The orifice at the top is 0.5 cm in diameter. From several similar observations elsewhere (e.g. Kamp *et al.* 1988) it is inferred that the pectinids acted as the main substrate for barnacle attachment.

Barnacle species occurring in the East Coast Te Aute limestones are *Balanus (Austrobalanus) vestitus/Notobalanus vestitus*, *Balanus (Megabalanus) decorus* and the now extinct *Balanus (Megabalanus) tubulatus/(Fosterella) tubulatus.* (Beu *et al.* 1980; Buckeridge 1983; Kamp *et al.* 1988). The Tahaenui Limestone hosts a very large proportion of these barnacle plates. With the life span of a barnacle being approximately one year (Kamp *et al.* 1988), there is a high turnover rate that results in a high rate of accumulation and sedimentation.

Through foraminiferal laboratory work and scanning electron microscopy (SEM) imaging, the underlying late Miocene mudstone contains very common specimens of the benthic foraminifera *Lenticulina*, rare fragmented echinoid spines, common *Nodosaria longiscata* and rare *Dentalina*, *Cibicides* and *Globorotalia pliozea* specimens (Figure 7.18). The several *Orbulina universa* specimens present have been pyritised.

The three separate regions with Tahaenui Limestone outcrops show some paleontological variations. The Nuhaka Syncline exposes numerous shell beds constructed of pectinid, brachiopod and oyster valves near the base of the limestone. The same situation occurs at Long Point on Mahia Peninsula. The sole componentry of barnacle plates that dominates the stratigraphically higher limestone on Taupiri Hill is also found at Tahaenui/Clonkeen but with greater admixed siliciclastic material. This could reflect different sources of siliciclastic supply, or perhaps because the limestone is thinner at Tahaenui/Clonkeen it did not reach the thickness needed to have accumulated solely barnacle dominated limestone.

Disarticulation of bivalves usually occurs very rapidly after death. Consequently therefore, concentrations of articulated brachiopods or bivalves can indicate a rapid burial event. However, some species of brachiopods actually ‘lock’ their hinges when dead, increasing the likelihood to find them articulated. Disarticulated specimens of this type imply a very high energy environment that has caused damage to the hinge teeth (Brett & Baird 1986). Within the Tahaenui Limestone, the *Neothyris* species of brachiopods that lock shut after death are present, none of which have been found disarticulated. This could imply quiet sedimentation conditions. For bivalves, however, disarticulated valves are more common, as upon death the joining elastic ligaments are relaxed, and the valves fall open (Brett & Baird 1986). All pectinid specimens identified in the Tahaenui limestone are single valves.

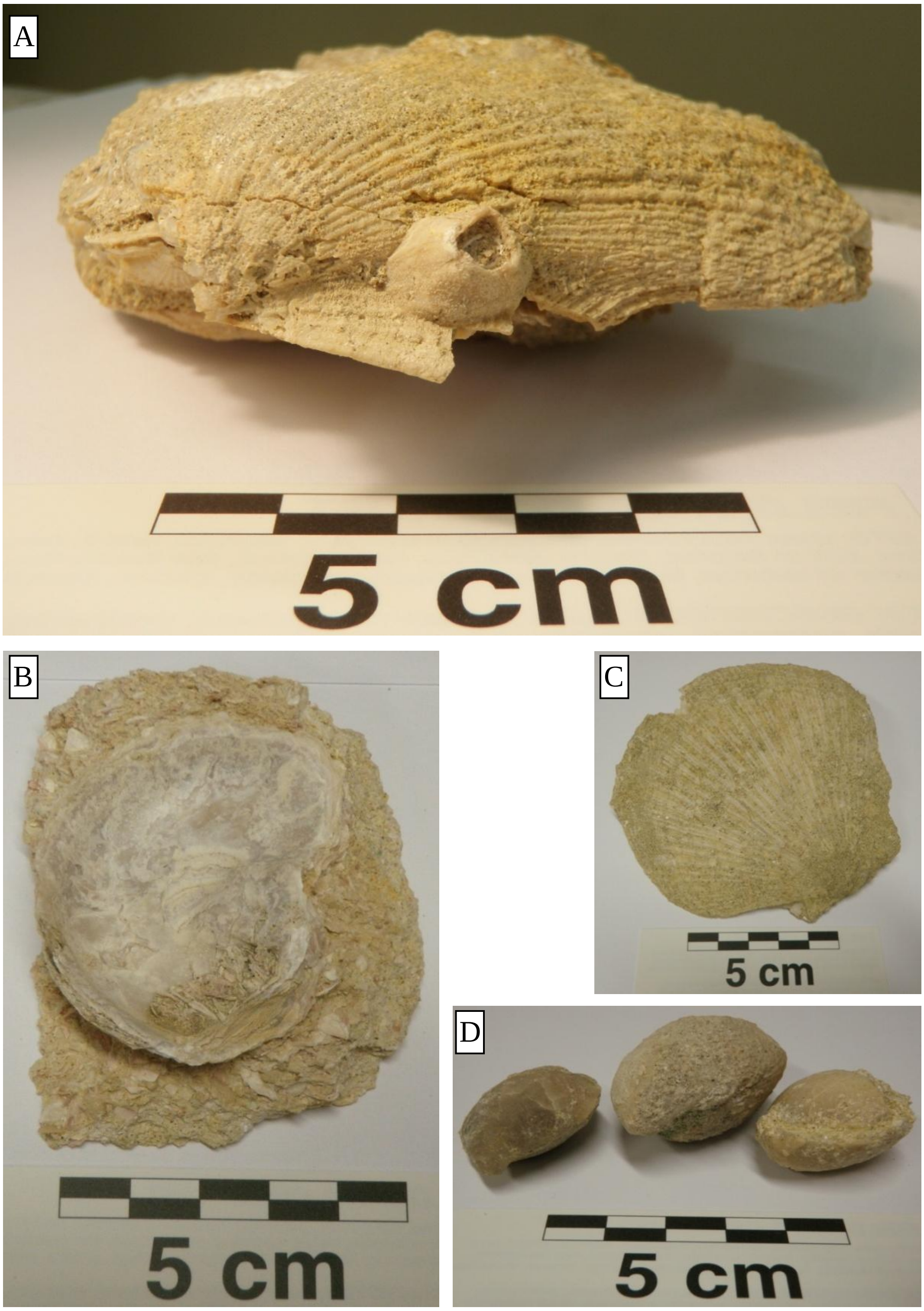


Figure 7.17 - Macrofossils from the Tahaenui Limestone. All specimens were *in situ*. **(A)** *Phialopecten marwicki* with attached barnacle from the Tahaenui/Clonkeen area. **(B)** Likely *Ostrea chilensis* from Long Point**,** Mahia Peninsula. **(C)** *Phialopecten marwicki* from the Tahaenui/Clonkeen area. **(D)** *Neothyris* brachiopods from the Tahaenui/Clonkeen area.

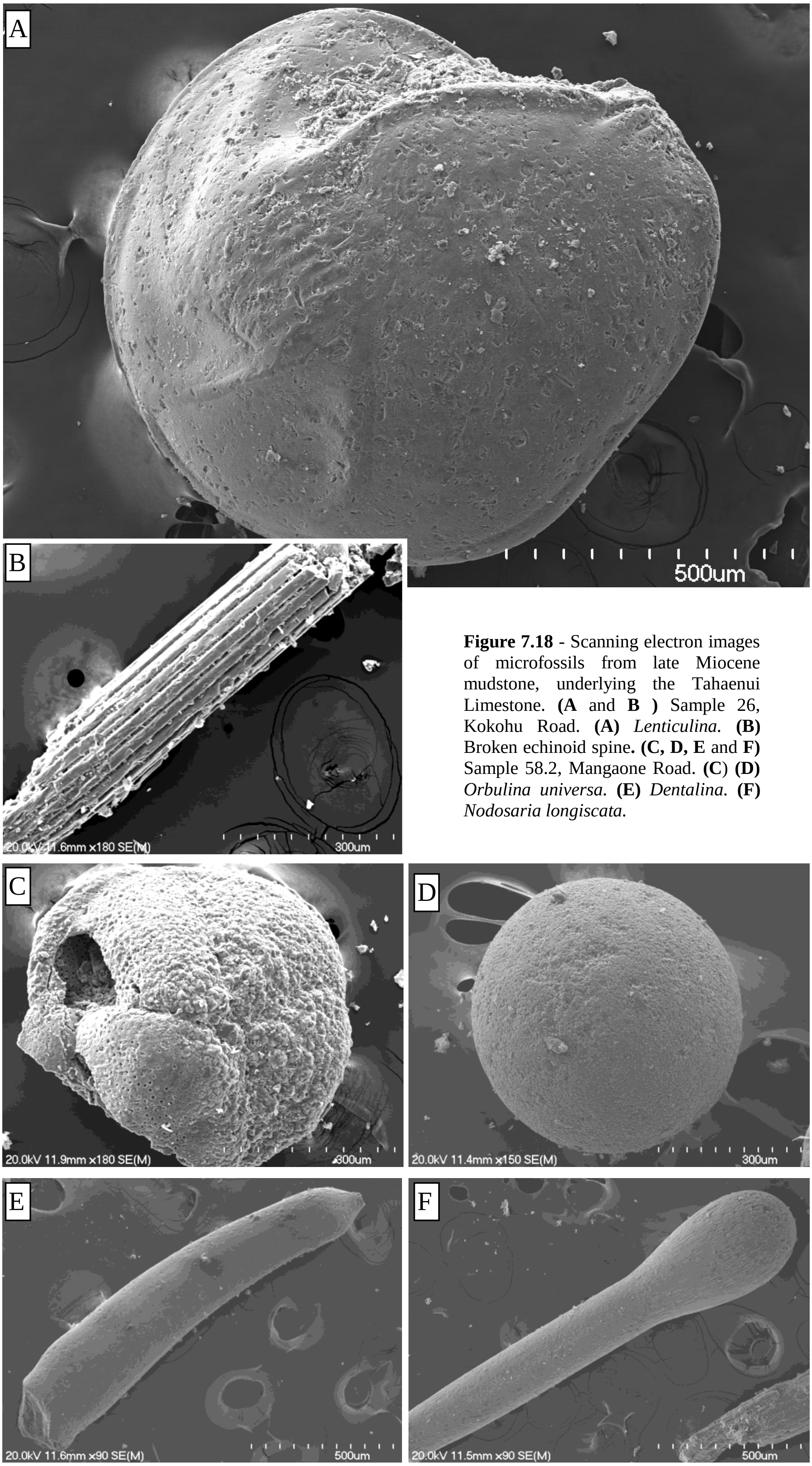


Figure 7.18 - Scanning electron images of microfossils from late Miocene mudstone, underlying the Tahaenui Limestone. **(A** and **B)** Sample 26, Kokohu Road. **(A)** *Lenticulina*. **(B)** Broken echinoid spine**. (C, D, E** and **F)** Sample 58.2, Mangaone Road. **(C**) **(D)** *Orbulina universa*. **(E)** *Dentalina*. **(F)** *Nodosaria longiscata*.

7.3 LABORATORY PROPERTIES

7.3.1 Calcium carbonate %

Calcium carbonate data are given in Appendix III. Figure 7.19 plots the calcium carbonate and siliciclastic values of the Tahaenui Limestone and Wairoa Formation D. Tahaenui Limestone has the highest carbonate content of the Pliocene limestones, reaching up to c.90% (Table 7.1). The fossiliferous sandstone, cropping out in the Nuhaka Syncline, has a moderately high carbonate value of c.32%. The overlying mudstone has <1% carbonate. Expectedly, the fossiliferous mudstone has a much higher carbonate content of c.17%. The single volcaniclastic unit within the Wairoa Formation D has a few percent carbonate. This is probably derived from occasional marine shells that were worked into the deposit.

Table 7.1 - Carbonate and siliciclastic percentages in the Tahaenui Limestone (lithofacies L1) and overlying Wairoa Formation D (lithofacies M4, S2, V1).

Sample Number	Facies	Carbonate %	Sand %	Mud %
3	L1	74.5	12.3	13.6
107	L1	90.8	2.1	7.7
57.4	S2	32.2	58.5	9.4
57.3	M4	17.6	31.6	51.3
57.2	V1	3.0	46.6	24.8

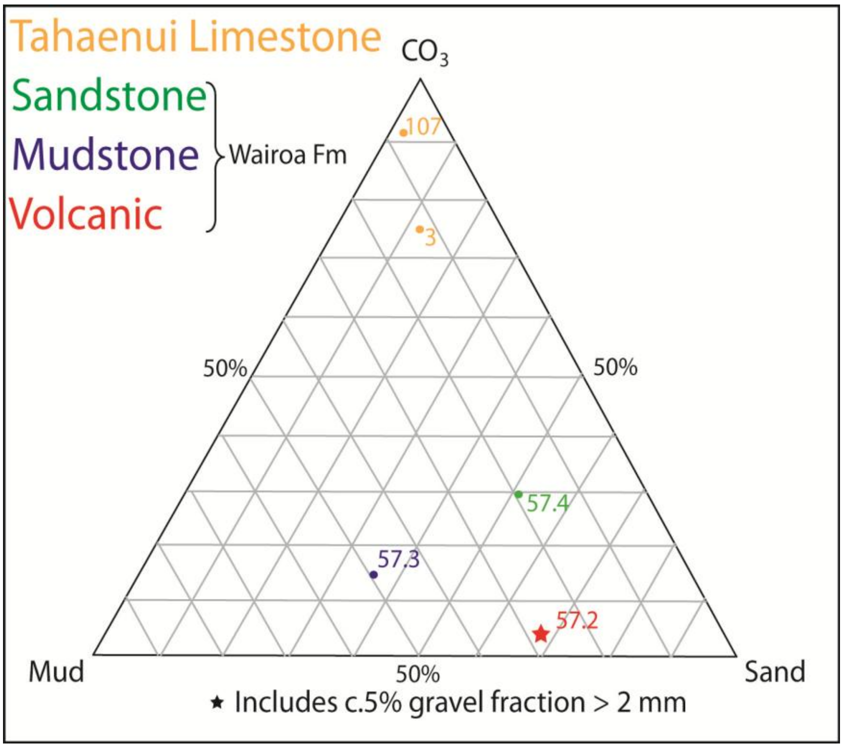


Figure 7.19 – Ternary plot depicting the carbonate-siliciclastic sand-siliciclastic mud composition for samples from the Tahaenui Limestone and overlying Wairoa Formation D. The Tahaenui Limestone has rather high carbonate percentages, owing to its near-pure bioclast composition.

7.3.2 Insoluble grain analysis

Malvern Mastersizer data and graphs are contained as Digital Appendix F on the accompanying CD. Figure 7.20 shows the sand-clay-silt grain sizes for the Tahaenui Limestone and overlying Wairoa Formation D, with percentages in Table 7.2. The Tahaenui Limestone shows two modal sizes, 11-27 µm and 149-152 µm, of fine-medium silt and fine sand respectively. The Wairoa Formation's shelly sandstone has a slightly coarser modal size of 158 µm while the associated mudstones have a model size of c.50 µm. The c.50 cm volcaniclastic unit within Wairoa Formation D shows a single modal size of 475 µm with c.4% of grains larger than 2 mm.

Table 7.2 - Siliciclastic percentages in the Tahaenui Limestone (lithofacies L1) and overlying Wairoa Formation D (lithofacies M4, S2, V1).

Sample Number	Facies	Gravel %	Sand %	Silt %	Clay %
3	L1	0.0	53.0	44.1	2.4
107	L1	0.0	21.4	69.9	8.6
57.4	S2	0.0	80.5	18.8	0.6
57.3	M4	0.0	38.6	58.7	2.6
57.2	V1	4.6	69.3	25.7	1.0

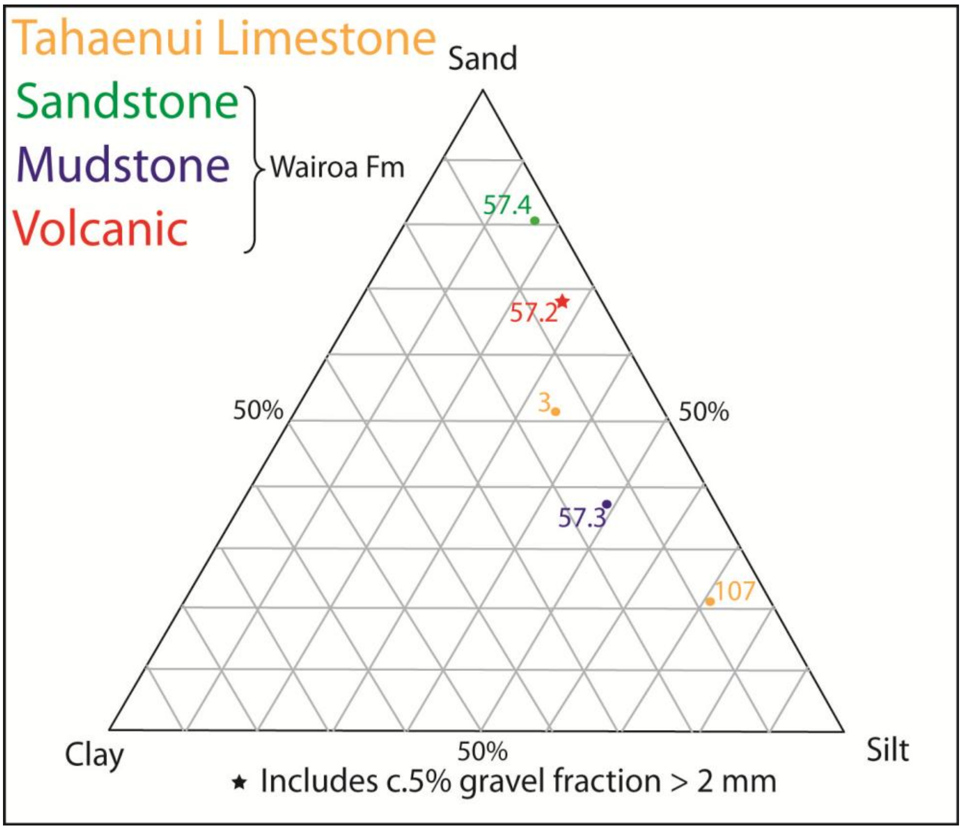


Figure 7.20 – Ternary plot depicting the acid insoluble sand-silt-clay grain sizes for the Tahaenui Limestone and overlying Wairoa Formation D. The Tahaenui Limestone has a range of siliciclastic grains sizes and do not plot close together. As expected the sandstone and mudstone lithologies have sand to silt sized grains respectively.

7.3.3 XRD

Table 7.3 presents XRD data for the Tahaenui Limestone, underlying late Miocene mudstone and overlying Wairoa Formation D. Complete XRD data and graphs are contained as Digital Appendix H on the accompanying CD. XRD spectra show calcite peaks of 700 and 900 counts for the Tahaenui Limestone, consistent with their high carbonate contents up to 90%. Quartz counts of 20 and 46 are low, as are plagioclase counts (up to c.50), also reflecting this purity. Clay minerals in the Wairoa Formation D mudstone are dominantly illite and chlorite (Refer to section 4.3.3). Aragonite and dolomite both have very low counts which are probably just background noise associated with the XRD analysis.

Table 7.3 – XRD count values for the Tahaenui Limestone and overlying Wairoa Formation D. Count values < c.20 may well be part of the background spectra and do not necessarily mean the mineral name indicated is present.

Sample	Quartz	Plagioclase	Calcite	Aragonite	Dolomite	Total Clays
2˚θ	**26.62**	**27.94**	**29.42**	**26.22**	**30.9**	**19.9**
L1 - 3	46	47	709	12	15	6
L1 - 107	20	9	878	11	2	7
S2 - 57.4	565	124	173	30	17	18
M4 - 57.3	668	127	57	22	22	40
V1 - 57.2	76	72	37	38	42	43

7.3.4 XRF

Table 7.4 shows a representative selection of bulk rock XRF results from the Tahaenui Limestone and overlying Wairoa Formation D. XRF analysis was carried out on c.60 bulk rock samples, from the Tahaenui Limestone, underlying late Miocene mudstone and Wairoa Formation D. Complete XRF data are given in Digital Appendix I. XRF shows the SiO_2 content of volcaniclastic samples 29, 47.2 and 57.2 to be 75.56%, 64.37% and 72.55%, respectively. These silica values are consistent with the volcaniclastics having a rhyolitic origin (Figure 2.4) (Francis & Oppenheimer 2004), which is reinforced by the presence of Y-shaped glass shards observed in petrographic analysis. Note the increase in SiO_2 from limestone to sandstone to mudstone (green), the decrease in CaO from sandstone to mudstone (blue), the CaO values of the carbonates (yellow) and the SiO_2 values of the volcaniclastics (red).

Table 7.4 – XRF data of the Tahaenui Limestone and overlying Wairoa Formation D from the Tahaenui/Clonkeen region.

	Sample	Limestone			Sandstone	Mudstone			Volcanic		
		13	**16**	**44.1**	**57.4**	**6**	**26**	**52**	**29**	**47.2**	**57.2**
Oxide (%)	Na^2O	< 0.063	< 0.049	< 0.070	1.55	2.56	3.07	2.70	4.61	3.82	3.54
	MgO	0.91	0.62	0.64	2.28	3.02	2.78	2.60	0.29	2.40	0.70
	Al_2O_3	1.83	0.96	1.99	11.53	16.20	15.45	15.79	14.53	18.14	13.50
	SiO_2	6.62	3.23	6.22	51.40	71.08	68.64	73.39	75.56	64.37	72.55
	P_2O_5	0.09	0.07	0.06	0.17	0.19	0.17	0.15	0.09	0.17	0.07
	K_2O	0.38	0.14	0.21	1.72	2.83	2.66	3.03	3.25	1.52	3.25
	CaO	52.00	56.12	52.14	14.54	1.60	4.04	1.80	2.87	6.66	2.42
	TiO_2	0.03	< 0.00083	0.04	0.43	0.67	0.64	0.60	0.27	0.69	0.30
	MnO	0.01	0.01	0.03	0.04	0.06	0.06	0.06	0.07	0.09	0.05
	Fe_2O_3	0.85	0.46	1.33	4.46	5.01	4.67	4.67	3.24	5.80	3.38

7.3.5 Petrography

Comprehensive petrographic analysis (PPL, XPL, and CL) of 28 thin sections from the Tahaenui Limestone and Wairoa Formation D are recorded in Digital Appendix D. Total petrographic componentry is shown in Figure 7.21.

Skeletal componentry

Skeletal components within the Tahaenui Limestone include very abundant barnacles, occasional to common brachiopods and rare bryozoans and planktic and benthic foraminifera (Figure 7.21). Skeletal components show typically strong to moderate abrasion and varying degrees of sorting. Barnacle fragments are typically c.2 mm size, and pectinid and brachiopod valves are up to c.2 mm thick (Figure 7.22 A) with some oyster valves up to 5 mm thick (Figure 7.22 B). Barnacle fragments show elaborate internal patterns in their shells (Figure 7.23 A). Oysters are commonly fractured and be infilled by precipitated cement (Figure 7.22 B).

Cements

Petrographically, the Tahaenui Limestone cements consist mainly of interparticle isopachous sparite rims (Figure 7.24 and 7.25) and some microbioclastic micrite (Figure 7.23 B) (refer to section 2.2.2 for definitions). Microbioclastic micrite appears as a jumbled mix of smashed up bioclasts and siliciclastic material in fine grained carbonate mud. Clear isopachous sparite rims tend to be host-specific, favouring barnacle and pectinid fragments, and are ‘dog toothed/scalenohedral’ in shape and c.0.1-0.3 mm thick. The isopachous rims show up clearly in bright orange colours under cathodoluminescence microscopy, most with two or three phases of crystal growth shown by a colour change from non-luminescent to bright orange, followed by a hint of thin bright yellow edging on individual crystals (Figure 7.24 B, 7.25 B). This colour change in sparite rims suggests a change in the chemical composition of percolating waters, perhaps with increasing but shallow burial depths. The initial non-luminescence, which occurs around most grains, is likely to have precipitated close to the sea floor (essentially marine cement), with the subsequent orange and yellow growths indicating slightly deeper burial zones.

Pressure dissolution and porosity

Pressure dissolution is common in samples that are dominated by microbioclastic micrite (Figure 7.22 B, 7.23 B), perhaps fostered by the fine-grained nature of the microbioclastic micrite. Pressure dissolution is rarely seen in sparite dominated samples where clear isopachous rims have completely grown around the edges of barnacle fragments preventing grain to grain contact. The isopachous rims have commonly grown outwards until they meet (Figure 7.24), cementing the carbonate grains together. The original interskeletal space (excludes cement) is quite high in all samples, and is followed by fairly high modern porosity, with open interparticle pore spaces (includes cement) up to c.15%. Some, likely originally aragonitic, subrounded biomoulds occur up to c.2 mm size (Figure 7.26 A), and now create secondary pore space.

Cathodoluminescence

Cathodoluminescence petrography of the Tahaenui Limestone skeletal components shows bright orange to light purple barnacles and pectinids (Figure 7.24 B) and highlights the sparite cements as brilliant orange. The purple hues indicate some trace element substitution within these calcitic skeletons and are not due to an aragonitic mineralogy as is the case with ‘typical’ common purple luminescence.

Classification

The Tahaenui Limestone samples range from rounded biosparites to packed biomicrites (Folk 1968) (section 2.2.2, p. 18).

Siliciclastic and authigenic componentry

Siliciclastic grain sizes range from 0.1-0.15 mm, or very fine sand, and are well to moderately sorted. Textures of the siliciclastic sand grains (mainly quartz and feldspar) are typically subrounded to subangular. The authigenic minerals glauconite and pyrite are common, the glauconite typically occurring as pellets (Figure 7.26 B).

Petrography of the overlying Wairoa Formation shows brachiopods with internal prismatic structure (Figure 7.27) and under CL shows interdigitating of the ‘two sided’ colour ramp from orange to dull purple (Figure 7.27 B). Pumice clasts (Figure 7.25 A) and Y-shaped glass shards (Figure 7.25 B) are common within the volcaniclastite unit. The presence of these shards is indicative of the volcaniclastites being rhyolitic in origin and imply an explosive eruption style (Fisher & Schmincke 1984).

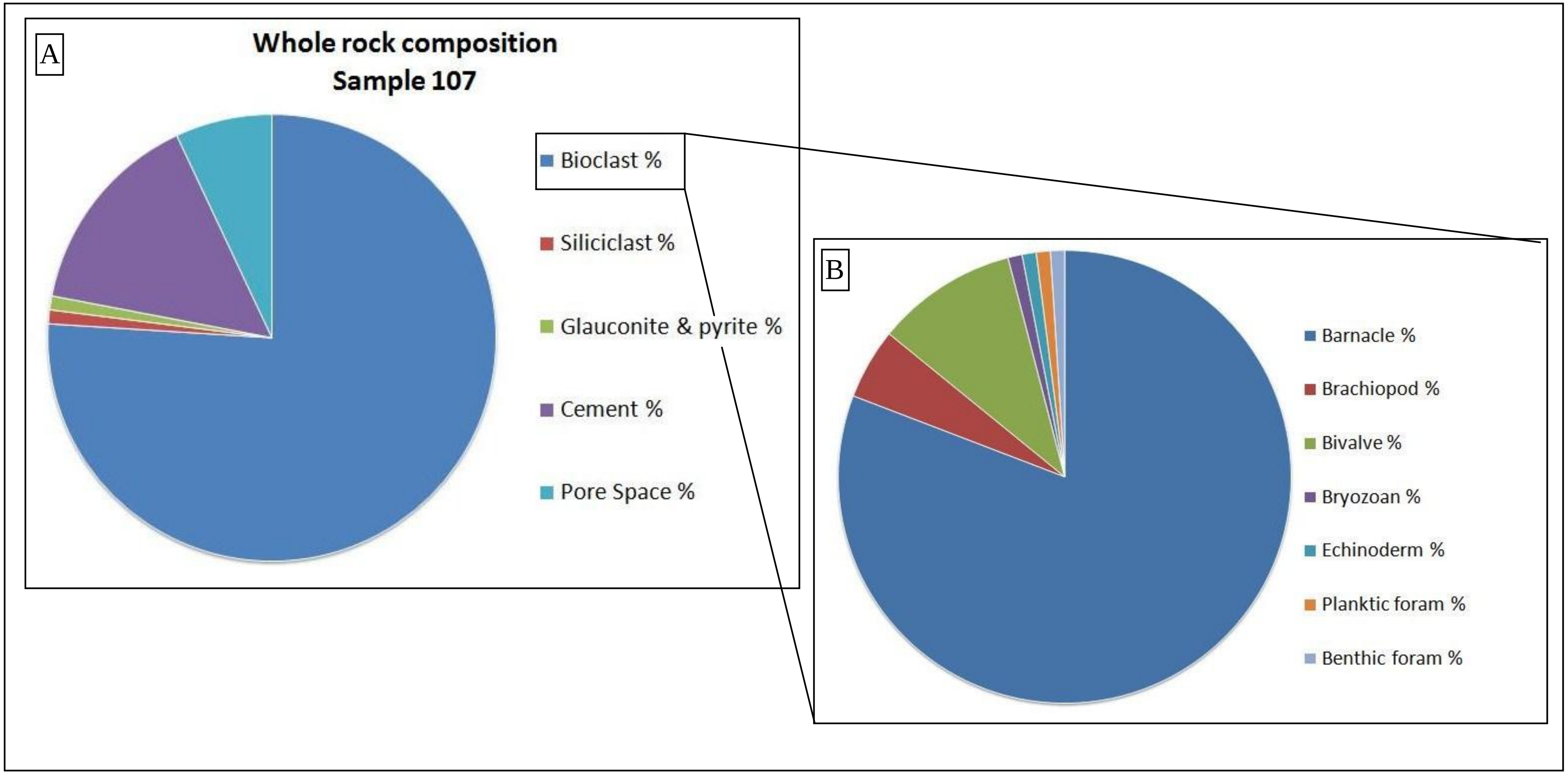
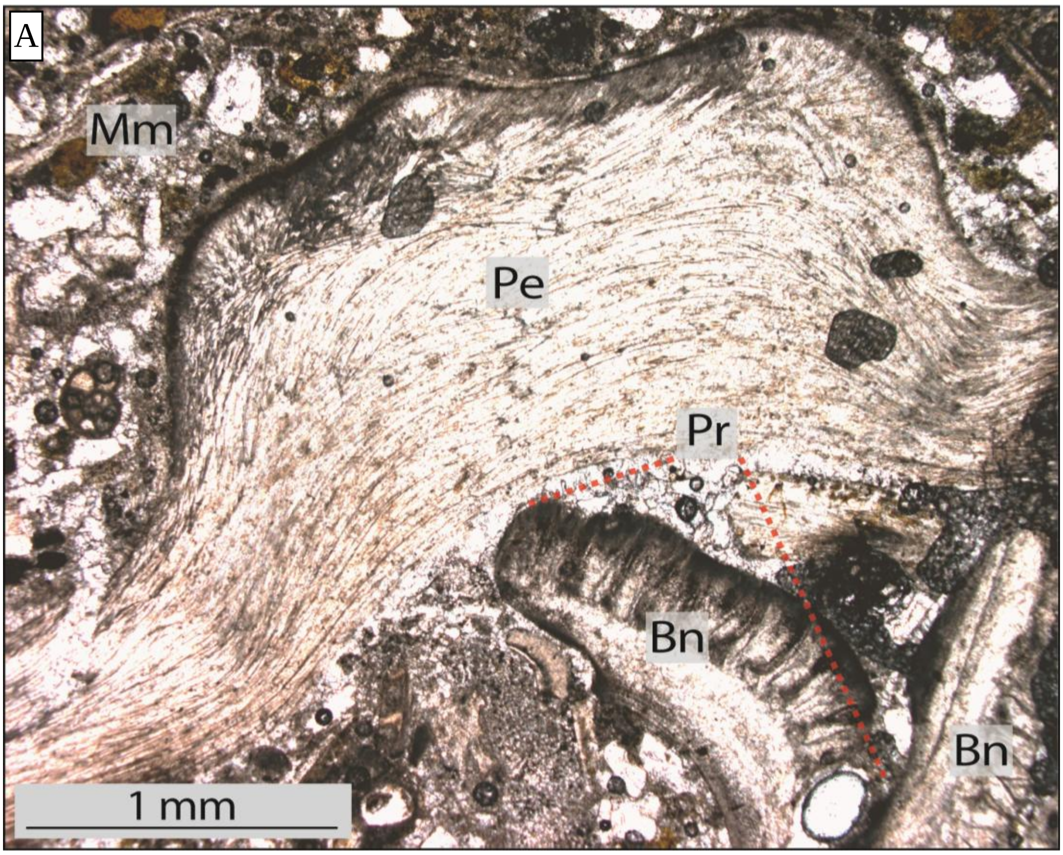


Figure 7.21 – Pie graphs showing the total petrographic componentry **(A)** and the primary skeletal componentry **(B)** of a representative sample from the Tahaenui Limestone. Sample 107 crops out at Long Point, west coast Mahia Peninsula.



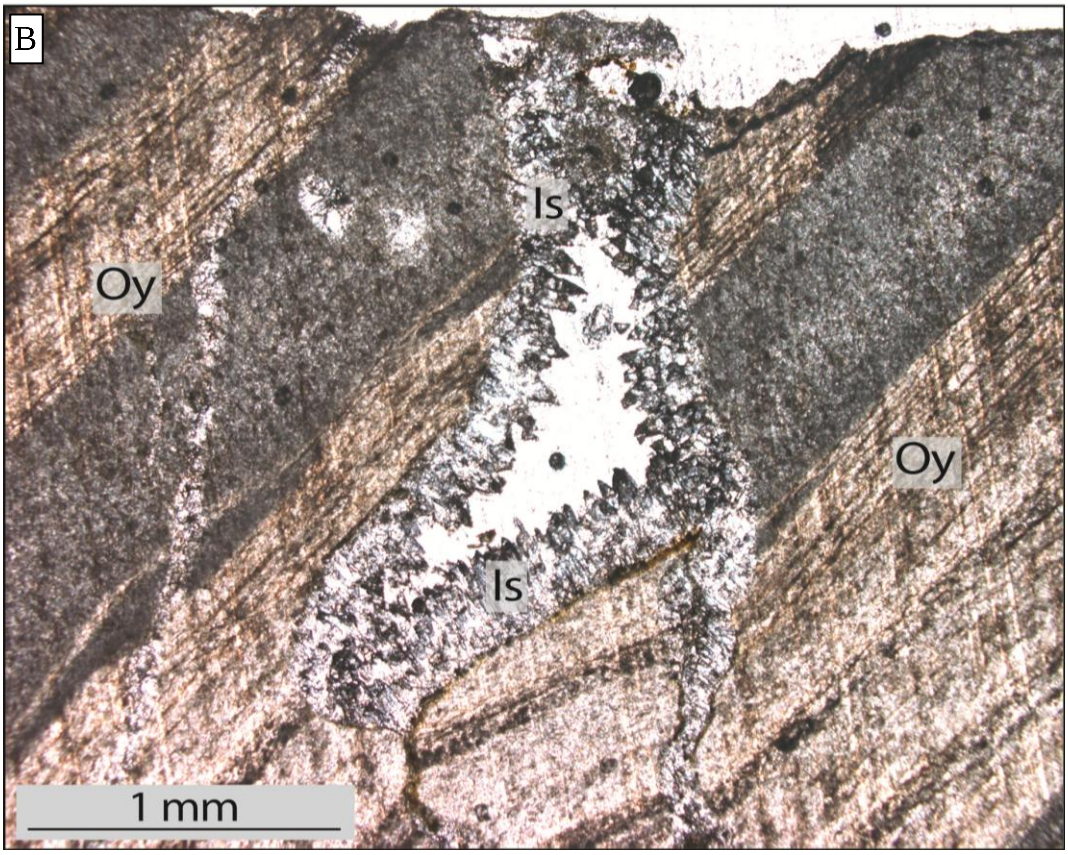
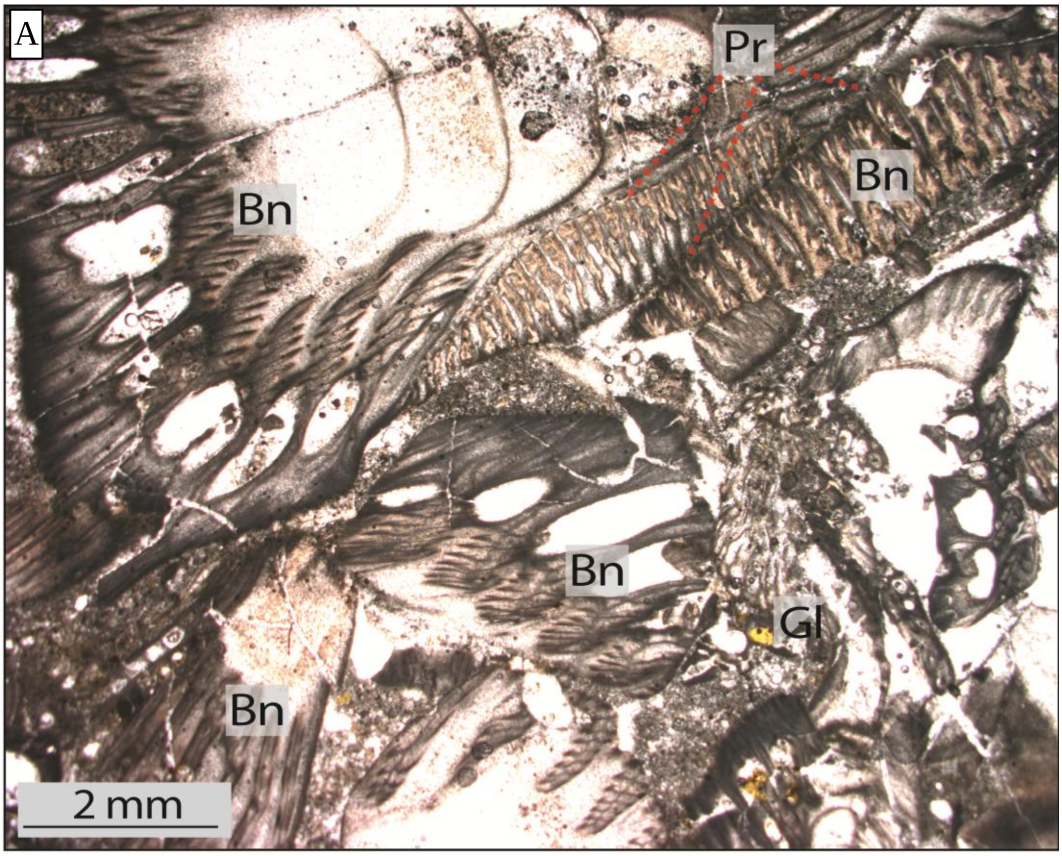


Figure 7.22 – Petrographic images from the Tahaenui Limestone at Clonkeen. **(A)** Sample C6.21.0 highlighting pressure dissolution (Pr) between a pectinid (Pe) fragment and a rounded barnacle fragment (Bn). Microbioclastic micrite (Mm) makes up the background matrix/cement. PPL. **(B)** Sample 58.1 illustrating a fractured oyster (Oy) partially infilled with dogtooth isopachous sparite fringe (Is). PPL.



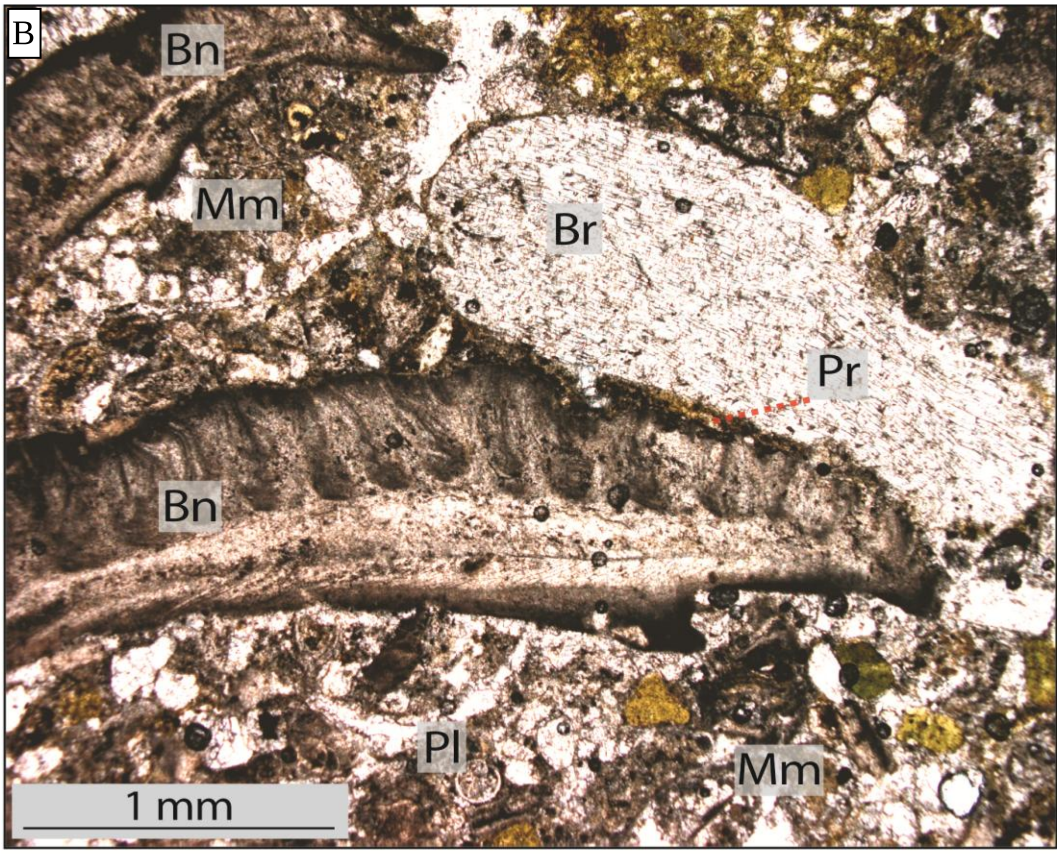


Figure 7.23 – Petrographic images from the Tahaenui Limestone at Mahia Peninsula. **(A)** Sample 107 illustrating a very coarse pure barnacle composition with some pressure dissolution (Pr) and small glauconite pellets (Gl). PPL. **(B)** Sample 98 shows direct contact and pressure dissolution (Pr) between a well rounded brachiopod (Br) fragment and a barnacle (Bn) grain, amongst microbioclastic micritic (Mm) matrix/cement. Rare planktic foraminifera (Pl) occur. PPL.

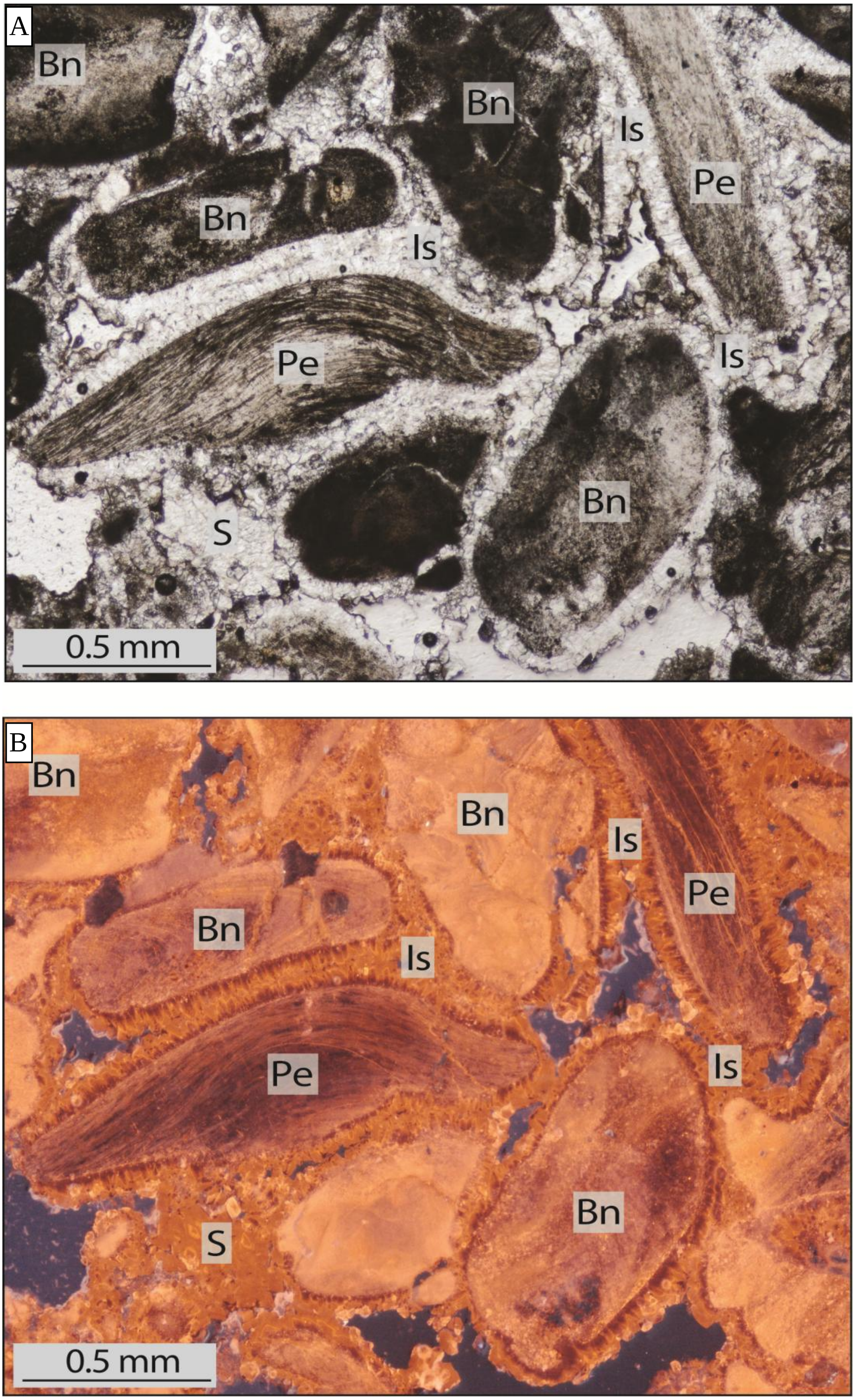


Figure 7.24 – Pair of images under plane and cathodoluminescent light from the Tahaenui Limestone, Kokohu Road. Sample 16. **(A)**. Well rounded barnacle (Bn) and pectinid (Pe) fragments cemented together with clear isopachous sparite fringes (Is) and coarse sparite (S). PPL. **(B)** Identical image under cathodoluminescent light illustrating exceptional two phase non luminescence and bright orange illumination in the isopachous sparite fringes (Is). Barnacle (Bn) and pectinid (Pe) fragments illuminate a dull orange to purple colour.

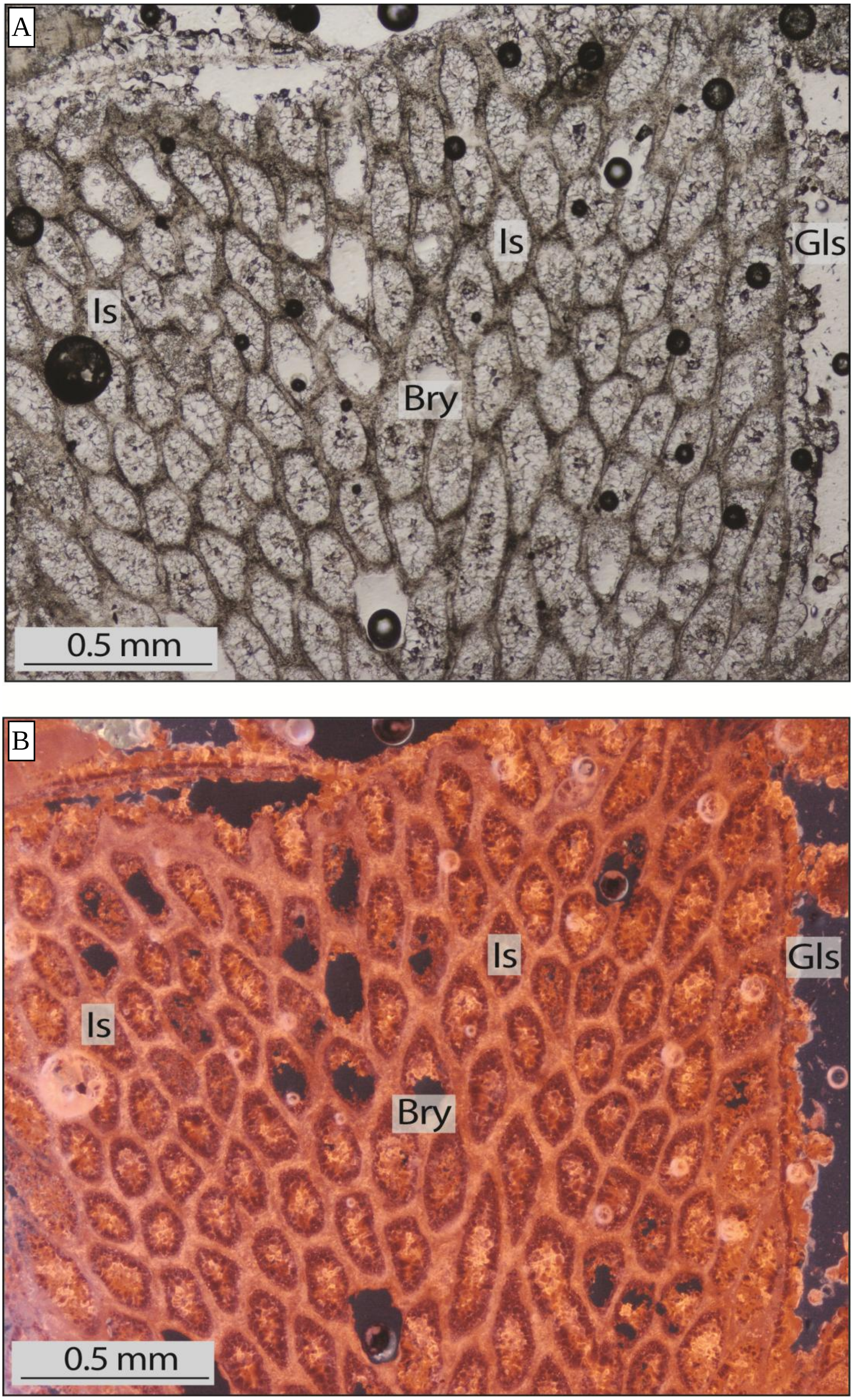


Figure 7.25 – Pair of images under plane and cathodoluminescent light from the Tahaenui Limestone, Kokohu Road. Sample 16. **(A)** A bryozoan (Bry) skeleton infilled with clear isopachous sparite fringes (Is). Gls – glass slide. PPL. **(B)** Identical image under cathodoluminescent light illustrating striking non luminescence to orange isopachous fringe illumination.

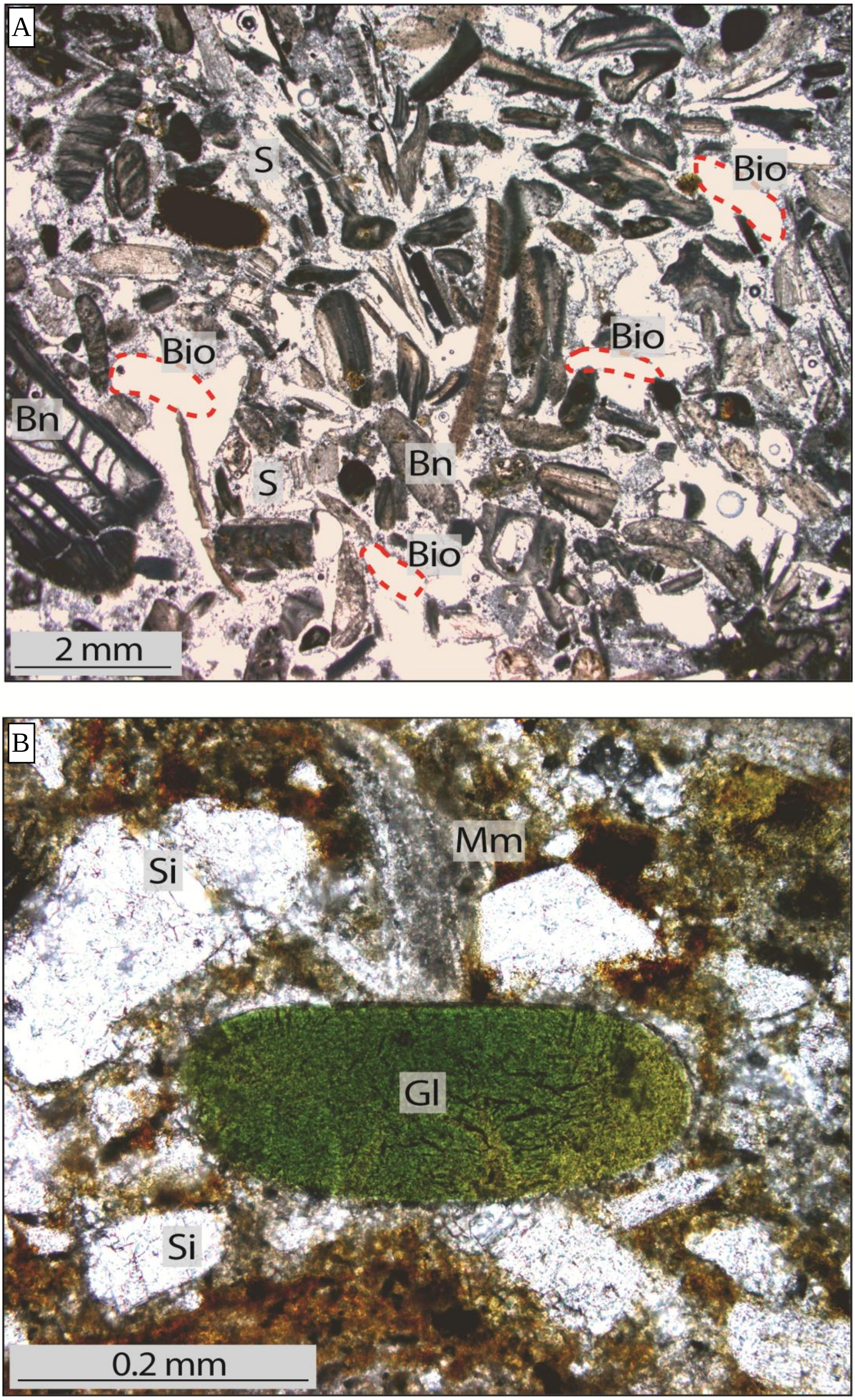


Figure 7.26 – Petrographic images from the Tahaenui Limestone at the Tahaenui Quarry (A) and Mt Moumoukai (B). **(A)** Sample 133.1 showing rounded bioclasts and barnacles (Bn) in a coarse sparite cement. Several biomoulds (Bio) have been identified indicating the presence of original aragonitic rounded skeletons that have since been dissolved. PPL. **(B)** Sample 74.2 illustrating an oval shaped glauconite pellet (Gl) within a siliciclastic (Si) dominated microbioclastic micrite (Mm) matrix/cement. PPL.

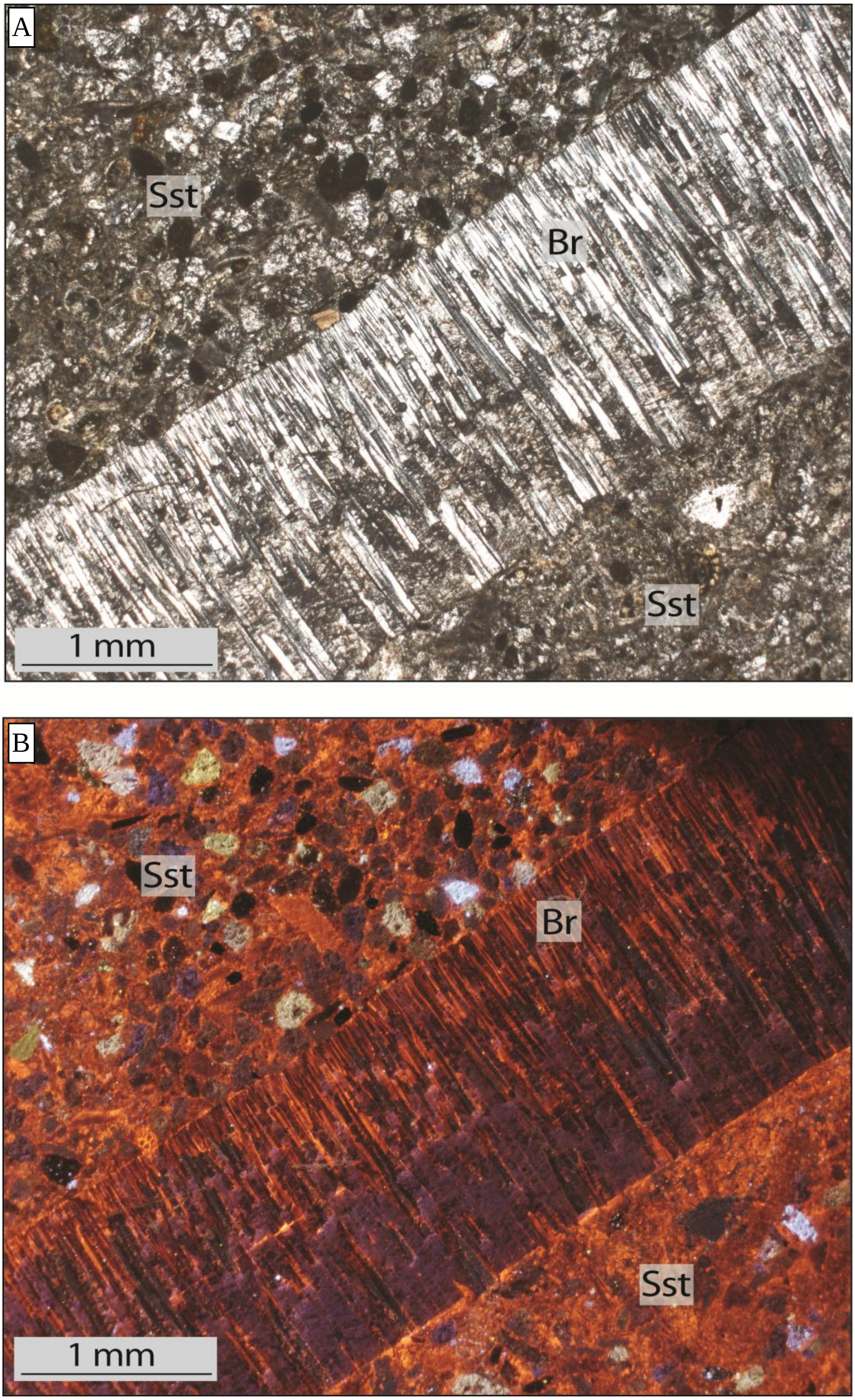
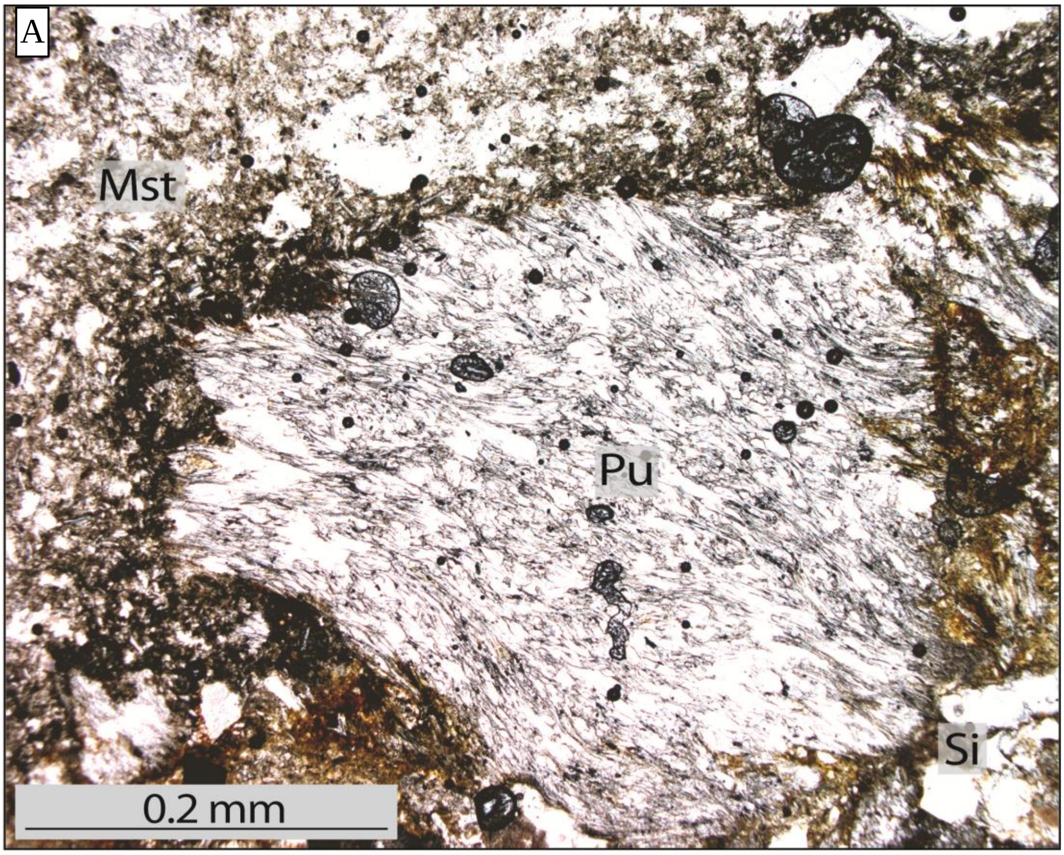


Figure 7.27 – Pair of images under plane and cathodoluminescent light from the Tahaenui/Clonkeen area of the shelly sandstone (Wairoa Formation D) overlying Tahaenui Limestone. Sample 54. **(A)**. Well sorted sandstone (Sst) with large brachiopod (Br) cut in cross section, illustrating its prismatic structure. PPL. **(B)** Identical image under cathodoluminescent light showing the various green, blue and silver colours of the siliciclastic grains (Sst) and the purple to orange interdigitating luminescence of the brachiopod (Br).



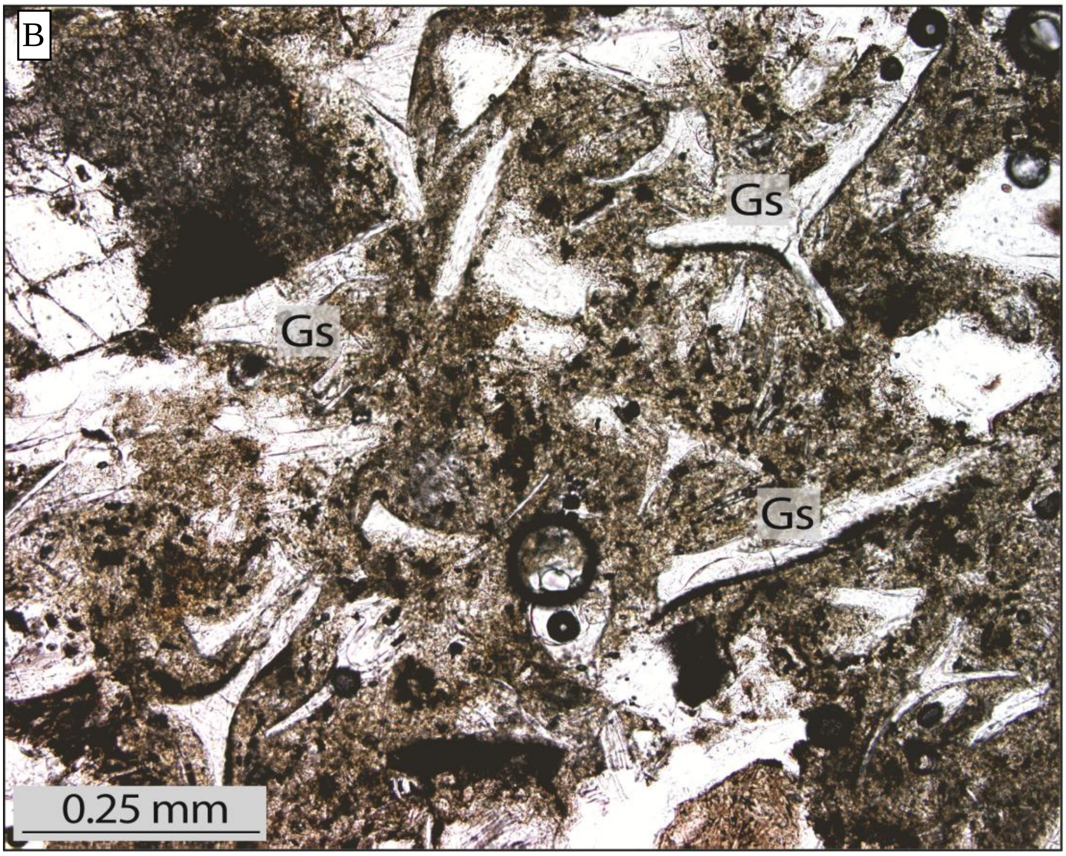


Figure 7.28 – Petrographic images from the volcaniclastite unit within the Wairoa Formation D in the Tahaenui/Clonkeen area. **(A)** Sample 47.2 illustrating a vesicular pumice clast (Pu) near the edge of a mudstone (Mst) lithology with common angular siliciclasts (Si). PPL. **(B)** Sample 57.2 showing Y-shaped glass shards (Gs) indicative of shattered vesicles from an explosive rhyolitic eruption style (Fisher & Schmincke 1984, p. 96). The presence of these shards coincides with the high SiO_2 content of samples (Table 7.3). PPL.

7.3.6 Stable isotope analyses

Table 7.5 presents stable isotope analyses for the Tahaenui Limestone. Some samples were run twice and thus have two sets of data. Figure 7.29 plots the stable isotope data against its $\delta^{18}O$ and $\delta^{13}C$ values. To help discriminate the isotope composition of the cements within the Tahaenui Limestone, the isotope values for the bulk limestone are compared to selected skeletons.

Table 7.5 – Stable isotope data from the Tahaenui Limestone and (Waipipian) skeletons.

Bulk sample	Facies	Locality	$\delta^{13}C$	$\delta^{18}O$
3	L1	Tahaenui	1.56	0.37
			1.43	0.15
107	L1	Long Point	0.57	-0.19
			0.56	-0.15
128.1	L1	Long Point	0.90	0.01

Skeletal sample			$\delta^{13}C$	$\delta^{18}O$
Barnacle	-	-	1.19	0.67
			1.19	0.63
Pectinid	-	-	1.16	0.66
Brachiopod	-	-	1.16	-0.20

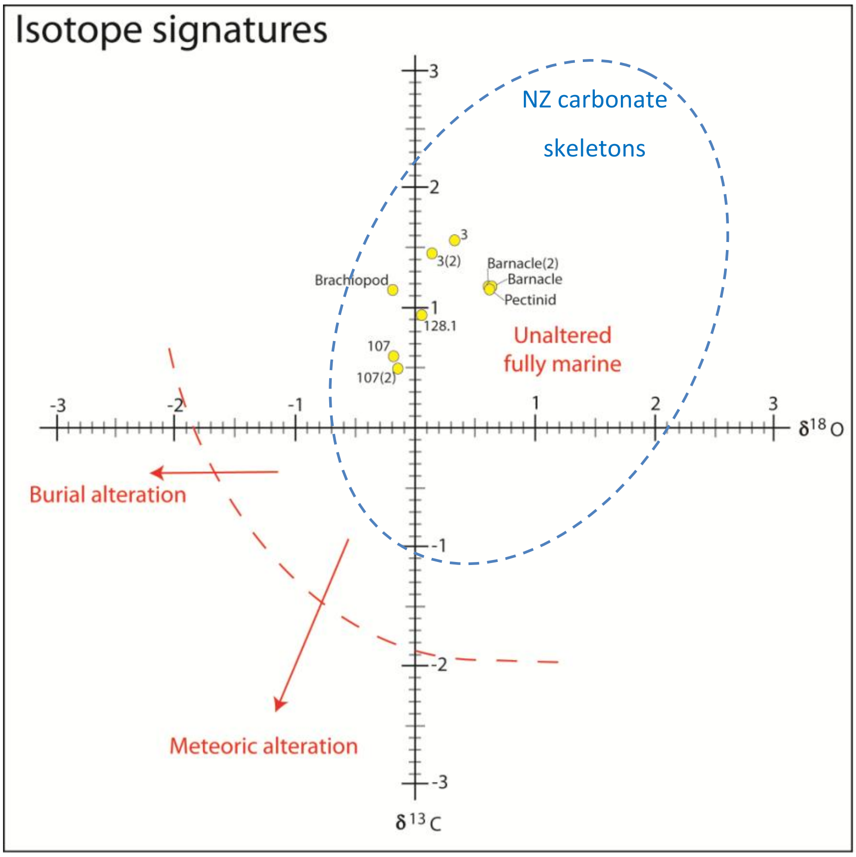


Figure 7.29 –Stable isotope results of the Tahaenui Limestone and barnacle, brachiopod and pectinid skeletal signatures. The Tahaenui Limestone groups within the unaltered area of the grid, yet shows a possible trend towards meteoric alteration. Boundaries of alteration and typical New Zealand skeletons taken from Nelson & Smith (1996).

Three skeletal types were analysed, (namely barnacle, pectinid and brachiopod shells), being the dominant skeletal types in the Tahaenui Limestone. All skeletal results from the Tahaenui Limestone plot within the area for New Zealand carbonate skeletons as defined by Nelson & Smith (1996) (circled in blue), and range from 1.16 to 1.19 $\delta^{13}C$ and -0.20 to 0.63 $\delta^{18}O$ (Table 7.5).

Three bulk samples from the Tahaenui Limestone were analysed and all came from lithofacies L1. The Tahaenui Limestone isotope signatures show a small range of oxygen and carbon values (0.56 to 1.56 $\delta^{13}C$ and -0.19 to 0.37 $\delta^{18}O$) (Table 7.5), and plot closely on the cross-plot. The trend of increasing oxygen and decreasing carbon values hints towards meteoric alteration (Figure 7.29). The bulk sample results plot close to the skeletal signatures (Figure 7.29), perhaps mainly because the volume of cement is relatively low compared with the bulk rock.

7.4 INITIAL PALEOENVIRONMENTAL ANALYSIS

The Tahaenui Limestone was deposited atop and (especially) on the flanks of upthrust anticlines in the vicinity of the northeastern margin of the Pliocene Ruataniwha Strait (Kamp *et al.* 1988; Beu 1995). Structures of the Tahaenui Limestone including massive to vague horizontal bedding with a rare occurrence of small 15 cm scale cross beds. Vague bedding dominates the overall limestone and indicates subtle carbonate shedding events that essentially built up the limestones. Figure 7.30 illustrates a possible depositional setting for the Tahaenui Limestone on the flanks of an upthrust antiform.

The high proportion of barnacle plates in the Tahaenui Limestone indicates a unique environment. The environment of deposition is likely to have been very similar to the environment in which the barnacles lived. The plate-like structure of a barnacle deteriorates rapidly, allowing only short, if any, transport of the barnacle from its living area to the depositional site (Milliman 1974). As filter feeders, barnacles thrive best in siliciclastic sediment-free water conditions. Hence, they are found living near shore on rocky flats or in deeper water where ocean currents sweep the seafloor free of loose sediment (Beu *et al.* 1980). Such ocean currents also prevent siliciclastic burial of barnacles. With a life span of approximately one year, barnacle replacement can occur quickly (Beu *et al.* 1980). With strong tidal currents clearing the eastern Ruataniwha Strait of siliciclastic sediment and a high turnover rate of barnacles, the thick carbonate accumulation of the Tahaenui Limestone could develop.

Based on observed whole barnacle(s), original sizes were up to c.1 cm in diameter and 0.7 cm high. However, the physical sizes of barnacle fragments ranged from approximately 1-3mm, illustrating the abrasion and resizing that sediment working can produce.

The Tahaenui Limestone skeletal components show typically strong to moderate abrasion and varying degrees of sorting. The degree to which these skeletons are reoriented and transported relates to the energy of environment, but also to the strength and shape of the organism (Brett & Baird 1986). In the case of the

Tahaenui Limestone, the large proportions of barnacle plates are tightly packed in parallel alignment to one another, following the gentle dip of the geological unit. This suggests alignment and sediment packing by prevailing marine currents. Petrography shows quite rounded barnacle plates, suggesting a period of high energy and sediment working (shedding from antiforms) before the barnacle fragments were deposited.

The minor amount of siliciclastic sediment in the Tahaenui Limestone (subrounded to subangular grains of fine-medium silt and fine sand size) may reflect deposition upon/about structural highs (where siliciclasts may not be supplied) or that strong tidal currents simply swept the depositional site, by-passing any fine terrigenous material.

Shell beds occur on relatively shallow, storm-dominated shelves (Brett & Baird 1986), the envisaged general environment in which the common shell beds in the lower c.10-15 m portion of the Tahaenui Limestone were deposited. The shell beds (20-50 cm thick) host epifaunal pectinids, brachiopods and oysters. The shell beds can also be interpreted as being *in situ*, with the whole and intact fossils being indicative of the primary area of carbonate formation on the shallowest parts of the antiforms. Stratigraphically higher, these bivalves and brachiopods become much less common and barnacle fragments become the major skeleton.

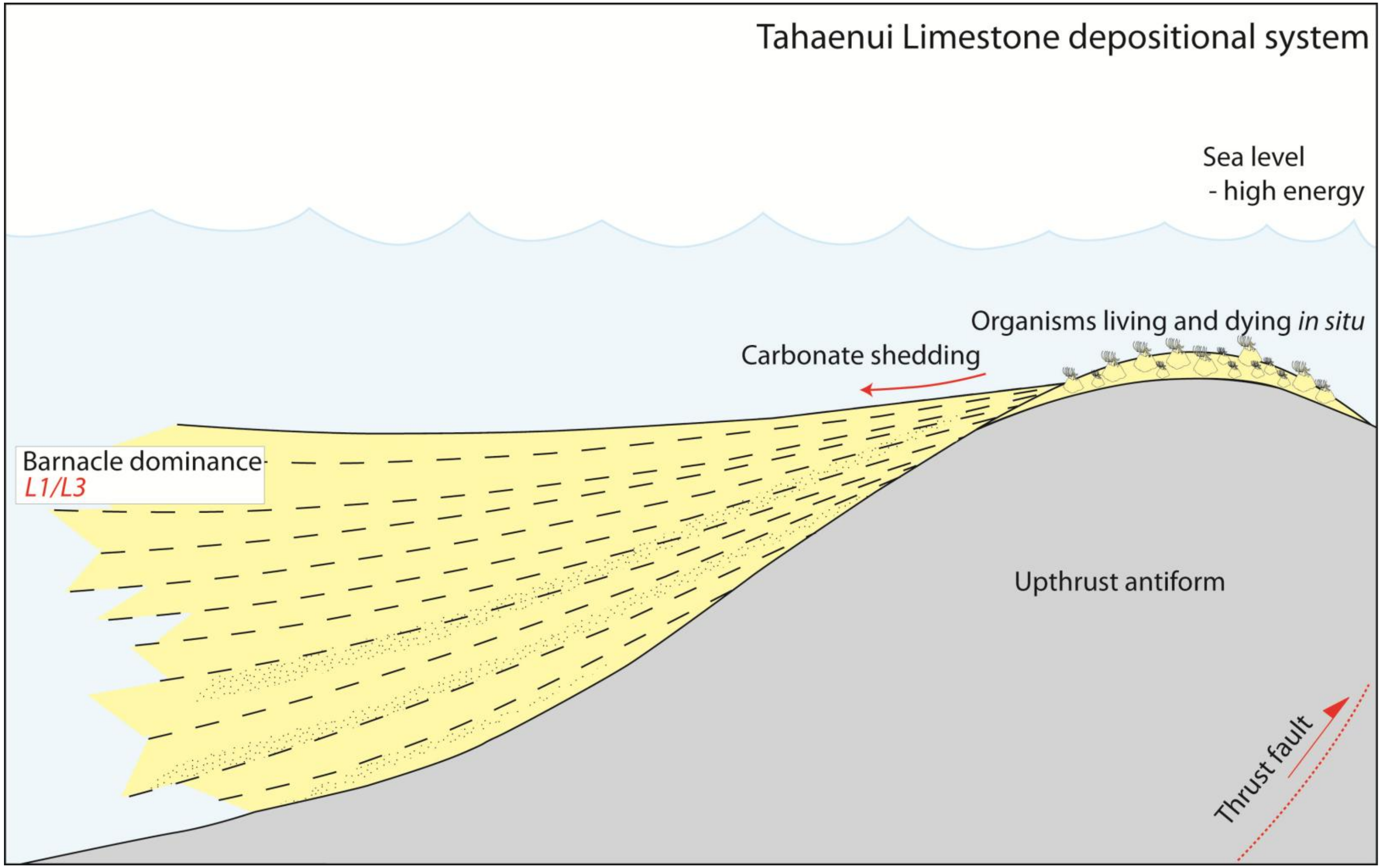


Figure 7.30 – Depositional system for the Tahaenui Limestone. Deposition occurred on and about the upthrust antiforms, with barnacle rich deposits accumulating in relatively shallow and high energy waters. Dashed lines denote vague bedding. Lithofacies are highlighted in red. Vertically exaggerated for clarity, with no scale implied.

CHAPTER EIGHT – DEPOSITIONAL PALEOENVIRONMENTS AND DIAGENETIC EVOLUTION

8.1 TE AUTE LIMESTONES

Within the Mangaheia Group, East Coast limestones are commonly and informally grouped as the **Te Aute limestones** (Lillie 1953; Kingma 1971; Nelson *et al.* 2003). A long standing term, the name 'Te Aute' is derived from the informal rural area in southern Hawke's Bay (Figure 8.1). However, the term has since been rejected as a formal lithostratigraphic name and is only used to informally describe and group the barnacle dominated limestones of the East Coast Basin of North Island (Beu 1995, p. 73). These cool water Pliocene coquina units are widely distributed in eastern North Island (Figure 8.1), forming prominent outcrop ridges and peaks. They are unequivocally non-tropical deposits on the basis of their paleolatitude of deposition (c.40-42˚S) (Nelson *et al.* 2003), their formation within an otherwise siliciclastic dominated basin, a dominance of barnacle, epifaunal bivalve and brachiopod remains, a lack of tropical components such as hermatypic corals, calcareous green algae, ooids and pellets, and a typically high proportion of calcite over aragonite amongst the carbonate mineral phases (Kamp *et al.* 1988).

Te Aute limestones are typically low-Mg calcite (< 5 mol% $MgCO_3$) rich (Kamp *et al.* 1988; Nelson *et al.* 2003) due to the dominance of barnacle and epifaunal bivalve remains. The limestones are coarse calcarenites and calcirudites, with common coquina beds and variable degrees of lithification and siliciclastic mineral content (Nelson *et al.* 2003). Aragonite can be common in some of the limestones, either as original infaunal skeletons (Nelson *et al.* 2003) or as biomoulds (Caron & Nelson 2009). However, most typically any original aragonite appears to have been dissolved prior to lithification, or sometimes afterwards (Kamp *et al.* 1988). Pore spaces can range from 25–50% (Nelson *et al.* 2003). Compositionally, the Te Aute limestones are characterised by their large component of barnacle plates, a rare phenomenon worldwide (Kamp 1992). Benthic and planktic foraminifera, echinoderms and bryozoans are also common, with common pectinid valves (Nelson *et al.* 2003). Deposition occurred within a tectonically derived tidal channelised seaway (Nelson *et al.* 2003) within the shallow subtidal-neritic zone (Ricketts & Nelson 2004). Overall sedimentation rates for the Te Aute carbonates are higher than those for more typical cool water limestones (Nelson *et al.* 2003). Rates of carbonate accumulation varied, with thick units having locally high rates of 10-100 cm/k.y. (Kamp *et al.* 1988; Nelson *et al.* 2003), but are more commonly in the vicinity of c.2-50 cm/k.y. (Caron *et al.* 2004a). Giant cross beds are observed in some southern outcrops of the Te Aute limestones and illustrate the strong tidal current influence on the depositional paleoenvironments, possibly in shallow submarine fans and deltas (Kamp *et al.* 1988).

The older Pliocene Te Aute limestones have greater dips than the younger ones (demonstrating longer exposure to tectonic compression and movement), and towards the eastern side of the Ruataniwha Strait the elevation of the older limestones is higher (illustrating the higher eastern antiforms on which the carbonate accumulated) (Kamp *et al.* 1988). Younger limestones occur closer to the axis of the forearc basin, whereas older limestones occur closer to the margins, where the forearc basin coincides with the antiforms of the subduction complex (Kamp *et al.* 1988).

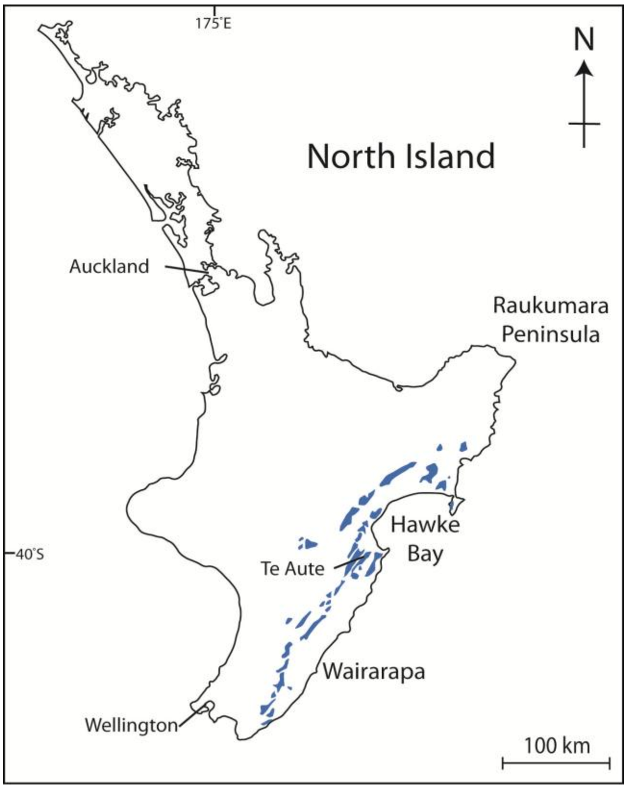


Figure 8.1 - Distribution of East Coast Te Aute Limestones. Adapted from Nelson *et al.* (2003).

8.2 TYPICAL DEPOSITIONAL SETTING

The Te Aute East Coast limestones are unique in New Zealand for their depositional setting. Deposition occurred in a tectonically active subduction zone setting in temperate climatic conditions (Kamp & Nelson 1988). Compressional tectonism resulted in numerous NE-SW striking upthrust antiforms and associated synforms. The antiforms consist of deformed Miocene and older lithologies (Kamp & Nelson 1988). Marine communities grew atop the antiforms which, from the build up of deceased organisms, became sites for carbonate accumulation – the carbonate factory (Figure 8.2). The top of these antiforms would tend to have been largely free of siliciclastic sediment, being swept by the tidal currents that dominated the seaway (Kamp *et al.* 1988).

Periods of limestone accumulation atop the antiforms were usually short lived (Ballance 1993), and occurred in different places at different times (Beu *et al.* 1980). Within such high energy settings the accumulating carbonate sediment could be shed from the growing antiforms into neighbouring synforms, so extending the distribution of reworked carbonate deposits about the antiforms. Prevailing flow patterns could produce giant cross bed structures in these reworked limestones (Ballance 1993).

The primary skeletal taxa living in these antiform settings were heterozoan (cool water, light independent (James 1997)) barnacles, pectinids, brachiopods and oysters. With no hard rock outcrop associated with the antiforms, the barnacle organisms likely used the large epifaunal pectinid (and other) shells as a substrate (Kamp & Nelson 1988), as evident in the Tahaenui area (Figure 7.17 A). Major factors that affected the living skeletal organisms were a high nutrient supply, varying water energy, light penetration and a varying siliciclastic input (Caron *et al.* 2004b). The high abundance of barnacle remains necessitates a high nutrient environment (Beu 1995) which presumably arose from the continual flushing and replenishment provided by the strong tidal flows over the antiformal depositional sites.

The antiformal setting gave rise to the unique shape of these limestone bodies, being more lensoidal rather than 'blanket-like' shelf limestones (Nelson *et al.* 2003). The lensoidal geometry accounts for the rapid thickness variations and patchy distributions of many of the limestone units, while variable thicknesses within a single limestone body could also be due to an uneven paleo-bathymetry (Caron *et al.* 2004a).

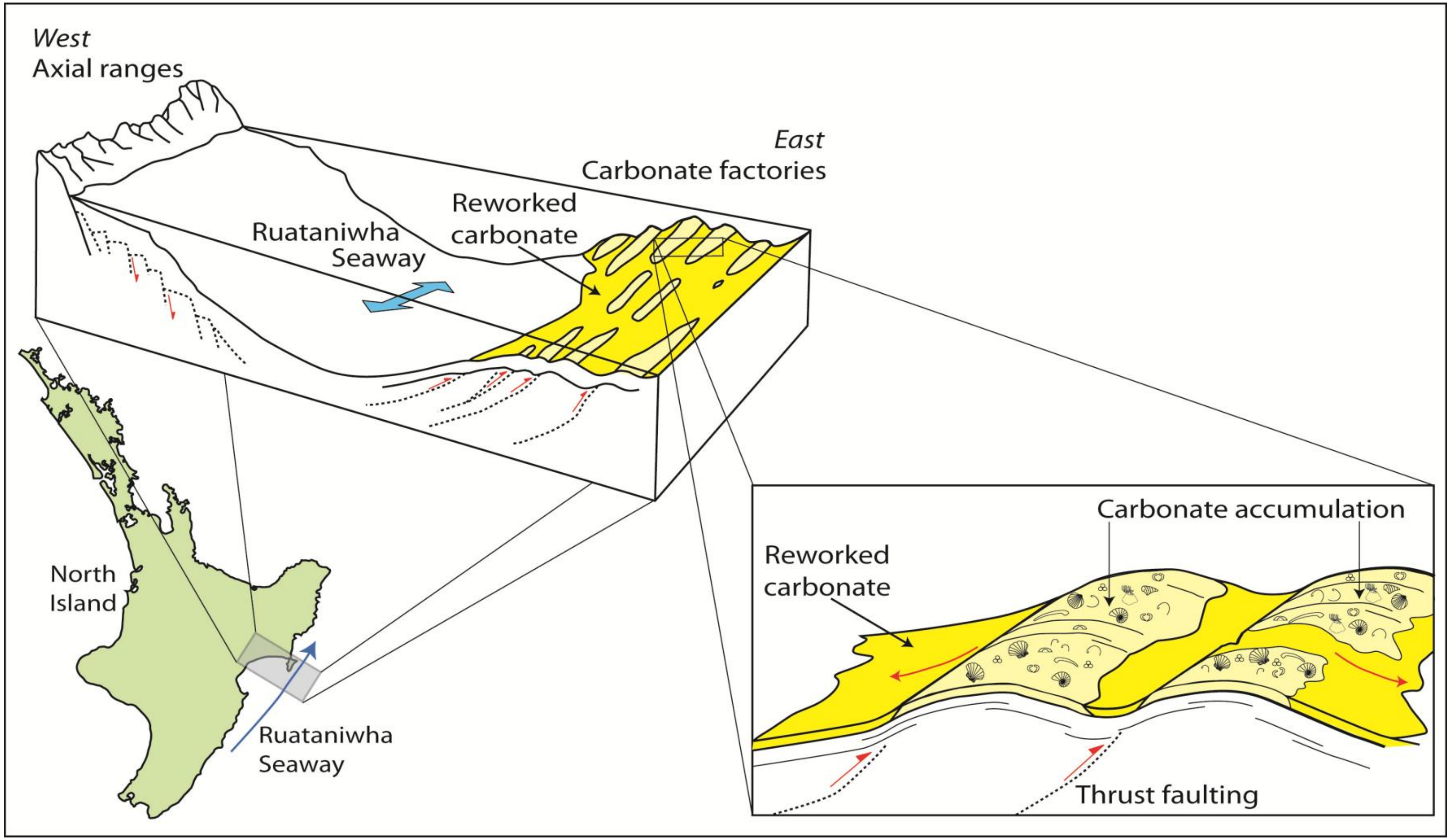


Figure 8.2 – 'Carbonate factory' depositional system for the East Coast Basin Pliocene limestones. Pale yellow areas illustrate sites of primary carbonate accumulation atop antiforms. Bright yellow areas show potential areas for reworked carbonate deposition about the antiforms. Adapted from Nelson *et al.* (2003) and Caron *et al.* (2004a).

8.3 PALEOGEOGRAPHY

Paleogeographic maps illustrating the position of land masses, sea water and different sediment facies during the Opoitian and Waipipian are shown in Figures 8.3 and 8.4 (Bland *et al.* 2008). The deposition of Opoiti Limestone on Mahia Peninsula is shown in Figure 8.3 A, followed by the rhythmic deposition associated with Whakapunake Limestone in Figure 8.3 B. Figure 8.4 A shows the area of Pliocene sediments that underwent a period of erosion before the Tahaenui Limestone was deposited unconformably upon late Miocene mudstones during the upper Waipipian (Figure 8.4 B). White stipple shows the widespread extent of the deposition of the siliciclastic dominated Wairoa Formation. Throughout the deposition of all limestones the sea water depths were likely less than 50 m (Figures 8.3, 8.4) (Bland *et al.* 2008).

The area that is presently a sandy isthmus connecting Mahia Peninsula to the mainland was probably a small marine strait (here name Mahia Paleostrait) during much of the Pliocene (Figure 8.3 B, Figure 8.5) (Bland *et al.* 2008). If so, this would have separated limestone formation in the Nuhaka area from that on Mahia Peninsula. On the western side, where the Tahaenui and Opoiti Limestones now seen at Tahaenui/Clonkeen and Mt Moumoukai occur within the Nuhaka Syncline, carbonate was accumulating associated with one antiform system. On the eastern side of the paleo-strait, on Mahia Peninsula, age equivalent limestones were formed about another antiform system. Both areas would have been dominated by high energy shallow marine conditions.

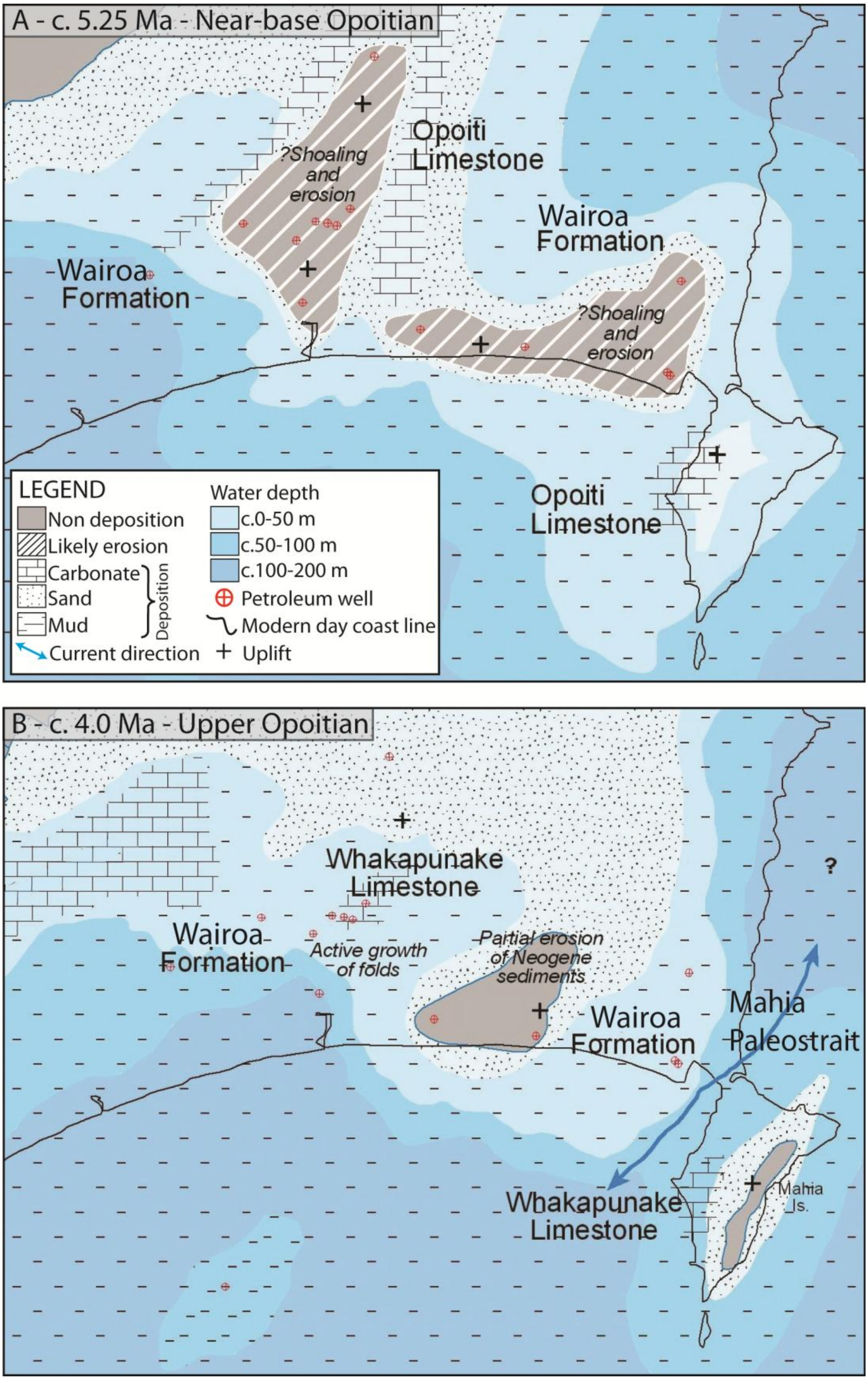
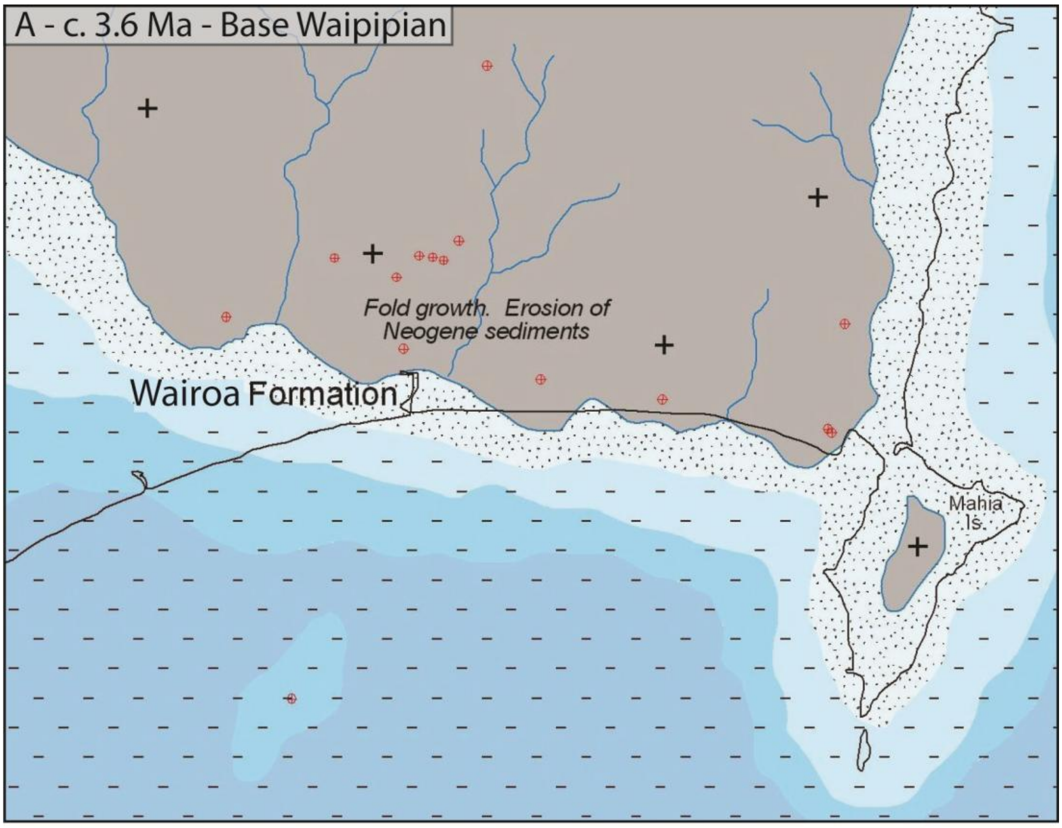


Figure 8.3 – Paleogeographic maps during the Opoitian. Deposition of the Opoiti (A) and Whakapunake (B) Limestone is shown. Legend in A applies to all maps in Figures 8.3 and 8.4. Adapted from Bland *et al.* (2008).



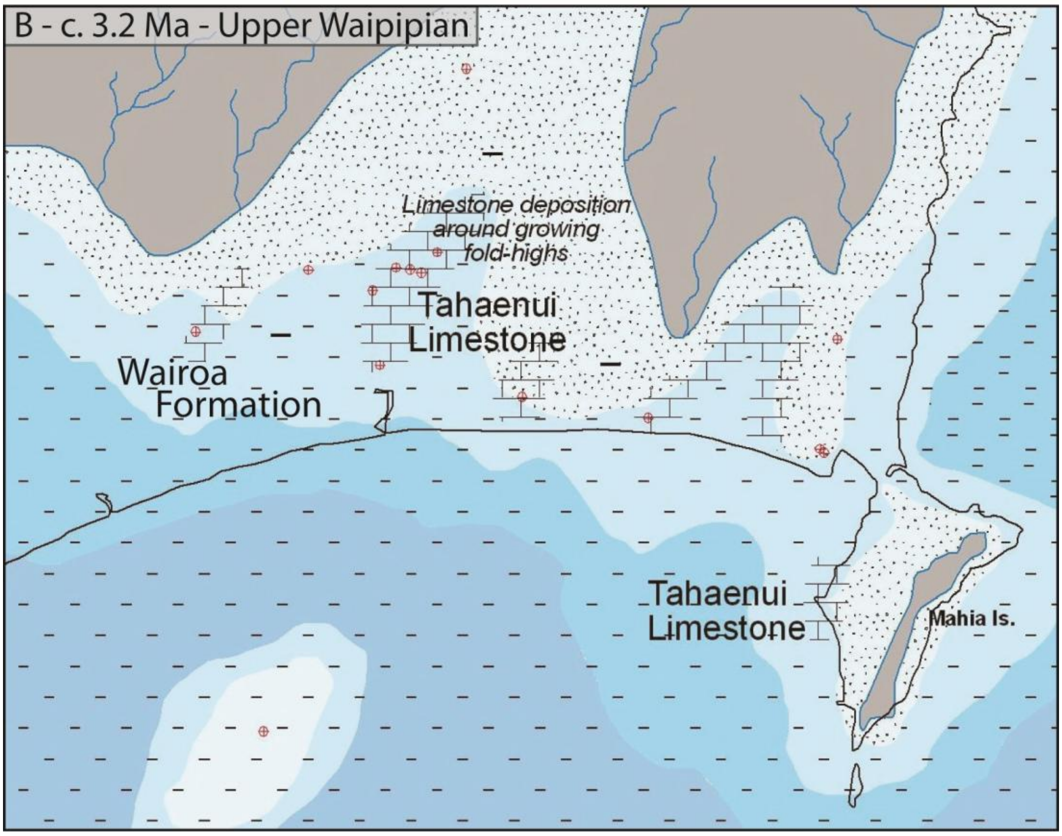


Figure 8.4 - Paleogeographic maps during the Waipipian. During the early Waipipian widespread erosion occurred, shown in A. Deposition of the Tahaenui Limestone is shown in B. Refer to Figure 8.3 A for legend. Adapted from Bland *et al.* (2008).

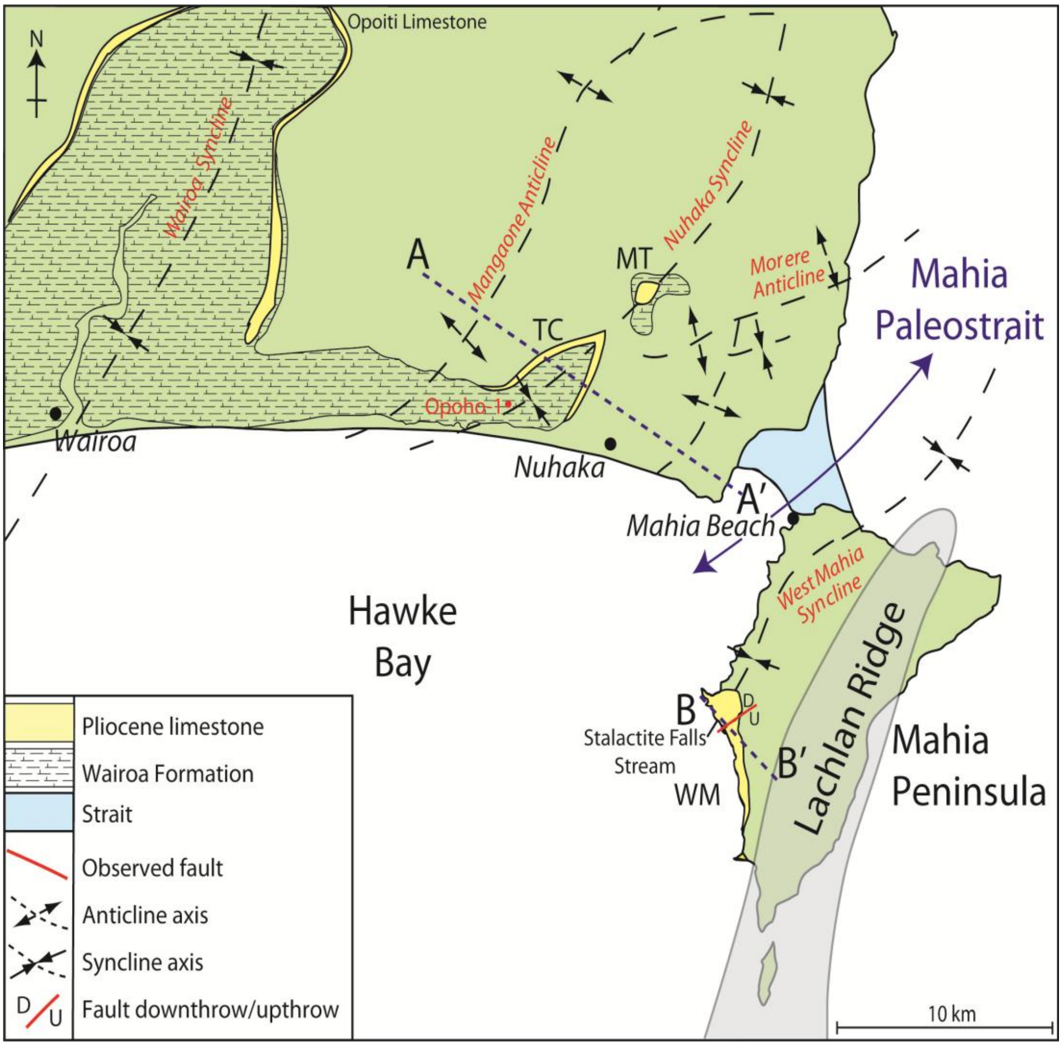


Figure 8.5 – Location of antiform and synform structures in the immediate field area in relation to the Pliocene limestone distributions (yellow). Throughout the Opoitian to Waipipian the Mahia Peninsula was probably separated from the Nuhaka area by the NE-SW oriented Mahia Paleostrait (Bland *et al.* 2008). The present day land mass (green) and coast line are shown for location reference. Land mass distribution during deposition of the Pliocene limestones is illustrated in Figures 8.3 and 8.4. Two cross sections at A-A' and B-B' are shown in Figures 8.7 and 8.9. TC – Tahaenui/Clonkeen area, MT – Mt Moumoukai area, WM – West Mahia area.

8.4 DEPOSITIONAL CONTROLS

The Te Aute limestones have been very much influenced during deposition by their active tectonic setting, both directly and indirectly. Tectonic movements, dominant tidal flows, varying siliciclastic sediment supply and changing sea levels have collectively produced a unique environment for carbonate production. Paleomagnetic pole considerations suggest that limestone deposition occurred at paleolatitudes near 40–42°S (Nelson *et al.* 2003). Between the middle Miocene and early Pleistocene when the Hawke's Bay limestones were accumulating, there was a general decline of oceanic temperatures (Beu 1990).

8.4.1 Tectonics

The antiformal structures derived during the Pliocene in the East Coast Basin are specifically tectonic in origin. Without these any limestone deposition would have been considerably different, and even perhaps mainly absent. The elongated but lensoidal shape of many of the limestone bodies reflects primarily the roughly northeast-southwest orientations of the antiforms on which the carbonates accumulated, but also the northeast-southwest tidal flow regime within the northeast-southwest directed seaway (Kamp 1988, p. 174).

The onset of the Miocene (c.23 Ma) in the forearc is characterized by a deepening of water depths, due to overall subsidence of the margin (Buret *et al.* 1997), and is characterised by common flysch deposits. The increase of carbonate production during the Pliocene in the forearc basin area resulted from tectonic shallowing (Kamp & Nelson 1987), widening the range of organisms that would find the antiformal environment suitable for living.

The overall subduction complex and antiform structures may have been slightly deeper during Opoiti Limestone deposition in the early Opoitian, allowing the dominant componentry of siliciclastic sediment to more easily reach the antiform summits. Through tectonic compression, the subduction complex and antiform structures would have grown in elevation into shallower water depths during deposition of the younger, barnacle pure, Tahaenui Limestone in the Waipipian. Tectonic subsidence during the late Waipipian (c.3.0 Ma) resulted in termination of the carbonate factories and burial by mud-dominated sediments (Ballance 1993).

8.4.2 Tidal influence

Factors suggesting that the Te Aute limestone were associated with a predominantly tidal current dominated setting include bedding patterns (e.g. bidirectional cross beds), paleogeographic interpretations and the unique primary barnacle composition (Kamp *et al.* 1988). Bound to the west by the axial ranges, the forearc basin became the site of a long tidal seaway, which Beu (1995) named the Ruataniwha Strait. Paleogeographic reconstructions show a long (450 km), narrow (30-50 km) structure (Kamp *et al.* 1988), open on its northern and southern ends, and bounded by western and eastern 'highs' (Figure 8.2). Accelerated tidal flows through this northeast-southwest seaway provided the high nutrient levels that attracted and supported the barnacle dominated communities, so giving the eastern North Island's Te Aute limestones their distinctive barnacle-rich make up.

Lithological bedding patterns within the limestones also show the nature in which they were deposited. Giant cross beds can be common, especially in central and southern Hawke's Bay (Kamp *et al.* 1988; Bland 2001). However, in the Nuhaka/Mahia Peninsula area sedimentary structures in the limestones are dominated by horizontal bedding with only occasional (10-20 cm high) cross beds. This may suggest that sufficient tidal flow capable of producing giant cross beds was not occurring in the northeastern portion as it was within the expanded Ruataniwha Strait, although locally strong tidal currents would be anticipated through the Mahia Paleostrait (Figure 8.5).

The tidal current dominated seaway setting was essential to the high proportion of barnacles that make up many of the Te Aute limestones, and in particular the Tahaenui Limestone in the present study area. Tidal flows continually renewed the seaway with fresh nutrient supplies and also tended to bypass much of the finer siliciclastic sediment allowing barnacle to thrive (Nelson *et al.* 2003).

8.4.3 Siliciclastic sediment supply

The overall Pliocene sedimentary succession in the Nuhaka-Mahia area is dominated by fine grained marine siliciclastic sediments (Wairoa Formation).

Greywacke basement and reworked Miocene sediments are the likely sources for siliciclastic sediment contributions in the area (Bland 2001), probably sourced from the northern Wairoa area or from shoaling between the 'main land' and the unconnected Mahia Peninsula (Figures 8.3, 8.4). Dominant clays in the Wairoa Formation are illite and chlorite (refer to section 4.3.3). Tectonic movements can influence the amount of supplied terrigenous sediment, which affects the type and abundance of organisms that inhabit an area (Kamp & Nelson 1987). Large amounts of siliciclastic sediment input would 'suffocate' any growing carbonate taxa. Consequently, where the limestones are thickest the siliciclastic input must have been relatively low. Pliocene volcaniclastic deposits also supplied small amounts of pumiceous material throughout the Wairoa Formation.

The Opoiti Limestone is considerably more siliciclastic rich than the younger limestones, suggesting that the supply of siliciclastic material was rather higher during this older period than during deposition of the overlying Whakapunake and Tahaenui Limestones. The Opoiti Limestone in the field area may have been more 'shore connected' as a continued 'sheet' near shore about the northern 'closure' end of the Ruataniwha Strait.

8.4.4 Sea level

The Pliocene-Pleistocene is a period of recognized fluctuations in sea level, based originally on cyclical variations in the value of oxygen ($\delta^{18}O$) isotopes measured on deep-sea foraminifera (see Figure 9.3, section 9.3.1) (Beu & Edwards 1984). These sea level fluctuations resulted primarily from alternating glacial and interglacial periods, with superimposed tectonic movements. The Pliocene strata in the East Coast Basin can record these high frequency glacio-eustatic oscillations (Caron *et al.* 2004a) and indicate that the late Pliocene carbonates only formed during glacial phases (Kamp & Nelson 1987). Sea level fluctuations in the East Coast region could be up to c.50 m in amplitude (Kamp & Nelson 1988). Sufficient sea level decrease to subaerially expose the three limestones did not occur until the mid-late Nukumaruan (Bland *et al.* 2008).

Because carbonate accumulation was relatively slow, the growing limestones would be quite sensitive to any sea level changes (Caron *et al.* 2004b). During sea level rise, the carbonates can become flooded with siliciclastic grains, ceasing carbonate accumulation (Caron *et al.* 2004b). Because the Pliocene limestones can often be quite thick deposits, the sea level and growing carbonates must have reached a balance.

8.5 PALEOENVIRONMENTS

The analysis of possible paleoenvironments is fundamental to developing a deposition model(s) for the limestones. The paleoenvironment for the Pliocene limestones was within a shallow water, moderate to high energy setting influenced by strong tidal currents that ensured a high nutrient supply. The main sites of primary carbonate accumulation, the antiformal ridges, are likely to have been at depths of 30-60 m (Kamp & Nelson 1987; Caron *et al.* 2004b).

Suspension/filter feeders (e.g. barnacles, bryozoans, pectinids and oysters) are sensitive to high rates of siliciclastic input (Caron *et al.* 2004a). The large abundance of these skeletal types in the limestones supports relatively low amounts of siliciclastic grains in the immediately overlying water column. The unique dominance of barnacles is due to environmental conditions that favoured and encouraged barnacle growth, but also that deterred the growth of other taxa. The very high proportions of barnacles in many of the studied limestones require an environment largely siliciclastic sediment free with a sufficiently high nutrient supply. The tidal swept, tectonically elevated antiforms acting as carbonate production sites would have been ideal for barnacle growth. Some bryozoans do occur throughout the Pliocene limestones, but do not compare with the large populations observed in other New Zealand limestones (e.g. Nelson 1978). The relatively low content of bryozoans in the Mahia district limestones could be due to competition with large populations of barnacles, or to the high energy environment (Kamp *et al.* 1988). As shown by the degree of disarticulation, fragmentation and abrasion, the skeletal components were frequently reworked and transported before final deposition and cementation as a limestone unit. Common shell beds occur throughout the Tahaenui Limestone, and occasionally within the Whakapunake and Opoiti Limestones, and may be indicative of current lag deposits (Kamp *et al.* 1988).

The sedimentary structures within the northern Hawke's Bay limestones - horizontal bedding and laminations in the Opoiti Limestone, rhythmic carbonate-siliciclastic storm event beds in the Whakapunake Limestone and small scale shallow cross bedding and vague horizontal bedding in the Tahaenui Limestone – highlight a tidal current influence on sedimentation patterns during deposition.

The small scale (10-20 cm) cross bedding observed on Long Point may indicate stratification derived from changing prevailing tidal flows. The eminent to vague horizontal bedding commonly seen in all limestones, and particularly in the Opoiti Limestone at Ahimanawa Station, represents shedding of carbonate from the antiforms highs.

The relationship of the carbonates to the anti/synforms is likely to be penecontemporaneous, with the carbonates accumulating and forming simultaneously to the anti/synforms being upthrust and deformed. If the antiforms had predated any limestone accumulation and were completely formed prior to any limestone deposition then more erosion of underlying (Miocene) lithologies could have occurred and the subsequent limestone would have been deposited with a basal unconformity which represents a greater period of time than the present unconformities. This situation is possible in the Nuhaka/Mahia study area where, in all localities, the base of Pliocene sediment is underlain unconformably by late Miocene mudstone. However, if carbonate deposition occurred before any tectonic anti/synform structures were apparent then limestone componentry would be considerably different (skeleton types, siliciclastic percents), and the limestone units would have had wider distribution and a more uniform thickness. Therefore limestone accumulation was likely syndepositional with the growing anti/synforms.

The summarising and comparing of field-laboratory characteristics of the northern Hawke's Bay limestones can hint at their paleoenvironment of deposition (Figure 8.6). Carbonate values can indicate the 'purity' of the environment, with siliciclastic values indicating the proximity or otherwise of a ready source of sandy material. For the Tahaenui Limestone, for example, a large content of carbonate vs. a small amount of siliciclastic material indicates that the paleoenvironment hosted beneficial conditions (sufficient light/substrate/nutrient supply) to attract and sustain a large population of organisms and that there was not a major source and input of siliciclastics from nearby. Skeletal componentry can indicate the paleoenvironment based on their known preferred living environments, (e.g. knowing that barnacles require a high nutrient supply implies a source of renewable nutrients).

Paleoenvironmental energy can be inferred from lithologies observed in the field. Typically mudstones are deposited in low energy waters (Figure 8.6) where fine grained siliciclastic sediment is able to settle. In contrast, cool water skeletal carbonates typify deposition in high energy environments.

8.5.1 Tahaenui/Clonkeen

The bedded Tahaenui Limestone, where it outcrops within the Nuhaka Syncline, is likely to represent rhythmic event deposits shed from, but proximal to, the upper portions of the developing Mangaone and Morere antiforms (Anticlines) (Figure 8.7). The variable dips recorded in the Tahaenui Limestone in the Nuhaka region might well have derived from a coeval asymmetrical synform system from which the accumulating carbonate sediments took their attitude. Because the tops of the modern day Mangaone and Morere Anticlines have been eroded *in situ*, no remains of the probably original carbonate factories are observed. Continued tectonic compression has likely 'tightened' the syncline further, enhancing the degree of dip. Carbonate sheddings from the Morere antiform towards the east into the Mahia Paleostrait was probable, but may never have been preserved due to the likely accelerated tidal flows that could have swept the seafloor clear of any loose sediment. The broad scale and relatively gentle dip (c.10˚) of the strata either side of the Wairoa Syncline meant that any carbonate shed in a westerly direction would have formed more 'sheet-like' deposits, a topic addressed in the companion MSc study by Jared Jiang.

The Tahaenui Limestone was encountered at a depth of c.200 m in the Opoho-1 well (Figures 8.5, 8.7) (Ian R Brown Associates 1998) located near the centre of the Nuhaka Syncline, which implies that the limestone reached, or came very near to, the synform trough. Here it is up to 32 m in thickness, although, because of the dip of the unit, this measure is not the vertical thickness. On the basis that the Tahaenui Limestone is apparent near the base of the Nuhaka Syncline, this suggests that the position of the paleo-antiforms/synforms in this area may have been quite close and narrow to allow carbonate to shed as far laterally as the near bottom of the synform (Figure 8.7).

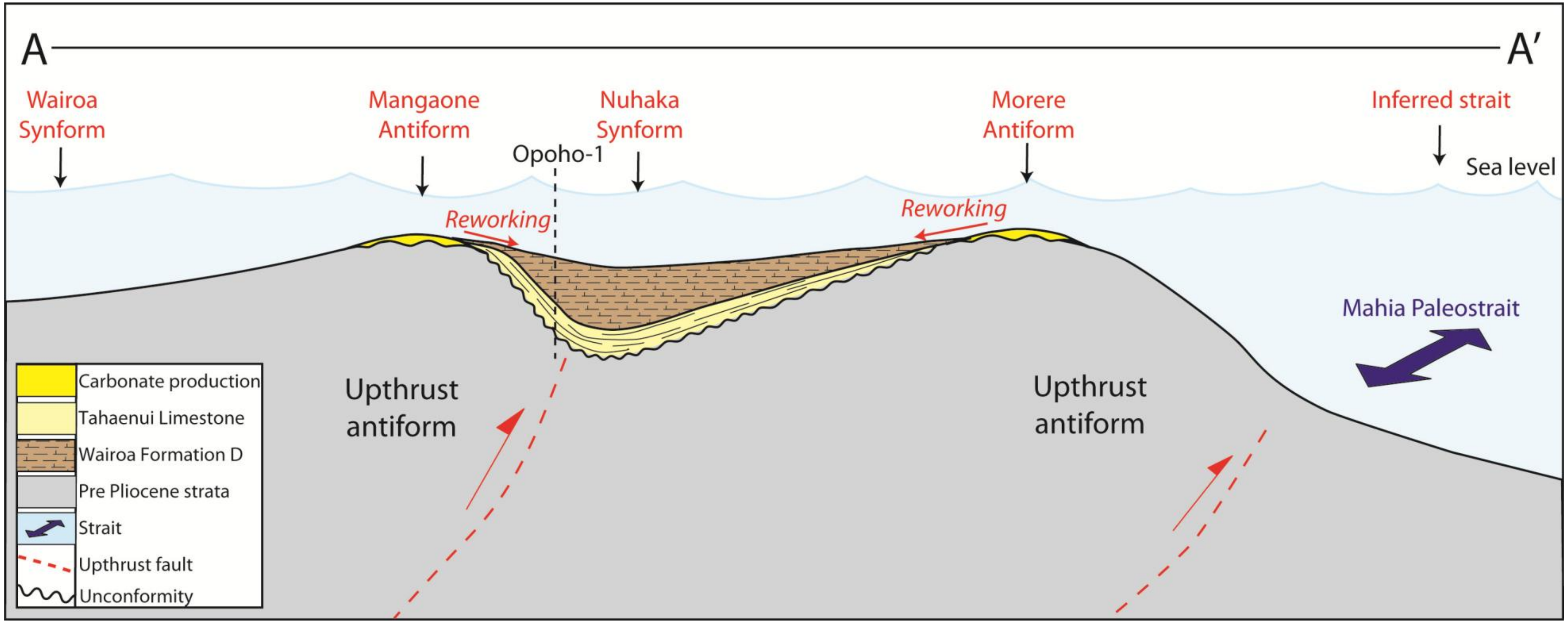


Figure 8.7 – Schematic cross section through A-A’ on Figure 8.5 illustrating the possible general setting for Tahaenui Limestone development in the Nuhaka area, in relation to neighbouring antiform and synform structures. No lateral or vertical scale implied.

8.5.2 Mt Moumoukai

The Opoiti Limestone that forms the base of Mt Moumoukai could possibly be a lateral extension of the larger 'sheet-like' Opoiti Limestone that crops out in the wider Wairoa district (Figure 8.5). However, because the two areas are separated by the Mangaone Anticline (Figure 8.5), it may simply be a small isolated area of carbonate production occurring at the same time as its main sheet-like counterpart to the westnorthwest. At Mt Moumoukai, the Opoiti Limestone unconformably overlies late Miocene mudstone. Opoitian aged transgressive sandstone (Wairoa Formation B) overlies the Opoiti Limestone (Figure 8.8.A), above which a mild transgressive erosional angular unconformity truncates the Opoitian lithologies (Figure 8.8.B) with deposition of the Waipipian aged Tahaenui Limestone (Figure 8.8.C) (Beu 1995; Field *et al.* 1997). Subsequent uplift and subaerial erosion has shaped the mountain into its present day topography. Mt Moumoukai hosts dominant L3 lithofacies in both the Tahaenui and Opoiti Limestones, deposited with a high influx of siliciclastic material, with some lithofacies L1 nearer to the top of the Tahaenui Limestone.

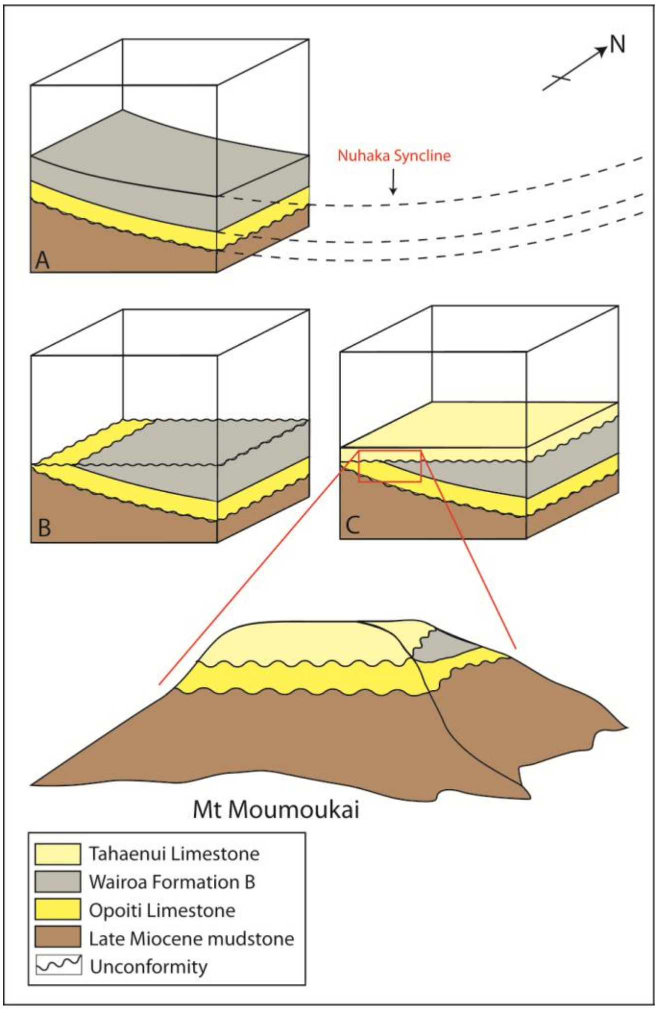


Figure 8.8 – Formation of Mt Moumoukai (Figure 5.2) with the deposition of the Opoiti Limestone unconformably overlying late Miocene mudstone. Tahaenui Limestone is separated from the Opoiti Limestone and Wairoa Formation B by a mild angular unconformity.

8.5.3 Mahia Peninsula

Mahia Peninsula is structurally dominated by the West Mahia Syncline and the Lachlan Ridge (Figure 8.5). Each of the three Pliocene limestones accumulated by carbonate shedding from near the 'crest' of the Lachlan Ridge westwards into the developing West Mahia Syncline. Opoiti Limestone, the oldest, was deposited during the early Opoitian upon a scoured unconformity surface across late Miocene mudstone. The relatively large amount of siliciclastic sediment within the Opoiti Limestone could have been sourced from the nearby shoaling Mahia Paleostrait that separates the peninsula from the 'main land' (Figures 8.3, 8.5). The Opoiti Limestone grades upwards into siliciclastic dominated Wairoa Formation B. The Whakapunake Limestone accumulated in the late Opoitian, with its unique limestone-sandstone couplets indicating rhythmic sedimentation, likely derived from storm events. As no lower contact is observed, initial sedimentation development remains unknown. The Whakapunake Limestone grades rapidly via sharp interbeds into Wairoa Formation C. The Whakapunake Limestone could be evidence for syndepositional tectonic movements while the carbonate was depositing, indicating likely tectonic highs and lows resulting in siliciclastic-bioclastic interbeds. Sedimentation styles on Mahia Peninsula are dominated by vague to eminent bedding (Opoiti Limestone, lithofacies L2/L3), rhythmic storm event couplets (Whakapunake Limestone, lithofacies L3/S4) and vague to massive bedding (Tahaenui Limestone, lithofacies L1).

Because the youngest limestone, the Tahaenui Limestone, on Mahia Peninsula unconformably overlies late Miocene mudstone, its depositional evolution is slightly more complex. There are two possible explanations. The first involves a lengthy time period during which the entire succession from the upper Whakapunake Limestone to the basal Opoiti limestone was completely eroded away, allowing the Tahaenui Limestone to sit directly on the late Miocene mudstone. Because this scenario involves a significant amount of erosion that is not alluded to elsewhere, it is considered the more unlikely. The second is that the Tahaenui Limestone was deposited in a different lateral section of the West Mahia Syncline where there had previously been minimal Pliocene deposition (Figure 8.9). This would rationalise the Tahaenui Limestone sitting directly atop late Miocene mudstone. The abundance of barnacles and rarity of siliciclasts in the limestone suggests distance from any immediate major source of sandy material.

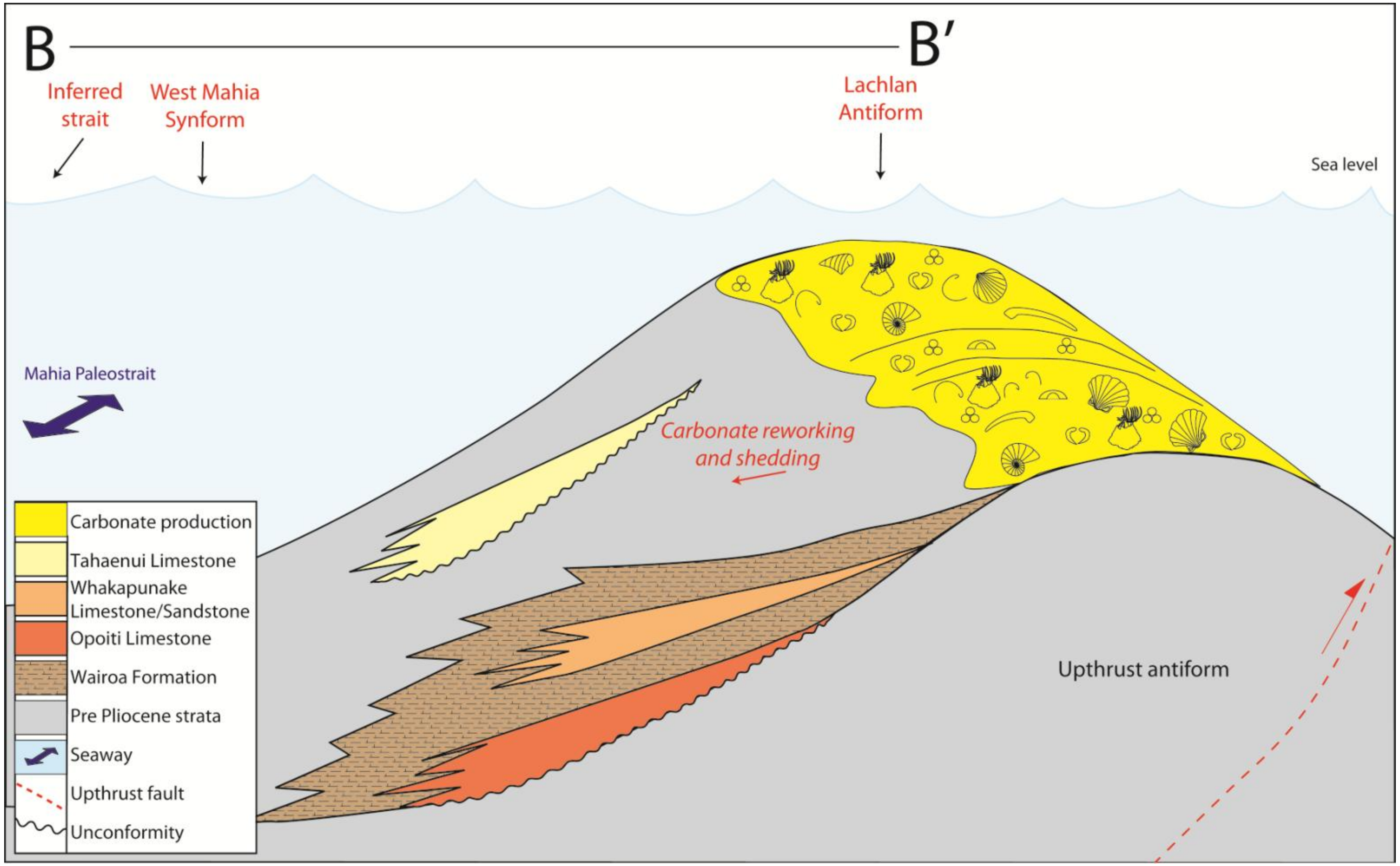


Figure 8.9 – Schematic cross section through B-B' on Figure 8.5 illustrating the possible general setting for Opoiti, Whakapunake and Tahaenui Limestone development in the West Mahia Syncline, in relation to the adjacent Lachlan Ridge. This model illustrates the Tahaenui Limestone being deposited in a different lateral portion of the Lachlan antiform/West Mahia synform system. The Opoiti and Whakapunake Limestones are encased within Wairoa Formation. No lateral or vertical scale implied.

8.6 DIAGENETIC CONSIDERATIONS

Through diagenesis the loose marine carbonate sediments are lithified into hard limestone. The cementation process where loose grains are fixed together usually preserves skeletal structures. Sparry calcite (sparite) precipitates in the inter- and intra-particle pore spaces of the skeletal carbonate grains as part of the lithification process. Plio-Pleistocene limestones in New Zealand have mainly not undergone significant burial (compared to many pre-Pliocene limestones) and are typically quite variably cemented with high porosities (Nelson 1978). These limestones are dominated by low-Mg calcite cements (Kamp & Nelson 1988). The stability sequence amongst carbonate minerals is low-Mg calcite > aragonite > high-Mg calcite (Milliman 1974; Nelson 1978). The preservation of skeletal grains may reflect their mineralogy. While low-Mg calcite secretors dominate the Pliocene limestones in northern Hawke's Bay, small amounts of original aragonite do occur. The content of aragonite could originally have been rather higher, sourced from infaunal bivalves, but can be selectively dissolved during diagenesis. Temperate water carbonate diagenesis is typically rather destructive involving considerable physical, biological and chemical abrasion and alteration of skeletal material (Smith & Nelson 2002).

During high energy conditions and rapid burial, the formation of pyrite within shell chambers can occur as an early diagenetic reaction (Brett & Baird 1986). Pyrite is ubiquitous throughout the Mangaheia Group limestones, especially inside foraminiferal tests (Figure 8.10).

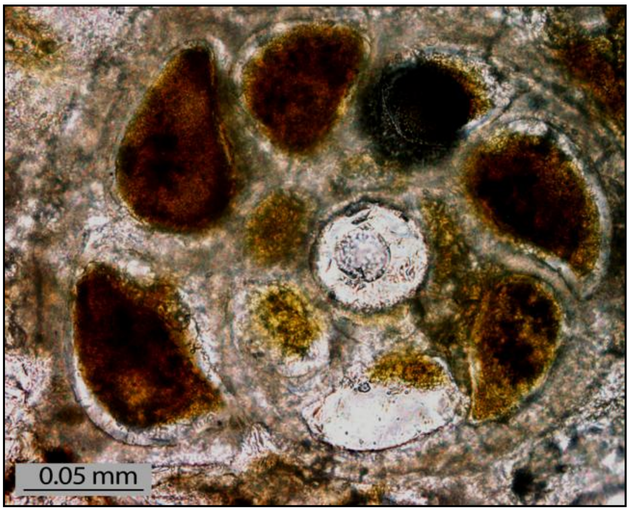


Figure 8.10 – Photomicrograph of pyrite infilled chambers of a benthic foraminiferal test, Opoiti Limestone at Hekerangi Point, Sample 129.8. PPL.

8.6.1 Petrography

The typical cementation scenario for the northern Hawke's Bay Pliocene limestones involves primarily the introduction and lithification of microbioclastic micrite (Figures 5.18 A, 8.11) and/or the precipitation of isopachous sparite fringes (Figures 7.24, 8.12). While both cement types occur in each limestone in all localities, microbioclastic micrite dominates in the Opoiti and Whakapunake Limestones and isopachous sparite rims in the Tahaenui Limestone. Rarely are the cements seen together in one sample. It is likely that different portions of the different skeletal carbonate sediments are cemented based on the availability of carbonate mud and fine grained broken shell material - microbioclastic micrite. Where microbioclastic micrite was generally unavailable, perhaps due to tidal current by-passing, cementation was dominated by sparite precipitation. Isopachous sparite rims typically precipitate at or near below the seafloor, under conditions of only shallow burial (e.g. Nelson & James 2000). Fresh water, or diluted sea water, originating as a ground water lens may be the source of any meteoric alteration of this sparite cement (Kamp & Nelson 1988).

The microbioclastic micrite appears as fine grained (up to c.0.2 mm) smashed up skeletal material, often including common siliciclasts. Isopachous sparite rims are typically clear, thin and can be wispy or dogtoothed in their crystal shapes (Figures 7.24 B, 8.12). These isopachous sparite rims especially favour barnacles as host grains, and to a lesser degree pectinids, indicating the preference of a siliciclastic sediment free environment for sparite cementation.

Interskeletal space is quite large in all samples, indicative of an uncompacted and open fabric prior to, and during, initial cementation. This allowed large amounts of cement, especially microbioclastic micrite, to permeate between the carbonate grains. Though limestone portions with current dominant microbioclastic micrite cements may have had the most open fabric initially (up to c.50%), the pore space has been infilled with microbioclastic micrite. Sparite dominated samples would have initially had less interskeletal space, but because of the thin nature of the precipitated isopachous rims the majority of this space is still open and the whole rock retains a more open porosity. The level of original permeability within a limestone unit would influence the amount of meteoric alteration, and associated cementation, that could occur (Hood & Nelson 1996), and is here seen by the original interskeletal space infilled with microbioclastic micrite or isopachous sparite rims.

Pressure dissolution is sporadic in the northern Hawke's Bay Pliocene limestones, partly a consequence of differing burial pressures and depths. It is most common in the oldest Opoiti Limestone, but can also to be observed in the Tahaenui Limestone to some degree. Generally a small amount of cement can be seen near or at the contact zones (Figure 7.22 A), suggesting that cementation occurred contemporaneously with burial.

Overall, the dominance of 'clean' isopachous sparite rims, of typically open fabrics, of preserved original porosities and of the CL growth patterns in sparite cements it is considered that most of the diagenetic changes during very shallow (c.10s of metres) burial phreatic conditions (Scholle & Ulmer-Scholle 2003).

Outcrops of the Te Aute limestones in southern Hawke's Bay tend to have mainly 'clean' cements with only small to rare amounts of microbioclastic micrite (e.g. Caron 2002). The commonness of microbioclastic micrite in the northern Hawke's Bay limestones suggests some subtly depositional-diagenetic settings compared to their southern counterparts.

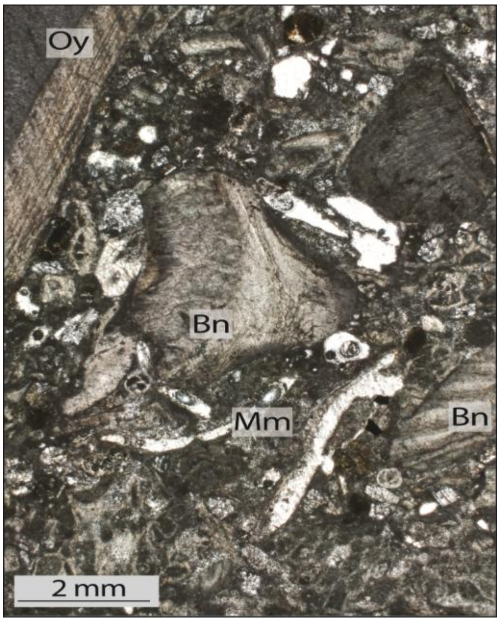


Figure 8.11 – Photomicrograph of coarse microbioclastic micrite. Note how the interskeletal space is quite large, but has been infilled with microbioclastic micrite. Sample 58.1, Tahaenui Limestone at Tahaenui/Clonkeen. PPL.

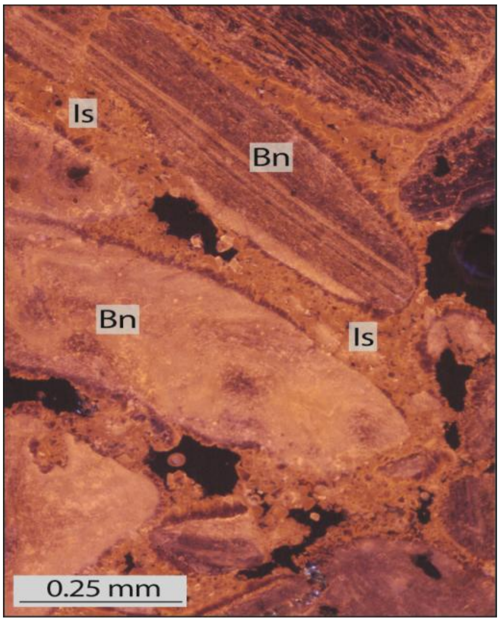


Figure 8.12 – Photomicrograph of dogtooth isopachous sparite rims under CL with non-orange to yellow illumination indicative of phreatic cementation in a shallow burial environment. Interskeletal space is lower than in microbioclastic samples (Figure 8.11) but hosts higher modern porosity. Sample 16, Tahaenui Limestone at Tahaenui/Clonkeen.

8.6.2 Stable isotope analyses

A combined $\delta^{18}O$ vs. $\delta\ ^{13}C$ plot involving samples from all the northern Hawke's Bay Pliocene limestone is shown in Figure 8.13. The $\delta^{18}O$ and $\delta\ ^{13}C$ values for the Te Aute limestones generally show a broad range, from small positive to moderately negative values, with an average of +1.5‰ carbon isotopes (Nelson *et al.* 2003).

To gauge some idea of the possible isotope composition of the cements within each limestone, the isotope values of bulk limestone samples are compared to those for some separated individual skeletons. Differences between these two groups could relate to the cementation environment. The approach was necessary because it was not possible to obtain discrete drilled powders of the different cement types. In the event the bulk samples plot close to their dominant skeletal samples, presumably reflecting the relatively small volume of cements in the bulk rock as a whole. The overall near 0 to positive $\delta^{18}O$ isotope values suggest that the limestones have not undergone much burial (Figure 8.13).

Having a bulk rock sample has a diluting effect on the cement signature and direction of any movement. If only the cement was analysed, its isotopic composition could well be further removed from the skeletal values.

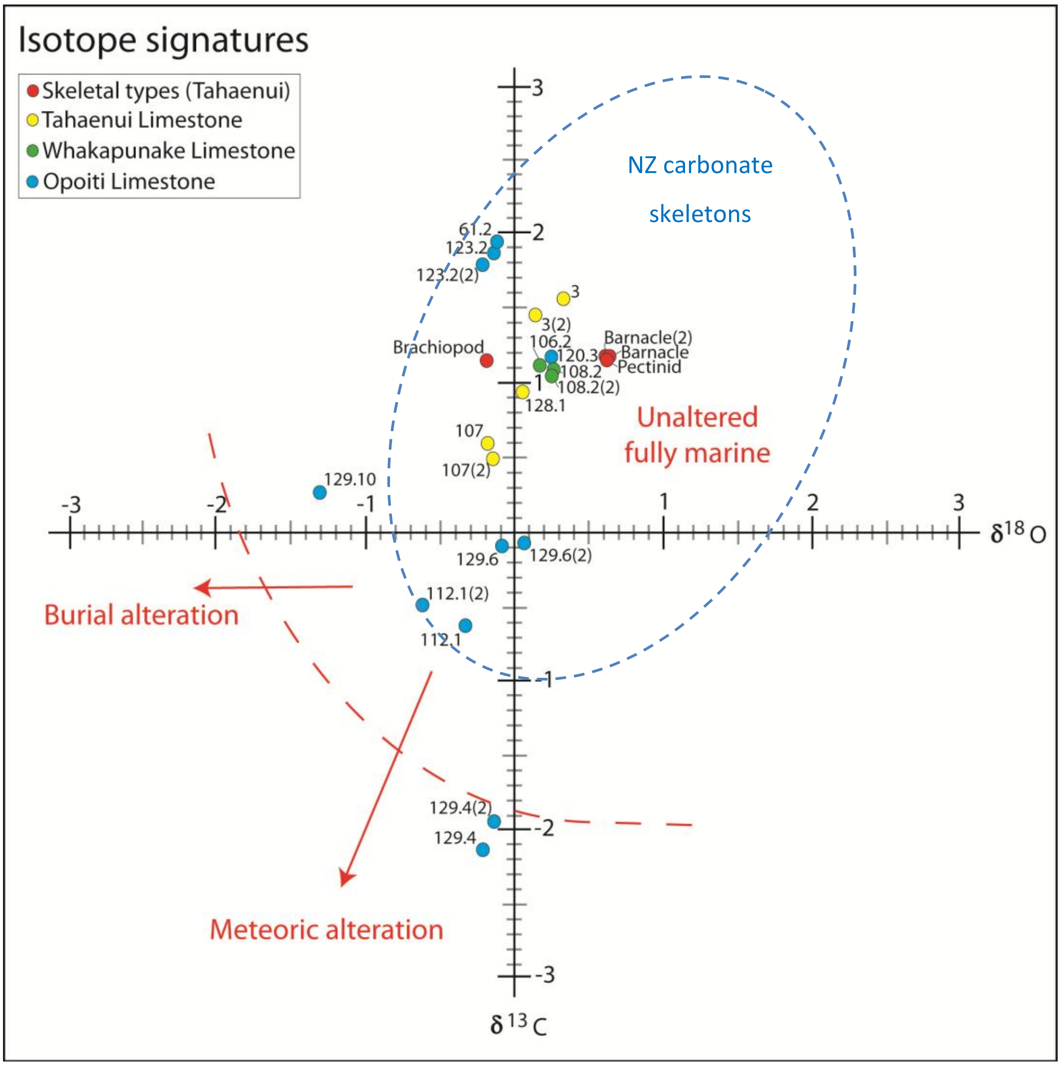


Figure 8.13 – Stable isotope results from the Opoiti, Whakapunake and Tahaenui Limestones. All data plot close to expected marine values with a hint of shallow burial. The Opoiti Limestone shows a general trend from marine towards meteoric alteration. The Whakapunake Limestone samples are in the marine field, but only a few samples were analysed. The Tahaenui Limestone groups within the unaltered marine portion of the grid with a weak trend towards meteoric alteration. Boundaries, directions of alteration and typical New Zealand skeleton fields come from Nelson & Smith (1996). (2) indicates a duplicate run of sample.

8.6.2.1 Opoiti Limestone

The Opoiti Limestone isotope values are widely scattered, spreading from the marine field down towards a suggestion of a degree of meteoric alteration (Figure 8.13). $\delta^{18}O$ values are near 0 to -1‰, while the $\delta^{13}C$ values range more widely from 2 to -2‰. The Opoiti Limestone is dominated by brachiopod skeletons and it appears the bulk rock isotope values best reflect a variable but generally small degree of both burial and meteoric cement precipitation and/or alteration. This would be consistent with the common occurrence of microbioclastic micrite in the Opoiti Limestone samples.

8.6.2.2 Whakapunake Limestone

The bulk Whakapunake Limestone samples plot close together in the unaltered marine field with small positive $\delta^{13}C$ and $\delta^{18}O$ values (Figure 8.13). There are insufficient analyses to detect any trend towards either meteoric or burial alteration. The Whakapunake Limestone is dominated by pectinid skeletons and the samples are only slightly displaced from this skeletal type.

8.6.2.3 Tahaenui Limestone

The Tahaenui Limestone samples plot near $\delta^{18}O$ values of 0‰ and with small positive $\delta^{13}C$ values (Figure 8.13). The Tahaenui Limestone is dominated by barnacle skeletons and shows a small negative shift in both isotope values from this skeletal type. The Tahaenui Limestone has very common isopachous sparite fringes of likely shallow burial (phreatic) origin (Caron 2002), which can account for the isotope shift.

CHAPTER NINE - SEQUENCE STRATIGRAPHY

9.1 INTRODUCTION

Sequence stratigraphy is the study of strata in relation to their depositional history, depositional patterns, relative sea level movements and characteristics of their sedimentary environments (Walker 1992). Emery & Myers (1996, p. 3) use the most preferred definition of sequence stratigraphy as 'the subdivision of sedimentary basin fills into genetic packages bounded by unconformities and their correlative conformities'. Sequence stratigraphy originated from Exxon's study of seismic stratigraphy in the 1970s (Emery & Myers 1996; Naish & Kamp 1997) and has been used since by exploration and academic geologists to aid in understanding subsurface stratigraphy. Sequence stratigraphy developed from interpretations made from seismic reflection profiles. Reflection profiles are large extended visual maps of the subsurface sedimentary architecture and are generated by measuring the two way travel times of reflected seismic waves (Keary *et al.* 2002). The traces on the seismic profiles represent rock units, unconformities, diagenetic differences, folds and faults from which geological interpretations can be made. Seismic reflection profiles can be used for academic purposes – to help unravel depositional history and controls – and as an exploration tool in economic exploration geology (see Chapter 10). Because of the direct link to the East Coast Te Aute limestones, this chapter draws heavily upin parts of Bland *et al.* (in prep.) as a primary reference.

By using a sequence stratigraphic approach to the northern Hawke's Bay Te Aute limestones an association can be made between the present day geology and the depositional, subsidence and uplift history. Relative sea level changes, regardless of cause, can be evident within a sedimentary geological section (Bland *et al.* in prep.).

9.2 SCHEMATIC SEQUENCE STRATIGRAPHY

Theoretical sequence stratigraphy hosts many internal features and individual components, the most common of which are mentioned below. Sequences can be classified in a hierarchical way as 'orders' based on the duration of the cycle involved in their formation (Table 9.1). Fossils within a stratigraphic sequence are important as paleodepth indicators (Brett 1998), and are generally closely linked with the depositional patterns (Brett 1995).

Table 9.1 – Cycle order and related duration and sea level movement. Adapted from Kerans & Tinker (1997) and Bland *et al.* (2004).

Cycle Order	Duration (My)	Sea level rise/fall rate (cm/1,000 yr)
1st	>100	<1
2nd	10-100	1-3
3rd	1-10	1-10
4th	0.1-1	40-500
5th	0.01-0.1	60-700
6th (Milankovitch)	0.041	c.700

9.2.1 Systems tracts and sequence boundaries

A sedimentary sequence can be divided into systems tracts based on internal stratigraphy (Emery & Myers 1996; Caron *et al.* 2004b). A sedimentary sequence is the product of a single sea level cycle, depositing sediment during both the sea level rise and fall. The size or duration of a sequence is not part of its definition, allowing sequence stratigraphy models to be developed based on a varying range of scales (Emery & Myers 1996). The sequence boundaries are the top and bottom surfaces of a sedimentary sequence, and can be identified by patterns of onlap, downlap and toplap (Figure 9.1). Because regressive systems tracts are not always preserved beneath a capping transgressive surface of erosion (TSE), Caron (2004b) proposed that sequence boundaries (the start and finish of one sea level cycle) be defined based on these TSEs.

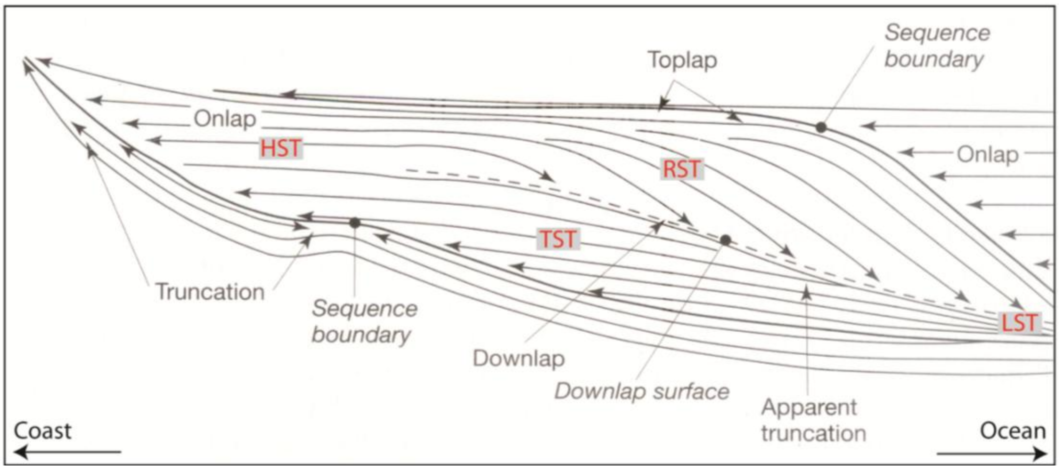


Figure 9.1 – Schematic diagram of a stratigraphic sequence. HST – highstand systems tract, LST – lowstand systems tract, RST – regressive systems tract, TST – transgressive systems tract. Adapted from Boggs (2006, p. 446).

9.2.2 Lowstand systems tract (LST)

A lowstand system develops when sea level is at/near its lowest point in a particular cycle (Figure 9.2). It is typically taken to occur at the base of a sequence and it therefore consists of the stratigraphically oldest deposits (Emery & Myers 1996). During a LST the coastal section has maximum subaerial exposure and erosion. Deposits associated with the LST can be submarine fans and clinoform structures (Emery & Myers 1996).

9.2.3 Transgressive systems tracts (TST)

A transgressive system involves a deepening of the sea water where the coast line rises and moves inland (Figure 9.2). This results in deeper water sediments (e.g. muds) being deposited above shallower water sediments, the reworking of existing deposits, and generation of a deepening upwards or retrogradational sequence. Actively forming carbonates may be drowned and buried (Jones & Desrochers 1992). Unconformities are often formed during transgression as the rising sea level erodes across existing sediments (Caron *et al.* 2004a) to form a transgressive surface of erosion (TSE). TSEs typically form the basal boundary of a sequence. The erosion that occurs when creating these surfaces can remove considerable sediment thicknesses (up to 40 m) from the geological record (Caron *et al.* 2004a). TSEs in the field can show sharp contacts, intensive burrowing, immediately overlying shell beds and an overlying deepening-upwards sequence (Caron *et al.* 2004b). TSTs onlap onto the older, underlying sequence (Figure 9.1). Shell beds formed during transgression are known as TST shell beds (Bland *et al.* in prep.).

9.2.4 Highstand systems tract (HST)

A highstand system occurs when sea level rise slows, stabilises and eventually begins to turn (Figure 9.2). Therefore HST deposits include both aggradational and progradational structures (Emery & Myers 1996). Because of the deepening of water level, HSTs often produce deposition of siliciclastic sediment above TST derived shallower water deposits. A highstand system tract displays offlap patterns (Figure 9.1) (Naish & Kamp 1997).

9.2.5 Regressive systems tract (RST)

The term 'regressive systems tract' was not part of the original sequence stratigraphic model (Walker 1992; Schlager 2005) because the regressing sea was considered to cause erosion, not deposition. However, given the right circumstances and balance between sea level and sediment supply, deposition can occur (Naish & Kamp 1997). Because of this, a regressive systems tract is a justifiable portion of a stratigraphic sequence. Schlager (2005) still considers the regressive systems tract to be less fundamental than its three counterparts. A regressive systems tract results from the shallowing of the sea where the coast line moves seawards (Figure 9.2). Unconformities can be formed by regressive movement, when erosion of existing (HST/TST) sediments occurs as the sea level drops (Caron *et al.* 2004a). Regressing sea levels expose the coastal section subaerially, causing erosion.

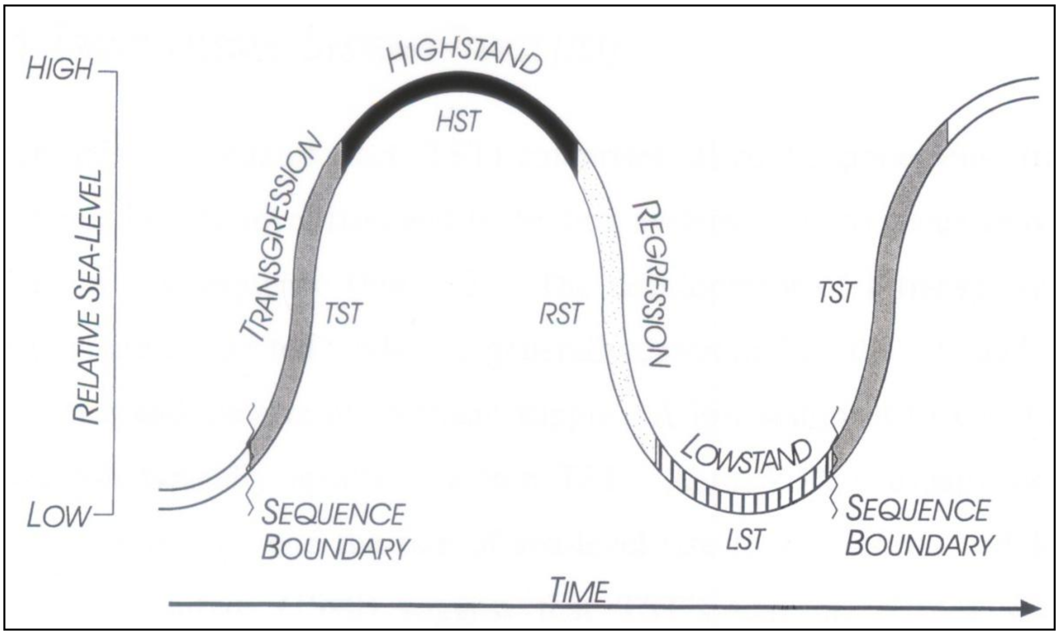


Figure 9.2 – Schematic diagram of single sea level rise and fall cycle within an idealised stratigraphic sequence. HST – highstand systems tract, LST – lowstand systems tract, RST – regressive systems tract, TST – transgressive systems tract. From Naish & Kamp (1997).

9.3 HAWKE'S BAY SEQUENCE STRATIGRAPHY

There have been a number of sequence stratigraphic interpretations made for the Pliocene deposists in the Hawke's Bay area (e.g. Beu & Edwards 1984; Bland 2001; Haywick et al. 1992; Baggs 2004; Dyer 2005) but they have tended to deal with stratigraphic sections in the central and southern Hawke's Bay. Oxygen isotope records indicate that Earth's climate during the Pliocene and early Pleistocene was regulated by c.41,000 year periodicity which determined the extension and retreat of ice sheets, causing associated sea level movements (Haywick *et al.* 1992; Naish & Kamp 1997; Naish *et al.* 2009). Tectonism is unlikely to have been the primary cause of such short-term sea level movements (Haywick *et al.* 1992), but may have played some role (Beu & Edwards 1984). Sea level shifts on the order of 75-150 m have been suggested (Haywick *et al.* 1992).

The occurrence of limestones separated vertically and laterally by typically thick mudstone sequences could relate to such changes in sea level (Haywick *et al.* 1992), with the mudstones accumulating during highstands and the limestones associated with the transgressive situations, both enhanced by simultaneous tectonic ups and downs. Regressive systems tracts do not appear to be well preserved in the field area, likely a result of removal during formation of TSEs.

The abundance and wide distribution of fine grained siliciclastic sediment (Wairoa Formation) in northern Hawke's Bay is consistent with dominant highstand conditions and shorter lowstand periods. The likely pattern of sea level movement involved rapid transgressions and slow regressions (Haywick *et al.* 1992). Due to the massive structure and thickness of the Wairoa Formation, estimation of how much sediment may have been removed during transgressions and therefore how much time is represented by the related unconformities, is difficult to assess.

The New Zealand East Coast Neogene succession is considered to represent a 2nd order sequence (Table 9.1). On a broad scale, the Miocene to early Pliocene Tolaga Group corresponds to transgressive and highstand characteristics, and was deposited over a 16-17 m.y. time span (Bland 2001). The Pliocene Mangaheia

Group represents a 3 m.y. highstand to regressive section, and the mid-Pleistocene Kidnappers Group accumulated over a 0.5 m.y. regressive to lowstand stage (Bland *et al.* in prep.). Within each of the above phases there is evidence of smaller cyclicity, which we see in the field as TST deposits typically overlain by HST deposits. The individual groups within the 2nd order sequence, bound by unconformities, are component systems tracts (Bland *et al.* in prep.). The Pliocene limestones units in the Hawke's Bay region range in age duration from c.0.1-0.25 m.y. (4th to 5th order cyclicity) (Caron *et al.* 2004a).

Groups of thick (up to 80 m) 6th-order sequences are present throughout the Mangaheia Group where it crops out in central and southern Hawke's Bay, with origins of 41 k.y. fluctuations in sea level (glacio-eustatically-driven) (Caron *et al.* 2005; Bland *et al.* in prep.).

9.3.1. Sequence stratigraphy in the Nuhaka/Mahia Peninsula area

Figure 9.3 shows the likely sea level movement for the periods of deposition involving the Opoiti, Whakapunake and Tahaenui Limestone and their associated Wairoa Formation mudstones (Lisiecki & Raymo 2005; Naish & Wilson 2009). Small fluctuations dominate the Opoitian to Waipipian with overall sea level quite steady, until the Mangapanian where overall sea level begins to regresses. Figures 9.4 to 9.7 show sequence stratigraphic interpretations for the Pliocene deposits in the study area. Clear evidence for sequence stratigraphic subdivisions of the Pliocene deposits is wanting. Compared to the Te Aute limestones in central and southern Hawke's Bay there is little evidence for repetitive cycles of sea level change in the three limestone units studied. However, as mentioned in section 9.3.1.3, the rhythmic couplets in the Whakapunake Limestone could indicate an origin from 41,000 yr Milankovitch driven oscillations. Regressive systems tracts are usually identified by a shallowing upwards lithological section, which is not observed or preserved in the Nuhaka/Mahia Peninsula area. This could be due to erosion dominating during regression or the subsequent transgression.

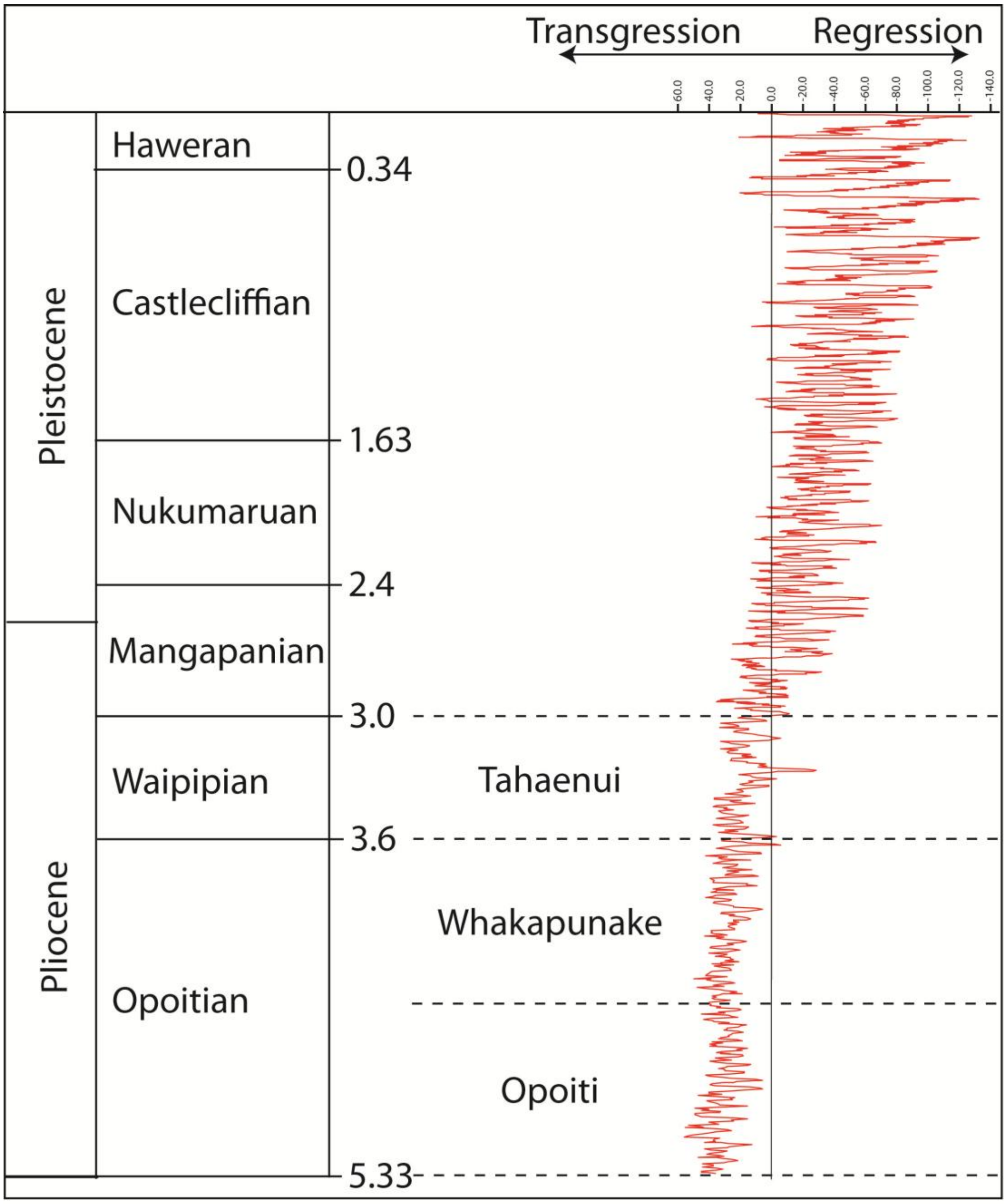


Figure 9.3 – Relative sea level rise and fall (metres) from the Opoitian to the Haweran plotted from benthic $\delta^{18}O$ records. Dashed lines show possible period of deposition for each limestone and associated Wairoa Formation. Adapted from Lisiecki & Raymo (2005). New Zealand stages and absolute ages (Ma) taken from Hollis *et al.* (2010).

9.3.1.1 Tahaenui/Clonkeen (Figure 9.4)

Within the Tahaenui/Clonkeen area the Tahaenui Limestone (TST – as deposited in relatively shallow waters) sharply overlies late Miocene mudstone (some earlier HST) with an unconformable contact, evident in all columns in Figure 9.4, and grades upwards into shelly sandstone and mudstone (TST/HST – deposited when sea level was nearing its highest level) (Figure 9.4, column 08). This sequence records a broad pattern of sea level rise. The limestone here is a product of an overall major transgressive shift of sea level (rise), with some superimposed small fluctuations that may have been responsible for the generation of up to c.5 shell beds within the Tahaenui Limestone (Figure 9.4, column 02).

9.3.1.2 Mt Moumoukai (Figure 9.5)

The Opoiti Limestone is a TST deposit (as deposited in relatively shallow waters) associated with sea level transgression (Figure 9.5, column 9, 12) and unconformably overlies late Miocene mudstone (some earlier HST – a deep water deposit) (Figure 9.5, column 12). The limestone is overlain by Opoitian aged calcareous sandstone, the Wairoa Formation B (possibly also TST or TST/HST) (Figure 9.5, column 10, 12).

Because the Tahaenui/Clonkeen and Mt Moumoukai localities both sit within the Nuhaka Syncline, it is considered that the two areas of Tahaenui Limestone are lateral deposits of the same overall sea level transgression (i.e. the Tahaenui Limestone at Mt Moumoukai that overlies the older Opoiti Limestone with mild angular unconformity is a result of the same sea level transgression that formed the Tahaenui Limestone at Tahaenui/Clonkeen (section 9.3.1.1)).

Therefore Mt Moumoukai represents at least two periods of major relative sea level cyclicity associated with two separate carbonate (TST) deposits that are separated by a TSE (angular unconformity) and the TST/HST sandstone deposit of the older Opoitian cycle.

9.3.1.3 Mahia Peninsula (Figures 9.6, 9.7)

The Opoiti Limestone crops out along the west coast of Mahia Peninsula and in all localities begins with a TSE truncating the underlying late Miocene mudstone (some earlier HST). A prominent shell bed occurs above this TSE at all localities, representing a TST onlap shellbed (Figure 9.6, column 23). The Opoiti Limestone itself is likely also a TST deposit and is overlain by Wairoa Formation mud (HST) (Figure 9.6, column 29).

The interbedded nature of the Whakapunake Limestone may be due to sea level fluctuations, resulting in carbonate and sandstone couplets (Figure 9.7, column 20). There are at least 20 subaerially observed couplets. The age of the Whakapunake Limestone is late Opoitian (Beu 1995), spanning perhaps c.850,000 year duration (roughly half of the entire Opoitian duration). On this basis each couplet set could equate to c.42,500 year oscillations. This is close to the 41 k.y. periodicity of Milankovitch driven sea level fluctuations. The Whakapunake Limestone is overlain by shelly sandstones and a HST mudstone (Figure 9.7, column 21).

Transgressive systems tracts often host common *Ophiomorpha* burrows (Naish & Kamp 1997), and it was previously suggested that the mudclasts within the Whakapunake Limestone succession on the west Mahia Peninsula coast might have originated as mud fills of such burrows (Figure 6.5 A).

It is likely that the same sea level transgression associated with the deposition of the Tahaenui Limestone in the Nuhaka Syncline also led to Tahaenui Limestone formation further east on Mahia Peninsula. Although there are no overlying lithologies to assist interpretations, the Tahaenui Limestone here is also considered to be a TST deposit (Figure 9.6, column 29, 17). The Tahaenui Limestone unconformably overlies late Miocene mudstone, an earlier HST deposit (Figure 9.6, column 17). Shell beds and small scale cross bedding may be indicative of low amplitude sea level fluctuations within the overall transgressive scheme, similar to those seen in the Tahaenui Limestone near Nuhaka (Figure 7.3, Stratigraphic column 2, Appendix VII).

9.3.1.4 Summary

The three limestones and their associated bounding mudstones (Wairoa Formation) present evidence for three main periods of overall sea level transgression during the Pliocene in the northern Hawke's Bay area. The connecting regressive intervals are not clearly evident in the field, perhaps due to erosion associated with the cutting of a TSE during initial transgression. At most localities, the base of the Opoiti Limestone includes a TST coquina shell bed. The mudstone that overlies the Opoiti Limestone marks the culmination into highstand conditions of this first sea level transgression. The Whakapunake Limestone records evidence for a second overall sea level transgression, with possible superimposed Milankovitch driven internal fluctuations. The Whakapunake Limestone is overlain by sandstone and mudstone, marking the movement into the highstand stage of the second sea level transgression. The Tahaenui Limestone, in all three areas, represents the third period of overall sea level transgression. Like its older counterparts, the Tahaenui Limestone is overlain by sandstone and mudstone marking transition into highstand conditions.

While sea level fluctuations are observed and do account for important changes within the northern Hawke's Bay Pliocene lithologies, it is important to understand that tectonic derived uplift and subsidence was simultaneously occurring, and that if the antiform structures were shallow enough then glacio-eustatic change could be superimposed over the ultimate tectonism.

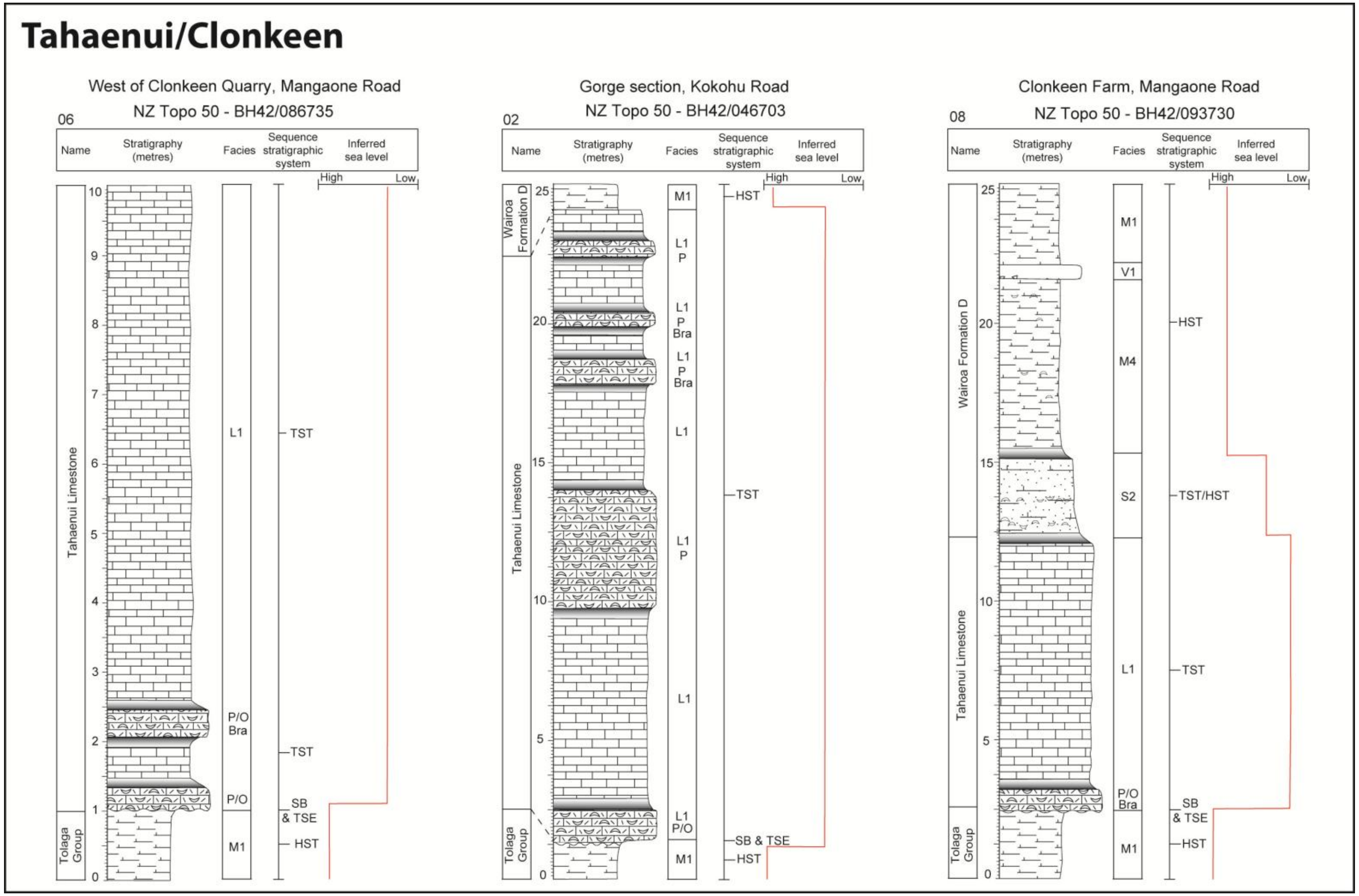


Figure 9.4 – Selected stratigraphic columns with associated sequence stratigraphic systems tracts in the Tahaenui/Clonkeen area. Relative changes in water depths are inferred from lithologies within the sequence. Refer to Appendix II for column localities and to Appendix VII for lithological legend.

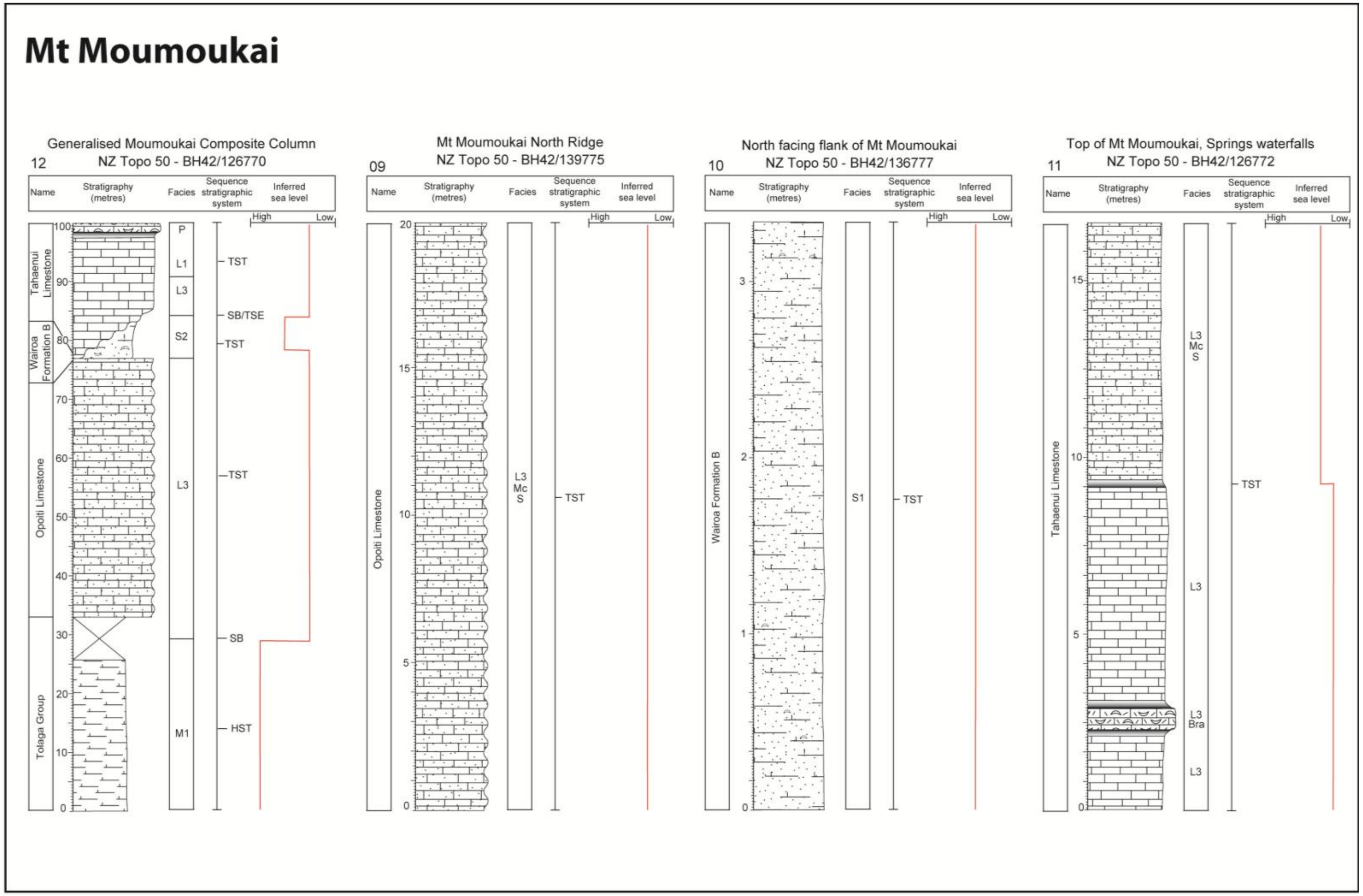


Figure 9.5 – Selected stratigraphic columns with associated sequence stratigraphic systems tracts in the Mt Moumoukai area. Relative changes in water depths are inferred from lithologies within the sequence. Refer to Appendix II for column localities and to Appendix VII for lithological legend.

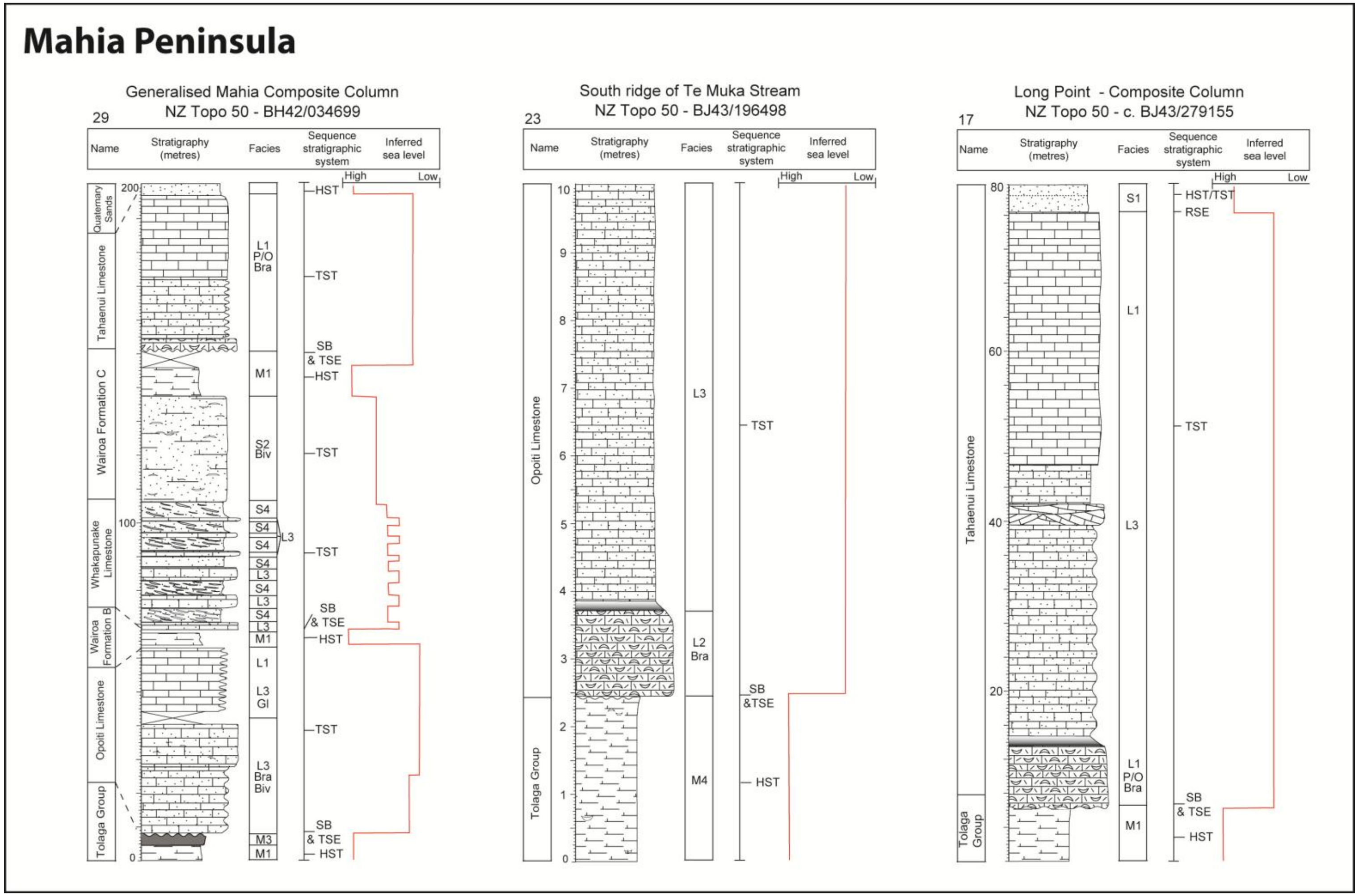


Figure 9.6 – Selected stratigraphic columns with associated sequence stratigraphic systems tracts from Mahia Peninsula. Relative changes in water depths are inferred from lithologies within the sequence. Refer to Appendix II for column localities and to Appendix VII for lithological legend.

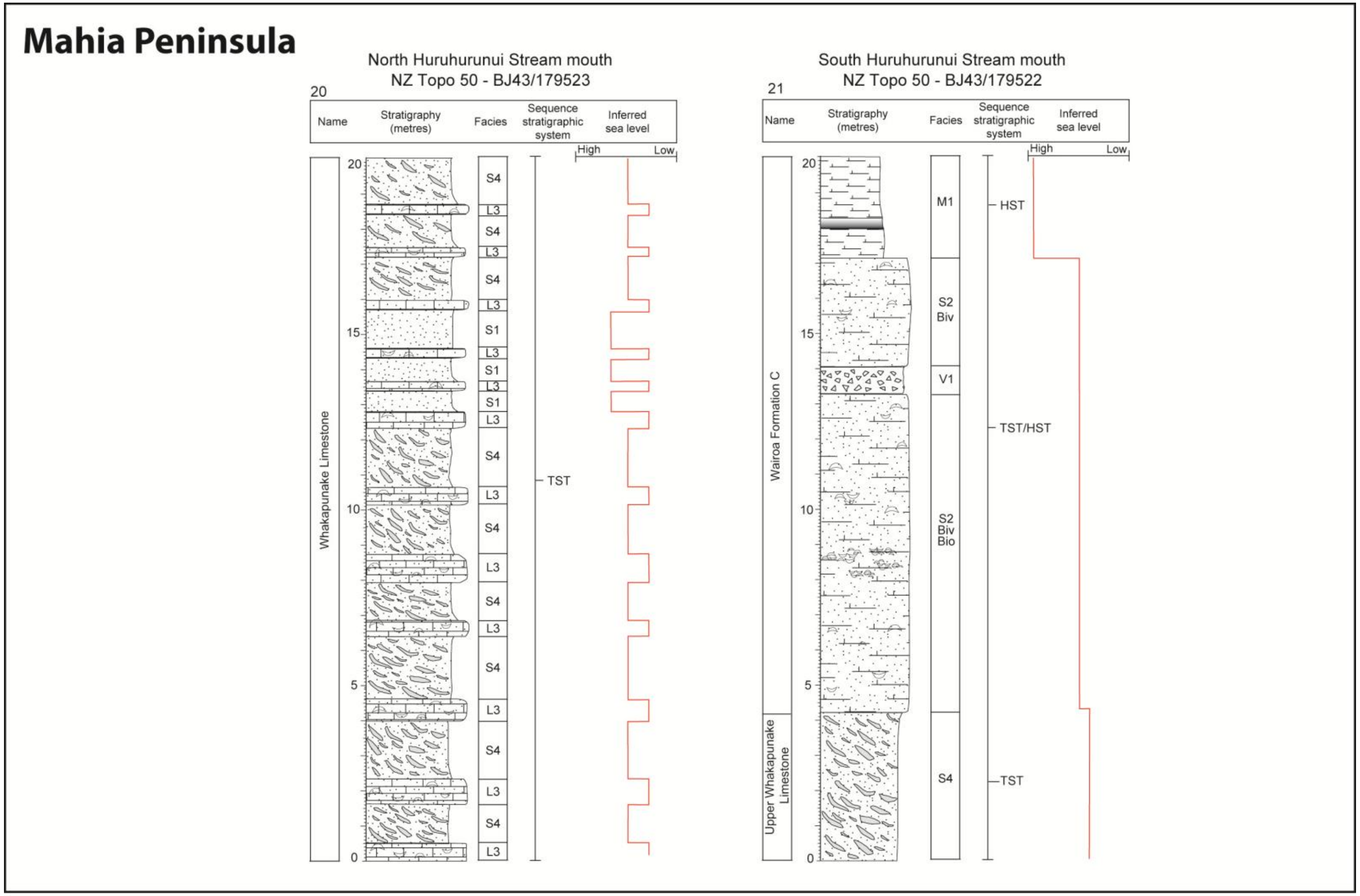


Figure 9.7 – Selected stratigraphic columns with associated sequence stratigraphic systems tracts from Mahia Peninsula. Relative changes in water depths are inferred from lithologies within the sequence. Refer to Appendix II for column localities and to Appendix VII for lithological legend.

CHAPTER TEN – ECONOMIC POTENTIAL

10.1 INTRODUCTION

These three Pliocene limestone units in northern Hawke's Bay have primary economic potential as subsurface hydrocarbon reservoirs, hard stone sources for aggregate and as a source of lime for agricultural or industrial purposes. In the recent past, Westech Energy has drilled hydrocarbon wells in the area which prove, with gas shows, the limestones to be prospective reservoir beds in the subsurface. This region, being fairly isolated and distant from hard greywacke basement rocks, lacks good quality road metal resources, and will benefit from further possible aggregate quarries. Expanded mining activities are highly likely in the northern Hawke's Bay area, and can contribute also to the extraction of lime from the carbonate rocks, for use in cement and fertiliser manufacture. Some suggestions regarding the economic potential of the limestones in northern Hawke's Bay derive from the field and laboratory work in this study.

Seismic reflection profiles (Figure 10.1) can be used in petroleum exploration geology to identify and map distribution of source and reservoir rocks, and to also highlight subsurface structures that might pose as traps or seals.

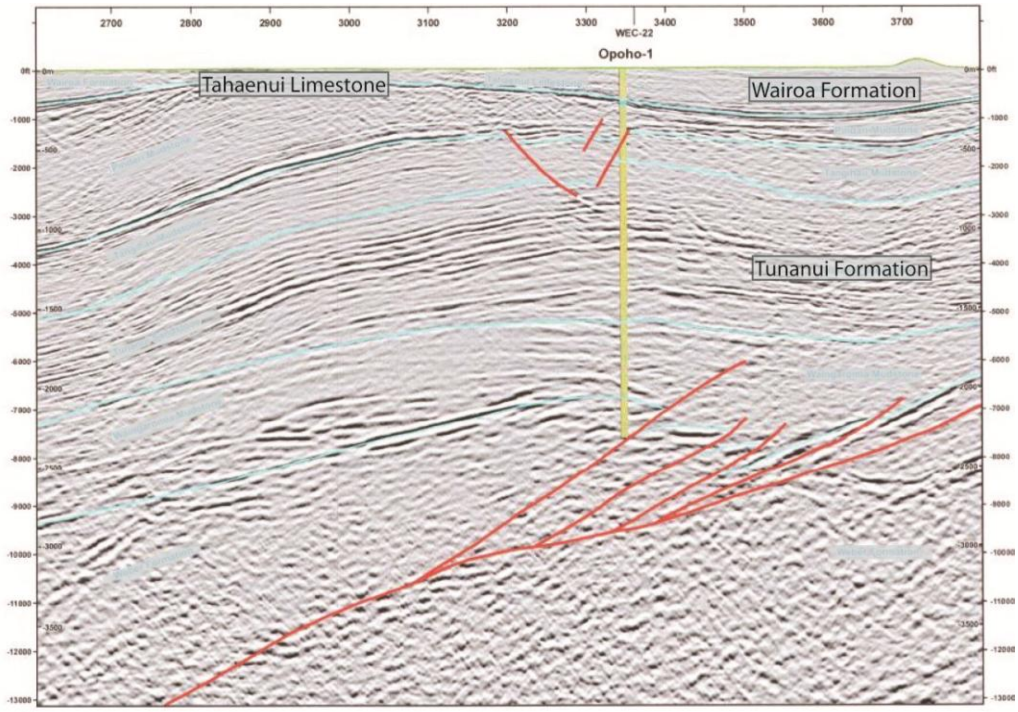


Figure 10.1 - An example of a seismic refection profile being used for exploration purposes. This interpreted Westech seismic line (WEC-8B – location in Figure 10.2) highlights geological formations. The subsurface structure is also visible, allowing interpretation of any structural hydrocarbon traps.

10.2 EAST COAST BASIN HYDROCARBONS

The sedimentary nature of the East Coast Basin is compatible with commercially viable quantities of hydrocarbons possibly being present, but the area is relatively under-explored (Bland *et al.* 2004). Indicative characteristics of a petroleum system include thick stratigraphy, rapid burial and suitable source, reservoir and trap rocks (Neef 1999). The presence of numerous oil seeps and gas shows at the surface confirm the existence of a mature and active petroleum system (Figure 10.2) (Francis 1995; Davies *et al.* 2000; Frederick *et al.* 2000). Such seeps are especially numerous in northern Hawke's Bay and on Raukumara Peninsula (Mazengarb & Speden 2000). The best known of these comprises several aligned oil seeps (c.2 m across) at Waitangi, Rotokautuku and Totangi (Figure 10.2) (Francis 1995). About Hawke Bay to the south there are fewer oil and gas seeps than elsewhere, possibly because of the younger and thick cover of strata (Crampton *et al.* 1993). The hydrocarbon shows are located primarily on the northeastern and eastern portions of the East Coast Basin, with the western side of the basin lacking shows due to Neogene uplift and erosion (Bland *et al.* 2008).

The oil seeps in the East Coast Basin do differ from those within the Taranaki Basin off western North Island by having a marine rather than terrestrial origin (Johnston *et al.* 1992). Brine and gas have been encountered in Miocene sandstones (Ian R Brown Associates 1998), with near-commercial gas quantities located near Wairoa, in the Kauhauroa wells (Figure 10.2) (Bland *et al.* 2008). Gas shows typically consist of 98% methane, c.0.3% ethane, c.1.5% nitrogen and c.0.05% carbon dioxide. Small amounts of propane sometimes occur (Davies *et al.* 2000).

The majority of the petroleum system lies within the thick (up to c.9000 m) Miocene and pre-Miocene rock, with only limited prospects in Pliocene strata. Only two offshore wells have been drilled in the East Coast Basin, compared with about 45 onshore wells (Figure 10.2) (Frederick *et al.* 2000; Francis *et al.* 2004).

The migration of any hydrocarbons is controlled primarily by fractures, faults and unconformity horizons (Crampton *et al.* 1993), with the development of trap structures being dominated by compression during the latest Miocene and Pliocene (Frederick *et al.* 2000; Bland *et al.* 2008).

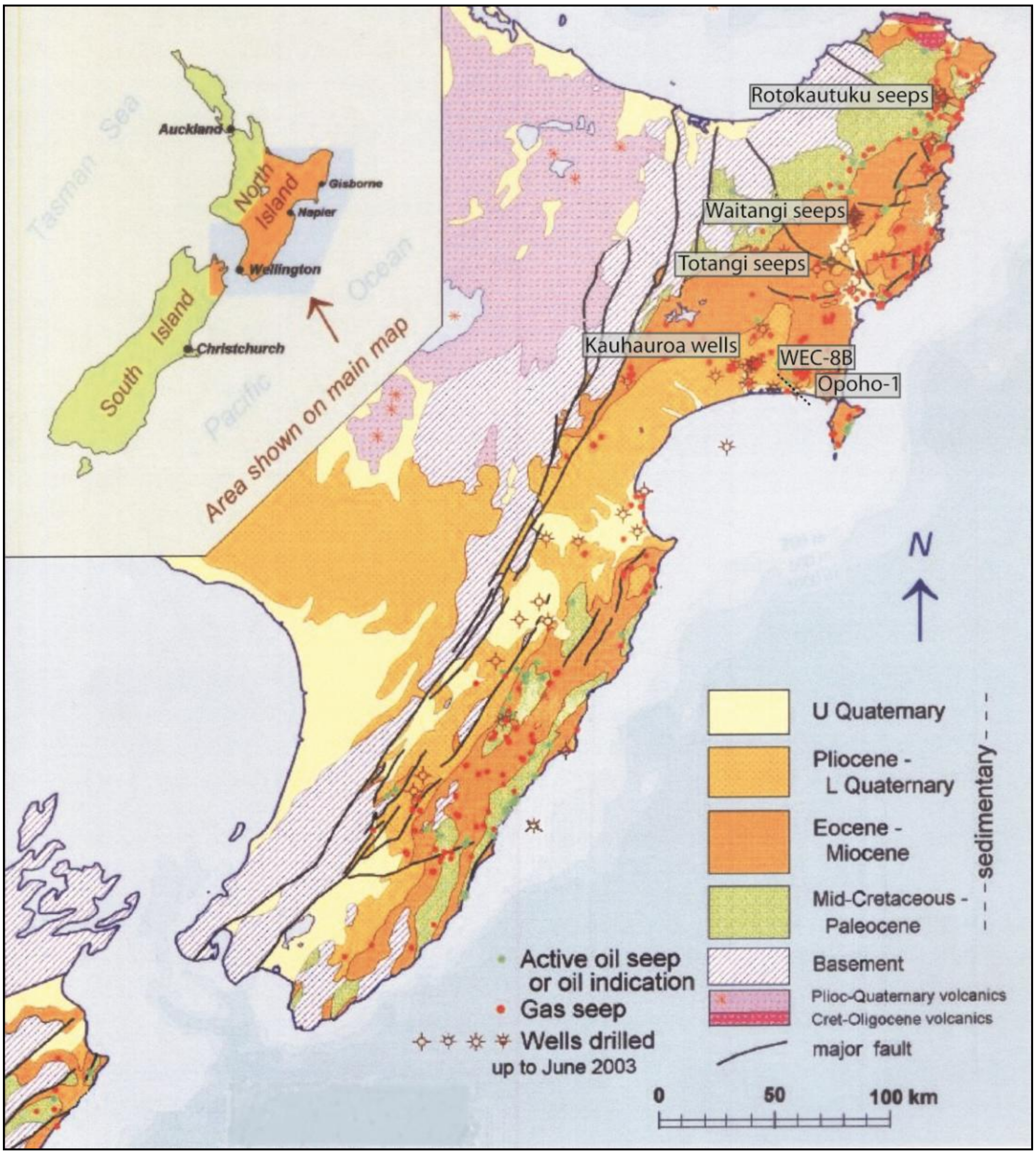


Figure 10.2 – Geological map of the eastern North Island illustrating the distribution of Cretaceous to Quaternary sedimentary strata. Onshore and offshore wells and gas and oil seeps are identified. Black dashed line indicates approximate position of seismic line WEC-8B, shown in Figure 10.1. Adapted from Francis *et al.* (2004, p. 4).

Source rocks

The Late Cretaceous to Paleocene Whangai Formation (siliceous mudstone) and especially the Paleocene Waipawa Black Shale (marine, carbonaceous, organic rich mudstone) are the two most prominent source rocks in the East Coast Basin (Crampton *et al.* 1993; Field *et al.* 1997; Ian R Brown Associates 1998). The latter is widespread in the southern Hawke's Bay to Wairarapa area and is about 10-50 m thick (Crampton *et al.* 1993; Field *et al.* 1997). Neither of these source rocks crop out within the present study area. However, the Waipawa Black Shale is identified in older strata on the eastern side of Mahia Peninsula (Francis 1993a).

Source rocks are unlikely in the Eocene to Pliocene deposits (Johnston *et al.* 1992). The source rocks are inferred to have reached their peak oil generation and began expulsion at c.5-6.5 km burial depth, from the middle Pliocene onwards (Francis *et al.* 2004).

Reservoir rocks

The large distribution of sandstone and limestone lithologies in the East Coast Basin illustrates the potential for subsurface reservoir beds (Bland *et al.* 2004). Thick, widely distributed, Miocene sandstones are widespread and are the most likely reservoir beds (Bland *et al.* 2008). These sandstone units have typical porosities of 10-15% (Crown Minerals 2003). The middle Miocene Tunanui Formation, which crops out in the Nuhaka area, is a prospective reservoir bed (Francis 1998).

The porosity of limestones in the East Coast Basin decreases with increasing age, the Plio-Pleistocene limestones typically having porosities in the 41-50% range while the older early Pliocene and late Miocene limestones have values of 11-20% (Harmsen 1984; Beu 1995; Field *et al.* 1997). Because limestones often have 'magnificent' (Francis 1998) reservoir properties, with better porosity and permeability than sandstones, they remain an excellent drilling target. However, the problem may be in the distribution of the Pliocene limestones and whether there is sufficient lateral coverage to host any possible hydrocarbons (Francis 1998). But where sufficient seal rock can recognized the East Coast Te Aute limestones remain good potential targets for hydrocarbons as they have a coarse grain size, have undergone relatively limited diagenetic alteration, so preserving their original porosity, and they are often well sorted (Bland *et al.* 2004). The uneven lateral distribution of the Pliocene limestones does cause a potentially problematic and complex structural situation, with hydrocarbon leakage possible. Nevertheless, some exhibit gas and oil shows (Nelson *et al.* 2003).

Seal rocks

Trap or seal rocks are in abundance, with thick units of mudstones overlying or encasing the Miocene sandstones and limestones. However, seal rocks are much more limited for any shallow Pliocene targets and, where overburden is present, are typically Quaternary aged, thin and sandy deposits (Crampton *et al.* 1993). For the northern Hawke's Bay Pliocene limestones the coeval siliciclastic mudstones of the Wairoa Formation are potentially the best seal rock. However, these same mudstones could restrict the reservoir potential of the Pliocene limestones.

10.2.1 Hydrocarbon potential in the Nuhaka/Mahia Peninsula area

Only one area in the immediate study area presents any evidence for mature hydrocarbons. A small area (c.20 m^2) with several gas seeps occurs within the silty Wairoa Formation on the coastal section near the mouth of Otunua Stream western Mahia Peninsula (Figure 5.1) (Francis 1993a), supportive of an active petroleum system in the subsurface Pliocene strata. Inferred to be distantly underlying this Wairoa Formation is the Opoiti Limestone, which may be the most likely reservoir bed. The Paleocene Waipawa Black Shale source rock does occur on the eastern coast of Mahia Peninsula and could possibly extend in the subsurface towards the west where it may contribute to the gas shows on the coast.

There are no indications of oil or gas shows in the Tahaenui/Clonkeen area nor Mt Moumoukai, and so an immediately underlying active petroleum system is unlikely. The general lack of observed hydrocarbons in the study area compared with the relatively more promising hydrocarbon potential elsewhere in the larger East Coast Basin may reflect the predominance of young muddy Pliocene strata in the region and a general lack of faults that could otherwise act as migration pathways.

10.3 AGRICULTURAL/INDUSTRIAL USE

Limestone can have many 'minor' economic uses (manufacture and processing of sugar, paper, glass, leather and soap (Morgan 1919; Leith 1922)) but is most commonly used as a source for aggregate and agricultural lime. Limestone in the Raukumara region is typically quarried for aggregate, but in the past has also been used for agricultural lime (Moore & Hatton 1985; Mazengarb & Speden 2000).

Due to the relative remoteness of the northern Hawke's Bay area, local sources of aggregate are essential for roading. Large volumes of primary aggregate can be sourced from the greywacke axial ranges, but much closer sources of aggregate include the Pliocene limestones. The Tahaenui and Clonkeen Quarries (Figures 10.3 B, C) are currently intermittently worked for local aggregate.

Presently only limited quarrying of limestone for agricultural purposes occurs, and could be partly a result of underestimating the high carbonate values and availability of the resource. Limestone used in cement manufacture requires $CaCO_3$ levels of 60-70% (Field *et al.* 1997). The high levels of $CaCO_3$ in the northern Hawke's Bay limestones (c.60-90%) makes them ideal for agricultural lime or industrial use (cement).

10.4 CURRENT ECONOMIC DEVELOPMENT

Current economic development of the Pliocene Limestones in the Nuhaka/Mahia area includes two intermittently working quarries, located at Tahaenui, Kokohu Road (BH42/035699) (Figure 10.3 B) and at Clonkeen, Mangaone Road (BH42/091738) (Figure 10.3 C). The Tahaenui and Clonkeen Quarries are operated by Quality Roading and Services Wairoa (QRS) who offer sources of both aggregate and agricultural lime. The Tahaenui Quarry limestone is predominantly used for local and forestry roading, with some processing of the finer material into aglime. At times the extracted quantities of aglime can make up to 30% of the total annual quarry yield (*pers. commun*. L.Aitken 2011). Testing carried out by QRS of the Tahaenui Quarry deposit consistently measures calcium carbonate levels of c.85%, well suited for use as agricultural lime. QRS recommends an application rate of 880 kg of agricultural lime per hectare to increase soil pH by one tenth of a unit (Quality Roading and Services (Wairoa) 2011). However, inadequate aglime infrastructure at QRS means more emphasis on the use of limestone as aggregate (*pers. commun*. L.Aitken 2011). The Clonkeen Quarry limestone has lower calcium carbonate contents compared to the Tahaenui Quarry (*pers. commun*. L.Aitken 2011), making it much less suitable for agricultural lime. Consequently almost 100% of the excavated rock is used as aggregate.

The workings of a small limestone quarry on Kinikini Road, Mahia Peninsula (BH43/178538) (Figure 10.3 E), operated by Fulton Hogan, Gisborne, are used primarily as a temporary roading aggregate.

All three of the quarries mentioned are within the Tahaenui Limestone. The properties (moderate hardness, high carbonate content – c.75-90%) of this limestone are more desirable than those in the Whakapunake or Opoiti Limestones, and are also much more accessible.

Westech Energy New Zealand is the primary drilling operator in the northern Hawke's Bay region, drilling mainly for hydrocarbon research. Numerous cores have been drilled in the region, only a few of which are located in the present study area. Core Opoho-1 (Westech) (Figure 10.3 D) is located near the coast, where the Nuhaka Syncline extends southwards into the subsurface (Ian R Brown Associates 1998). The Opoho well penetrated a 32 m thick portion of the Tahaenui Limestone at a below ground depth of 200 m, within a thick succession of mudstone (Ian R Brown Associates 1998). The thickness matches that seen in outcrop nearby, of 10-40 m. Also here is where a small hydrocarbon gas show occurs (Ian R Brown Associates 1998).

Quality Roading and Services Wairoa (QRS) have previously (2005) undertaken local drilling as a means of exploration for the distribution of limestone for potential aggregate use. Two holes were drilled (to depths of 37.5 and 27 m), on the flat plateau above the Clonkeen Quarry, into the Tahaenui Limestone. Cores taken (Figure 10.3 A) were briefly analysed by D.A Francis (Geological Research Ltd). Both cores encountered moderately hard Tahaenui Limestone to their final depths.

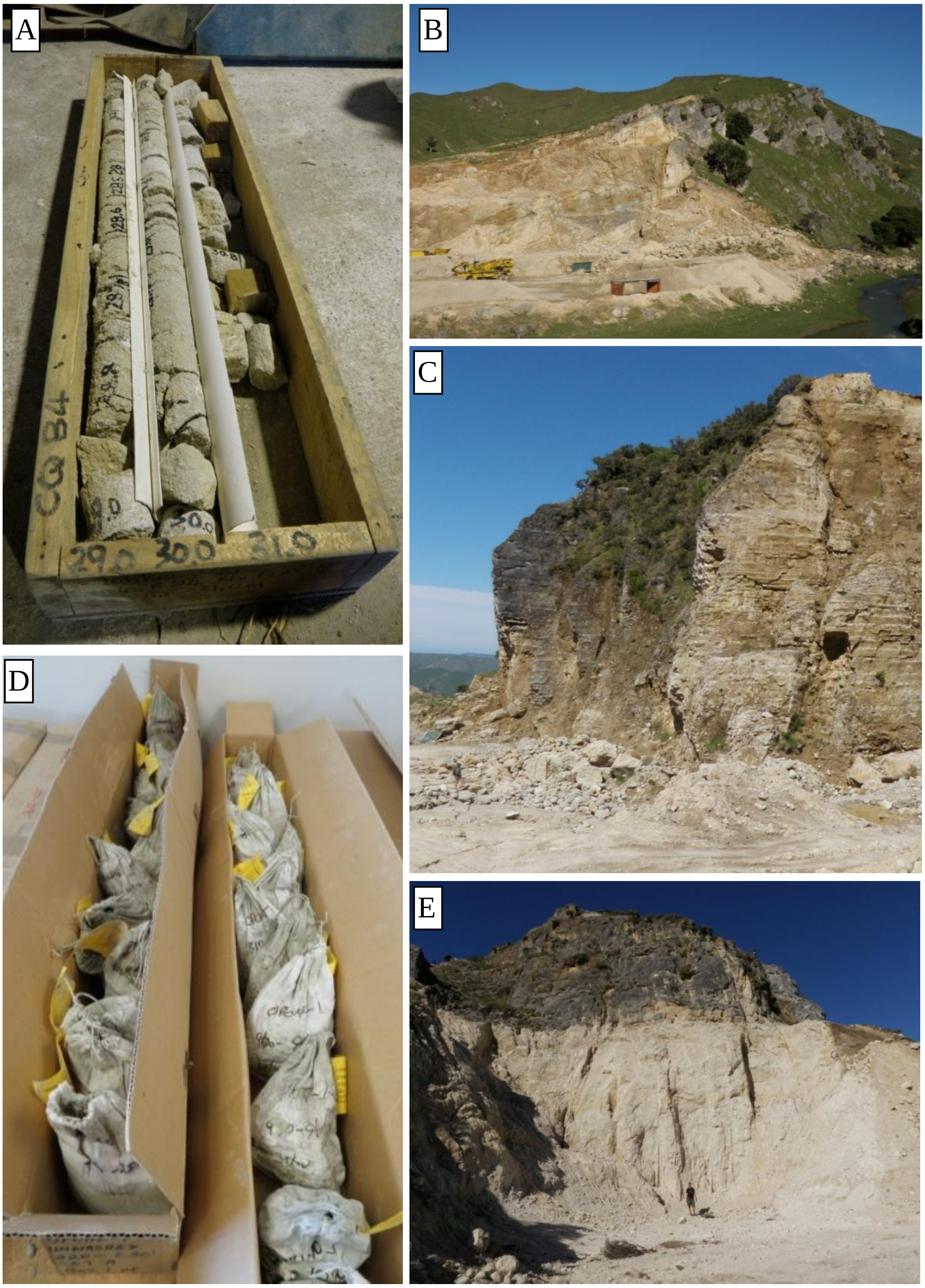


Figure 10.3 – Exploration and economic development in the Nuhaka/Mahia region. **(A)** Drilled cores of the Tahaenui Limestone near the Clonkeen Quarry, Mangaone Road. Cores described and analysed by D.A Francis of Geological Research Ltd for QRS Wairoa. **(B)** The Tahaenui Quarry at the end of Kokohu Road, and **(C)** the Clonkeen Quarry on Mangaone Road, are quarried intermittently by QRS targeting the Tahaenui Limestone as a roading aggregate. **(D)** Unwashed bags of cuttings taken from the Opoho-1 well, drilled by Westech Energy. Cuttings were analysed by Westech for hydrocarbon reservoir potential. **(E)** The Mahia Quarry on Kinikini Road is operated by Fulton Hogan, Gisborne and is primarily used as an aggregate source.

10.5 ECONOMIC RECOMMENDATIONS

The recommendations made here are based on the subaerial geological exposures of the limestones in the Nuhaka/Mahia area.

Expansion of the small quarry on Mahia Peninsula (Figure 10.3 E) would produce significant volumes of economically viable limestone. Here the limestone is gained with easy access and has very little overburden. Further Tahaenui Limestone cropping out in this area, including at Taupiri Hill and Long Point, is particularly soft (easy to extract and crush), has very high calcium carbonate contents (c.90%) and is readily accessible with minimal overburden. This limestone would be ideal for processing as lime for agricultural/industrial use but less so as a source of aggregate. Mr D. Dallmeier, Kinikini Station land owner, has commented that this particular limestone has been used on the gravel road in the past as a temporary repair, but soon 'turned to porridge' with rain and time.

Limestone excavation at both the Tahaenui and Clonkeen Quarries (Figures 10.3 B, C) is suited for aggregate, with agricultural lime a more likely product from the Tahaenui Quarry. The Tahaenui Limestone here is much harder than its Mahia counterpart and would have higher weight load tolerances, needed in roading aggregate. High calcium carbonate values range from c.70-85%, suitable for agricultural lime. As Clonkeen Quarry is situated in the axis of a syncline (Nuhaka Syncline), the limestone bed is quite uniform in thickness, and quarrying could continue for some distance. The Tahaenui Quarry removes the rock on the west flank of the same syncline and quarrying extension may be more limited. Vehicle accessibility is good at both the Tahaenui and Clonkeen quarries.

The Whakapunake Limestone, west coast Mahia Peninsula, has little economic value and very limited accessibility. The Opoiti Limestone cropping out on the east flank of Mt Moumoukai (Figure 5.4 E) may have some economic potential. Here the limestone can be up to 30 m thick and is quite indurated. Aggregate use would be most suited for this limestone. As carbonate values vary greatly and can be quite low (c.55-75%), use as agricultural or industrial lime is not recommended. Access is via a small farm track, and so accessibility is limited but not impossible. The Opoiti Limestone that forms large bluffs at Ahimanawa Station on Mahia Peninsula (Figure 5.8 C) would have good potential as both an aggregate source and for agricultural/industrial lime, but it is very limited by accessibility as it outcrops on the higher portion of a steep ridge.

CHAPTER ELEVEN - SUMMARY AND CONCLUSIONS

11.1 LITHOSTRATIGRAPHY

The Pliocene age Opoiti, Whakapunake and Tahaenui Limestones crop out within the northern Hawke's Bay area from north of Wairoa in the west to Mahia Peninsula in the east. This study is restricted to the eastern portion of this distribution, specifically in the vicinity of Tahaenui/Clonkeen, Mt Moumoukai and on the west coast of Mahia Peninsula. The distribution of the limestones in these localities is patchy and they show highly variable thicknesses from c.10-60 m. The distinctiveness of the limestones within the encasing mudstones warrants them being treated as formations, despite some past inconsistencies in this regard. Moreover historically the encasing mudstones have received different stratigraphic names, including at some positions the Wairoa Formation. Because these Pliocene mudstones (and local sandstones) are all lithologically very similar, in this study the name Wairoa Formation is used for all of them. If appropriate, subdivision according to their position below or above the limestone units can be made using Wairoa Formation A, B, C or D. The three limestone formations and the Wairoa Formation are contained within a part of the Pliocene Mangaheia Group.

The oldest limestone, the early Opoitian aged **Opoiti Limestone** (Figure 5.1), is up to c.20 m thick and occurs at the base of Mt Moumoukai, near Nuhaka. It consists of sandy, indurated, wavy to horizontally bedded limestone. On Mahia Peninsula the limestone is up to c.40 m thick and varies from prominently interbedded, barnacle rich limestone and siliciclastic rich limestone couplets at Ahimanawa Station to a very sandy, near-massive limestone with a brachiopod dominated basal shell bed at Reef Station to an indurated vaguely bedded sandy limestone at Hekerangi Point. At all sites the Opoiti Limestone rests unconformably on late Miocene mudstone. At Mt Moumoukai the limestone grades rapidly into massive, calcareous sandstone of the Wairoa Formation B, while an upper contact into mudstone is seen in the Otunua Stream on Mahia Peninsula. In most localities the Opoiti Limestone typically forms steep bluffs, and has distinctive horizontal to wavy bedding which is enhanced by physical weathering The Opoiti Limestone unconformably overlies late Miocene mudstone in all occurrences.

The Opoiti Limestone has a generally moderate carbonate content only, ranging from c.55-75%. Macrofossils within the Opoiti Limestone include common barnacles, brachiopods (*Neothyris (?obtusa)*, pectinids (*Towaipecten ongleyi*), the bivalve *Glycymeris mahiana*, and some oysters and foraminifera.

The late Opoitian aged **Whakapunake Limestone** (Figure 6.1) has very limited exposure in the study area, cropping out only in one small area on the west coast of Mahia Peninsula. Here the limestone is up to 40 m thick, but with no lower contact exposed its true thickness is unknown. The Whakapunake Limestone has a unique appearance involving prominent interbeds of limestone (10-100 cm thick) and sandstone (20-100 cm thick) in reoccurring couplets. The limestone beds are well indurated, sandy and comprise densely packed, usually indeterminate, skeletal material. The sandstone interbeds include unusual elongated ‘mudclasts’, up to 20 cm long, oriented at high angles to bedding. Different degrees of cementation in the limestone and sandstone beds have resulted in differing hardnesses which is evident through their slightly protruding and recessive nature, respectively, in weathered outcrop. The Whakapunake Limestone grades via sharp interbeds into coarse grained, shelly sandstone and mudstone of Wairoa Formation C, the sandstone portion of which includes a distinctive 1 m thick pumiceous volcaniclastite deposit.

In the Whakapunake Limestone the limestone beds have carbonate contents near 70%, while the interbedded mudclast-bearing shelly sandstones have values nearer 40%. The Whakapunake Limestone hosts common barnacles and frequent pectinids (*Mesopeplum waikohuense* (Marwick), *Phialopecten marwicki* and *Mesopeplum crawfordi*), oysters up to 5 cm size, and brachiopods (*Neothyris*).

The youngest limestone, the Waipipian aged **Tahaenui Limestone** (Figure 7.1), is widely but discontinuously distributed across the study area and varies in thickness from 10-60 m. At Tahaenui/Clonkeen the limestone is moderately indurated, vaguely planar or horizontally bedded and hosts a barnacle dominated skeletal matrix. Siliciclastic material is rare. At Mt Moumoukai the Tahaenui Limestone rests with mild angular unconformity on the Opoiti Limestone or Wairoa Formation B. Here the Tahaenui Limestone is indurated, massive to vaguely bedded with a very sandy skeletal matrix. On Mahia Peninsula, the Tahaenui Limestone forms Taupiri Hill and Long Point (Figure 7.1). The limestone here is massive to vaguely horizontal bedded, rather soft, and consists of densely packed barnacle plates (4-5 mm size) with very rare siliciclastic grains. The Tahaenui Limestone unconformably overlies late Miocene mudstone at Tahaenui/Clonkeen and Mahia Peninsula. Wairoa Formation D is seen above the Tahaenui Limestone in the Tahaenui/Clonkeen area only and comprises shelly sandstone and mudstone with a 1 m thick pumiceous volcaniclastite interbed.

Tahaenui Limestone has the highest carbonate content of the three Pliocene limestones in the study area, reaching up to c.90%. The Tahaenui Limestone typically hosts abundant barnacles, common brachiopods (*Neothyris* cf. *obtusa* or *Neothyris campbellica elongata*), pectinids (*Phialopecten marwicki*) and oysters (*Ostrea chilensis* and *Crassostrea ingens*) and rare foraminifera.

11.2 LITHOFACIES ANALYSIS

Twelve lithofacies were established in the field for the Pliocene strata in northern Hawke’s Bay. Four primary divisions were made based on lithology (Limestone-L vs Sandstone-S vs Mudstone-M vs Volcanic-V) with further field characteristics distinguishing the various lithofacies (Table 4.1). For each limestone and its associated Wairoa Formation, the lithofacies are distinguished in carbonate-siliciclastic sand-siliciclastic mud triangular plots.

Everywhere the **Opoiti Limestone** is dominated by the sandy limestone lithofacies L3. Bioclastic limestone lithofacies L1 occurs typically only in the stratigraphically higher portion at Ahimanawa Station, with the coquina lithofacies L2 occurs only, yet commonly, at the base of the limestone. Wairoa

Formation B includes one calcareous, massive sandstone lithofacies (S1), the massive and concretionary mudstone lithofacies (M1, M3) and one volcanic lithofacies (V1). A lithofacies panel diagram (Figure 5.12) shows similar vertical stacking orders of the Opoiti Limestone and Wairoa Formation B lithofacies across the study area, with the sandy limestone lithofacies L3 common throughout.

The interbedded nature of the **Whakapunake Limestone** involves alternations of sandy limestone lithofacies L3 and mudclast-bearing sandstone lithofacies S4. The overlying Wairoa Formation C includes abundant and thick bioclastic sandstone lithofacies S2, some massive sandstone lithofacies S1 and rare massive mudstone lithofacies (M1) and volcanic (V1) lithofacies. The panel diagram (Figure 6.9) shows simple distribution of the Whakapunake Limestone and Wairoa Formation C lithofacies.

The **Tahaenui Limestone** hosts very common bioclastic limestone lithofacies L1 in all localities, with some sandy limestone lithofacies L3 at Mt Moumoukai. The overlying Wairoa Formation D involves one common bioclastic sandstone lithofacies (S2), massive and fossiliferous mudstone lithofacies (M1, M4) and a volcanic lithofacies (V1) (Figure 7.15). The panel diagram (Figure 7.16) shows good vertical similarities of the Tahaenui Limestone and Wairoa Formation D lithofacies across the study area.

11.3 PETROGRAPHY

The **Opoiti Limestone**, typically a sandy biomicrite to a variably sandy, poorly washed/rounded biosparite or bioclastic arenite, hosts common moderately abraded brachiopod and barnacle fragments, planktic and benthic foraminifers, rare to common bryozoans and rare echinoderm and bivalve material. Aragonite is not observed in the Opoiti Limestone, but under CL, dark purple gastropods suggest the rare presence of aragonite in the overlying Wairoa Formation B. Cements in the Opoiti Limestone consist mainly of primary microbioclastic micrite and rare homogenous micrite with some isopachous sparite. Glauconite pellets and pyrite are ubiquitous, but sparse, throughout the Opoiti Limestone, with disseminated pyrite common within microbioclastic micrite. Interskeletal space in microbioclastic micrite dominated samples is high (c.50%), but much lower (c.15%) in samples dominated by isopachous sparite. The Opoiti Limestone has a modal acid insoluble grain size of 123-177 µm (very fine to fine sand).

The **Whakapunake Limestone** limestone interbeds are mainly packed biomicrites to poorly washed biosparites, while the sandstone interbeds are muddy bioclastic arenites. The skeletal componentry (0.5-3 mm) is fragmented and moderately abraded and includes common barnacles, occasional brachiopods, rare planktic and benthic foraminifera and rare bryozoans and echinoderms. Under CL the barnacle fragments are predominantly non-luminescent but show some dull orange internal structures. Cements in the Whakapunake Limestone are usually thin (0.01 mm) isopachous sparite rims and microbioclastic micrite with common included siliciclasts. Glauconite pellets and pyrite are common within the limestone beds. Interskeletal space in microbioclastic micrite dominated samples can be up to 40%, compared to lower values (c.15%) in isopachous sparite dominated samples. The Whakapunake Limestone shows two modal sizes for the acid insoluble fraction in the limestone samples, 15-29 µm (medium silt) and 199-213 µm (fine sand), while the sandstone interbeds also shows two modal sizes of 183-779 µm (fine to coarse sand) and 42-87 µm (coarse silt to very fine sand) that can be referenced back to the sandy matrix and the elongated mudstone clasts, respectively.

The **Tahaenui Limestone**, typically a rounded biosparite to packed biomicrite, includes strongly to moderately abraded abundant barnacles, occasional to common brachiopods, and rare bryozoans and planktic and benthic foraminifera. Cements in the Tahaenui Limestone consist mainly of interparticle, host specific, scalenohedral shaped isopachous sparite rims which display two to three-phase crystal growth under CL, and common microbioclastic micrite. Glauconite (pellets) and pyrite infills are both common. Interskeletal space in the isopachous sparite samples is up to 15%. Some subrounded, empty biomoulds occur up to c.2 mm size, generating secondary porosity, and are likely tied to former aragonitic skeletons. The Tahaenui Limestone shows two modal sizes for its acid insoluble grains, 11-27 µm (fine-medium silt) and 149-152 µm (fine sand).

The overall near zero to small positive $\delta^{18}O$ values for bulk samples is suggestive of relatively little burial alteration of the limestones (Figure 8.13). Therefore the origin of the cements occurred from precipitation near below or at the sea floor. Uplift and subaerial exposure of the three Pliocene limestones did not occur until mid to late Nukumaruan times (Bland *et al.* 2008).

11.4 DEPOSITIONAL ENVIRONMENTS

Cool water deposition of these northern Hawke's Bay Pliocene limestones occurred in the East Coast Basin within a tectonically active subduction zone. This active tectonism caused numerous NE-SW striking upthrust antiforms and associated bounding synforms to develop, the former of which can become habitation sites for marine carbonate taxa (carbonate factories) when waters shoaled to less than about 60 m depth (Kamp & Nelson 1987; Caron *et al.* 2004b). The Ruataniwha Strait (Beu 1995) developed to the west of these anti/synform structures within the forearc basin proper. Due to the high energy water conditions, derived from strong tidal currents in the strait, shell litter and debris was continually shed and reworked from the tops of the antiforms, accumulating about the flanks of the antiforms and even into the adjacent synforms. The crests of these antiforms would have been relatively free of siliciclastic material, which was swept away or by-passed by the strong by the tidal current flows (Kamp *et al.* 1988), allowing and encouraging growth of suspension/filter feeders such as barnacles and pectinids (Kamp & Nelson 1987). Periods of limestone accumulation were typically short-lived, occurring in different areas at different times (Beu *et al.* 1980; Ballance 1993), resulting in a patchy distribution and a range of ages for these unique limestones. Varying carbonate-siliciclastic deposition was primarily tectonically driven with possible superimposed eustatic sea level changes.

The Mahia Paleostrait was open during much of the Pliocene, separating limestone formation in the Nuhaka area from that on Mahia Peninsula.

The main skeletal taxa living in the antiform settings were barnacles, pectinids, brachiopods and oysters. As no hard rock outcrops were readily available in this setting, the barnacles utilised the large epifaunal pectinid (and other) shells as a substrate (Kamp & Nelson 1988). The major environmental factors that controlled the productivity of the living skeletal organisms included a high nutrient supply, varying water energy, light penetration and a varying siliciclastic input (Caron *et al.* 2004b).

The prominently bedded couplets in the **Opoiti Limestone** are probably event deposits associated with storm emplaced shedding and reworking of carbonate sediment about the flanks of the upthrust Morere, Mangaone and Lachlan antiforms. A high amount of sandy material in the deposits suggests a relatively proximal source of siliciclastic grains.

The **Whakapunake Limestone** is the result of rhythmic carbonate-siliciclastic deposition about the upthrust Lachlan antiform system. The mechanism is uncertain and could relate to cyclic storm emplacements or repeated sea level rises and falls. The elongated clasts of mudstone within the sandstone interbeds illustrate some quite marked periodic changes in sedimentation patterns. The origin of the mudclasts remains problematic; possibly they mark the positions of original *Skolithos/Ophiomorpha* burrows later modified by seismic shaking.

The **Tahaenui Limestone** in the study area was likely also deposited high on the flanks of the upthrust Morere, Mangaone and Lachlan anticlines. The high abundance of barnacle fragments in the deposits reflects the sediment free, high nutrient and high energy of the antiform crest. The repetitive thinly bedded appearance (‘flaggy’ nature) is suggestive of storm shedding as skeletal carbonate sheets.

11.5 SEQUENCE STRATIGRAPHY

Seismic reflection profiles can demonstrate the subsurface geology and structure, and can illustrate any sequence stratigraphic patterns. The regional Mangaheia Group, in which the Opoiti, Whakapunake and Tahaenui Limestone occur, is an overall regressive sequence (Figure 9.3) (Cashman *et al.* 1992; Bland *et al.* in prep.).

The three limestones and their associated bounding lithologies (the Wairoa Formation) delineate at least three major periods of overall sea level transgressive movements during the Pliocene in the northern Hawke's Bay area. The related regressive intervals are not obviously preserved in the field, likely due to erosion during ?lowstand and transgressive periods. In most places in the study area a TST coquina shell bed occurs at the base of the Opoiti Limestone. The mudstone that overlies the Opoiti Limestone marks the culmination into highstand conditions of the oldest transgressive event. The Whakapunake Limestone provides records evidence for the second overall transgressive event and possibly includes deposits associated with superimposed Milankovitch driven fluctuations. The Whakapunake Limestone is overlain by sandstone and mudstone, regarded as marking the transition into a period of highstand for the second major transgressive period. The Tahaenui Limestone at all localities represents the third period of overall sea level transgression and deepening. The Wairoa Formation sandstone and mudstone observed at Tahaenui/Clonkeen marks the transition into highstand conditions.

11.6 ECONOMIC POTENTIAL

The Opoiti, Whakapunake and Tahaenui Limestones have variable economic viability. Existing economic development in the Nuhaka/Mahia area includes two intermittently working quarries in the Tahaenui Limestone located at Tahaenui and at Clonkeen. These are both managed by QRS Wairoa and are primarily used for aggregate. The use of the Tahaenui Limestone for agricultural lime is worth considering. The Whakapunake Limestone lacks accessibility and tonnage for any commercial productivity. The Opoiti Limestone may be suitable for aggregate quarrying at Mt Moumoukai and at Ahimanawa, although access would need to be improved from the present situation.

Despite the limestones affording potentially good reservoir beds due to their high porosities, it is unlikely that there is any hydrocarbon prospects in the immediate area. No surface indications of oil or gas seeps occur in either the Tahaenui/Clonkeen or Mt Moumoukai areas, suggesting the unlikelihood of a developed petroleum system. On the other hand, it could be that if the limestones in the subsurface held any hydrocarbons these could well be fully trapped by the encasing Wairoa Formation mudstones. The lack of faulting in the study area would also contribute to the trapping of any potential subsurface hydrocarbons.

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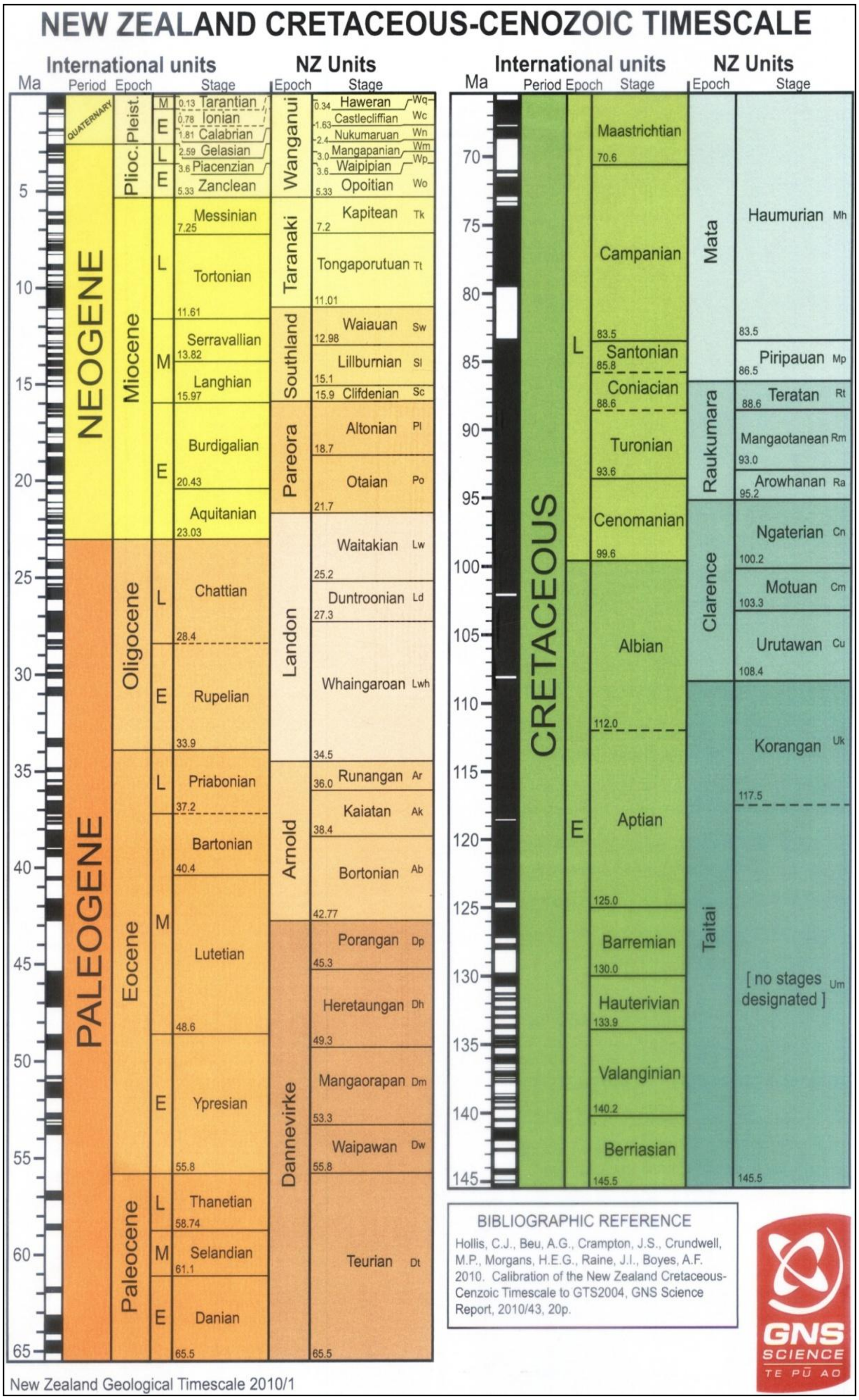
APPENDIX I – TIME SCALE

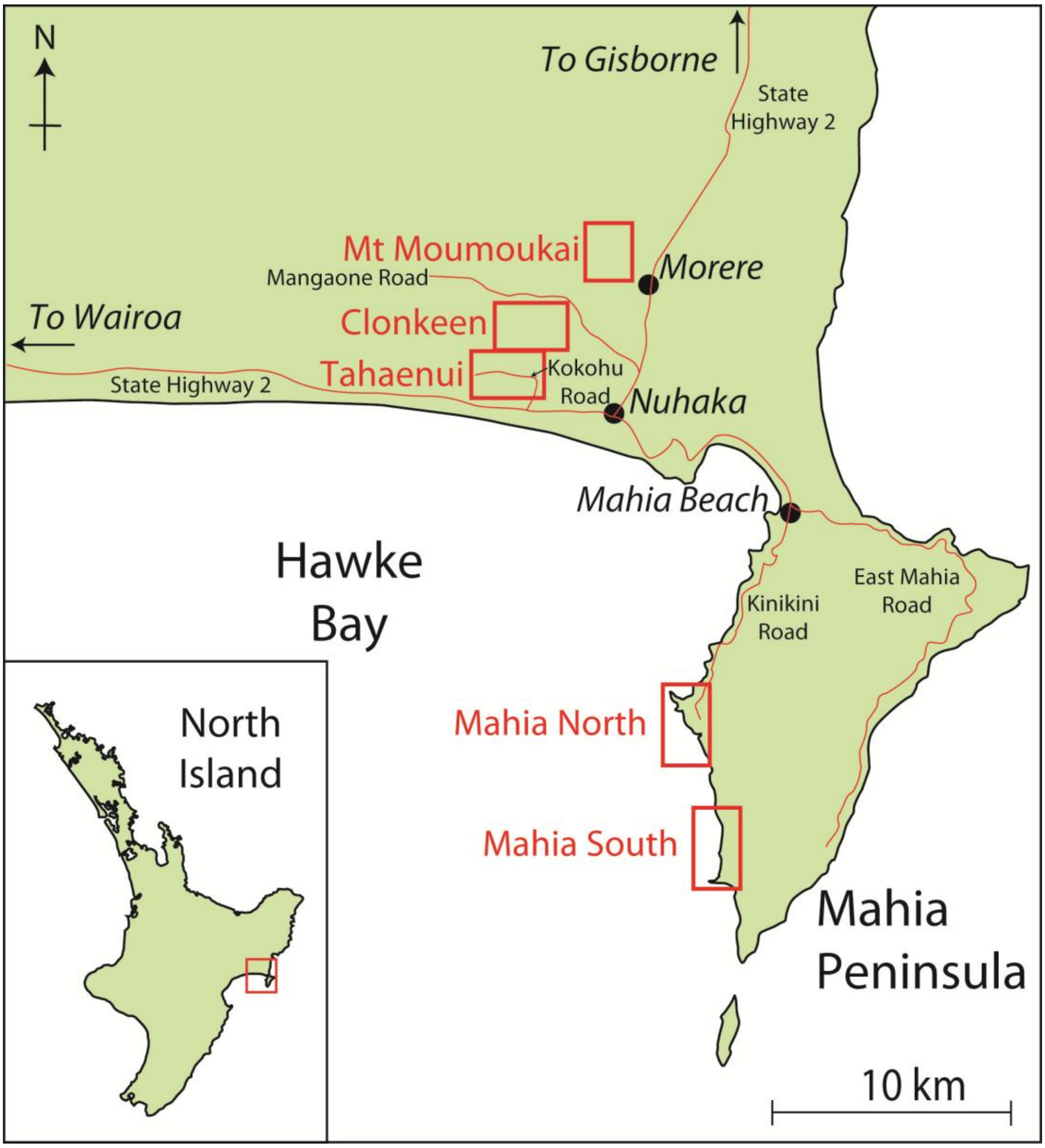


APPENDIX II – LOCALITY MAPS

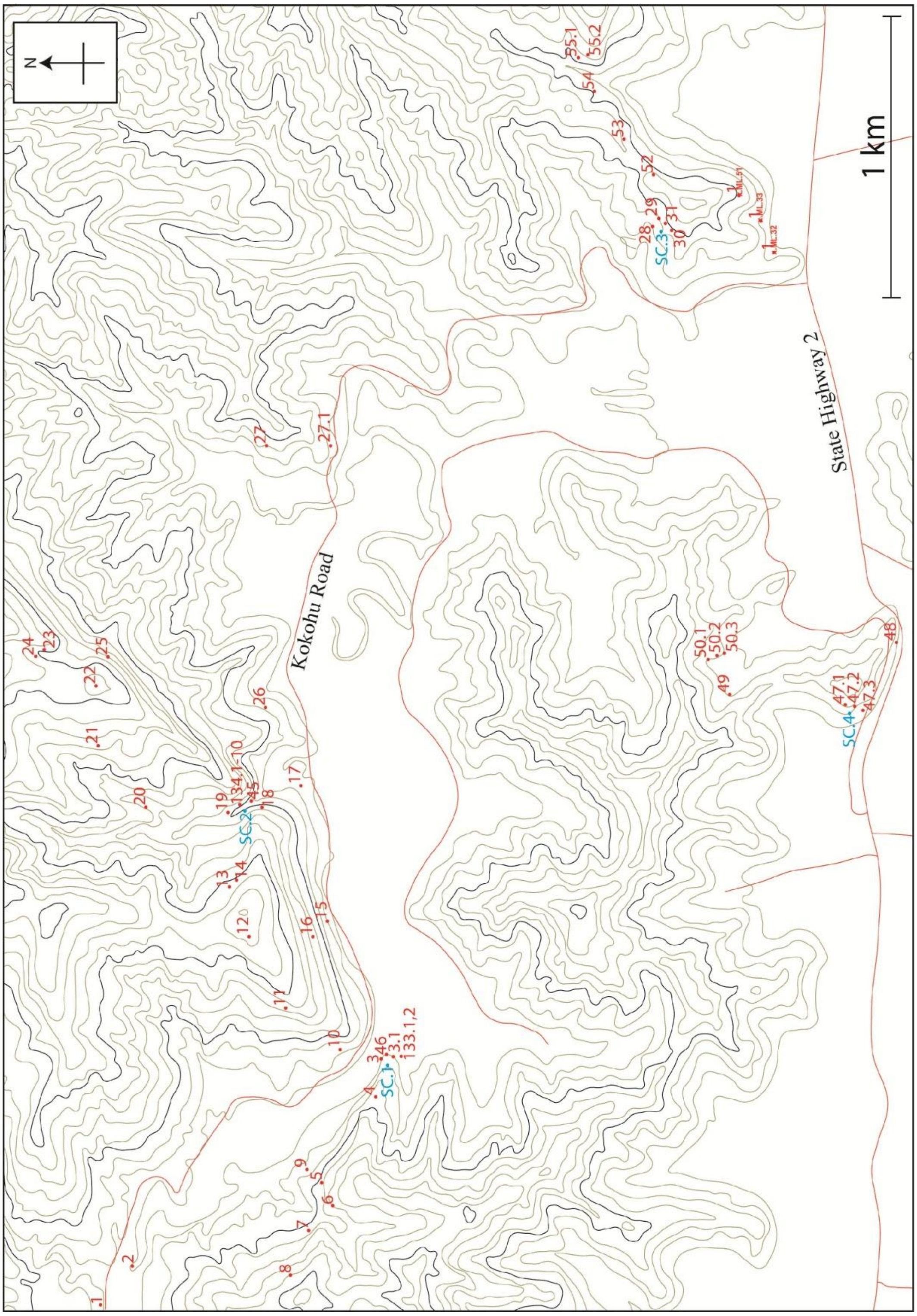
Sample localities ….. .58.2

Stratigraphic Column Localities … SC.5

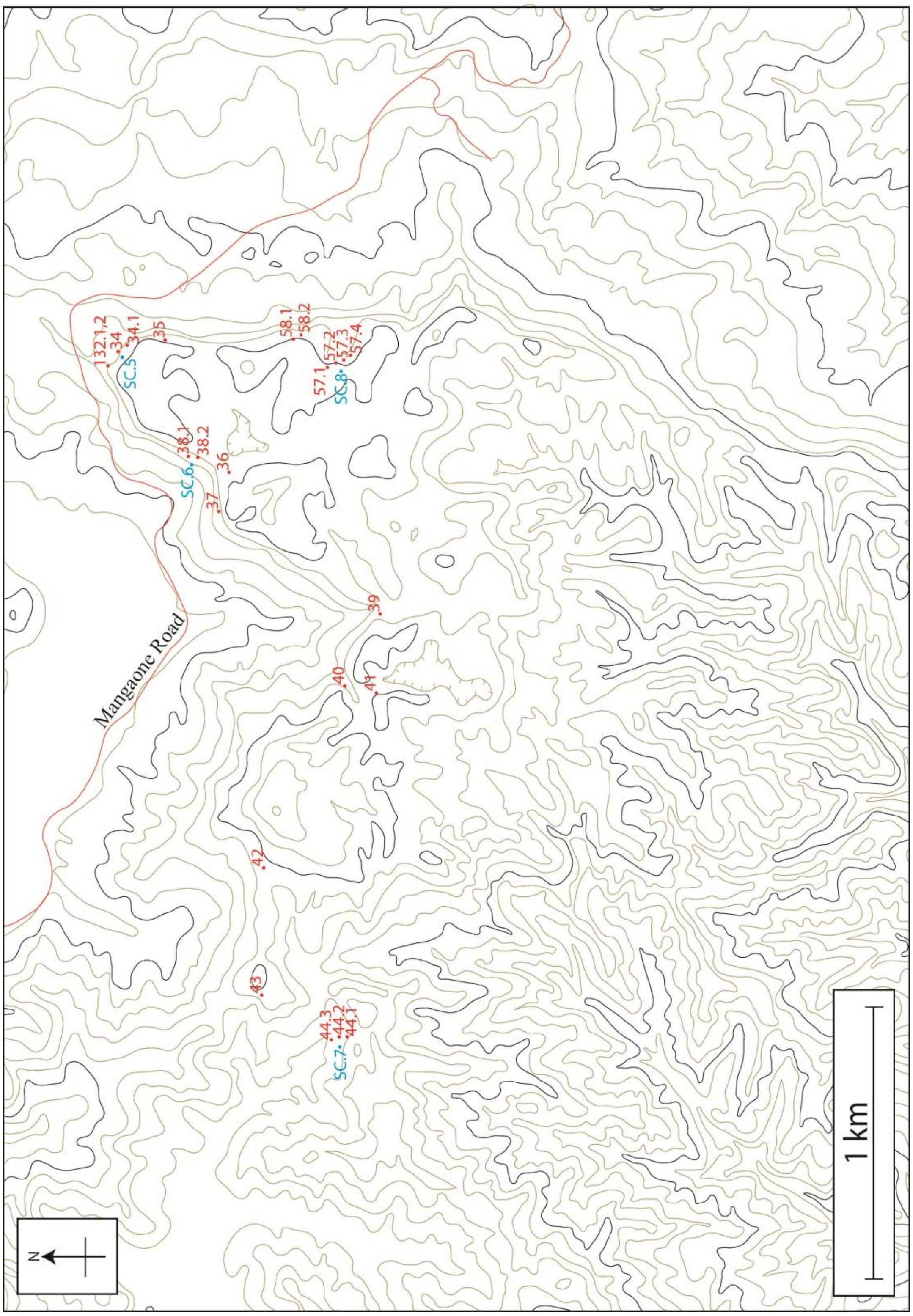
Contour interval is 20 m



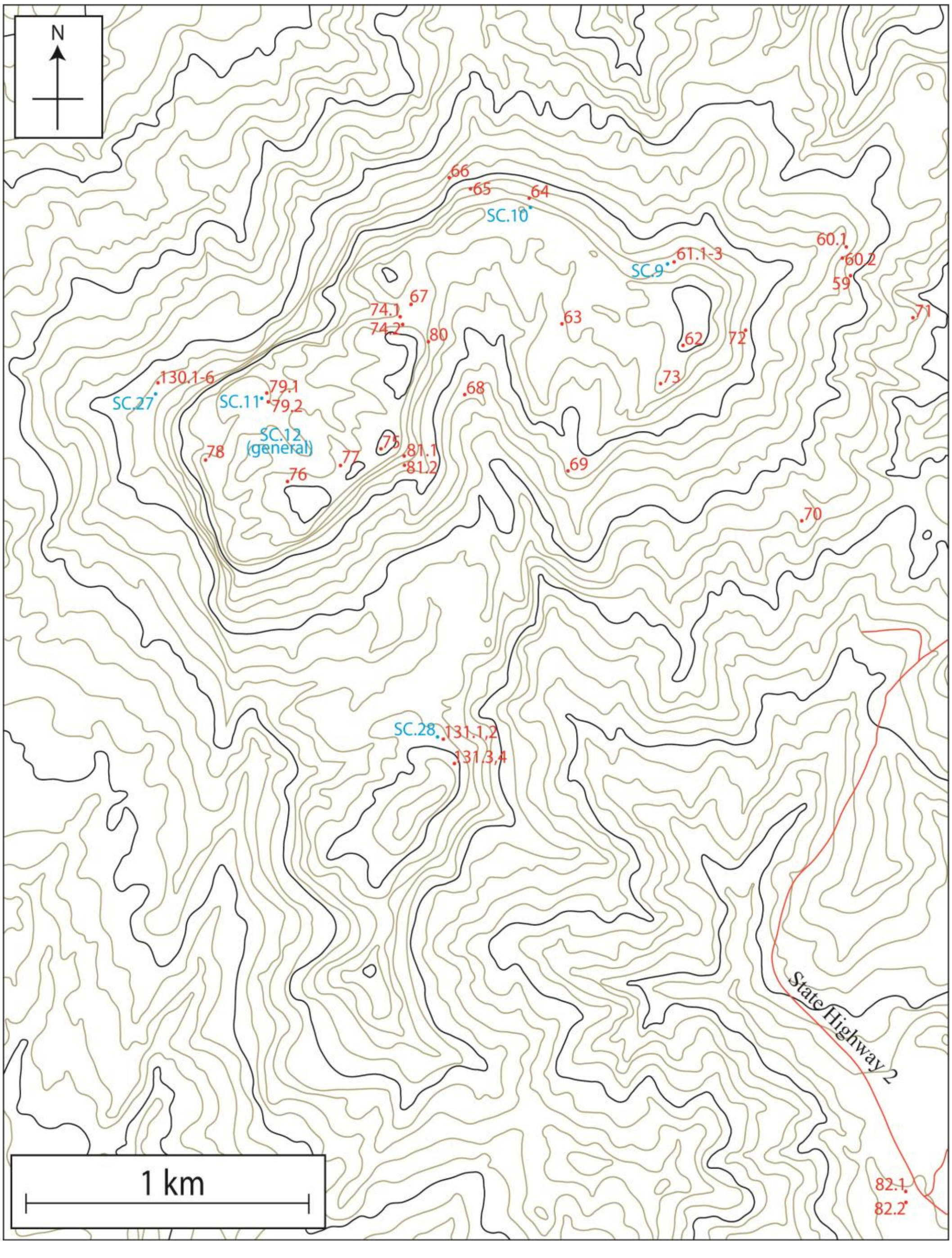
Tahaenui



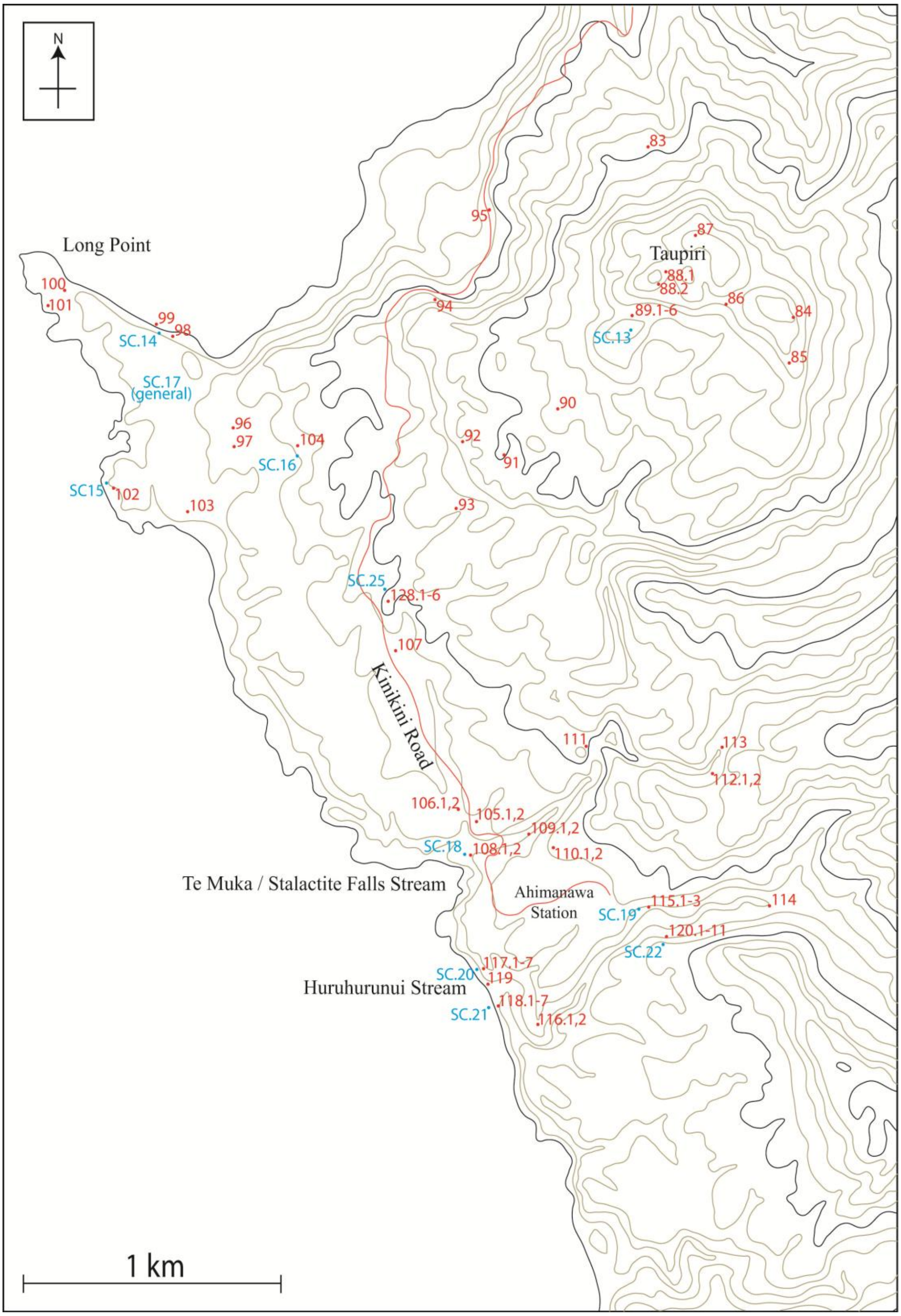
Clonkeen


Mangaone Road
132.1,2
34
34.1
35
SC.5
58.1
58.2
57.1
57.2
57.3
57.4
SC.8
38.1
38.2
36
SC.6
37
39
40
41
42
43
44.3
44.2
44.1
SC.7
1 km
N

Mt Moumoukai

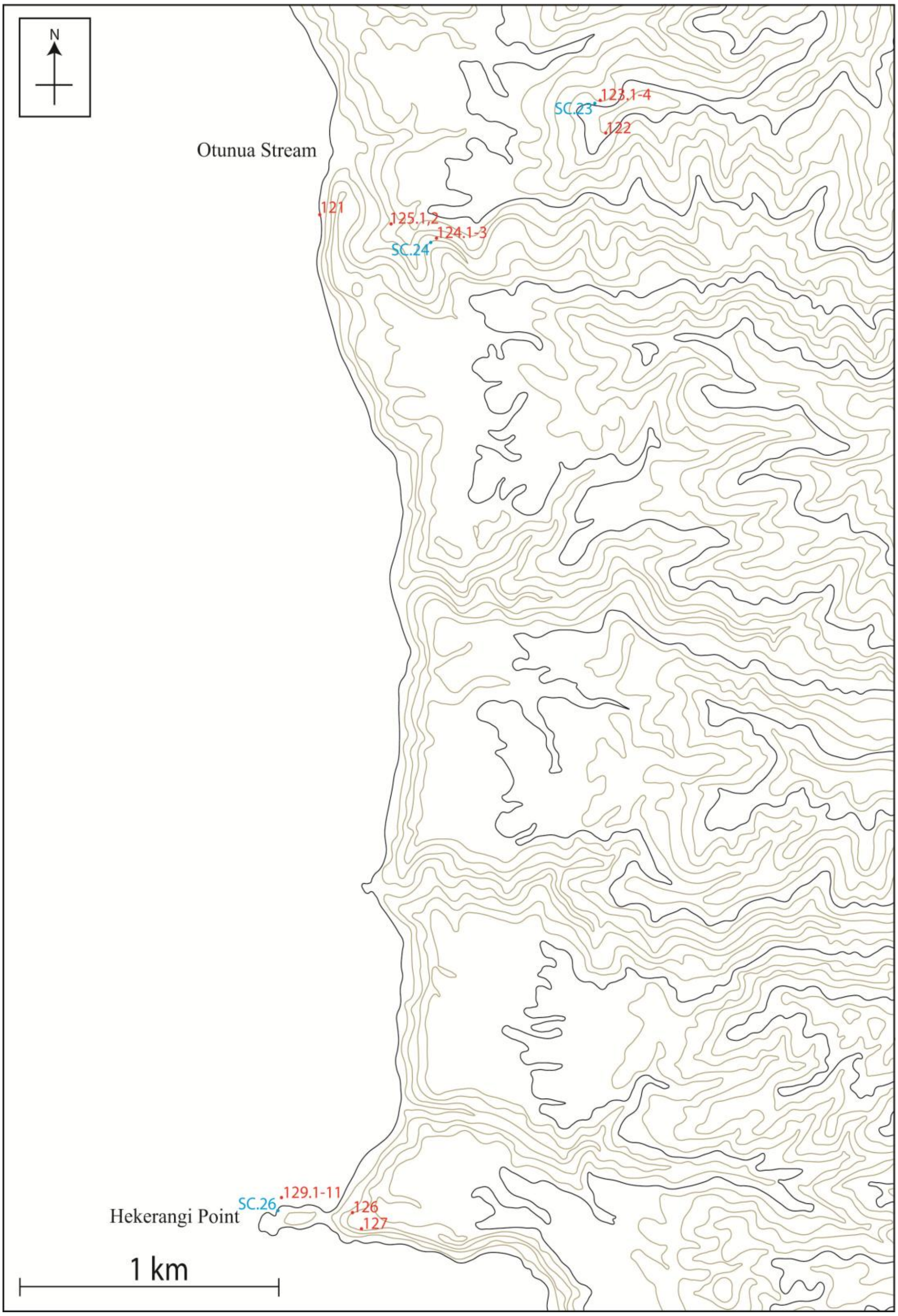


Mahia North



N
Long Point
Taupiri
Kinikini Road
Te Muka / Stalactite Falls Stream
Ahimanawa Station
Huruhurunui Stream
1 km
83
95
87
88.1
88.2
86
84
89.1-6
SC.13
85
100
101
99
98
SC.14
94
SC.17 (general)
90
96
97
104
92
91
SC.16
SC15
102
103
93
SC.25
128.1-6
107
111
113
112.1,2
106.1,2
105.1,2
109.1,2
SC.18
108.1,2
110.1,2
115.1-3
114
SC.19
120.1-11
SC.22
117.1-7
SC.20
119
118.1-7
SC.21
116.1,2

Mahia South



N
Otunua Stream
SC.23
123.1-4
122
121
125.1,2
124.1-3
SC.24
Hekerangi Point
SC.26
129.1-11
126
127
1 km

APPENDIX III - CALCIUM CARBONATE ANALYSIS

Sample No.	Unit	Locality	Sample (g)	Filter Paper (g)	Filter Paper + Residue (g)	Residue (g)	CO_3 (g)	%CO_3
L1 - 3	Tahaenui Limestone	Tahaenui/Clonkeen	10.003	2.618	5.17	2.552	7.451	**74.5**
L1 - 107	Tahaenui Limestone	Mahia Peninsula	10.023	2.608	3.527	0.919	9.104	**90.8**
L2 - 129.4	Opoiti Limestone	Mahia Peninsula	10.048	2.582	4.989	2.407	7.641	**76.0**
L2 - 112.1	Opoiti Limestone	Mahia Peninsula	10.079	2.62	5.958	3.338	6.741	**66.9**
L3 - 129.6	Opoiti Limestone	Mt Moumoukai	10.021	2.613	6.94	4.327	5.694	**56.8**
L3 - 62	Opoiti Limestone	Mt Moumoukai	10.022	2.615	6.952	4.337	5.685	**56.7**
L3 - 131.2	Opoiti Limestone	Mt Moumoukai	5.022	2.619	6.014	3.395	1.627	**32.4**
L3 - 106.2	Whakapunake Limestone	Mahia Peninsula	10.093	2.623	4.757	2.134	7.959	**78.9**
L3 - 108.2	Whakapunake Limestone	Mahia Peninsula	10.048	2.61	6.242	3.632	6.416	**63.9**
S1 - 63	Wairoa Formation B	Mt Moumoukai	5.057	2.597	6.751	4.154	0.903	**17.9**
S1 - 64	Wairoa Formation B	Mt Moumoukai	5.024	2.599	6.16	3.561	1.463	**29.1**
S1 - 118.7	Wairoa Formation C	Mahia Peninsula	5.011	2.605	7.235	4.63	0.381	**7.6**
S2 - 57.4	Wairoa Formation D	Tahaenui/Clonkeen	5.01	2.608	6.007	3.399	1.611	**32.2**
S2 - 118.3	Wairoa Formation C	Mahia Peninsula	5.052	2.615	5.76	3.145	1.907	**37.7**
S4 - 117.2	Whakapunake Limestone	Mahia Peninsula	5.047	2.598	6.033	3.435	1.612	**31.9**
S4 - 105.1	Whakapunake Limestone	Mahia Peninsula	10.039	2.622	7.87	5.248	4.791	**47.7**
M1 - 134.10	Wairoa Formation D	Tahaenui/Clonkeen	5.002	2.599	7.573	4.974	0.028	**0.6**
M1 - 70	Late Miocene mudstone	Mt Moumoukai	5.023	2.618	7.426	4.808	0.215	**4.3**
M3 - 129.5	Late Miocene mudstone	Mahia Peninsula	5.087	2.601	4.949	2.348	2.739	**53.8**
M3 - 129.2	Opoiti Limestone concretion	Mahia Peninsula	5.064	2.612	5.078	2.466	2.598	**51.3**
M4 - 57.3	Wairoa Formation D	Tahaenui/Clonkeen	5.01	2.567	6.696	4.129	0.881	**17.6**
V1 - 57.2	Wairoa Formation D	Tahaenui/Clonkeen	5.086	2.6	7.535	4.935	0.151	**3.0**
V1 - 118.5	Wairoa Formation C	Mahia Peninsula	5.013	2.578	7.232	4.654	0.359	**7.2**

Sieve mesh	(mm)	(μm)	Phi (ϕ)	BS Sieve	Wentworth size class
5	4	4000	-2		
6	3.36		-1.75		
7	2.83		-1.5		Granule
8	2.38		-1.25		
10	2.00	2000	-1.0	2000	
12	1.68		-0.75	1700	
14	1.41		-0.5	1400	Very Coarse Sand
16	1.19		-0.25	1180	
18	1.00	1000	0	1000	
20	0.84	840	0.25	850	
25	0.71	710	0.5	710	Coarse Sand
30	0.59	590	0.75	600	
35	0.50	500	1.0	500	
40	0.42	420	1.25	425	
45	0.35	350	1.5	355	Medium Sand
50	0.30	300	1.75	300	
60	0.25	250	2.00	250	
70	0.210	210	2.25	212	
80	0.177	177	2.5	180	Fine Sand
100	0.149	149	2.75	150	
120	0.125	125	3.00	125	
140	0.105	105	3.25	106	
170	0.088	88	3.50	90	Very Fine Sand
200	0.074	74	3.75	75	
230	0.063	63	4.00	63	
270	0.053	53	4.25	53	
325	0.044	44	4.5	45	Coarse Silt
	0.037	37	4.75	38	
	0.031	31	5		
					Medium Silt
	0.156	15.6	6		
					Fine Silt
	0.0078	7.8	7		
					Very Fine Silt
	0.0039	3.9	8		
					Very Coarse Clay
	0.0020	2.00	9		
					Coarse Clay
	0.00098	0.98	10		
					Medium Clay
	0.00049	0.49	11		
					Fine Clay
	0.00024	0.24	12		
	0.00012	0.12	13		Very Fine Clay
	0.00006	0.06	14		

Grainsize scale for sediments (Folk 1968, p25)

APPENDIX V - FORAMINIFERAL DATA

All size fractions – 150-1000 µm

Sample 26 – Late Miocene mudstone, underlies Tahaenui Limestone

Box	Count	Species/Description	Foram type
13-20	28	*Lenticulina* - fragmented to whole, pearlescent white, often infilled with dry mudstone grains	Benthic
25	3	Broken echinoid spines - hollow, white and delicate	-
38	1	*Orbulina universa* - broken	Planktic

Sample 58.2 – Late Miocene mudstone, underlies Tahaenui Limestone

Box	Count	Species/Description	Foram type
1	1	*Globorotalia pliozea* – dextral spiral, has lost last chamber	Planktic
13	2	*Cibicides* - perforated test	Benthic
14	1	*Dentalina* - long chambers	Benthic
25-27	21	*Nodosaria longiscata* - hollow, delicate	Benthic
29	2	Fragments of *Nodosaria longiscata* - bulbous ends of tubes	Benthic
37	9	Pyritised *Orbulina universa*	Planktic
38	2	Broken *Orbulina universa*	Planktic

Sample 109.1 - within Whakapunake Limestone

Box	Count	Species/Description	Foram type
13	1	*Lenticulina* - fragmented to whole, pearlescent white	Benthic
25	4	Broken echinoid spines - hollow, white and delicate	-
37-39	8	Bryozoans – broken stems with 'ponga tree' pattern	-
40	10	Glauconite - smooth green pellets	-
49	4	Quartz – sharp, clear	-
SEM	1	*Notorotalia*	Benthic
SEM	1	*Textularia* aff. *barnwelli* - agglutinating	Benthic

Sample 130.1 – Late Miocene mudstone, underlies Opoiti Limestone

Box	Count	Species/Description	Foram type
1-7	33	*Orbulina universa* - slightly compaction, smooth surface from secondary calcite	Planktic
13	2	*Globigerina* - spiral	Planktic
14	1	*Globigerina uvola* - spiral, 4-10 chambers	Planktic
25	4	Broken echinoid spines - hollow, white and delicate	-
37	1	Pyritised *Orbulina universa*	Planktic
38	1	Broken *Orbulina universa*	Planktic

APPENDIX VI – STABLE ISOTOPE DATA

Cement Samples Waikato (Dec 2010)

1. Precision of Measurements

All values reported relative to vPDB, where $\delta^{13}C$ has a value of +1.95‰ and $\delta^{18}O$ has a value of -2.20‰ for NBS19 calcite. Additional NBS18 standard, due to submitter suggested results, where $\delta^{13}C$ has a value of -5.014‰ and $\delta^{18}O$ has a value of -23.20‰. Internal precision of measurements is 0.02-0.08‰ for $\delta^{18}O$ and 0.01-0.06‰ for $\delta^{13}C$, external precision is 0.03‰ for $\delta^{18}O$ and 0.02‰ for $\delta^{13}C$, relative to vPDB.

Samples were reacted with 3 drops of H_3PO_4 at 75°C in an automated individual-carbonate reaction (Kiel IV) device coupled with a Finnigan MAT253 mass spectrometer.

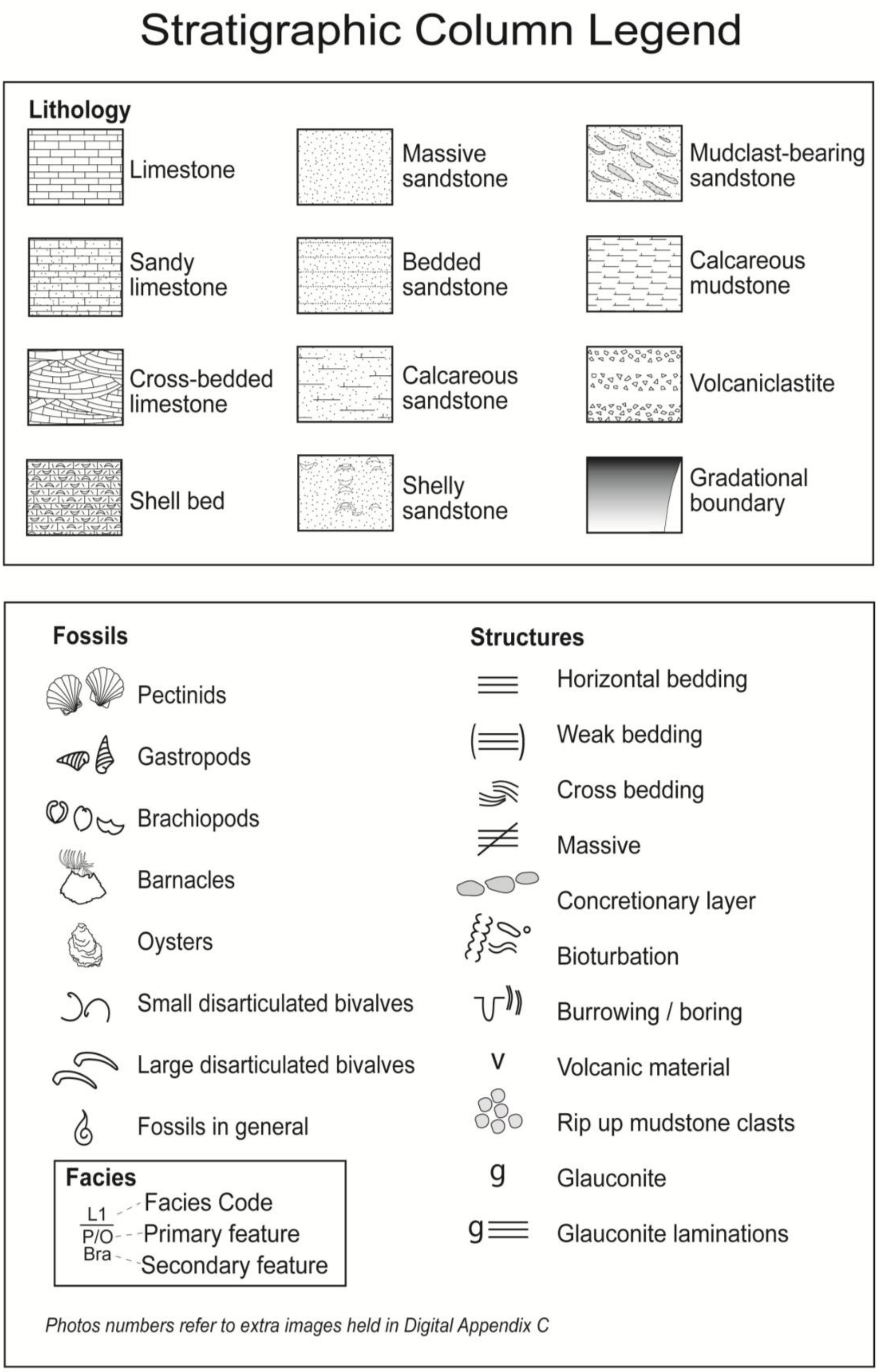
	Precision	**$\delta^{18}O$**	**$\delta^{13}C$**
NBS19	Run 1	0.02	0.03
NBS19	Run 2	0.06	0.04
NBS18	Run 2	0.04	0.03

Balance is used as an indicator of result reliability, values approaching or less than 0.80 should be used with caution if they are associated with a single point or outlier. Voltages below 1.2 are usually considered unreliable irrespective of balance.

2. Results

Bulk limestone and skeletal samples

	Run	$\delta^{13}C$	$\delta^{18}O$	Sample		SA44[mV]	ST44[mV]	Balance
1	1	1.16	0.26	L1	120.3	5212.36	5723.38	0.91
2	1	1.56	0.37	L1	3	5580.64	7201.74	0.77
3	2	1.43	0.15	L1	3	4606.66	5202.85	0.89
4	1	0.57	-0.19	L1	107	7739.17	6413.22	0.83
5	2	0.56	-0.15	L1	107	4704.69	5208.37	0.90
6	1	0.90	0.01	L1	128.1	5041.72	5725.55	0.88
7	1	-2.15	-0.21	L2	129.4	6255.05	6938.90	0.90
8	1	-1.98	-0.14	L2	129.4	4383.36	4887.37	0.90
9	1	0.63	-0.33	L2	112.1	7646.04	9439.81	0.81
10	2	0.47	-0.62	L2	112.1	7349.91	7905.43	0.93
11	1	0.30	-1.31	L2	129.10	7472.87	8447.11	0.88
12	1	1.89	-0.17	L2	123.2	4164.97	4633.11	0.90
13	2	1.80	-0.22	L2	123.2	5614.03	6413.73	0.88
14	1	-0.11	-0.04	L3	129.6	4490.81	4934.66	0.91
15	2	-0.05	0.06	L3	129.6	7957.92	10192.00	0.78
16	1	1.91	-0.14	L3	61.2	5559.62	6352.17	0.88
17	1	1.13	0.19	L3	106.2	5560.73	6107.64	0.91
18	1	1.10	0.27	L3	108.2	3440.50	3796.24	0.91
19	2	1.04	0.27	L3	108.2	4662.48	5168.36	0.90
20	1	1.19	0.67	Barnacle		5530.44	5024.81	0.91
21	2	1.19	0.63	Barnacle		4294.99	4755.78	0.90
22	1	1.16	0.66	Pectinid		6752.23	7645.04	0.88
23	1	1.16	-0.20	Brachiopod		3855.49	4268.99	0.90


Stratigraphic Column Legend
Lithology
Limestone
Massive sandstone
Mudclast-bearing sandstone
Sandy limestone
Bedded sandstone
Calcareous mudstone
Cross-bedded limestone
Calcareous sandstone
Volcaniclastite
Shell bed
Shelly sandstone
Gradational boundary
Fossils
Pectinids
Gastropods
Brachiopods
Barnacles
Oysters
Small disarticulated bivalves
Large disarticulated bivalves
Fossils in general
Facies
L1
P/O
Bra
Facies Code
Primary feature
Secondary feature
Structures
Horizontal bedding
Weak bedding
Cross bedding
Massive
Concretionary layer
Bioturbation
Burrowing / boring
v
Volcanic material
Rip up mudstone clasts
g
Glauconite
g
Glauconite laminations
Photos numbers refer to extra images held in Digital Appendix C

Stratigraphic Column Number 01

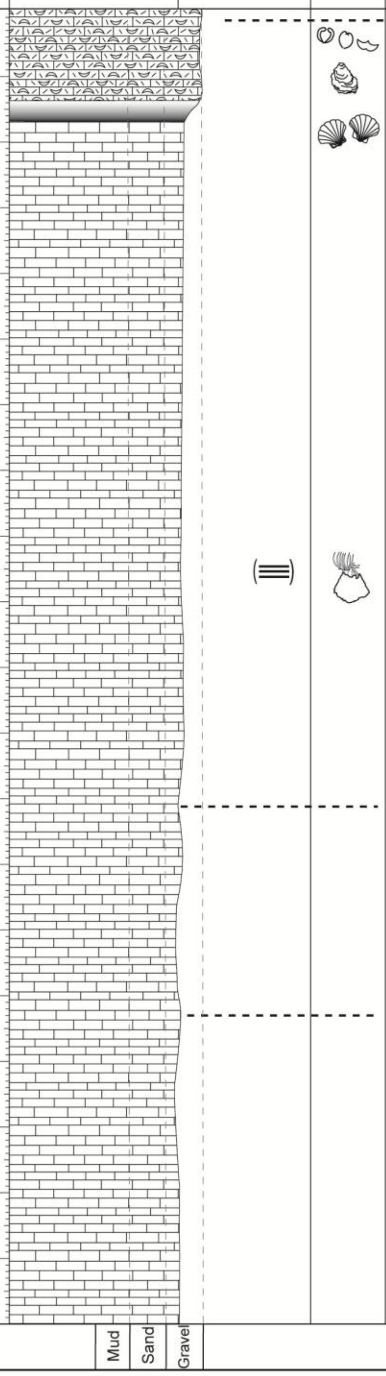
Region Nuhaka

Location Tahaenui Quarry, Kokohu Road

NZ Topo50 - BH42/034699

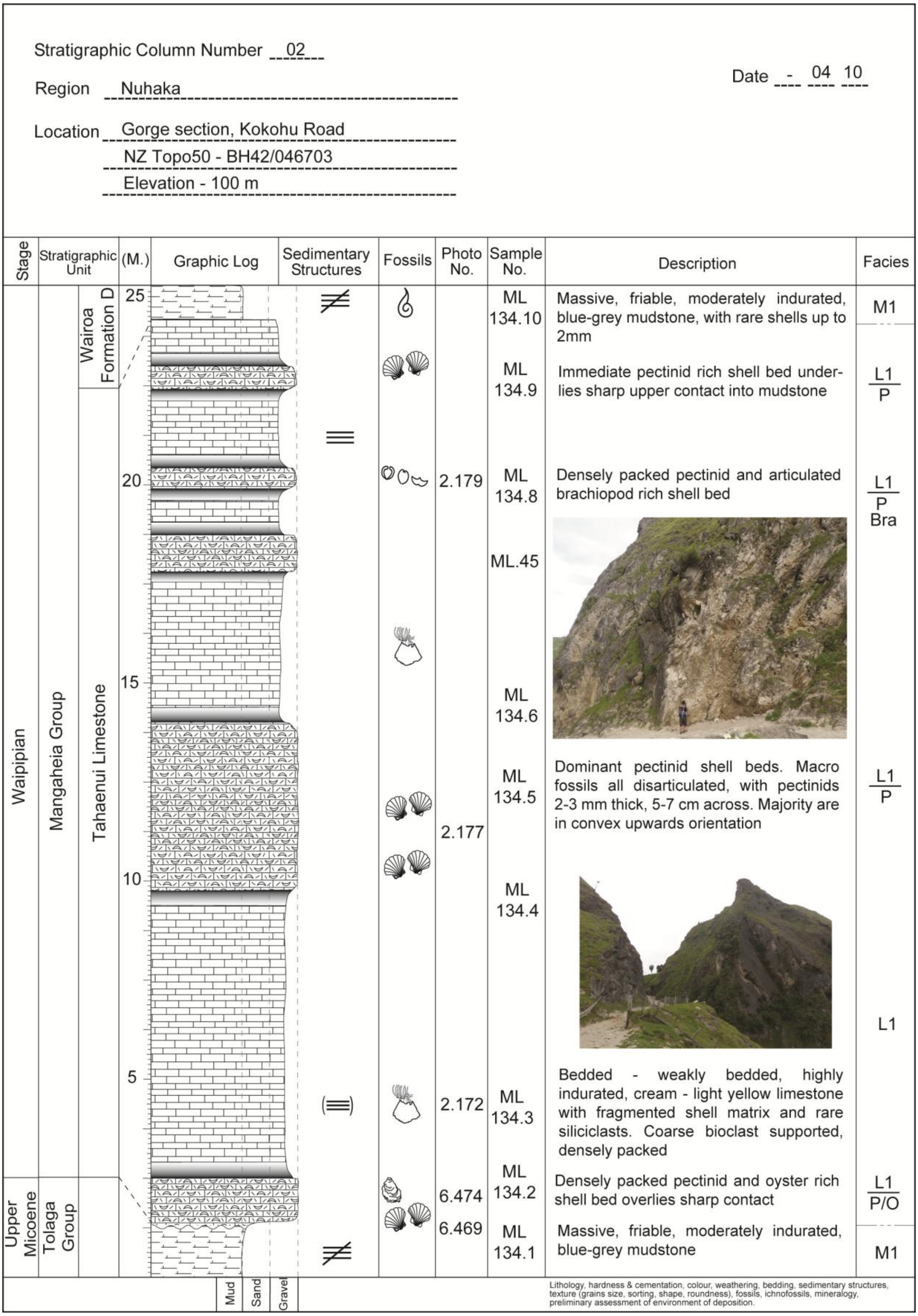
Elevation - 110 m

Date - 04 10



Stage	Stratigraphic Unit		(M.)	Sedimentary Structures	Photo No.	Sample No.	Description	Facies
Waipipian	Mangaheia Group	Tahaenui Limestone	40		1.217 2.61	ML.3 ML.4 ML.5	Densely packed shell bed - Oysters, brachiopods and pectinidae very common. Disarticulated pectinidae, all of one adult species, 2-3 mm thick, 7-10 cm across, some smaller at 4 cm. Disarticulated oysters up to 4 cm thick, 6-7 cm across. Articulated brachiopods 3-4 cm across. Macrofossils generally intact with common fractures, in convex upwards orientation. Occasional small worm tubes/annelids	L1 / P/O Bra
			30 20	(≡)	6.465	ML 133.2	Weakly interbedded, cream - pale yellow, highly indurated, calcareous, pure limestone. Densely packed fragmented barnacle matrix, with rare - no siliciclasts. Slight lapiez weathering	L1
			10		6.465	ML 133.1		

Lithology, hardness & cementation, colour, weathering, bedding, sedimentary structures, texture (grains size, sorting, shape, roundness), fossils, ichnofossils, mineralogy, preliminary assessment of environment of deposition.


Stratigraphic Column Number 02
Region Nuhaka
Location Gorge section, Kokohu Road
NZ Topo50 - BH42/046703
Elevation - 100 m
Date - 04 10
Stage
Stratigraphic Unit
(M.)
Graphic Log
Sedimentary Structures
Fossils
Photo No.
Sample No.
Description
Facies
Waipipian
Mangaheia Group
Wairoa Formation D
Tahaenui Limestone
Upper Micoene
Tolaga Group
25
20
15
10
5
ML 134.10
Massive, friable, moderately indurated, blue-grey mudstone, with rare shells up to 2mm
M1
ML 134.9
Immediate pectinid rich shell bed underlies sharp upper contact into mudstone
L1/P
2.179
ML 134.8
Densely packed pectinid and articulated brachiopod rich shell bed
L1/P Bra
ML.45
ML 134.6
ML 134.5
Dominant pectinid shell beds. Macro fossils all disarticulated, with pectinids 2-3 mm thick, 5-7 cm across. Majority are in convex upwards orientation
L1/P
2.177
ML 134.4
L1
Bedded - weakly bedded, highly indurated, cream - light yellow limestone with fragmented shell matrix and rare siliciclasts. Coarse bioclast supported, densely packed
2.172
ML 134.3
ML 134.2
6.474
Densely packed pectinid and oyster rich shell bed overlies sharp contact
L1/P/O
6.469
ML 134.1
Massive, friable, moderately indurated, blue-grey mudstone
M1
Mud
Sand
Gravel
Lithology, hardness & cementation, colour, weathering, bedding, sedimentary structures, texture (grains size, sorting, shape, roundness), fossils, ichnofossils, mineralogy, preliminary assessment of environment of deposition.

Stratigraphic Column Number 03

Region Nuhaka

Location Kokohu Road East

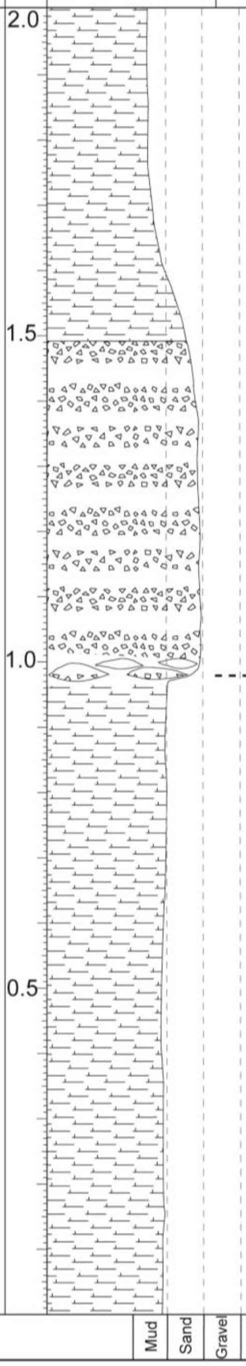
NZ Topo50 - BH42/068689

Elevation - 80 m

Date - 04 10

Stage	Stratigraphic Unit		(m.)	Sedimentary Structures	Fossils	Photo No.	Sample No.	Description	Facies
Waipipian	Mangaheia Group	Wairoa Formation D	2.0–1.5			2.228	ML.28	Massive, calcareous, fine grained, friable, blue grey mudstone	M1
			1.5–1.0	V			ML.29	Massive - incipiently laminated, very soft, non calcareous, well sorted, pumiceous, sandy, volcanic deposit	V1
			1.0			2.226	ML.30	Lenses, up to 6 cm, of upper volcanic pumiceous unit	
			1.0–0.0			2.225	ML.31	Massive, calcareous, fine grained, friable, blue grey mudstone with rare bivalves up to 2-3cm	M4

Graphic Log



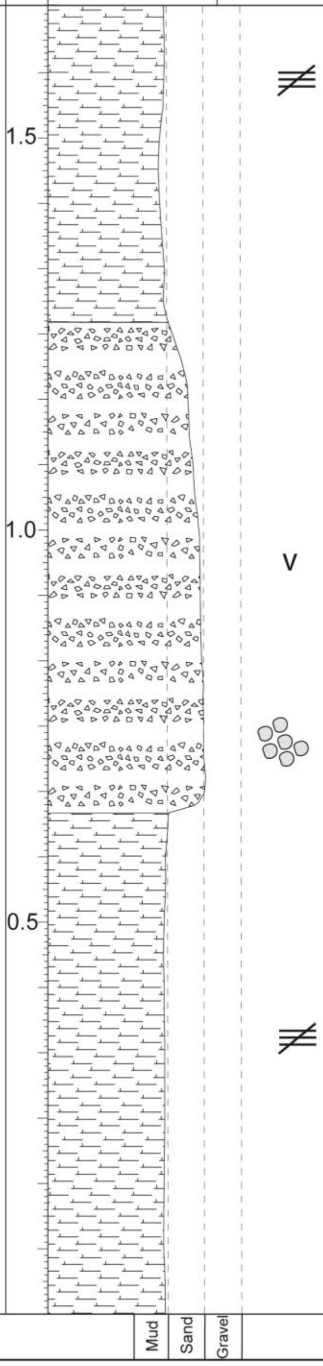
Lithology, hardness & cementation, colour, weathering, bedding, sedimentary structures, texture (grains size, sorting, shape, roundness), fossils, ichnofossils, mineralogy, preliminary assessment of environment of deposition.

Stratigraphic Column Number 04

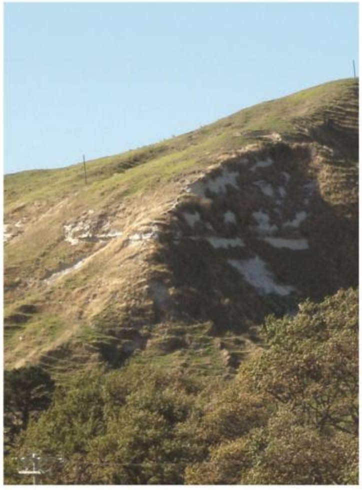
Date - 04 10

Region Nuhaka

Location Front hills adjacent to SHW 2.
NZ Topo50 - BH42/049681
Elevation - 73 m



Stage	Stratigraphic Unit		Sedimentary Structures	Fossils	Photo No.	Sample No.	Description	Facies
Waipipian	Mangaheia Group	Wairoa Formation D				ML 47.1	Massive, calcareous, fine grained, friable, blue grey mudstone	M1
			V		6.481	ML 47.2	Massive - incipiently laminated, very soft, non calcareous, well sorted, pumiceous, sandy, volcanic deposit. May include rounded mudstone clasts 3 cm in size	V1
						ML 47.3	Massive, calcareous, fine grained, friable, blue grey mudstone	M1



Lithology, hardness & cementation, colour, weathering, bedding, sedimentary structures, texture (grains size, sorting, shape, roundness), fossils, ichnofossils, mineralogy , preliminary assessment of environment of deposition.

Stratigraphic Column Number 05

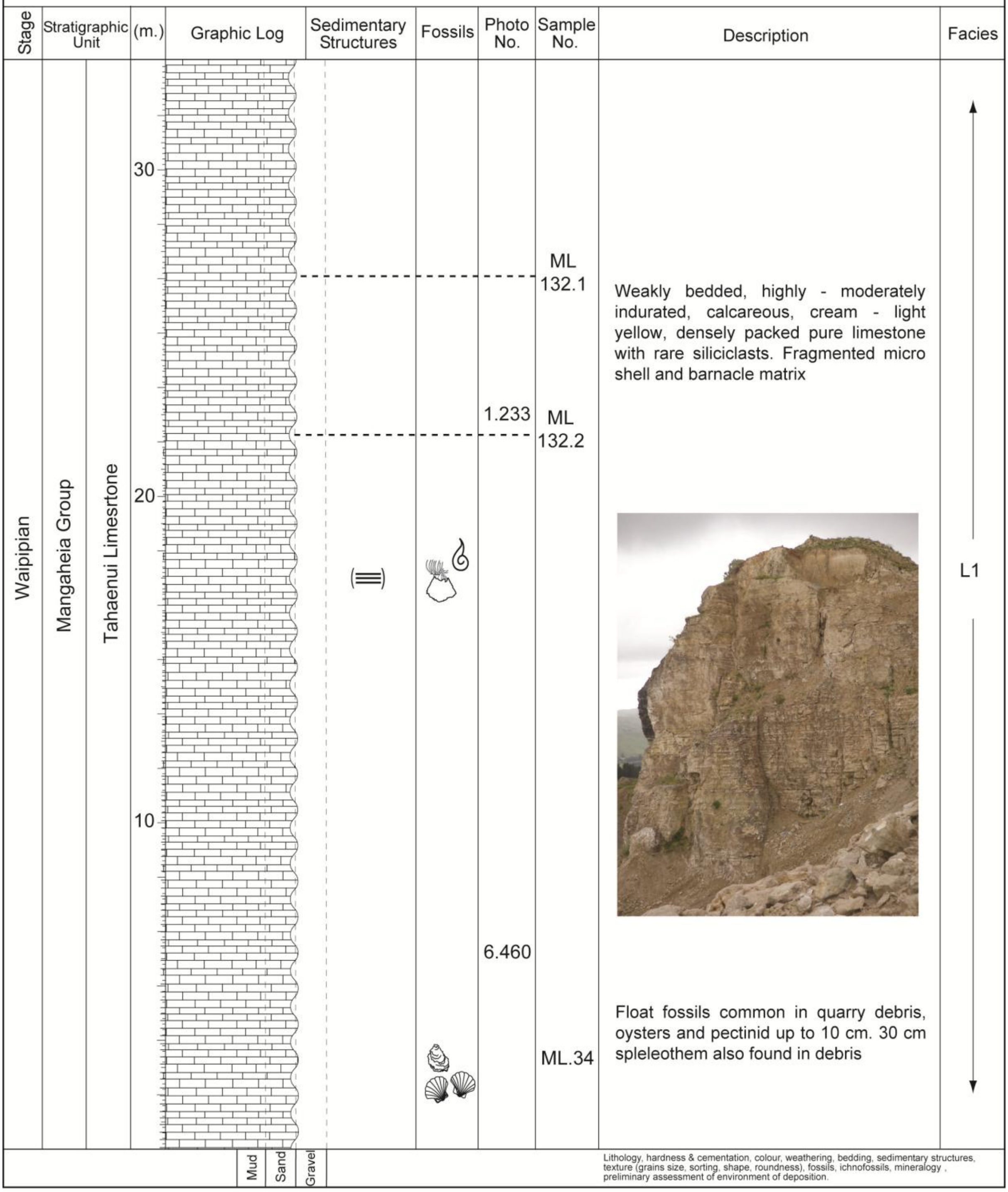
Region Clonkeen

Location Clonkeen Quarry, Mangaone Road

NZ Topo50 - BH42/092737

Elevation - 380 m

Date - 04 10

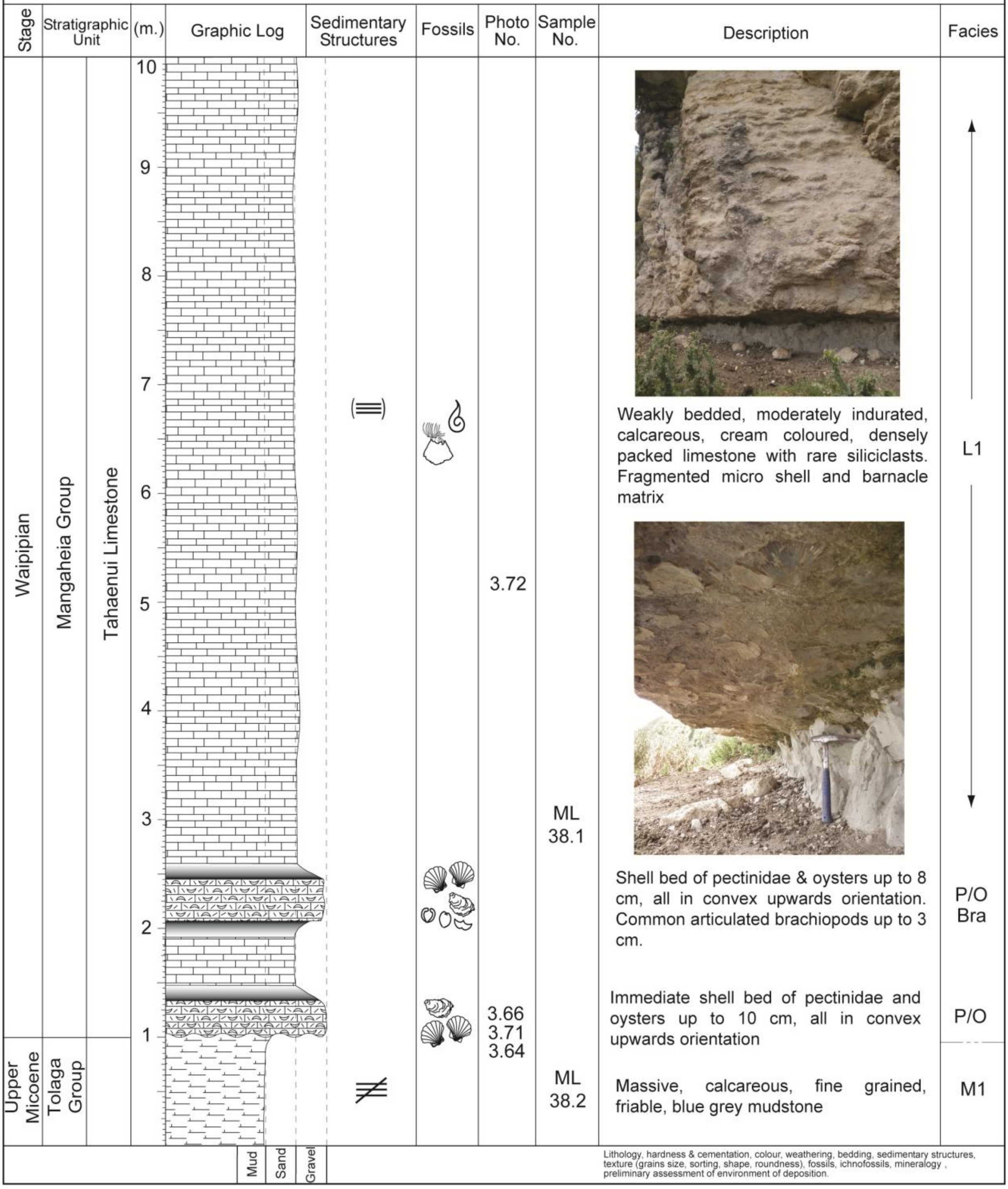


Stratigraphic Column Number 06

Region Clonkeen

Location West of Clonkeen Quarry, Mangaone Road
NZ Topo50 - BH42/086735
Elevation - 377 m

Date - 04 10



Stratigraphic Column Number 07

Region Clonkeen

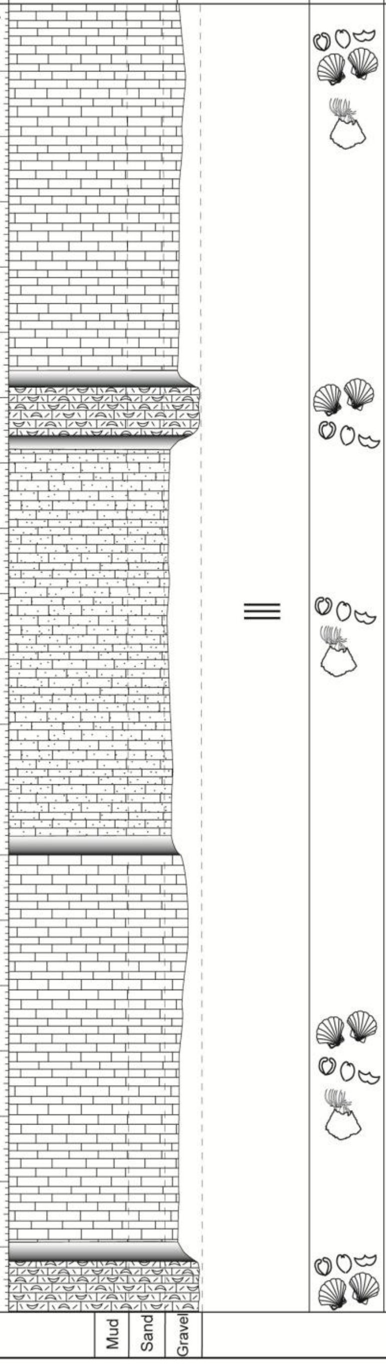
Location West flank of Tahaenui Syncline

NZ Topo50 - BH42/068730

Elevation - 337 m

Date - 04 10

Stage	Stratigraphic Unit		(m.)	Graphic Log	Sedimentary Structures	Fossils	Photo No.	Sample No.	Description	Facies
Waipipian	Mangaheia Group	Tahaenui Limestone	0.4					ML 44.1	Weakly bedded, cream coloured, densely packed, moderately indurated limestone, in barnacle rich matrix with scattered pectinidae up to 7 cm	L1 / P / Bra
			0.3						Pectinid and brachiopod dominant shell bed. Pectinidae all convex upwards, up to 7 cm. Articulated brachiopods up to 3 cm	
			0.2		≡		3.117	ML 44.2	Weakly bedded, cream coloured, densely packed, moderately indurated limestone, in barnacle rich matrix with rare - common siliciclasts	
			0.1					ML 44.3	Pectinid and brachiopod dominant shell bed. Pectinidae all convex upwards, up to 7 cm. Articulated brachiopods up to 3 cm	



Lithology, hardness & cementation, colour, weathering, bedding, sedimentary structures, texture (grains size, sorting, shape, roundness), fossils, ichnofossils, mineralogy, preliminary assessment of environment of deposition.

Stratigraphic Column Number 08

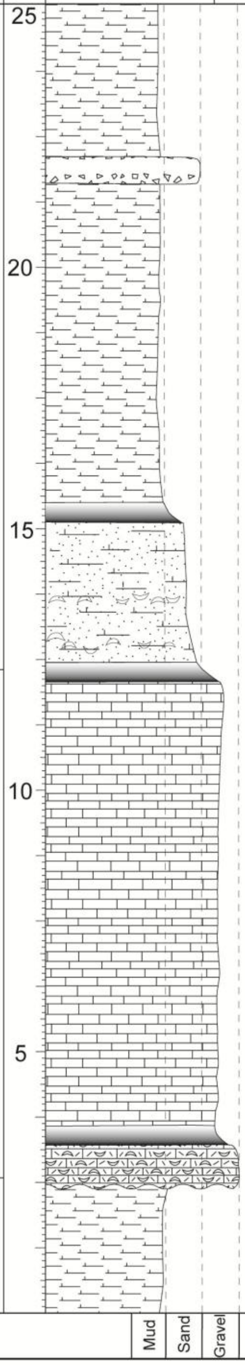
Region Clonkeen

Location Clonkeen Farm, Mangaone Road

NZ Topo50 - BH42/093730

Elevation - 360 m

Date - 04 10



Stage	Stratigraphic Unit	Sedimentary Structures	Photo No.	Sample No.	Description	Facies
Waipipian	Mangaheia Group / Wairoa Formation D	≢	6.449 6.450	ML 57.1	Massive, calcareous, fine grained, friable, grey-brown mudstone	M1
Waipipian	Mangaheia Group / Wairoa Formation D	V	6.446 6.447	ML 57.2	Massive - incipiently laminated, white coloured, pumiceous, sandy volcaniclastite	V1
Waipipian	Mangaheia Group / Wairoa Formation D	≢	6.444	ML 57.3	 Massive, calcareous, fine grained, friable, blue-grey mudstone. Rare bivalves up to 3 cm	M4
Waipipian	Mangaheia Group / Wairoa Formation D		6.441	ML 57.4	Moderately indurated, grey - brown, medium grained sandstone with dominant fragmented bivalves up to 4 cm, including rare small pectindae	S2
Waipipian	Mangaheia Group / Tahaenui Limestone	(≡)		ML 58.1	 Weakly bedded, moderately - highly indurated, calcareous, cream coloured, densely packed limestone. Fragmented micro shell and barnacle matrix	L1
Waipipian	Mangaheia Group / Tahaenui Limestone		6.457		Immediate densely packed shell bed of disarticulated pectinidae up tp10 cm, all in convex upwards orientation and of common adult species	O P Bra
Upper Micoene	Tolaga Group	≢		ML 58.2	Massive, calcareous, fine grained, friable, blue - grey mudstone	M1

Lithology, hardness & cementation, colour, weathering, bedding, sedimentary structures, texture (grains size, sorting, shape, roundness), fossils, ichnofossils, mineralogy, preliminary assessment of environment of deposition.

Stratigraphic Column Number 09

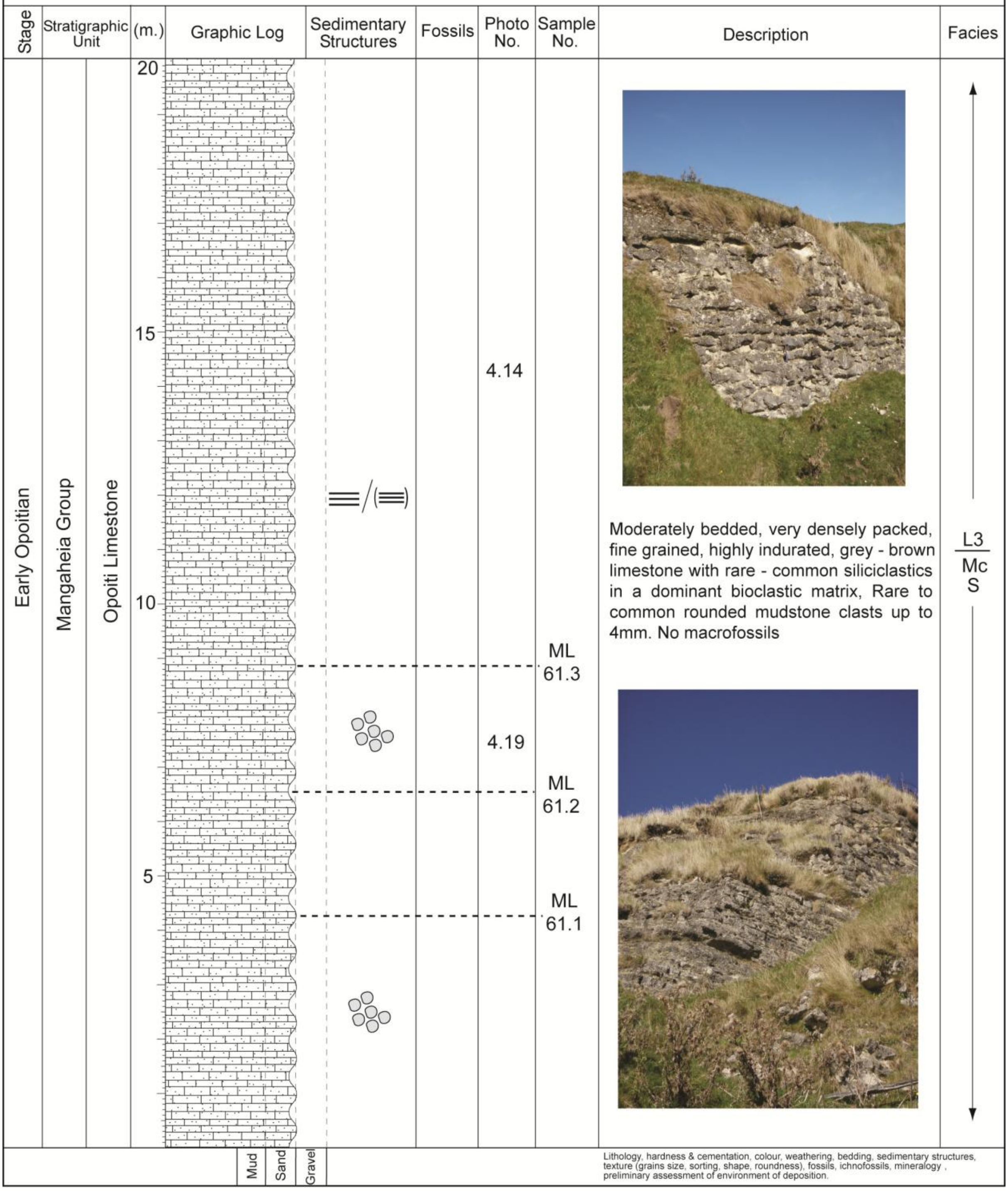
Date 3 04 10

Region Mt Moumoukai

Location Mt Moumoukai North Ridge

NZ Topo50 - BH42/139775

Elevation - 559 m

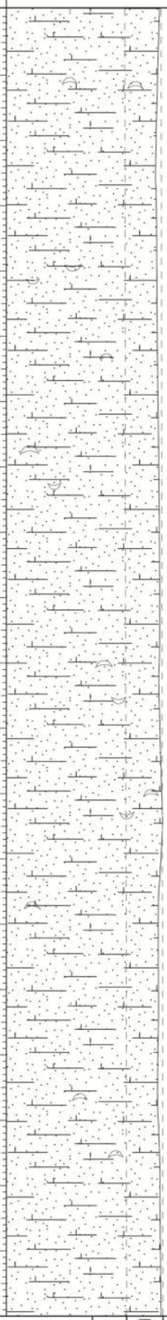


Stratigraphic Column Number 10

Date 3 04 10

Region Mt Moumoukai

Location North facing flank of Mt Moumoukai
NZ Topo50 - BH42/136777
Elevation - 553 m

Stage	Stratigraphic Unit		(m.)	Graphic Log	Sedimentary Structures	Fossils	Photo No.	Sample No.	Description	Facies
Late Opoitian	Mangaheia Group	Wairoa Formation B	3 2 1		≠		4.50	ML.64	Massive, blue-grey, calcareous, slightly to moderately indurated, fine to medium grained sandstone, very well sorted. Rare fossils up to 3 cm. Slight honeycomb weathering	S1

Mud Sand Gravel

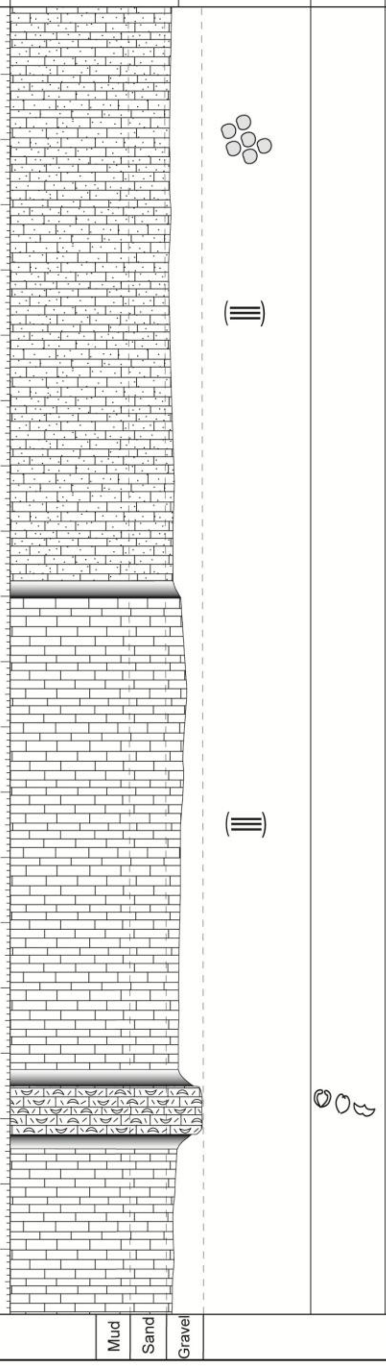
Lithology, hardness & cementation, colour, weathering, bedding, sedimentary structures, texture (grains size, sorting, shape, roundness), fossils, ichnofossils, mineralogy, preliminary assessment of environment of deposition.

Stratigraphic Column Number 11

Region Mt Moumoukai

Location Top of Mt Moumoukai, Springs waterfalls
NZ Topo50 - BH42/126772
Elevation - 529 m

Date 3 04 10

Stage	Stratigraphic Unit		(m.)	Graphic Log	Sedimentary Structures	Fossils	Photo No.	Sample No.	Description	Facies
Waipipian	Mangaheia Group	Tahaenui Limestone	15, 10, 5				4.151	ML 79.2	Massive to weakly bedded, cream coloured, moderately indurated, siliciclastic rich limestone with rounded mudstone clasts - 4 mm in a fragmented shelly matrix. No evident macrofossils. Well developed lapiez weathering and case hardening 	L3 / Mc
									Massive to weakly bedded, moderately indurated, densely packed limestone with rare siliciclastics. Common articulated brachiopods up to 3cm 	L3
							4.154	ML 79.1	Articulated brachiopod shell bed	L3 / Bra
				Mud Sand Gravel					Lithology, hardness & cementation, colour, weathering, bedding, sedimentary structures, texture (grains size, sorting, shape, roundness), fossils, ichnofossils, mineralogy, preliminary assessment of environment of deposition.	

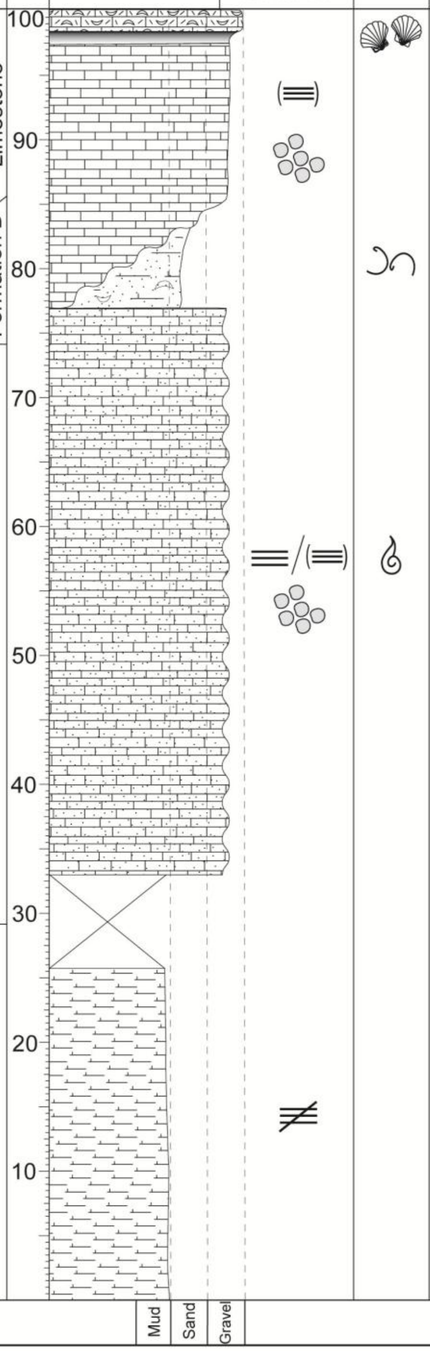
Stratigraphic Column Number 12

Region Mt Moumoukai

Location Generalised Moumoukai Composite Column
NZ Topo50 - BH42/126770
Elevation - 600 m

Date 3 04 10

Stage	Stratigraphic Unit		(m.)	Graphic Log	Sedimentary Structures	Fossils	Photo No.	Sample No.	Description	Facies
Waipipian	Mangaheia Group	Tahaenui Limestone	100–77						Shell bed of adult pectinidae up to 8 cm, all in convex upwards orientation	P
									Massive - weakly bedded, cream coloured, moderately indurated, densely packed limestone with rare siliciclasts. Rare rounded mudstone clasts - 4 mm in a fragmented shelly matrix	L1/L3
		Wairoa Formation B							Massive, light grey, calcareous, slightly to moderately indurated, fine to medium grained sandstone, very well sorted. Rare fossils up to 3 cm	S1
Opoitian		Opoiti Limestone	77–33						Moderately bedded, very densely packed, highly indurated, grey to brown limestone with rare - common siliciclastics in a dominant bioclastic matrix, Rare to common rounded mudstone clasts up to 4mm. No macrofossils	L3
Upper Micoene	Tolaga Group		26–0						Massive, calcareous, fine grained, friable, light grey mudstone	M1



Lithology, hardness & cementation, colour, weathering, bedding, sedimentary structures, texture (grains size, sorting, shape, roundness), fossils, ichnofossils, mineralogy, preliminary assessment of environment of deposition.

Stratigraphic Column Number 13

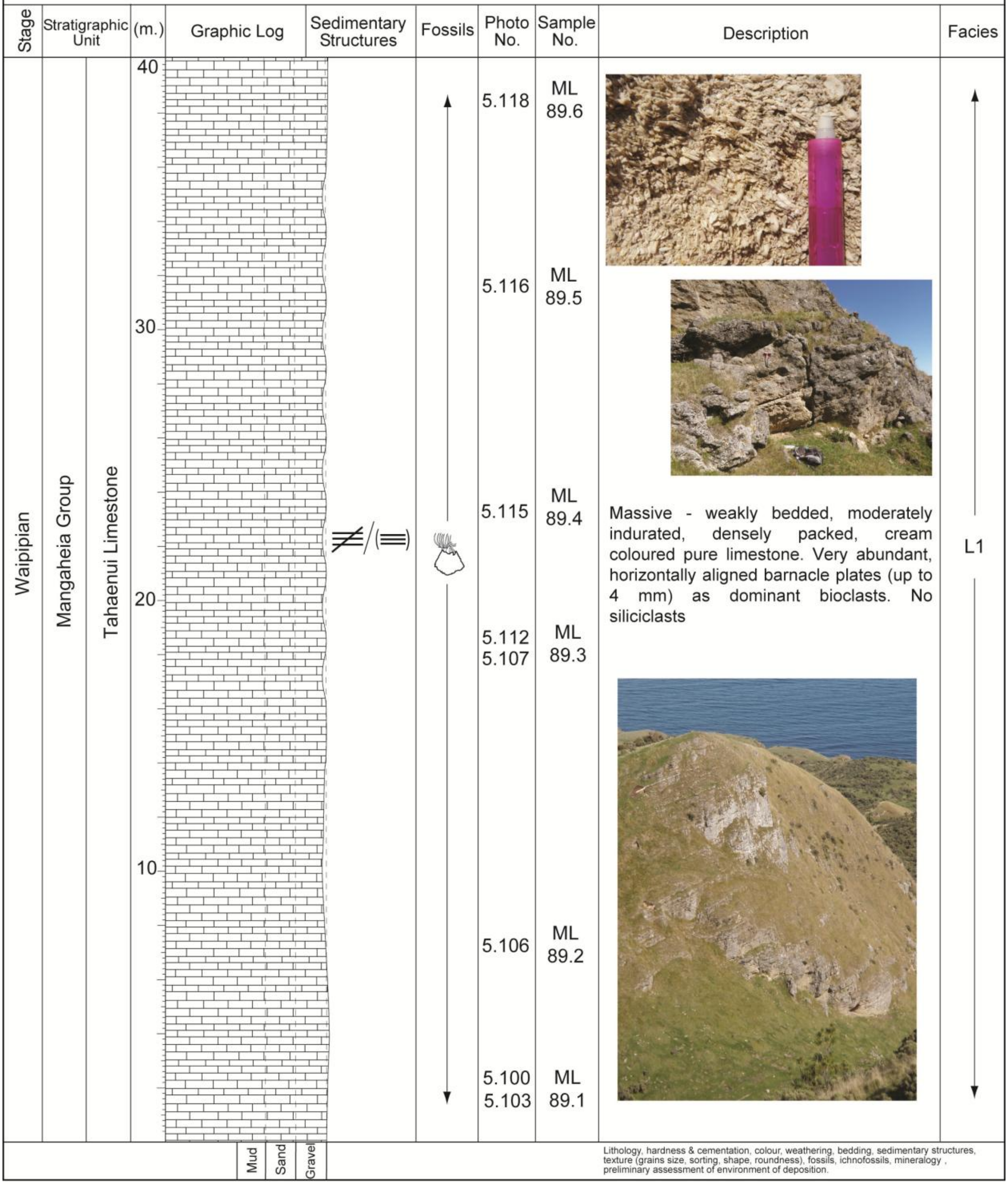
Date 15 04 10

Region Mahia Peninsula

Location Central Taupiri Hill

NZ Topo50 - BJ43/183543

Elevation - 295 m

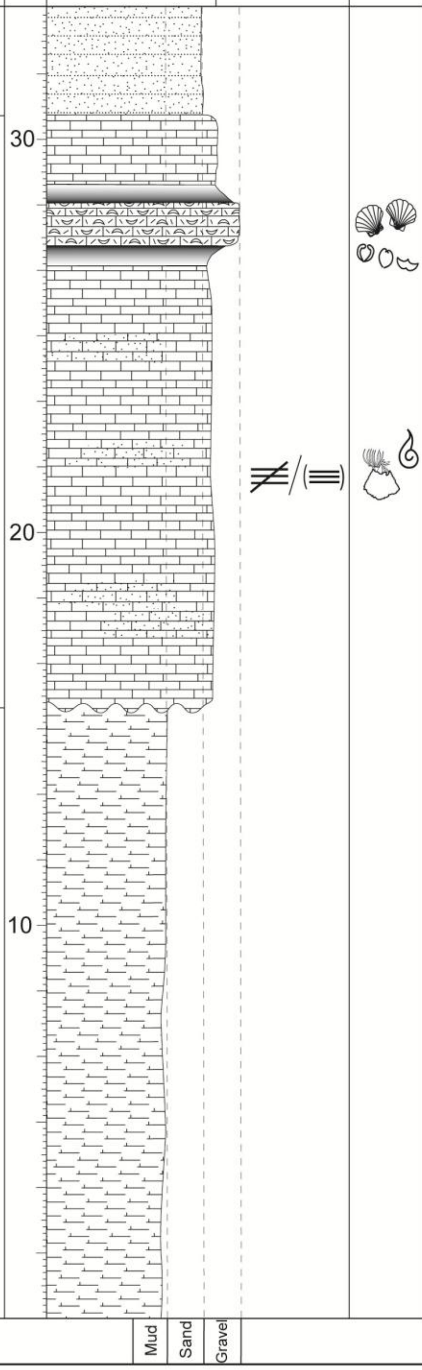


Stratigraphic Column Number 14

Date 15 04 10

Region Mahia Peninsula

Location Long Point, north face
NZ Topo50 - BJ43/169537
Elevation - 20 m



Stage	Stratigraphic Unit		Photo No.	Sample No.	Description	Facies
Castlecliffian	-	-	5.201	ML.99	Non indurated, rippled - laminated, orange sands. Very well sorted and coarse grained	-
Waipipian	Mangaheia Group	Tahaenui Limestone	5.198	ML.98	Weathered shell bed of adult pectinidae up to 7 cm Massive - weakly bedded, moderately indurated, densely packed, cream coloured bioclastic limestone. Some siliciclasts	L1 / P / Bra
Upper Micoene	Tolaga Group		6.323		Massive, moderately indurated, calcareous, fine grained, friable, blue grey mudstone	M1

Lithology, hardness & cementation, colour, weathering, bedding, sedimentary structures, texture (grains size, sorting, shape, roundness), fossils, ichnofossils, mineralogy, preliminary assessment of environment of deposition.

Stratigraphic Column Number 15

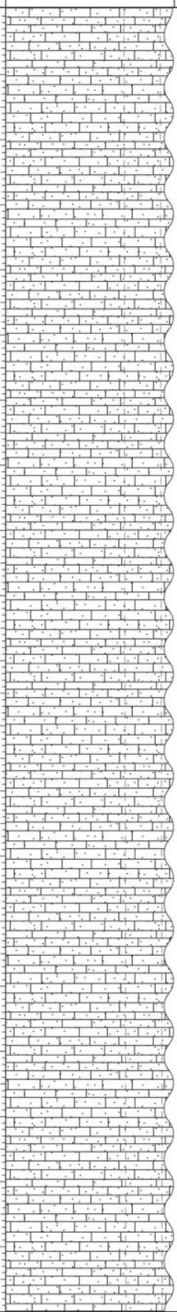
Date 16 04 10

Region Mahia Peninsula

Location Tip of Long Point

NZ Topo50 - BJ43/168537

Elevation - 17 m

Stage	Stratigraphic Unit		(m.)	Graphic Log	Sedimentary Structures	Fossils	Photo No.	Sample No.	Description	Facies
Waipipian	Mangaheia Group	Tahaenui Limestone	40 30 20 10		≡		5.236 5.238	ML 102	 Bedded to weakly bedded, highly indurated, densely packed, cream coloured, siliciclastic limestone with rare macro fossils. Forms large vertical coastal cliffs 	L1/L3 Bra Hb
				Mud Sand Gravel					Lithology, hardness & cementation, colour, weathering, bedding, sedimentary structures, texture (grains size, sorting, shape, roundness), fossils, ichnofossils, mineralogy, preliminary assessment of environment of deposition.	

Stratigraphic Column Number 16

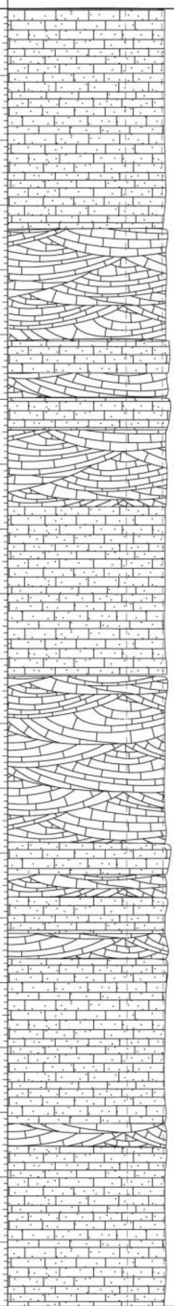
Date 16 04 10

Region Mahia Peninsula

Location Inland of Long Point

NZ Topo50 - BJ43/174540

Elevation - 73 m

Stage	Stratigraphic Unit		(m.)	Graphic Log	Sedimentary Structures	Fossils	Photo No.	Sample No.	Description	Facies
Waipipian	Mangaheia Group	Tahaenui Limestone	5 4 3 2 1				5.264 5.265 5.267	ML 104	 Weakly bedded, moderately indurated, cream to light brown, densely packed, sandy bioclastic limestone with 20 cm shallow cross beds. No macro fossils 	L1/L3 Xb
				Mud Sand Gravel					Lithology, hardness & cementation, colour, weathering, bedding, sedimentary structures, texture (grains size, sorting, shape, roundness), fossils, ichnofossils, mineralogy , preliminary assessment of environment of deposition.	

Stratigraphic Column Number 17

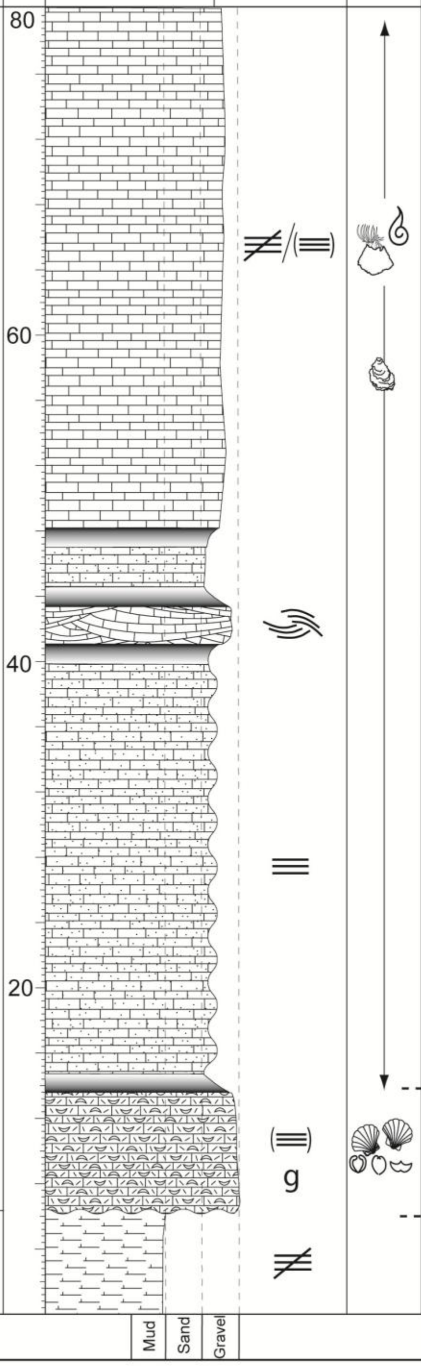
Date 16 04 10

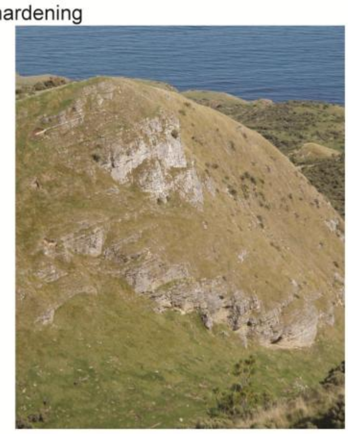
Region Mahia Peninsula

Location Long Point - Composite Column

NZ Topo50 - c. BJ43/279155

Elevation - c. 200 m



Stage	Stratigraphic Unit	Sedimentary Structures	Photo No.	Sample No.	Description	Facies
Waipipian	Mangaheia Group – Tahaenui Limestone	≢/(≡)	5.89 5.85 5.97 5.94 5.131 5.132 5.133 5.184	ML.87 ML.86 ML.88 ML 89.1-6 ML.92 ML.93 ML.96	 Weakly bedded, highly porous, moderately to lightly indurated, cream coloured, densely packed, coarse grained limestone with horizontally-aligned barnacle plates up to 4 mm. Rare macro fossils and rare - some siliciclasts. Case hardening 	L1
			5.265	ML.104		Xb
		≡	5.258	ML.102	Bedded, moderately indurated, cream to brown coloured, densely packed, coarse grained barnacle limestone with common siliciclasts	L3
		(≡) g	5.208 5.210 5.198	ML.100 ML.101 ML.98	Weakly bedded, moderately indurated, cream coloured, densely packed, coarse grained barnacle limestone shell bed with some siliciclasts. Pectinidae and oysters abundant up to 7 cm, brachiopods (4 cm) very dominant in mixed orientations. Glauconite common	L1
Upper Micoene	Tolaga Group	≢	6.323 5.138	ML.83, 94, 95	Massive, very well sorted, calcareous, fine grained, friable, blue grey mudstone	M1

Lithology, hardness & cementation, colour, weathering, bedding, sedimentary structures, texture (grains size, sorting, shape, roundness), fossils, ichnofossils, mineralogy, preliminary assessment of environment of deposition.

Stratigraphic Column Number 18

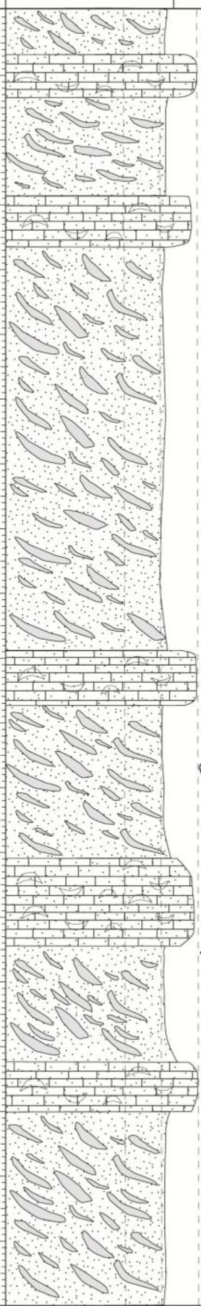
Date 25 04 10

Region Mahia Peninsula

Location Stalactite Falls Stream

NZ Topo50 - BJ43/179527

Elevation - 20 m

Stage	Stratigraphic Unit	(m.)	Graphic Log	Sedimentary Structures	Fossils	Photo No.	Sample No.	Description	Facies
Late Opoitian	Mangaheia Group; Whakapunake Limestone	3, 2, 1		=		6.1-3			S4; L3/P/O; S4; L3/P/O; S4/Bra; L3/P/O
							ML 108.1	Moderately to highly indurated, red to brown, fragmented shelly sandstone, with common and regularly spaced elongated mudstone clasts up to 20 cm. Some whole brachipods up to 5 cm	S4/Bra
							ML 108.2	Highly indurated, sandy coquina beds with fragmented shell matrix. Common pectinidae, up to 6 cm, in convex upwards orientaion, with occasional 5 cm oysters	L3/P/O
									S4/Bra; L3/P/O; S4/Bra

Mud Sand Gravel

Lithology, hardness & cementation, colour, weathering, bedding, sedimentary structures, texture (grains size, sorting, shape, roundness), fossils, ichnofossils, mineralogy, preliminary assessment of environment of deposition.

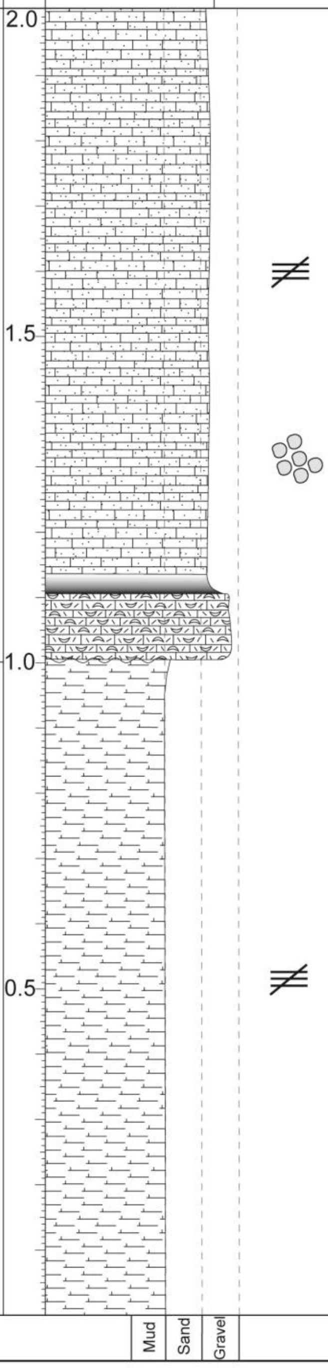
Stratigraphic Column Number 19

Date 25 04 10

Region Mahia Peninsula

Location Ahimanawa Station
NZ Topo50 - BJ43/184525
Elevation - 40 m

Stage	Stratigraphic Unit		(m.)	Graphic Log	Sedimentary Structures	Fossils	Photo No.	Sample No.	Description	Facies
Early Opoitian	Mangaheia Group	Opoiti Limestone	2.0					ML 115.3	Massive, moderately indurated, well sorted, brown - red, sandy limestone with rare mudstone inclusions up to 3 mm	L3
			1.5				6.67			
							6.70 6.71	ML 115.2	Immediate shell bed, sandy, friable and very weathered. Brachiopods up to 3 cm	L3 / Bra
Upper Micoene	Tolaga Group		1.0 0.5							M1
							6.69	ML 115.1	Massive, moderately indurated, calcareous, fine grained, friable, blue grey mudstone	



Lithology, hardness & cementation, colour, weathering, bedding, sedimentary structures, texture (grains size, sorting, shape, roundness), fossils, ichnofossils, mineralogy, preliminary assessment of environment of deposition.

Stratigraphic Column Number 20

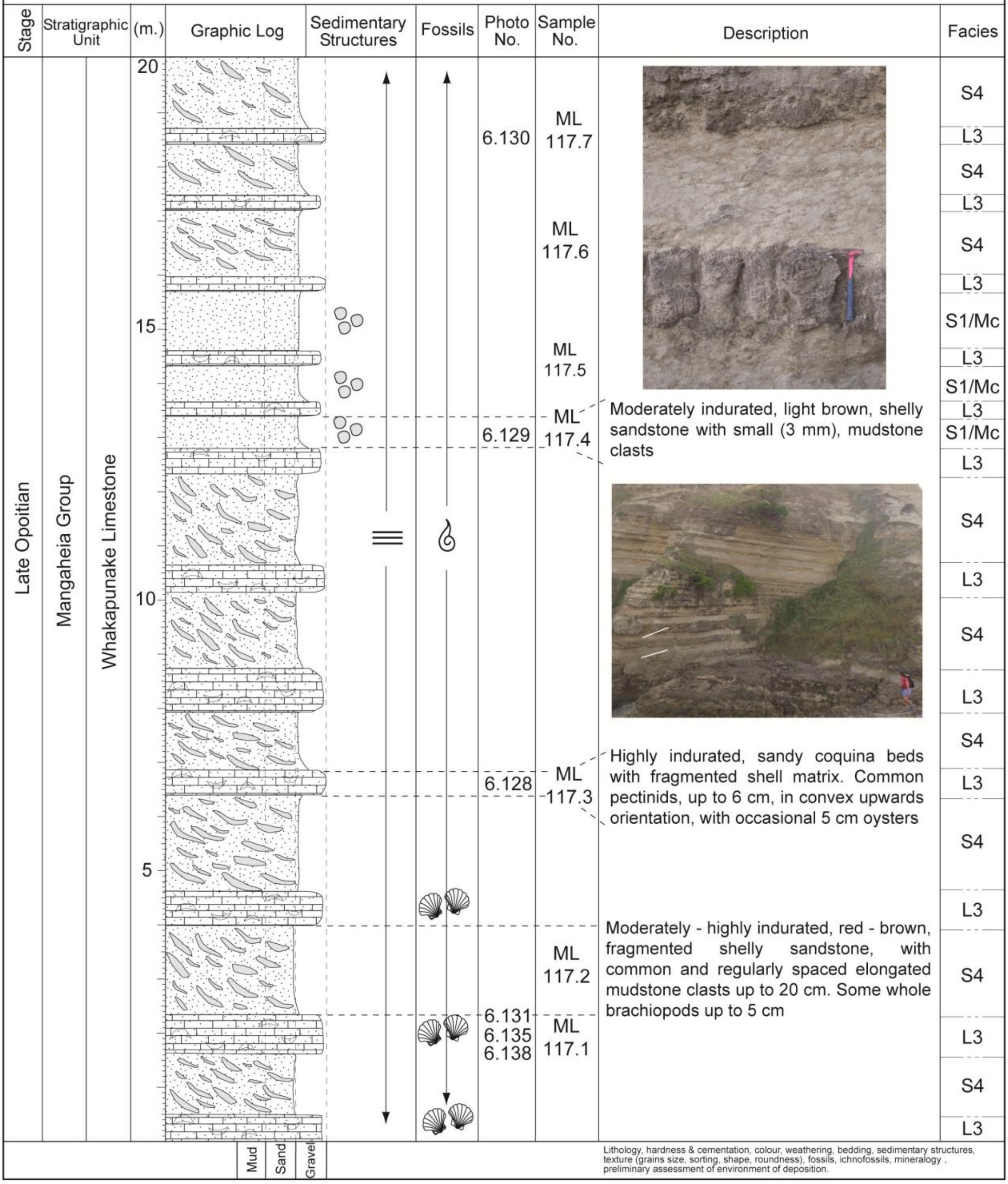
Date 26 04 10

Region Mahia Peninsula

Location North Huruhurunui Stream mouth

NZ Topo50 - BJ43/179523

Elevation - 5 m

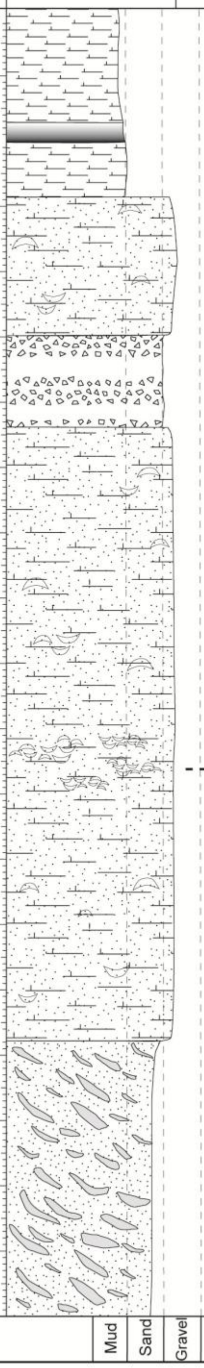


Stratigraphic Column Number 21

Region Mahia Peninsula

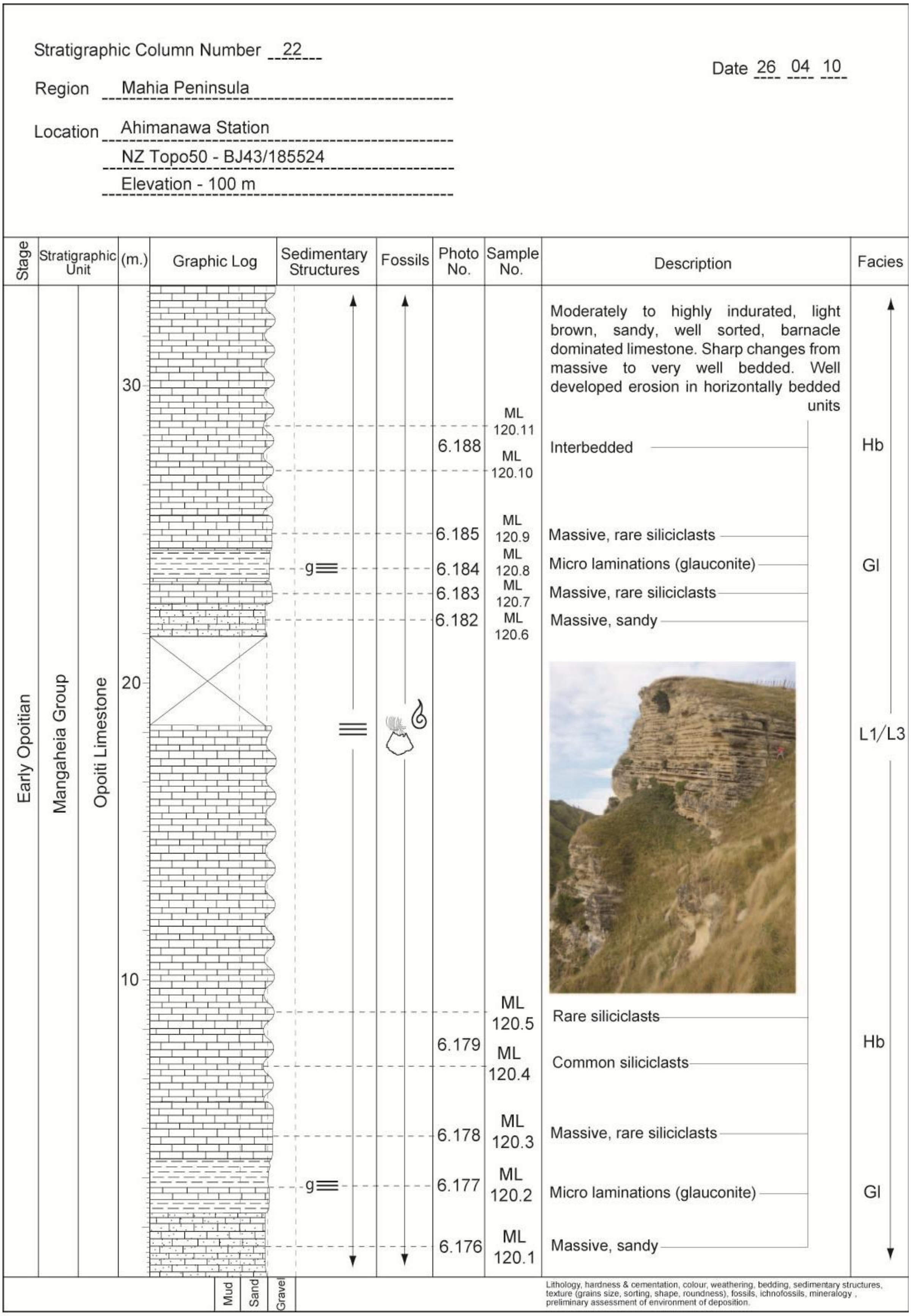
Location South Huruhurunui Stream mouth
NZ Topo50 - BJ43/179522
Elevation - 5 m

Date 15 04 10



Stage	Stratigraphic Unit		(m.)	Sedimentary Structures	Fossils	Photo No.	Sample No.	Description	Facies
Late Opoitian	Mangaheia Group	Wairoa Formation C	20	≠		6.162	ML 118.7	Massive, moderately indurated, very well sorted, calcareous, fine grained, friable, cream coloured, sandy mudstone	M1
					bivalves, brachiopods, gastropods	6.158	ML 118.6	Massive, moderately indurated, dark grey, fossiliferous sandstone. Well sorted and medium grained siliciclastic matrix. Rare - common bivalves, brachiopods and gastropods	S2/Biv
			15	V		6.160	ML 118.5	Massive - incipiently laminated, very soft, non calcareous, well sorted, pumiceous, sandy, volcanic deposit	V1
			10	≠	bivalves, brachiopods, gastropods	6.152 6.151	ML 118.4 ML 118.3	 Massive, moderately indurated, dark grey, fossiliferous sandstone. Well sorted and medium grained siliciclastic matrix. Common small bivalves/brachiopods with rare gastropods throughout, can be concentrated in 15 cm nests. Common bioturbation up to 10 cm	S2/Biv/Bio
			5	bioturbation		6.148 6.150	ML 118.2		
		Upper Whakapunake Limestone		clasts	brachiopods	6.145	ML 118.1	Moderately - highly indurated, red - brown, fragmented shelly sandstone, with common and regularly spaced elongated mudstone clasts up to 20 cm. Some whole brachipods up to 5 cm	S4

Lithology, hardness & cementation, colour, weathering, bedding, sedimentary structures, texture (grains size, sorting, shape, roundness), fossils, ichnofossils, mineralogy , preliminary assessment of environment of deposition.



Stratigraphic Column Number 22
Region Mahia Peninsula
Location Ahimanawa Station
NZ Topo50 - BJ43/185524
Elevation - 100 m
Date 26 04 10
Stage
Stratigraphic Unit
(m.)
Graphic Log
Sedimentary Structures
Fossils
Photo No.
Sample No.
Description
Facies
Early Opoitian
Mangaheia Group
Opoiti Limestone
30
20
10
Moderately to highly indurated, light brown, sandy, well sorted, barnacle dominated limestone. Sharp changes from massive to very well bedded. Well developed erosion in horizontally bedded units
ML 120.11
6.188
ML 120.10
Interbedded
Hb
6.185
ML 120.9
Massive, rare siliciclasts
g
6.184
ML 120.8
Micro laminations (glauconite)
Gl
6.183
ML 120.7
Massive, rare siliciclasts
6.182
ML 120.6
Massive, sandy
L1/L3
ML 120.5
Rare siliciclasts
6.179
ML 120.4
Common siliciclasts
Hb
6.178
ML 120.3
Massive, rare siliciclasts
g
6.177
ML 120.2
Micro laminations (glauconite)
Gl
6.176
ML 120.1
Massive, sandy
Mud
Sand
Gravel
Lithology, hardness & cementation, colour, weathering, bedding, sedimentary structures, texture (grains size, sorting, shape, roundness), fossils, ichnofossils, mineralogy , preliminary assessment of environment of deposition.

Stratigraphic Column Number 23

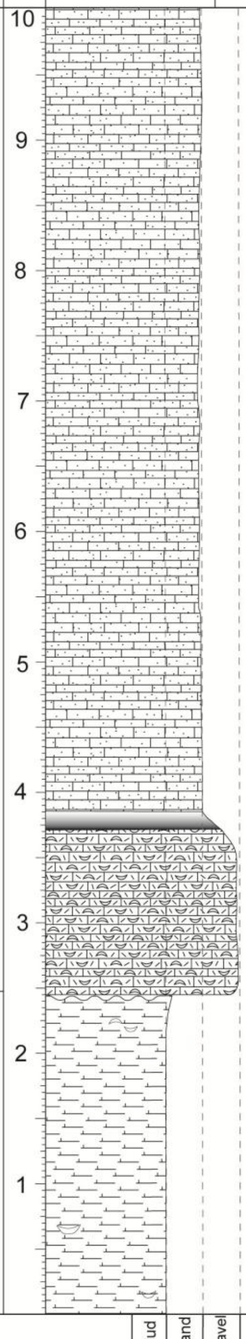
Region Mahia Peninsula

Location South ridge of Te Muka Stream

NZ Topo50 - BJ43/196498

Elevation - 220 m

Date 27 04 10



Stage	Stratigraphic Unit	Photo No.	Sample No.	Description	Facies
Early Opoitian	Mangaheia Group – Opoiti Limestone	6.232	ML 123.4	Massive, moderately indurated, very sandy limestone with common shell fragments up to 1 cm. Rare intact brachiopods up to 4 cm	L3
			ML 123.3	Massive, moderately indurated, sandy limestone with rare intact shell fragments	
		6.227 6.228 6.221 6.223	ML 123.2	Massive, weakly to moderately indurated, highly weathered, sandy shell bed with very abundant articulated brachiopod in mixed orientations, up to 4 cm. Rare pectindae up to 6 cm	L2/Bra
Upper Micoene	Tolaga Group	6.224	ML 123.1	Massive, moderately indurated, calcareous, fine grained, friable, blue grey mudstone with rare shell fragments up to 2 mm	M4

Lithology, hardness & cementation, colour, weathering, bedding, sedimentary structures, texture (grains size, sorting, shape, roundness), fossils, ichnofossils, mineralogy, preliminary assessment of environment of deposition.

Stratigraphic Column Number 24

Region Mahia Peninsula

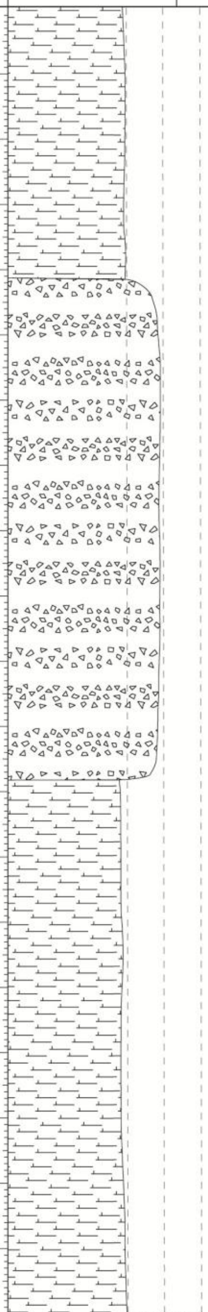
Location Otunua Stream

NZ Topo50 - BJ43/189493

Elevation - 24 m

Date 27 04 10

Stage	Stratigraphic Unit		(m.)	Graphic Log	Sedimentary Structures	Fossils	Photo No.	Sample No.	Description	Facies
Late Opoitian	Mangaheia Group	Wairoa Formation B	0.3		V			ML 124.3	Massive, moderately indurated, fine grained, sandy, grey mudstone with rare shell fragments up to 3 mm and rare pumice clasts up to 1 mm near contact	M4
			0.2		V		6.255 6.245 6.252	ML 124.2 ML 124.2	Massive - incipiently laminated (3 - 4 mm), very soft, non calcareous, well sorted, pumiceous, sandy, volcanic deposit. Rare bivalve sampled from upper area - 5 cm	V1
			0.1				6.251 6.244	ML 124.1	Massive, moderately indurated, fine grained, blue grey mudstone with occasional bivalves and gastropods up to 3 mm. Very common burrows (Height - 10 cm, width - 1 cm)	M4 / Bio



Mud | Sand | Gravel

Lithology, hardness & cementation, colour, weathering, bedding, sedimentary structures, texture (grains size, sorting, shape, roundness), fossils, ichnofossils, mineralogy, preliminary assessment of environment of deposition.

Stratigraphic Column Number 25

Date 28 04 10

Region Mahia Peninsula

Location Kinikini Road

NZ Topo50 - BJ43/177532

Elevation - 70 m

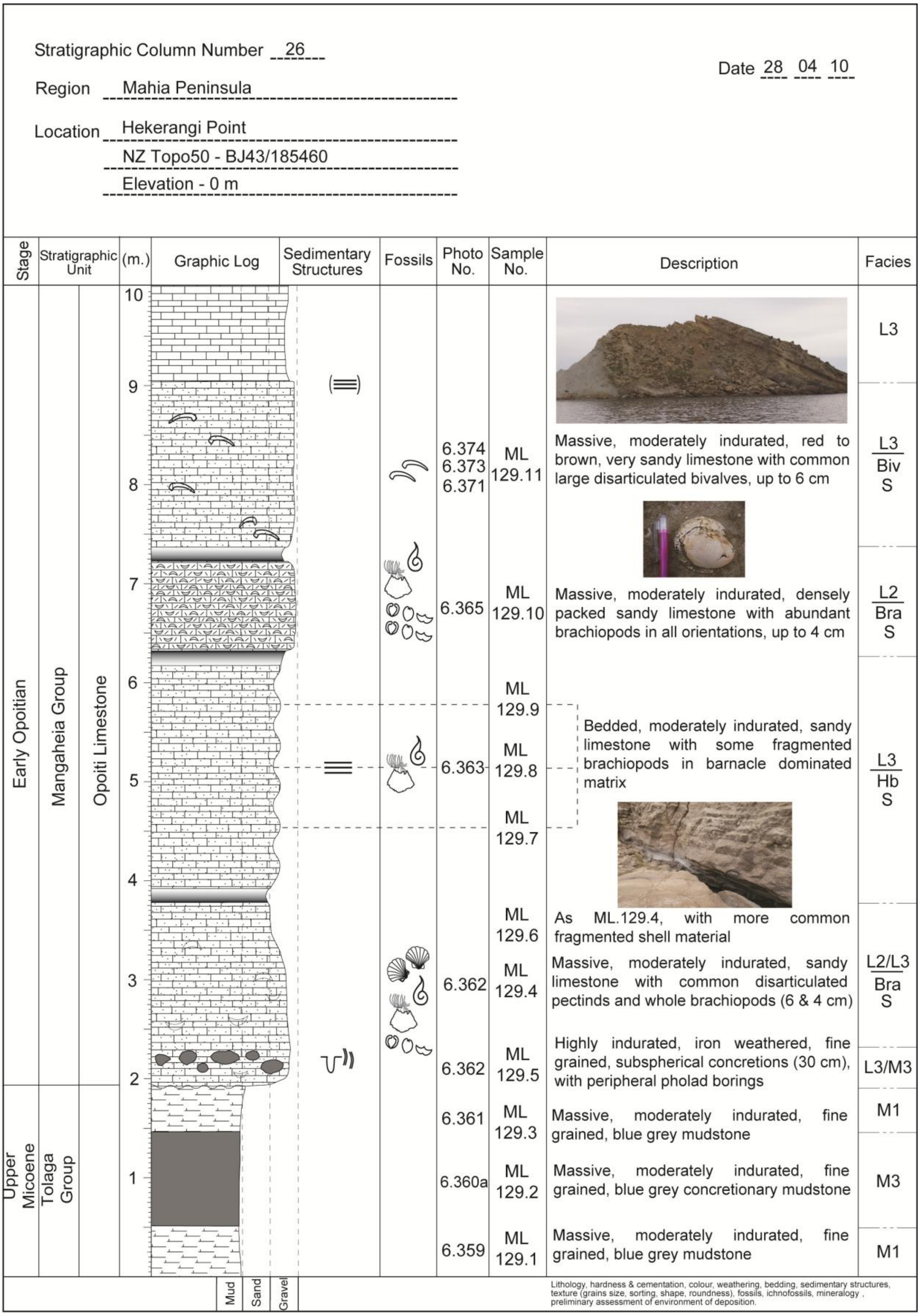
Stage	Stratigraphic Unit		(m.)	Photo No.	Sample No.	Description	Facies
Waipipian	Mangaheia Group	Tahaenui Limestone	50			Bedded to weakly bedded, moderately indurated, densely packed, cream coloured, barnacle rich limestone with varying siliciclasts. Rare macro fossils. Case hardening	L1
				6.305	ML 128.6	Common siliciclasts	
			40	6.304	ML 128.5	Very rare siliciclasts	
			30	6.303	ML 128.4	Very rare siliciclasts	
			20	6.301	ML 128.3	Very rare siliciclasts	
				6.300	ML 128.2	Rare siliciclasts	
			10	6.299	ML 128.1	Some siliciclasts	

Graphic Log: Mud, Sand, Gravel

Sedimentary Structures

Fossils

Lithology, hardness & cementation, colour, weathering, bedding, sedimentary structures, texture (grains size, sorting, shape, roundness), fossils, ichnofossils, mineralogy, preliminary assessment of environment of deposition.


Stratigraphic Column Number 26
Date 28 04 10
Region Mahia Peninsula
Location Hekerangi Point
NZ Topo50 - BJ43/185460
Elevation - 0 m
Stage
Stratigraphic Unit
(m.)
Graphic Log
Sedimentary Structures
Fossils
Photo No.
Sample No.
Description
Facies
Early Opoitian
Mangaheia Group
Opoiti Limestone
Upper Micoene
Tolaga Group
L3
6.374
6.373
6.371
ML 129.11
Massive, moderately indurated, red to brown, very sandy limestone with common large disarticulated bivalves, up to 6 cm
L3 Biv S
6.365
ML 129.10
Massive, moderately indurated, densely packed sandy limestone with abundant brachiopods in all orientations, up to 4 cm
L2 Bra S
ML 129.9
6.363
ML 129.8
ML 129.7
Bedded, moderately indurated, sandy limestone with some fragmented brachiopods in barnacle dominated matrix
L3 Hb S
ML 129.6
As ML.129.4, with more common fragmented shell material
6.362
ML 129.4
Massive, moderately indurated, sandy limestone with common disarticulated pectinds and whole brachiopods (6 & 4 cm)
L2/L3 Bra S
6.362
ML 129.5
Highly indurated, iron weathered, fine grained, subspherical concretions (30 cm), with peripheral pholad borings
L3/M3
6.361
ML 129.3
Massive, moderately indurated, fine grained, blue grey mudstone
M1
6.360a
ML 129.2
Massive, moderately indurated, fine grained, blue grey concretionary mudstone
M3
6.359
ML 129.1
Massive, moderately indurated, fine grained, blue grey mudstone
M1
Mud
Sand
Gravel
Lithology, hardness & cementation, colour, weathering, bedding, sedimentary structures, texture (grains size, sorting, shape, roundness), fossils, ichnofossils, mineralogy , preliminary assessment of environment of deposition.

Stratigraphic Column Number 27

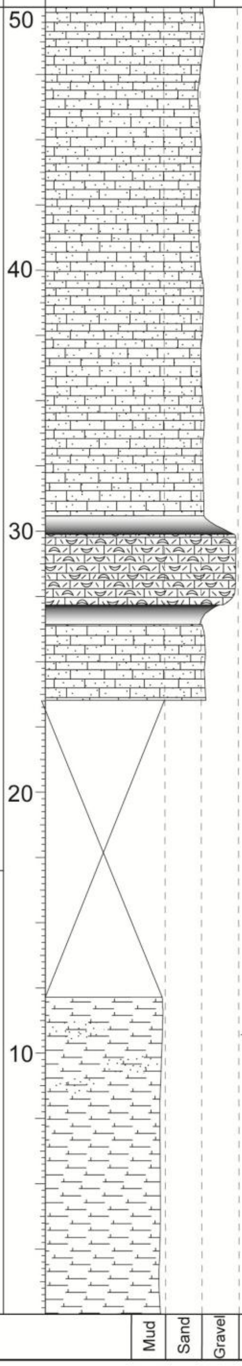
Date 29 04 10

Region Mt Moumoukai

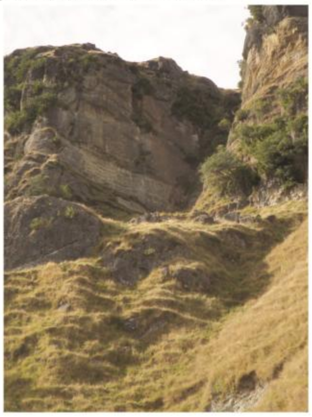
Location West flank of Mt Moumoukai

NZ Topo50 - BH42/123772

Elevation - 450 m



Stage	Stratigraphic Unit		(m.)	Sedimentary Structures	Fossils	Photo No.	Sample No.	Description	Facies
Early Opoitian	Mangaheia Group	Opoiti Limestone	50–24	(≡)		6.400	ML 130.6, ML 130.5, ML 130.4	Massive, highly to moderately indurated, well sorted, densely packed, sandy limestone. No macrofossils. Case hardening	L3/S
			~30–27			6.398	ML 130.3	Massive, moderately to highly indurated, densely packed, sandy limestone with very abundant brachiopods in all orientations, up to 4 cm	L2/Bra
			~27–24				ML 130.2	Massive, highly to moderately indurated, densely packed sandy limestone with fragmented barnacle matrix.	L3/S
Upper Micoene	Tolaga Group		12–0	V, ≠		6.392	ML 130.1	Massive, moderately indurated, well sorted, fine grained, blue grey mudstone with rare lenses of individual ?pumiceous clasts	M1



Lithology, hardness & cementation, colour, weathering, bedding, sedimentary structures, texture (grains size, sorting, shape, roundness), fossils, ichnofossils, mineralogy, preliminary assessment of environment of deposition.

Stratigraphic Column Number 28

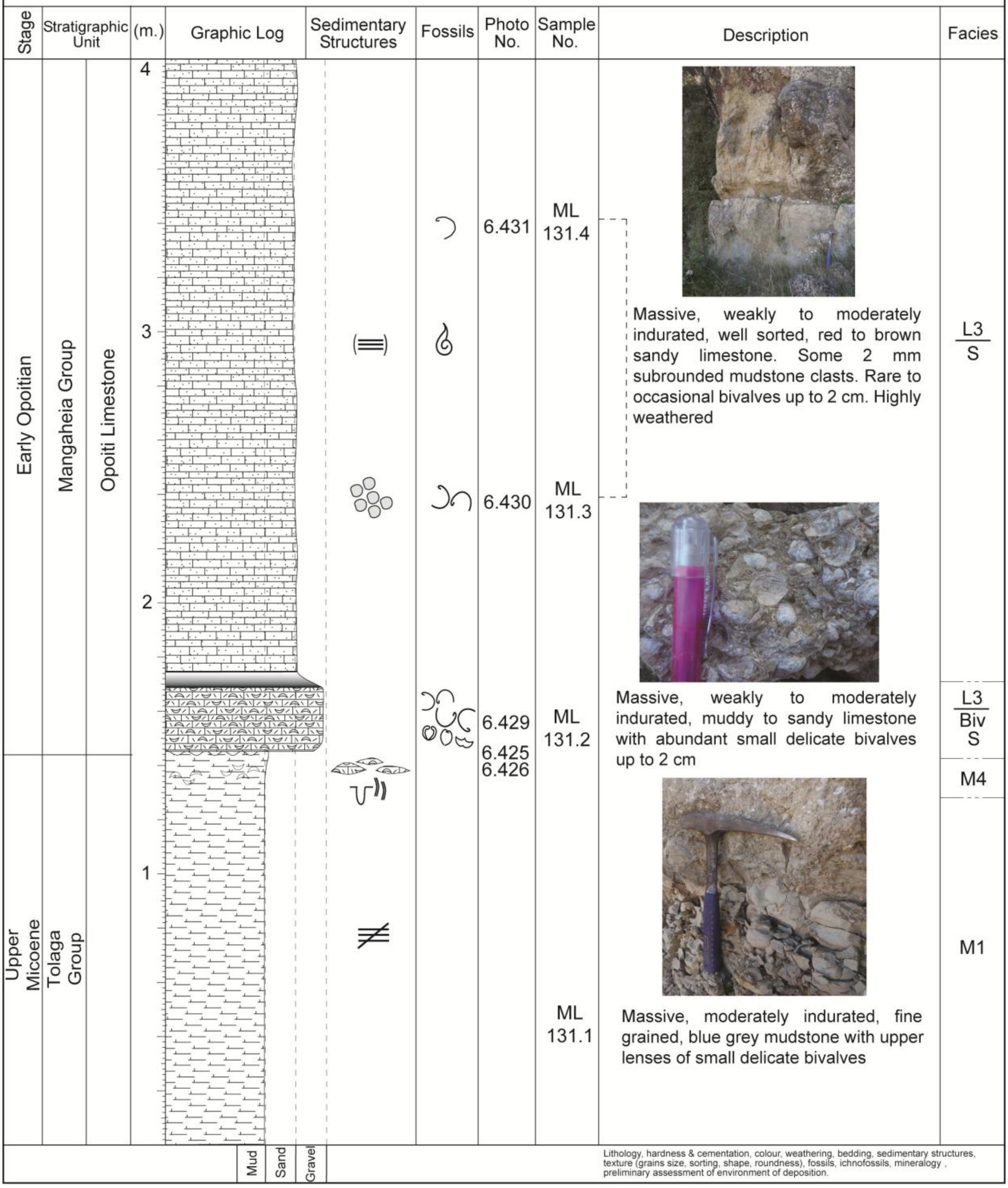
Date 29 04 10

Region Mt Moumoukai

Location North Ridge

NZ Topo50 - BH42/133759

Elevation - 315 m



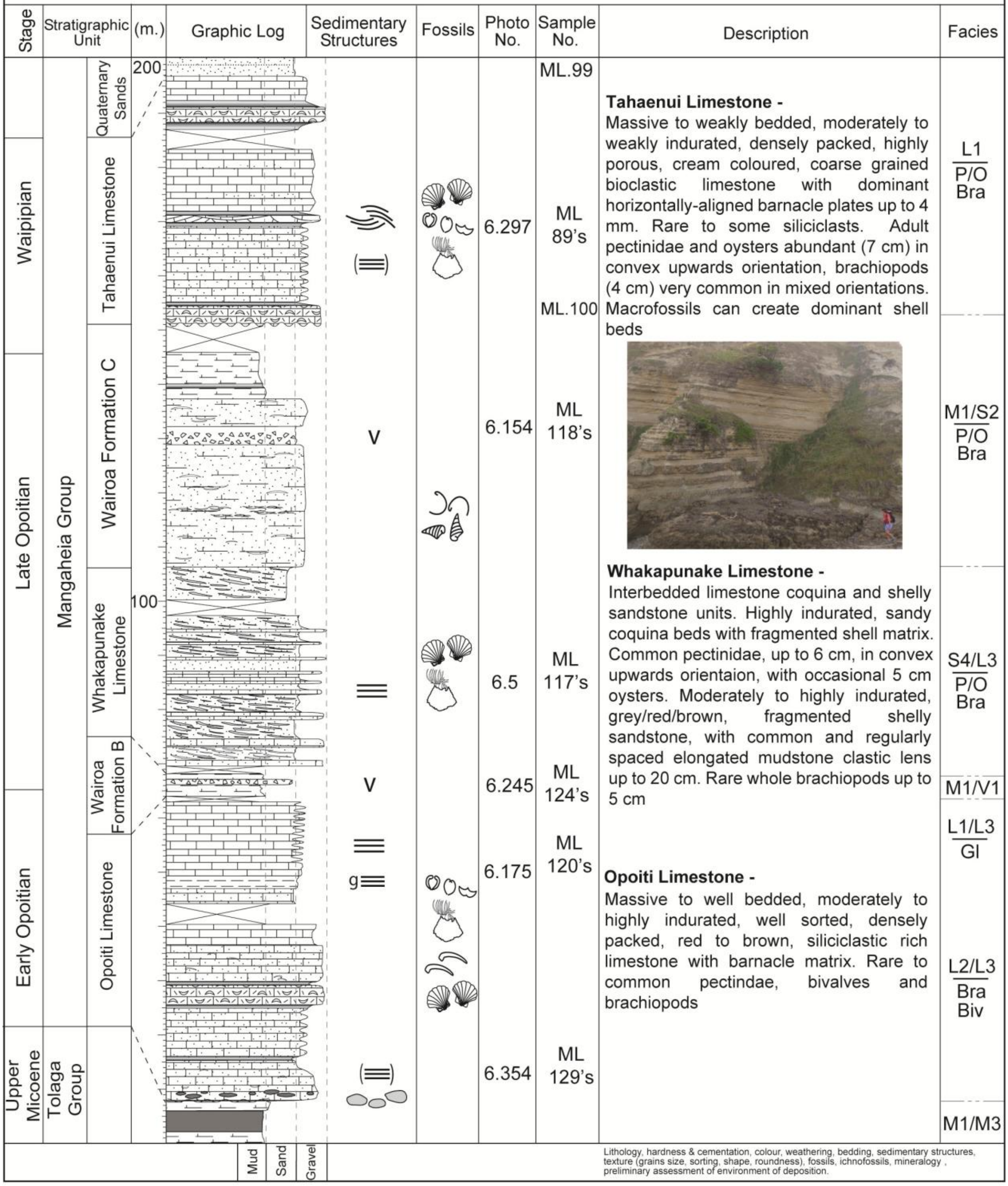
Stratigraphic Column Number 29

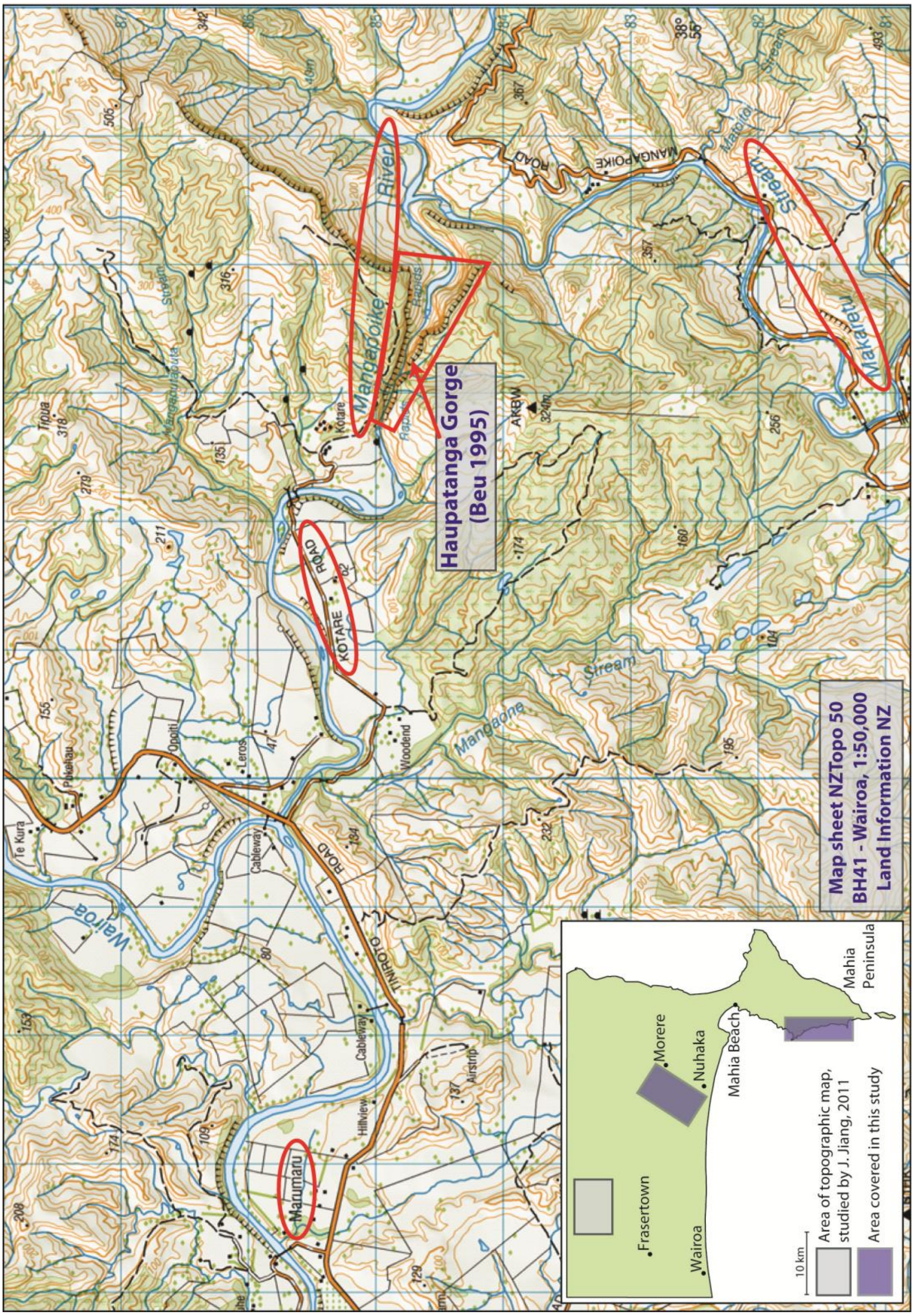
Region Mahia Peninsula

Location Generalised Mahia Composite Column

NZ Topo50 - BH42/034699

Date 13 08 10




Haupatanga Gorge
(Beu 1995)
Map sheet NZTopo 50
BH41 - Wairoa, 1:50,000
Land Information NZ
Mangapoike
River
Makaretu
Stream
MANGAPOIKE ROAD
KOTARE ROAD
Kotare
Marumaru
Wairoa
Mangaone
Stream
TIHIROTO ROAD
Woodend
Te Kura
Morere
Nuhaka
Mahia Beach
Mahia Peninsula
Frasertown
Wairoa
10 km
Area of topographic map, studied by J. Jiang, 2011
Area covered in this study

DIGITAL APPENDICES

Due to large amounts of data and images, these appendices are held on the enclosed compact disc.

Digital Appendix A – Legend of Mt Moumoukai

Digital Appendix B - Sample log

Sample log in excel format, containing the collection number, collection date, locality, GPS, elevation, site description, brief lithological description and age of all samples collected in the field.

Digital Appendix C - Field photographs

Further images in JPEG format that relate to numbers shown on various stratigraphic columns.

Digital Appendix D – Petrographic data

Digital Appendix E - Petrographic images

All standard and cathodoluminescence petrographic images, organised by locality.

Digital Appendix F - Insoluble residue textural analysis

Digital Appendix G - Scanning Electron Microscopy images

All SEM images in JPEG format, organised by locality.

Digital Appendix H - XRD data

Digital Appendix I - XRF data