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**SUBSURFACE STRATIGRAPHY AND PETROLOGY
OF A COOL-WATER CARBONATE FRACTURE
RESERVOIR – THE MID-TERTIARY TIKORANGI
FORMATION, TARANAKI BASIN, NEW ZEALAND**

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submitted in fulfilment
of the requirements for the Degree
of
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by

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ABSTRACT

The totally subsurface Oligocene-Early Miocene Tikorangi Formation in Taranaki Basin is New Zealand's only commercially-producing fractured-carbonate reservoir, but is poorly understood in a stratigraphic-sedimentological-diagenetic context. Based on correlation between laboratory and geophysical well log data a carbonate facies-based lithostratigraphy has been established for the first time for the entire formation. Petrogenesis of this complex siliciclastic-carbonate-dominated sequence, (re)deposited as a mix of retrogradational, progradational, and aggradational sedimentary sequences across a range of shallow-shelfal, foredeep and basinal settings, has been controlled by proximity to a rapidly evolving convergent Australian-Pacific plate boundary, to changes in relative sea level within an overall transgressive regime, to foredeep trough accommodation, to location within a cool-water temperate latitude setting, and to the changing availability and sources of carbonate and siliciclastic supply.

The history and nature of burial diagenesis have been instrumental in the creation and subsequent modification of fracture porosity within the Tikorangi Formation by producing a tight, low porosity/permeability rock; burial replacive dolomitisation with no associated secondary porosity development; intense fracturing, thrusting, and folding in association with compression at the Australian-Pacific plate boundary; and precipitation of a complex suite of ferroan calcite, baroque dolomite, celestite, and quartzine minerals within fracture systems. Petrographic, trace element, stable isotope ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$), and fluid inclusion data record a complex history of changing pore fluid chemistry and heating during burial, punctuated by relative changes in the input of downward circulating meteoric and upwelling basinal fluids. Precursory hydrocarbon-bearing fluids from Eocene terrestrial source rocks have migrated along with aqueous fluids after about 8 Ma, with major hydrocarbon emplacement within the fracture systems since the Early Pliocene.

The Tikorangi Formation's mixed siliciclastic-carbonate nature, heterozoan biotic carbonate make-up, low-Mg calcite mineralogy of skeletons and cements, and delayed deep burial diagenetic history are key features of current cool-water carbonate models. However, these evolving models of temperate carbonate sedimentation generally remain to incorporate several features exemplified by the Tikorangi Formation deposits, including: the recognition of a full spectrum of shelf-slope-basin facies and not simply shallow platform carbonates; the importance of mass emplacement events in producing complex mixed shelfal and deeper water skeletal assemblages; the textural diversity of deposits in which mudstones, wackestones and packstones are more common than grainstones; the ubiquitous occurrence of late diagenetic dolomite in the deposits; and the fact that cool-water carbonate facies can form economically important fracture reservoir rocks. While this study has provided new insights into the subsurface stratigraphy, petrology and diagenesis of the cool-water Tikorangi Formation carbonate fracture reservoir, an important research focus for the future is to further our understanding of temperate carbonate-dominated depositional and diagenetic systems as a whole, thereby enabling more concise assessment of their potential economic significance.

EXTENDED ABSTRACT

The totally subsurface Oligocene-Early Miocene Tikorangi Formation, Taranaki Basin, is New Zealand's only commercial carbonate and fracture-producing reservoir. Despite its economic importance, the temperate-latitude Tikorangi Formation is poorly understood in a stratigraphic-sedimentological-diagenetic context in comparison to age-equivalent non-reservoir-bearing temperate limestones exposed in onland New Zealand. This study is based on geophysical and laboratory derived data from core material from seven onshore wells (Hu- Rd-1/1A, Ngaere-2, Toko-1, Waihapa-2, -4, -5, -6) within the greater producing Waihapa-Ngaere Field, Tarata Thrust Zone, and a single offshore well, Maui-1. Correlation of laboratory-determined data with geophysical log data has defined four major facies: Facies A – calcareous siliciclastites (siliciclastic-dominated, slightly to moderately calcareous claystone to mudstone with <25% carbonate); Facies B – very calcareous siliciclastites (moderately to highly calcareous siliciclastic siltstone to fine sandstone with 25-50% carbonate); Facies C – muddy limestones (muddy, very fine to fine sandy carbonates with 50-75% carbonate); and Facies D – sparry limestones (pure, typically coarse sparry carbonates with >75% carbonate). These facies form the basic framework for constructing a previously unavailable full lithostratigraphy for the formation, comprising nine major correlatable units as either single or interbedded combinations of the four facies. Lower and upper boundaries are redefined while Waihapa-5 is nominated as the best reference section for the Tikorangi Formation due to the availability of core material, which is non-existent in the current type section at Mangahewa-1 well.

The formation comprises a vertically and laterally varied, and lithostratigraphically complex, mixed siliciclastic-carbonate-dominated sequence. Detailed petrography has delineated a spectrum of five petrofacies: I - mudstones; II – wackestones; III – packstones; IV - poorly washed grainstones; V - sparry grainstones. Skeletal varieties within these petrofacies have aided in the identification of three texturally and compositionally distinctive megafacies for the Tikorangi Formation: an earliest Miocene (Waitakian), near-situ, shallow-shelfal limestone (bryozoans, barnacles, calcareous red algae, large benthic

foraminifera) defined by Hu Rd-1A; an earliest Miocene (Waitakian) foredeep megafacies (dominantly bivalves, echinoderms, planktic foraminifera) including a prominent component of reworked and redeposited siliciclastics and shelfal bioclasts; and an Oligocene-Early Miocene (Whaingaroan-Altonian) deeper-water basinal megafacies (planktic foraminifera, nannofossils) at Maui-1. Depositional settings for the three contrasting megafacies were controlled largely by the interplay of the complex and evolving Australian-Pacific plate boundary setting, including associated development of a foredeep trough, changes in relative sea level within an overall transgressive regime, and the changing availability and sources of carbonate and siliciclastic supply.

Geophysical well-log characterisation has provided a surrogate chronostratigraphic framework within which five major geophysical log sequences, representative of sedimentary phases within the Tikorangi Formation, have been identified and correlated. Phase I and II - retrogradation resulting from deepening associated with foredeep subsidence. Phase III - progradation associated with declining subsidence rates and movement of carbonate facies basinward. Phase IV - prograding aggradation. Phases III and IV comprise often thick, periodically mass-emplaced carbonate-rich units separated by thin, shale-like units representing background sedimentation. Phase V - retrogradation and the reintroduction of siliciclastic material following uplift of basement sources.

Tikorangi Formation sediments record a history of substantial porosity/permeability reduction by physical and chemical compaction and late stage burial cementation occurring from about 0.5–1.0 km burial, including the formation of replacive and ubiquitous (5–50%) concentrically zoned nonstoichiometric Ca- and Fe-rich dolomite rhombohedra formed at 1.0–1.5 km and 36–50°C. Mg sources were probably from clay-rich micrite, with Fe supplied from siliciclastics and from within clay mineral structures. No secondary porosity development was associated with dolomitisation, limiting the Tikorangi Formation's ability to act directly as a hydrocarbon reservoir outside of fracture porosity. Dolomite is atypical of New Zealand and temperate carbonates generally. Major controls on dolomitisation were: the rapid transition into, and continued residency at, significant burial depths; the matrix/micritic-rich nature of

the original sediments; and the formation of diagenetically closed microenvironments by destructive burial diagenesis. Dolomite has resulted in elevated trace element concentrations in the Tikorangi Formation carbonates in comparison with wholly calcitic cool-water equivalents, giving them some false affinities with warm-water carbonates.

From about 21-19 Ma (Early Miocene - Otaian) the Tikorangi Formation in the Tarata Thrust Zone underwent intense thrusting, folding, and brittle fracturing associated with compression at the Australian-Pacific plate boundary, creating fracture porosity. A complex ferroan calcite, baroque dolomite, celestite, and quartzine mineral assemblage precipitated within fracture systems, substantially reducing porosity and permeability prior to hydrocarbon emplacement. Petrographic, trace element, stable isotope ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$), and fluid inclusion data record a complex history of changing pore fluid chemistry and heating during burial, punctuated by relative changes in the input of downward circulating meteoric and upwelling basinal fluids. First generation vein calcite precipitated as ferroan LMC from Fe-rich, meteorically-modified marine fluids at temperatures of 50-60°C and at burial depths of 1.4-1.8 km, from about 20-18 Ma. Baroque dolomite formed later, mainly as a primary cement but also as a calcite replacement at temperatures of 65-80°C, corresponding to burial depths of 2-2.5 km, and was associated with also volumetrically minor quantities of quartz and celestite. Lastly second generation ferroan LMC formed at 53-65°C and shallower depths of burial (1.6–2.0 km) following a period of inversion. The presence of petroleum fluid inclusions in calcite phase II suggests in some cases precursory hydrocarbon-bearing fluids have migrated along with aqueous fluids from 8 Ma, while major hydrocarbon emplacement has occurred in the last 5 m.y. since the Early Pliocene (Opoitian).

While carbonates, both as limestones and dolomites, form globally important oil reservoirs, the Tikorangi Formation is fundamentally different in character from many of the worlds well studied limestone reservoirs because it formed in a cool-water setting. The mixed siliciclastic-carbonate nature, cool-water carbonate biotic make-up (echinoderms, planktic/benthic foraminifera, bivalves, calcareous red algae, bryozoans, barnacles), low-Mg calcite mineralogy of skeletons and

cements, and delayed deep burial diagenetic history are key features characteristic of formation in temperate-latitude cool waters. While the complex sedimentary and diagenetic history of the Tikorangi Formation is broadly appreciated, much work remains to be able to better understand not only this hydrocarbon reservoir, but temperate-latitude carbonates more generally. Evolving temperate carbonate facies models do not easily incorporate much of the diversity and complexity of a broad spectrum of skeletal facies and diagenetic features such as identified in this study. Features such as redeposition, dolomitisation and tectonic fracturing enabling them to host hydrocarbons will necessitate an expansion and greater diversification of the shallow-marine temperate carbonate model in the future. Further development of the temperate carbonate facies model will require considerably more extensive and detailed studies in order to continue to better understand the complexities of the burial diagenetic realm, dolomitisation, and the geochemical changes involved with uplift and exposure to meteoric pore fluids. Moreover the potential of cool-water carbonate facies to form petroleum host rocks remains to be properly evaluated.

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Plate 5.2 Photomicrograph pairs under plane polarised light (left) and cathodoluminescence light (right) of CL petrotypes in the Tikorangi Formation. (A) Petrotype IIc occurring in dark micrite/matrix (B) comprising large very dull- to non-luminescent cores with a dull- to moderately-bright yellow/orange Z2 (sample NG2.4.1). (C, D) Petrotype IIIa, the most common CL petrotype, with rhombs displaying oscillatory zoning (sample W5.4.6). (E, F) Petrotype IIIb dolomites commonly exhibit six oscillatory concentric zones and show evidence of tectonic pressure dissolution (sample W2.2.7). (G) Core showing horse-tail stylolite resulting from tectonic compression occurring largely post-dolomitisation as evidenced by pressure dissolved rhombs in (F) (sample NG2.4.10). (H) Tectonically-induced hydrocarbon-bearing fracture-porosity partially healed by carbonate minerals, both post-dating dolomite formation (sample W4.7.2B).

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NG2.4.3, CPL & CL). (G) Hydrocarbon-bearing fluid inclusions occurring within second generation calcite. (H) White luminescence is produced by hydrocarbon-bearing fluid inclusions under UV light. Inset shows inclusions containing high-pressure CH₄ which has formed a solid gas-hydrate (clathrate), PPL (sample NG2.4.3).

PREFACE

The opportunity to study the Tikorangi Formation beneath Taranaki Peninsula, Taranaki Basin, New Zealand, arose following my involvement in an out-of-house report (Kamp & Hood 1994) commissioned by Petrocorp Exploration Ltd (now Fletcher Challenge Energy Ltd) which made a preliminary investigation of the petrography and geochemistry of vein mineralisation within the Tikorangi Formation fracture systems. The study was conducted without reference to any stratigraphic or other data.

During completion of this report, it became apparent that the Tikorangi Formation was a poorly known and little studied carbonate-rich unit which provided many exciting research opportunities. On approaching Petrocorp about the prospect of continuing further research on the Tikorangi Formation, they consented to assist with such a project and allow access to what was then closed file core material (Ngaere-2 well) and publicly unavailable internal reports. Petrocorp also provided digital wire-line data for the eight wells used in this study, for which some core material was also available.

The Oligocene-Early Miocene Tikorangi Formation has afforded this study with the opportunity to examine the formation from several viewpoints: (1) as a unique and important oil producer in Taranaki Basin, the only non-sandstone reservoir and the only fracture-producing reservoir within the basin; (2) as an example of a temperate-latitude, cool-water carbonate-rich sequence; and (3) as a totally subsurface carbonate quite compositionally, diagenetically, and geochemically distinct from most uplifted and exposed age-equivalent deposits in onland New Zealand.

Until this time the Tikorangi Formation has been scantily studied and poorly understood in comparison to age-equivalent mid-Tertiary non-reservoir-bearing limestones exposed onshore to the south (Takaka Limestone of the Nile Group,

South Taranaki Basin) (Leask 1980) and northeast (Orahiri and Otorohanga Limestones, Te Kuiti Group, North Wanganui Basin) (Nelson 1973, 1978; Nelson et al. 1988, 1994). To date there has been no formally published articles written specifically about the Tikorangi Formation, and in a sense it has consequently remained hidden from the wider scientific community. This, coupled with a need for a more comprehensive and detailed stratigraphic, sedimentologic, and diagenetic evaluation of this important reservoir rock, has been the impetus for the current research, the first detailed study of the Tikorangi Formation.

The study has been a challenging one for many reasons, but particularly because of the completely subsurface nature of the formation (i.e., no outcrop), the lack of core material away from the Waihapa-Ngaere Field wells, and the lack of a complete core section through the entire Tikorangi interval. Despite this, the research has shown the Tikorangi Formation to be a stratigraphically, compositionally, structurally, geochemically, and diagenetically complex unit.

Another logistical difficulty for the study related to the location of petroleum industry literature in the Ministry of Commerce library in Wellington and of core material in the core store in Lower Hutt, posing constraints on ready accessibility, viewing, and sampling of material. Descriptive rock terminology within the petroleum literature is sometimes not that widely adopted within the sedimentological community, while stratigraphic nomenclature used within well completion reports is often “sloppy” and uses names derived from outcrop in neighbouring North Wanganui (North Island) and West Coast (South Island) Basins. For example, the nomenclature for the Tikorangi itself is often misleading, and the unit has commonly been referred to as the Tikorangi Limestone despite its mixed siliciclastic-carbonate nature.

Initial intentions of this study were for a basinwide study of the formation, but a lack of core material outside of petroleum prospect areas has meant the study had to be limited to seven wells in the greater oil-producing Waihapa-Ngaere Field in Taranaki Peninsula (Fig. 1.4), and a single offshore well, Maui-1 (Fig. 1.7). The physical study of this rock unit is therefore limited to glimpses provided by drill core material whose nature, quantity, and location within the Waihapa-Ngaere

Field have been controlled by the economic and spatial constraints of petroleum exploration practices. This study is therefore based largely upon a north-south cross-section through the Waihapa-Ngaere Field area, and then offshore to the west to Maui-1 well. It is relevant to mention that while side-wall cores were collected during drilling of many wells outside the Waihapa-Ngaere Field, these have mainly been exhausted through use in previous work, particularly for microfossil dating. Drill cuttings, although available for many wells, were highly unsuitable for this study primarily because of their pulverised nature.

This thesis is written as a series of self-contained topics, as opposed to running chapters, each with their own abstract, conclusions, and references. A complete reference list for the thesis is contained after the Topic 8 reference list. This format has been adopted to help facilitate the later submission of formal papers for publishing. As a result there is some repetition of background information and locality and stratigraphic figures between the eight topics presented. Topic 1 provides a background and historical overview of the Tikorangi Formation without any input of new data derived from this study. Topic 2 develops a detailed and previously unavailable carbonate and geophysical log-based lithostratigraphy for the formation. Topic 3 examines well-log trends and builds on the little known and poorly understood depositional history of the formation. Topic 4 explores the petrogenesis of the formation and defines three megafacies which provide a shelf-to-basin perspective for the formation. Topic 5 documents for the first time the occurrence of dolomite in the Tikorangi Formation, explores its possible origin, and seeks explanations for its paucity in exposed onland age-equivalent deposits. Topic 6 builds on the paucity of geochemical data for cool-water carbonates in general and provides insights into the diagenetic and dolomitisation history of the formation. Topic 7 investigates the nature of hydrocarbon-bearing fracture systems in the formation and provides a paragenetic sequence for the complex history of vein mineralisation. Finally, Topic 8 provides a summary and integrative synthesis of data, including the development of a paragenetic sequence of events for the formation.

The referencing format in this thesis generally conforms to that of the New Zealand Journal of Geology and Geophysics. However, for some references,

particularly well completion reports where no author is recorded, less formal notation has been necessary. For example the Ngaere-2 Well Completion Report, produced by Petrocorp Exploration Ltd, is referenced with the company as author in abbreviated form (i.e., PEL 1995).

Ages used in this study are mainly based on the biostratigraphic ages given in well completion reports, and in the King & Thrasher (1996) geological synthesis of Taranaki Basin, and refer to New Zealand stages (Appendix 1.2). Lithostratigraphic nomenclature for the strata in Taranaki Basin is based on Palmer (1985) and King & Thrasher (1996). Depths are generally reported as mAH (metres along hole), unless otherwise stated.

Formal classification schemes for rock names are limited to petrographically defined facies (petrofacies) and use the carbonate rock classification scheme of Dunham (1962). The scheme has been applied in this study to rocks ranging across the spectrum of siliciclastic-carbonate facies, and which are therefore not always limestones in the strictest sense (>50% carbonate). However, rock textures/fabrics are representative of the range defined by Dunham (1962), involving a spectrum of grain-supported through matrix-supported to matrix-dominant types. Where textural size terms are used they follow the Wentworth grade scale (Folk 1962).

Department of Earth Sciences rock store numbers are included in the sample catalogue in Appendix 2.2, but otherwise in the thesis collector sample numbers are used. For completeness, a few samples taken from sidewall cores are included in the sample catalogue, and if thin-sections were prepared also in the petrographic data sheets; otherwise these data have not been directly incorporated into the study.

Finally, it is noteworthy, and perhaps of some concern, that a recent publication in the New Zealand Journal of Geology and Geophysics erected the formal lithostratigraphic name Tikorangi Ignimbrite for an ignimbrite sheet in the Matahina Basin, Taupo Volcanic Zone, North Island (Hildyard et al. 2000). The lithostratigraphic name Tikorangi has been used in Taranaki Basin studies since

its introduction by van Rijen & van der Abeele (1963) for a carbonate-dominated sequence recorded in the subsurface in the Mangahewa-1 well. That the name is being used separately by sedimentologists and volcanologists for two distinctly different formations is a problem that requires addressing in the future by the geoscientific community.

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TOPIC 1:

BACKGROUND AND HISTORICAL OVERVIEW OF THE FRACTURED MID-TERTIARY TIKORANGI FORMATION, A CARBONATE-DOMINATED RESERVOIR IN TARANAKI BASIN, NEW ZEALAND

1.1 ABSTRACT

The Tikorangi Formation is a unique and important oil producer in the onshore Waihapa-Ngaere Field, Taranaki Basin, being the only non-sandstone reservoir and the only fracture-producing reservoir within the basin. The carbonate-dominated Tikorangi Formation represents a totally subsurface, temperate-latitude, carbonate-rich sequence formed during a tectonically quiescent, sediment starved period of basin history at the peak of a regional marine transgression. Two major facies are recognised. In western and northern parts of the basin, non-producing, largely tectonically undisturbed, condensed deep-water basinal facies comprising carbonate oozes accumulated during the Oligocene to Early Miocene (Whaingaroan – Otaian) on the Western Stable Platform. A change in tectonic regime in the late Early Oligocene produced sudden and rapid subsidence of the basin's eastern margin with development of a carbonate slope and foredeep. From a narrow, probably fault-controlled shelf in the east, biota were reworked and redeposited westwards in the earliest Miocene (Waitakian) to accumulate a "shelfal" (outer shelf to upper slope) facies of fine- to coarse-grained skeletal carbonate. Southern margins of the basin experienced shallow shelfal conditions, with deposition of the laterally equivalent Takaka Limestone, while age equivalent Te Kuiti Limestones formed in the adjacent North Wanganui Basin. In central and southwestern areas of the Taranaki Peninsula the Tikorangi Formation is absent. Tectonic compression following the earliest Miocene (Waitakian) brought about: (a) a change from carbonate to terrigenous-dominated sedimentation; (b) the fracturing and allochthonous emplacement of low-angle overthrusts of Tikorangi Formation in the Miocene; while Pliocene-Pleistocene sediment packages are undeformed; and (c) the associated formation of domed and

overthrust structures along the eastern margin of Taranaki Basin (Tarata Thrust Zone), including the Waihapa asymmetric north-south trending anticline. Hydrocarbons were generated from Eocene terrestrial coals and migration took place late in the basin's history as indicated by the Miocene or younger age of trapping structures.

Despite its economic importance, the carbonate-dominated Tikorangi Formation has been scantily studied and is poorly understood in a stratigraphic-sedimentological-diagenetic context in comparison to age equivalent non-reservoir bearing limestones exposed onshore to the south (Takaka Limestone of the Nile Group, South Taranaki Basin) and northeast (Orahiri and Otorohanga Limestones, Te Kuiti Group, North Wanganui Basin). The Tikorangi Formation will continue to be regarded as an important potential hydrocarbon reservoir within Taranaki Basin, necessitating a better understanding of its geological and sedimentological properties.

Keywords Ngatoro Group; Tikorangi Formation; Oligocene-Miocene; Taranaki Basin; hydrocarbons; Waihapa-Ngaere Field; fractured reservoir; limestone

1.2 INTRODUCTION

The Tikorangi Formation is a productive hydrocarbon reservoir unit within Taranaki Basin, currently New Zealand's only commercial hydrocarbon-producing sedimentary basin (Fig. 1.1A). The relatively recent discovery of the Waihapa oil field in 1988 (Fig. 1.1B), struck within the fractured carbonate-rich rocks of the Oligocene-Miocene Tikorangi Formation, proved to be one of the most exciting finds in recent times that has opened up a new and substantial play in Taranaki Basin. Up until this time, production of hydrocarbons had been exclusively from Paleocene to Pliocene marine sandstones (Fig. 1.2). With the newly discovered economic importance of the formation, the Tikorangi carbonates have become a focus of continued exploration and development activity within the Waihapa Field and its more recently discovered extension, the Ngaere Field. The combined Waihapa-

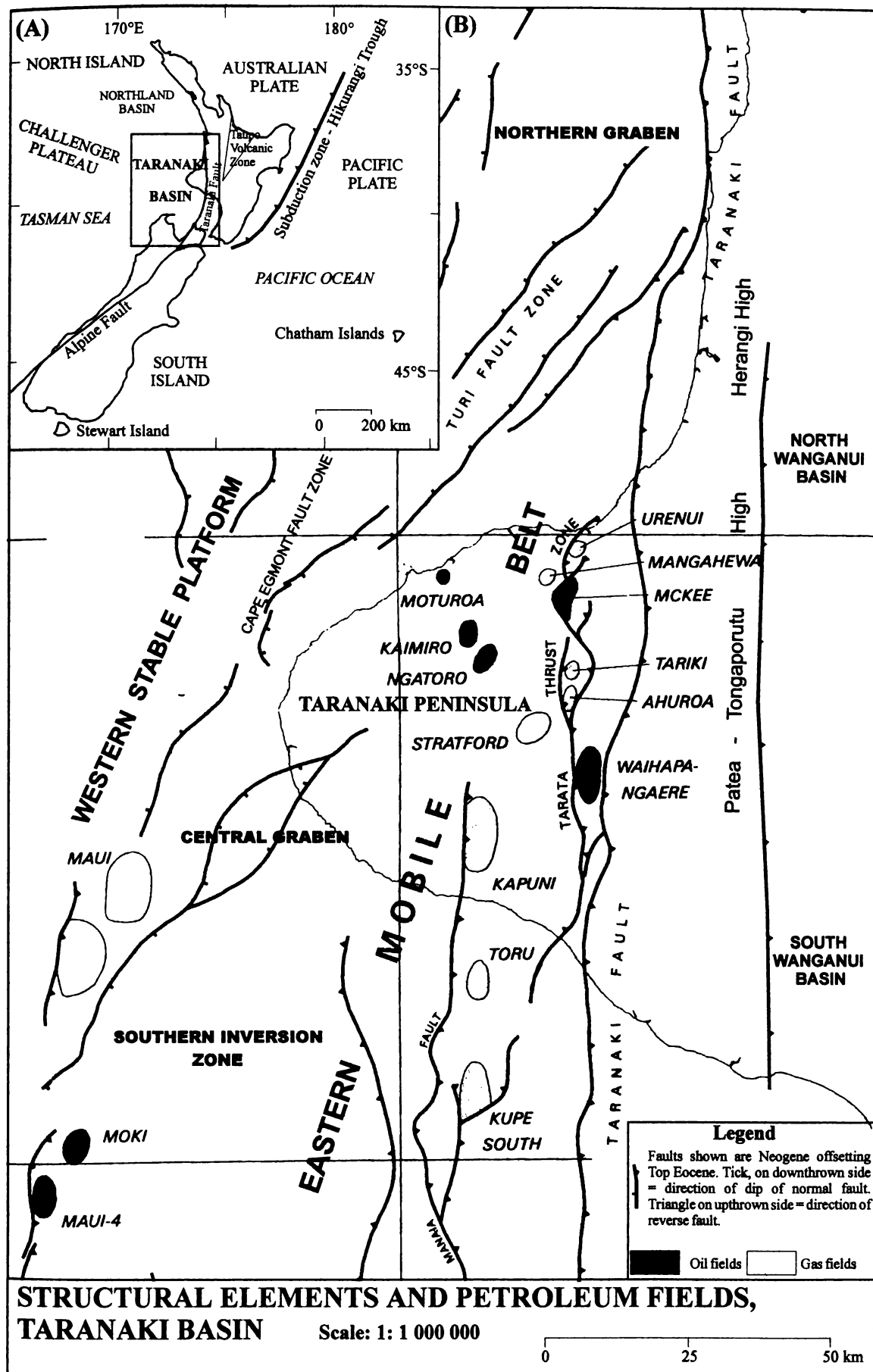


Fig. 1.1 (A) Location of Taranaki Basin in New Zealand. (B) Major structural and tectonic elements and main oil/condensate accumulations within Taranaki Basin. Modified from King & Thrasher (1996).

Ngaere Field (Fig. 1.1B) is ranked fifth in size in New Zealand, with estimated reserves of 28 MMBBL (million barrels of oil equivalent) (King & Thrasher 1996), and has achieved to date the highest production rates of oil per well in the country.

The Tikorangi Formation is unique in Taranaki Basin, not only as the first non-sandstone producing unit (Fig. 1.2), but also as the first fracture porosity-producing reservoir. The carbonate-rich rocks themselves exhibit virtually no porosity and production is entirely from extensive fracture networks. These networks were formed by Neogene tectonic movements associated with the evolution of the Australian/Pacific plate boundary through New Zealand (Fig. 1.3). The same tectonism resulted in allochthonous sheets of Tikorangi Formation being thrust into less competent overlying rocks. This active convergent plate margin setting has played an instrumental role in Taranaki Basin's hydrocarbon generation.

The subsurface position of the Tikorangi Formation, currently lying about 3 km below Taranaki Peninsula, negates the opportunity to view and study this rock unit in the familiar and ideal field setting. The physical study of this rock unit is therefore limited to glimpses provided by drill core material whose nature, quantity, and location within the Waihapa-Ngaere Field have been controlled by the economic and spatial constraints of petroleum exploration practises (Fig. 1.1B, 1.4). The study of core samples has inherent drawbacks because many of the sedimentological (e.g., sedimentary and biogenic structures) and diagenetic (e.g., dissolution seams and stylolites) features commonly visible in outcrop, having been highlighted by weathering, are masked by the rough and ribbed external surface of the drill core. It is therefore not surprising that the Tikorangi Formation has been poorly studied, with published general information being largely limited to the wider Taranaki Basin geological synthesis made by King & Thrasher (1996).

Given the ever increasing need to discover new petroleum reserves in New Zealand, Taranaki Basin remains the key centre of exploration activity. An improved understanding of currently producing reservoirs and hydrocarbon systems such as the Tikorangi Formation will aid in the identification and evaluation of new prospects

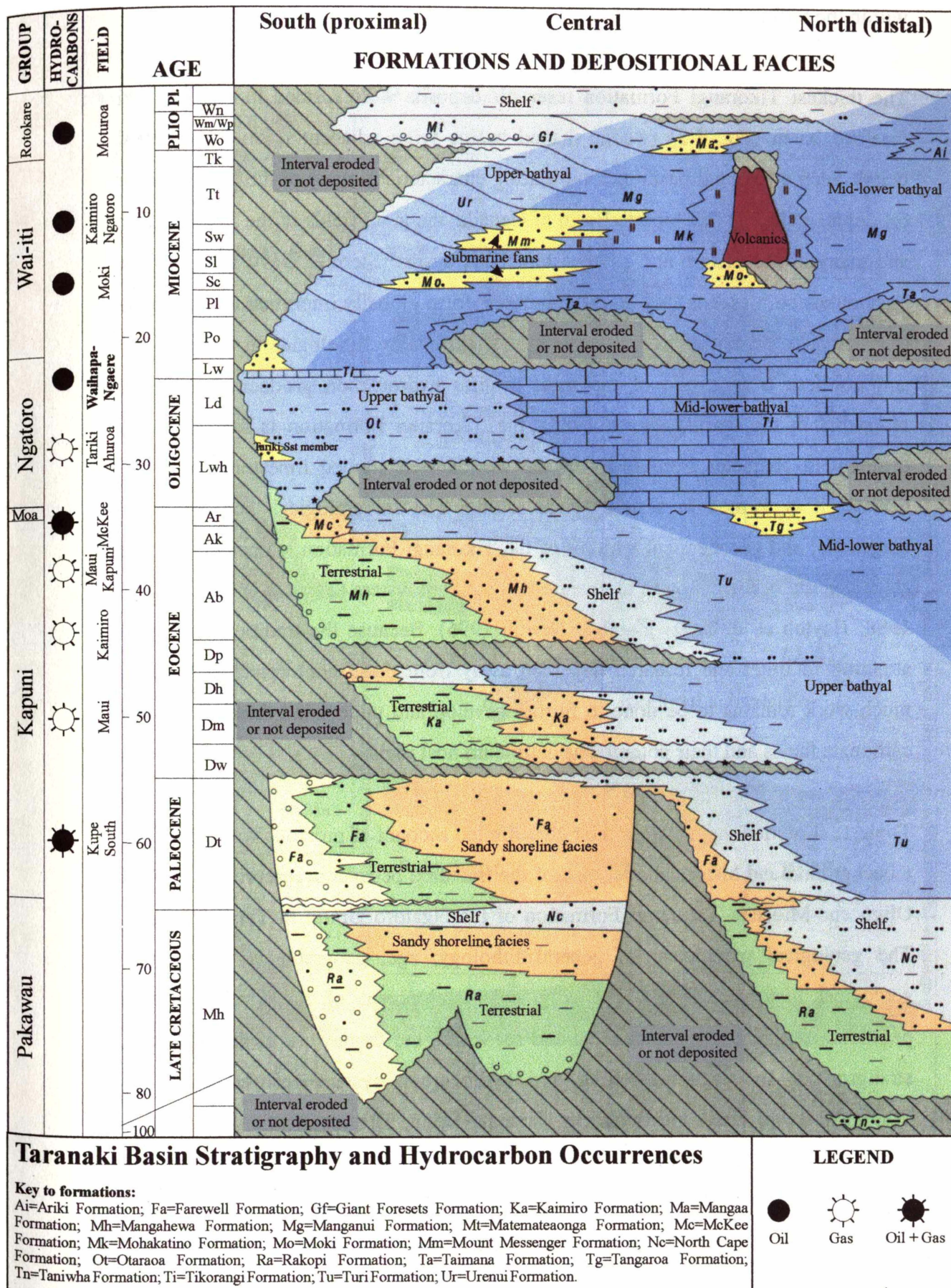


Fig. 1.2 Taranaki Basin stratigraphy, depositional facies, and hydrocarbon fields and occurrences. The Tikorangi Formation carbonates form part of the Ngatoro Group. Modified from King & Thrasher (1996).

within the basin.

The thickest Tikorangi Formation reservoir deposits were formed in the Taranaki foreland basin (Fig. 1.5) (wedge-shaped basins lying adjacent to fold and thrust belts). Such a foreland basin tectonic setting characterises many of the worlds major oil fields, including the Alberta Basin of Canada, the giant fields of the Persian Gulf, and many of the eastern and southeastern USA basins (Stern & Davy 1990). While carbonates, both as limestones and dolomites, form globally important oil reservoirs (e.g., Asmari Formation of dolomitic marly and chalky lithologies in onshore Iran and northern Iraq is one of the most prolific hydrocarbon producing carbonate reservoirs in the world) (North 1985), the Tikorangi Formation is fundamentally different in character from many of the worlds well studied limestone reservoirs because it is formed in a nontropical setting. The mineralogical, compositional, diagenetic, and geochemical features of the Tikorangi Formation are generally those characteristic of formation in temperate-latitude cool waters (Table 1.1) (e.g., Nelson 1988; Hayton et al. 1995; Hood & Nelson 1996). Because the traditional focus of attention in limestone research has been away from these nontropical carbonates, much work remains to be done to further develop and understand these cool-water carbonate facies and their potential as petroleum host rocks.

Topic 1, compiled mainly from the rather limited account of previous work, provides a background and historical overview of the fractured petroleum reservoir that is the Oligocene-Miocene Tikorangi Formation of the Ngatoro Group in Taranaki Basin. The geological parameters of general lithology, age, geographical distribution, geological history, and the discovery and development of the formation as a petroleum reservoir are documented and set within the framework of the structural, stratigraphic, and tectonic setting and hydrocarbon systems of the producing Waihapa-Ngaere Field and the wider Taranaki Basin. The justification for such an overview derives from the paucity of published data on the Tikorangi Formation, and the fact that most of the information that is available is scattered through petroleum company reports which can be difficult to access due to commercial sensitivity and confidentiality.

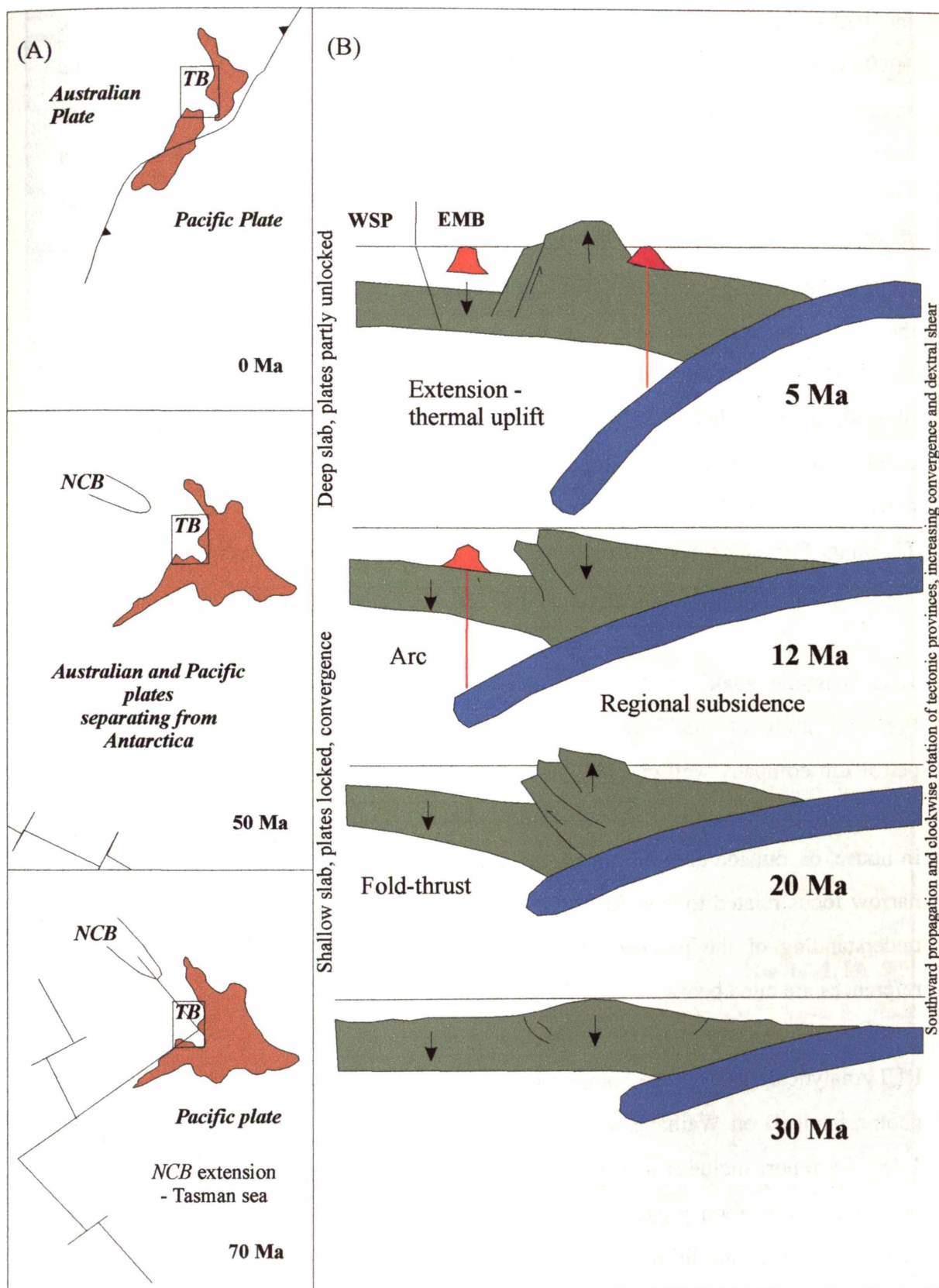


Fig. 1.3 Plate tectonic developments in (A) the New Zealand region in plan view and in (B) the northeast Taranaki Basin in cross sectional view. WSP = Western Stable Platform; EMB = Eastern Mobile Belt; TB = Taranaki Basin; NCB = New Caledonia Basin. Adapted from King & Thrasher (1996).

Formal stratigraphic nomenclature for the Tikorangi Formation has been inconsistent, the terms Tikorangi Limestone (Simpson 1992) and Tikorangi Formation (King 1990; King & Thrasher 1992, 1996) both being used synonymously. At its type section (Fig. 1.6) the Tikorangi Formation is described as a sandy limestone, calcareous sandstone, and white crystalline limestone interbedded with calcareous mudstone (van Rijen & van den Abeele 1963). Generally speaking, the Tikorangi Formation is dominated by limestone with common thin interbeds of mudstone and/or siltstone. Given the often subordinate and interbedded nature of other facies, the use of the term Tikorangi Limestone might appear defensible. However, this is not so when the broad range of carbonate contents of the unit is considered, values often dropping well below 50% (see Topic 2). Nelson (1978) showed that “true” limestones in the laterally equivalent onland Te Kuiti Group had carbonate percentages over 70%. Until more data are available we prefer to use the name Tikorangi Formation for this carbonate-rich unit, but accept the usage of the terms Tikorangi limestone, Tikorangi carbonates and Tikorangi facies in an informal sense.

1.2.1 Previous work

Previous study of the Tikorangi Formation is mainly documented in in-house petroleum company well completion reports (WCRs) by the Petroleum Corporation of NZ (Exploration) Ltd (Petrocorp) (now Fletcher Challenge Energy), or in specific in-house or outside-commissioned reports. These reports typically have a rather narrow focus related to specific and often technical aspects for gaining an improved understanding of the prospectivity of the limestone. Some of the more relevant references are cited below.

RUI Analytical (1989) were commissioned to undertake core analysis (chemical and geomechanical) on Waihapa well core samples from Waihapa-2,-4,-5, and -6 (Fig. 1.4). The report includes a petrographic appraisal of the Tikorangi Formation as a potential hydrocarbon prospect with a view to determining a relationship between natural fracturing and lithology. Martin (1989) undertook a petrographic study of the Tikorangi Formation and Moki Formation in the Northern Taranaki Basin to

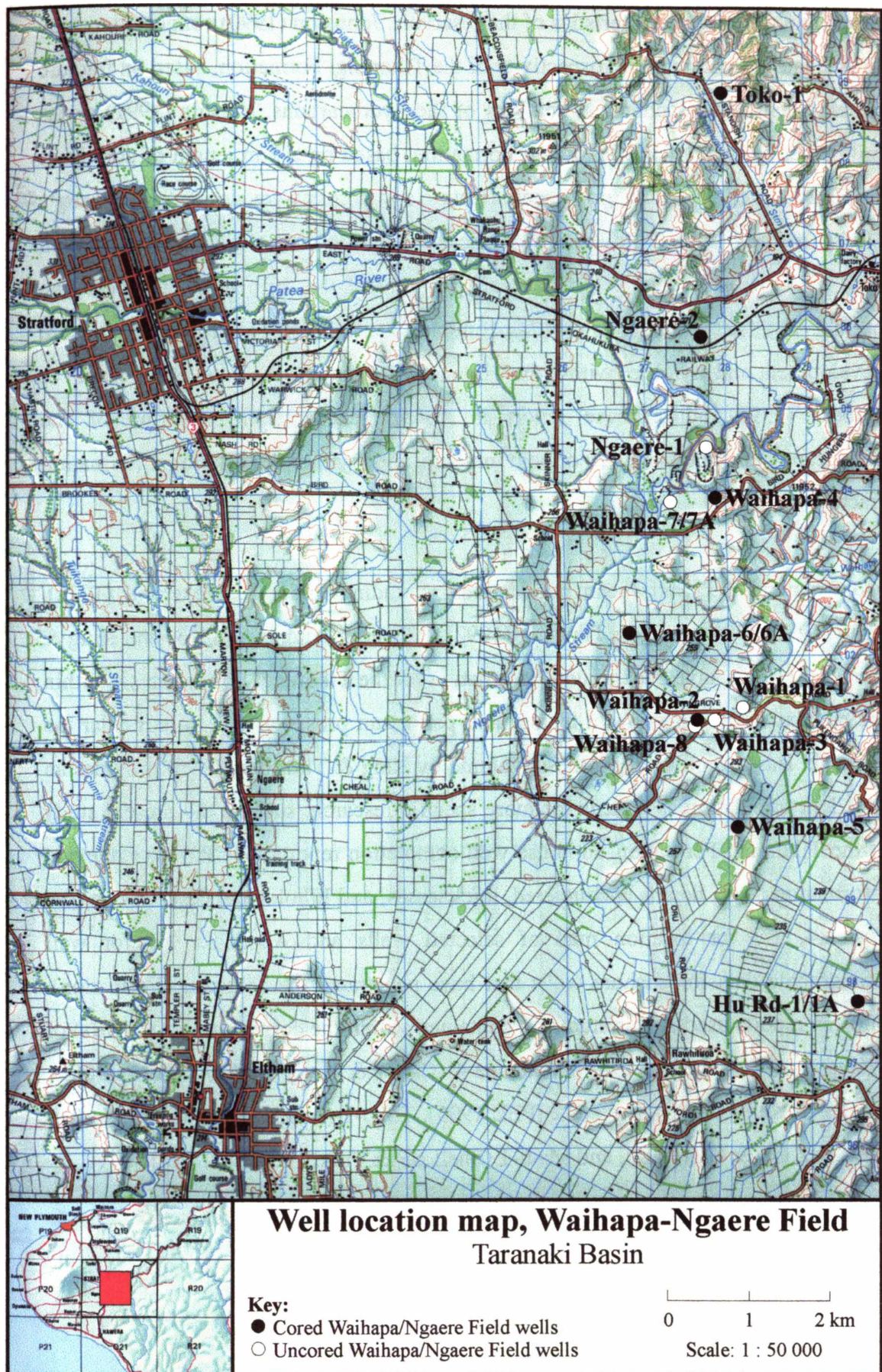


Fig. 1.4 Well location map for cored drill holes within the Waihapa-Ngaere Field, and including some other wells mentioned in the text for which no core was drilled.

determine porosity characteristics of the reservoir. Johnston (1990) conducted a study to evaluate the nature and prospectivity of the Tikorangi Formation, based on fracture development and geochemical analyses of the hydrocarbons. Naish's (1991) report on the petrography of the Tikorangi Formation, based on a 2 m length of core from the Toko-1 well (Fig. 1.4), documents fracture and porosity development. Simpson's (1992) in-house report provides a technical evaluation of the Tikorangi Formation with the aim of predicting the reservoir potential of the formation throughout the basin. Van der Lingen's (1993) commissioned report focuses on fracture development and stylolites within the Tikorangi Formation, Waihapa Field. Kamp & Hood's (1994) out-of-house report is a comprehensive investigation of the petrography and geochemistry of vein mineralisation within the Tikorangi Formation fracture systems.

More general Taranaki Basin publications, including Pilaar & Wakefield (1978), King (1990, 1994), King & Thrasher (1992), Palmer & Andrews (1993) and King & Thrasher (1996), give background information for the Tikorangi Formation set within the context of Taranaki Basin history and petroleum prospectivity. In particular the Taranaki Basin geological synthesis volume by King & Thrasher (1996) provides an excellent foundation as a basis for more specific research, such as the present study of the Tikorangi Formation. In-house well completion reports (WCRs) give relevant information about depths encountered, thicknesses, and lithological descriptions (see Fig. 1.4, 1.7 for location map of selected wells and Appendix 1.1 for well stratigraphic data for onshore wells that have penetrated the Tikorangi Formation). The key reports used in this study are contained within the corresponding (WCRs) of Waihapa-2 (Carter et al. 1988), Waihapa-4 (Carter & Kelly 1989a), Waihapa-6/6A (Carter & Kelly 1989b), Ngaere-2 (PEL 1995), Toko-1 (Adams et al. 1980), Hu Rd-1/1A (NZ Oil & Gas 1992), and Maui-1 (Shell BP & Todd 1969).

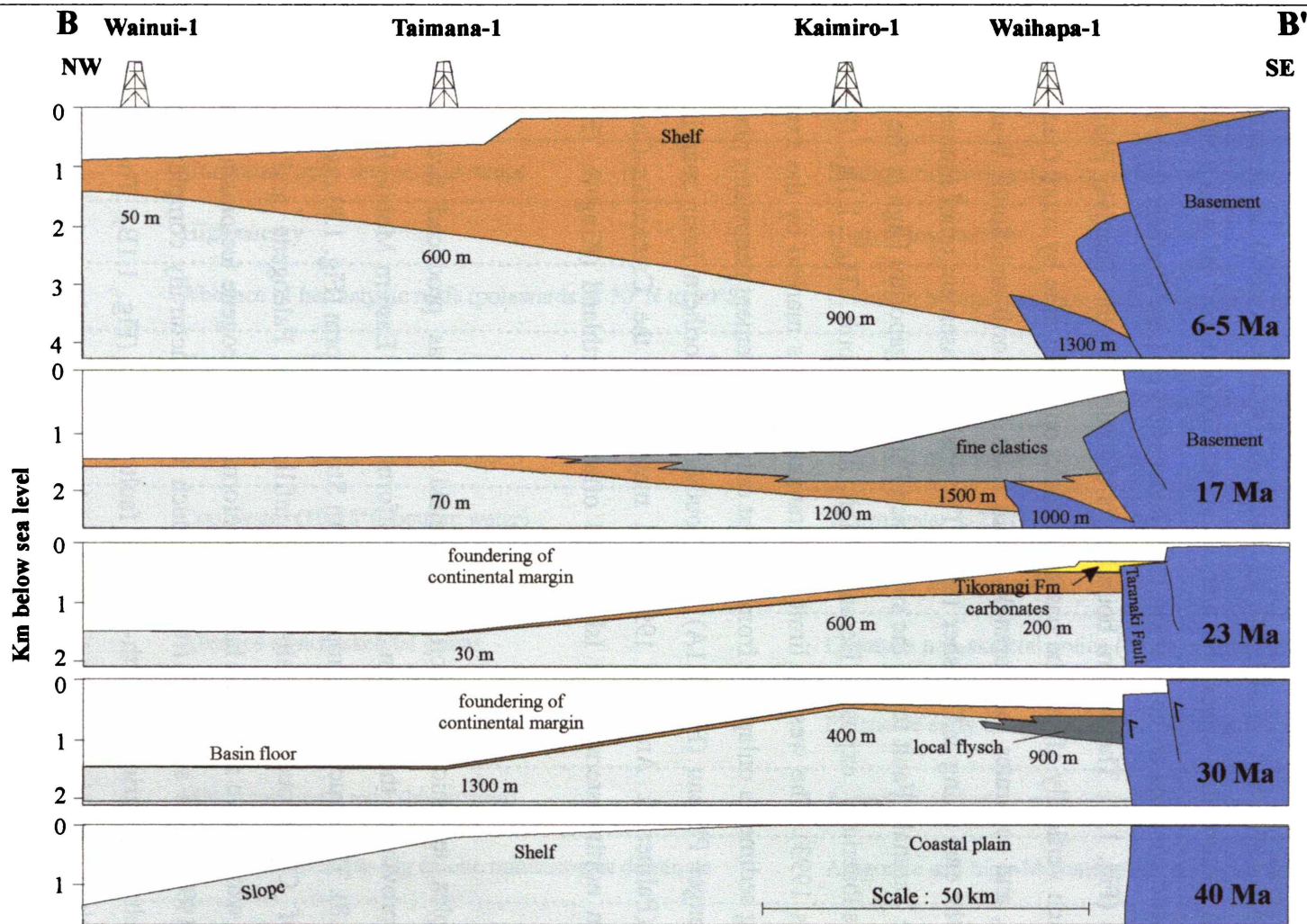


Fig. 1.5 Cross sections through Taranaki Basin showing the magnitude and distribution of incremental Oligocene-Miocene subsidence (in metres), and progressive deformation of the Oligocene-Eocene boundary shown by base of brown colouring. Early Miocene subsidence in the east (17 Ma) was the result of foreland loading by overthrust basement (blue). See Fig. 1.7 for cross section location. Adapted from King & Thrasher (1996).

1.3 GEOLOGIC SETTING

1.3.1 Structural elements

Taranaki Basin is one of several New Zealand Late Cretaceous-Cenozoic aged sedimentary basins that is centred immediately offshore central-western North Island (Fig. 1.1A). The basin as defined by King & Thrasher (1996) is essentially a subsurface feature that covers an area of about 100,000 km² of which 90% lies offshore, and contains an up to 9 km thick succession of Late Cretaceous to Recent sediments (Fig. 1.2). The eastern boundary is delimited by the Taranaki Fault (Fig. 1.1B) which vertically offsets the basement rocks on either side by more than 5 km (Fig. 1.8), and separates the Taranaki Basin from the North and South Wanganui basins to the east (King & Thrasher 1996). The positive basement relief immediately east of the Taranaki Fault forms the subsurface Patea-Tongaporutu High in the south, and the subaerially exposed Herangi High in the north (Fig. 1.1B) (Palmer & Andrews 1993). The western limit of Taranaki Basin is marked by the extent of prograding sediments onlapping from the east onto the basement deepwater platform, the Challenger Plateau (Fig. 1.1A). The southern and northern basin margins are arbitrary (Palmer & Andrews 1993) and merge with the Cretaceous-Cenozoic sections in northwestern South Island and offshore Northland (King & Thrasher 1996).

The complex tectonic evolution of Taranaki Basin has produced two unique structural provinces, the Western Stable Platform and the Eastern Mobile Belt (Fig. 1.1, 1.3, 1.8). The structurally simple Western Stable Platform (Fig. 1.8) comprises a number of Cretaceous rift half-grabens infilled with Paleogene and younger sediments which have remained largely undeformed by Neogene tectonism (King & Thrasher 1996). It is separated from the much more structurally complex Eastern Mobile Belt by a series of north-trending fault systems (Fig. 1.1B). The Eastern Mobile Belt is further subdivided into a number of sub-provinces that include the Northern and Central Grabens, Tarata Thrust Zone, and Southern (Inversion) Zone (Fig. 1.1B).

Table 1.1 Some contrasting environmental, compositional, and diagenetic features of temperate (nontropical) and tropical shelf carbonates (modified after Hood & Nelson 1996; James 1997).

PROPERTY	TEMPERATE (NONTROPICAL) CARBONATES	TROPICAL SHELF CARBONATES
<i>Setting</i>	Unrimmed open shelves and ramps	Shallow rimmed shelves, open shelves, ramps, reefs
<i>Energy</i>	High energy	High to low energy
<i>Hermatypic reefs</i>	Absence of hermatypic reefs (polewards of 30°N to 30°S)	Common hermatypic coral reefs (from 30°N to 30°S)
<i>Skeletal assemblages/types</i>	Heterozoan (Foramol) skeletal types - bryozoans, echinoderms, bivalve molluscs, foraminifera	Photozoan (Chlorozoan) skeletal types - Corals, calcareous green algae, molluscs, benthic foraminifera
<i>Sediment texture</i>	Gravel and sand textures dominate	Sand and mud textures dominate
<i>Water temperature</i>	Cool water (10-18°C bottom water)	Warm water (>22°C bottom water)
<i>Carbonate saturation</i>	Saturated/undersaturated	Saturated/supersaturated
<i>Non-skeletal grains</i>	Absence of non-skeletal grains	Common non-skeletal grains (ooids, aggregates)
<i>Cementation</i>	Minor early cementation; late burial cements dominate	Extensive early cementation by marine and meteoric cements
<i>Carbonate mud</i>	Minor carbonate mud (bioerosion)	Abundant carbonate mud (micritisation, precipitation,
<i>Mineralogy</i>	Low- and moderate-Mg calcite mineralogies dominate	Aragonite and high-Mg calcite mineralogies dominate
<i>Diagenesis</i>	Destructive diagenesis (dissolution, maceration)	Constructive diagenesis (early cementation)
<i>Sedimentation rate</i>	Typically low accumulation rates	Typically high accumulation rates

The Northern Graben is bounded to the west by the Cape Egmont Fault Zone and to the east by the Turi Fault zone (Fig. 1.1B). The Central Graben lies to the south of the Northern Graben, is slightly younger, and is similarly bounded to the west and to the east by normal northeast-southwest-striking faults. The Southern Zone is characterised by Late Miocene-Pliocene inversion of Cretaceous-Paleocene rift half grabens, and contains a number of reverse fault-bounded anticlines (King & Thrasher 1996).

The Tarata Thrust Zone (Fig. 1.1B) lies immediately west of the Taranaki Fault in the eastern Taranaki Peninsula and northern offshore. The Tarata Thrust Zone is an area of Early Miocene thin-skinned overthrusting associated with the Taranaki Fault (King & Thrasher 1996). Here the Tikorangi Formation, together with the Upper Kapuni Group (Fig. 1.2), primarily comprise allochthonous sheets which have been thrust into less competent overlying mudstones (Fig. 1.9). The Tarata Thrust Zone contains over 6000 m of Upper Cretaceous to Tertiary sedimentary rocks with a depth to basement in the Waihapa area of about 7000 m (Fig. 1.8). Several anticlinal structures with closure occur west of the Tarata Thrust Zone, formed variously in the Oligocene to Early Miocene at approximately the same time as the Tarata Thrust Zone (King 1994; King & Thrasher 1996).

1.3.2 Taranaki Basin sedimentary history

The sedimentary and tectonic evolution of the Taranaki basin, although complex, can be divided into three main phases of development (King & Thrasher (1996)). The first phase of basin development was a Late Cretaceous to Paleocene phase of intra-continental extensional rifting (Fig. 1.3A) which saw New Zealand separate from Australia developing a series of rift half-grabens and normal-faulted sub-basins (King & Thrasher 1996). Non-marine sediments were deposited into these fault-controlled basins during the Late Cretaceous and subsequently were to become important hydrocarbon source rocks. The terrestrial sediments included sands, silts, carbonaceous mudstones, and coals (Rakopi Formation) of the Pakawau Group (Fig. 1.2). During the latest Cretaceous, rift sub-basins were flooded from the north by a marine transgression with deposition of marine silts and sands of the North Cape

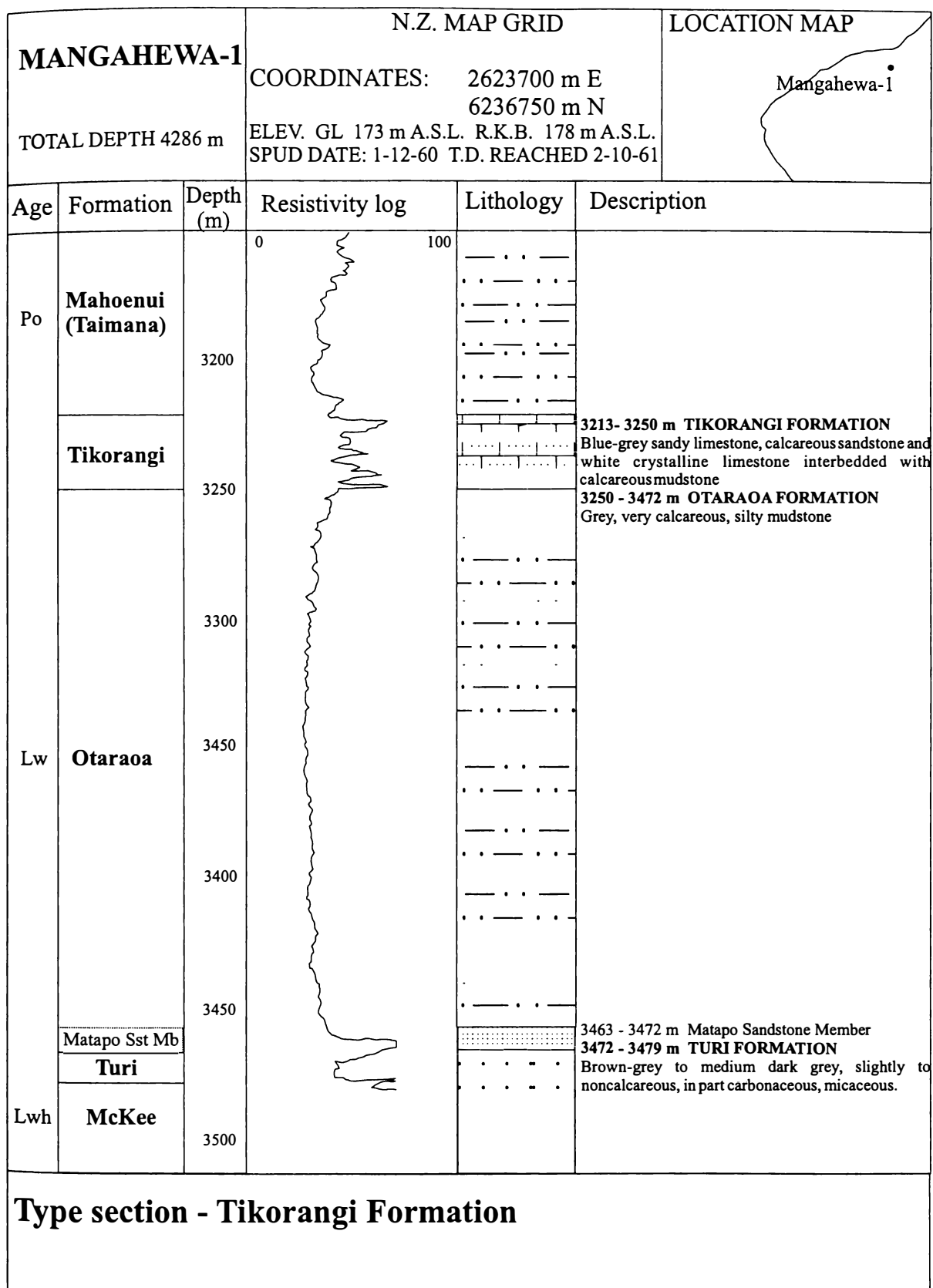


Fig. 1.6 Type section for the Tikorangi Formation in the Mangahewa-1 well as described by van Rijen & van den Abeele (1963).

Formation (Fig. 1.2) (King & Thrasher 1996).

A second phase of Eocene to earliest Oligocene in Taranaki Basin was characterised by a passive margin setting associated with post-rift and regional subsidence, during which the laterally equivalent Kapuni and Moa Groups formed (Fig. 1.2). The Kapuni Group comprises predominantly terrestrial but also some marginal marine sediments and includes the Farewell, Kaimiro, Mangaheua, and McKee Formations. The Moa Group comprises Turi Formation shelf and slope mudstones and Tangaroa Formation submarine fan sandstones. Basinwide sedimentation patterns were characterised by comparative tectonic quiescence, peneplanation, and marine transgression (King & Thrasher 1996).

The third phase of Oligocene to Recent Taranaki Basin history has been an active marginal basin associated with evolution of the Australia-Pacific convergent plate boundary through New Zealand (Fig. 1.3B). The basin became separated into two contrasting tectonic settings, as an active eastern zone (Eastern Mobile Belt) and a passive western zone (Western Stable Platform) (Fig. 1.1B, 1.3, 1.8). A change to sudden and rapid subsidence occurred in the late Early Oligocene. It resulted from oblique extension and westerly downthrow on the Taranaki Fault, possibly related to the development of a proto-transform plate boundary through New Zealand (Holt & Stern 1994; King & Thrasher 1992, 1996; Nelson et al. 1994). This foreland basin subsidence (Fig. 1.5) was especially pronounced along the basin's eastern margin where an asymmetric foredeep/foreland basin developed west of the Taranaki Fault. All but southern areas of the basin had reached bathyal depths by this time. Calcareous siltstones and mudstones of the Otaraoa Formation were deposited in the trough while in the east condensed carbonate sequences of the laterally equivalent western Tikorangi Formation oozes accumulated (Fig. 1.2). Basin foundering in the Oligocene and the initiation of a basinwide marine transgression, caused by foreland thrust loading (Stern & Holt 1994), saw deposition of the earliest Miocene Tikorangi Formation within the foreland basin, whose wedge-shaped development was thickest in the east towards the Taranaki Fault, coinciding with the geometry of the foredeep trough (King & Thrasher 1996).

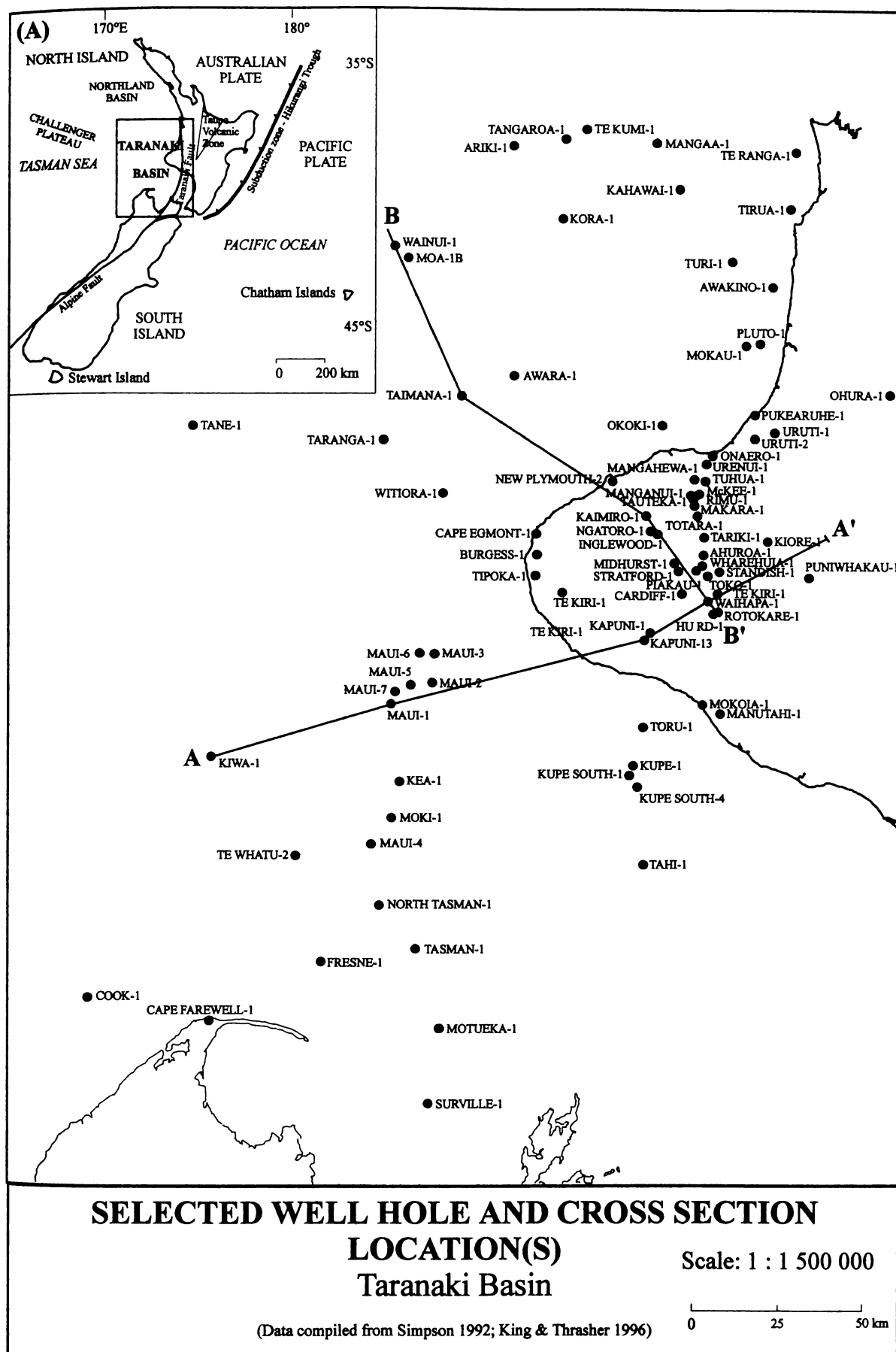


Fig. 1.7 Selected petroleum drill hole and cross section location(s), Taranaki Basin. For additional wells within the Waihapu-Ngaere Field see Fig. 1.4.

Peak transgression was reached in the earliest Miocene and culminated in the maximum extent of deposition associated with the Tikorangi Formation. Eastern areas of the carbonate foredeep (Fig. 1.5) were where the thickest sequences (up to 350 m) of the predominantly calcareous Ngatoro Group accumulated. The group includes calcareous sandstones and siltstones in the east (Otaraoa Formation), Tikorangi Formation limestones and marls, and Taimana Formation calcareous mudstones and marls (Fig. 1.2).

Since Early Miocene, a dramatic change from carbonate- to terrigenous-dominated sedimentation occurred as a result of major compression and basement thrusting from the east, associated with accelerated plate convergence (Fig. 1.3B). A marked increase in rates of uplift adjacent to the plate boundary provided a source for a greatly increased terrigenous supply, initiating a major regression, and progradation of the continental shelf edge north and northwestwards. Terrigenous clastic sedimentation deposited a thick succession (up to x km) of deepwater lithologies forming the Manganui, Moki, and Mt Messenger Formations (Fig. 1.2) (King & Thrasher 1996). This compressional-convergent phase saw several phases of fault reversal and sub-basin inversion in the east, while the Western Platform remained largely unaffected. Low-angle thin-skinned overthrusts were emplaced along the eastern margin associated with formation of the Tarata Thrust Zone. Several domed and overthrust structures formed along the leading edge of the mobile fold/thrust belt, including the Waihapa structure, which developed as an anticline initiated by deep seated strike-slip movement on faults splaying off the main Taranaki Fault (King & Thrasher 1996). The associated series of overthrust systems and structures have been instrumental in the formation of the fractured Tikorangi Formation reservoir.

The Miocene Wai-iti Group (including Manganui Formation shelf to basin mudstones and Urenui Formation slope mudstones and siltstones) (Fig. 1.2) is a regressive sequence that records the influx of siliciclastic sediments into the basin following convergent uplift, with rapid slope progradation towards the northwest and expansion of southern and eastern shelf areas (King & Thrasher 1996). Sandstones

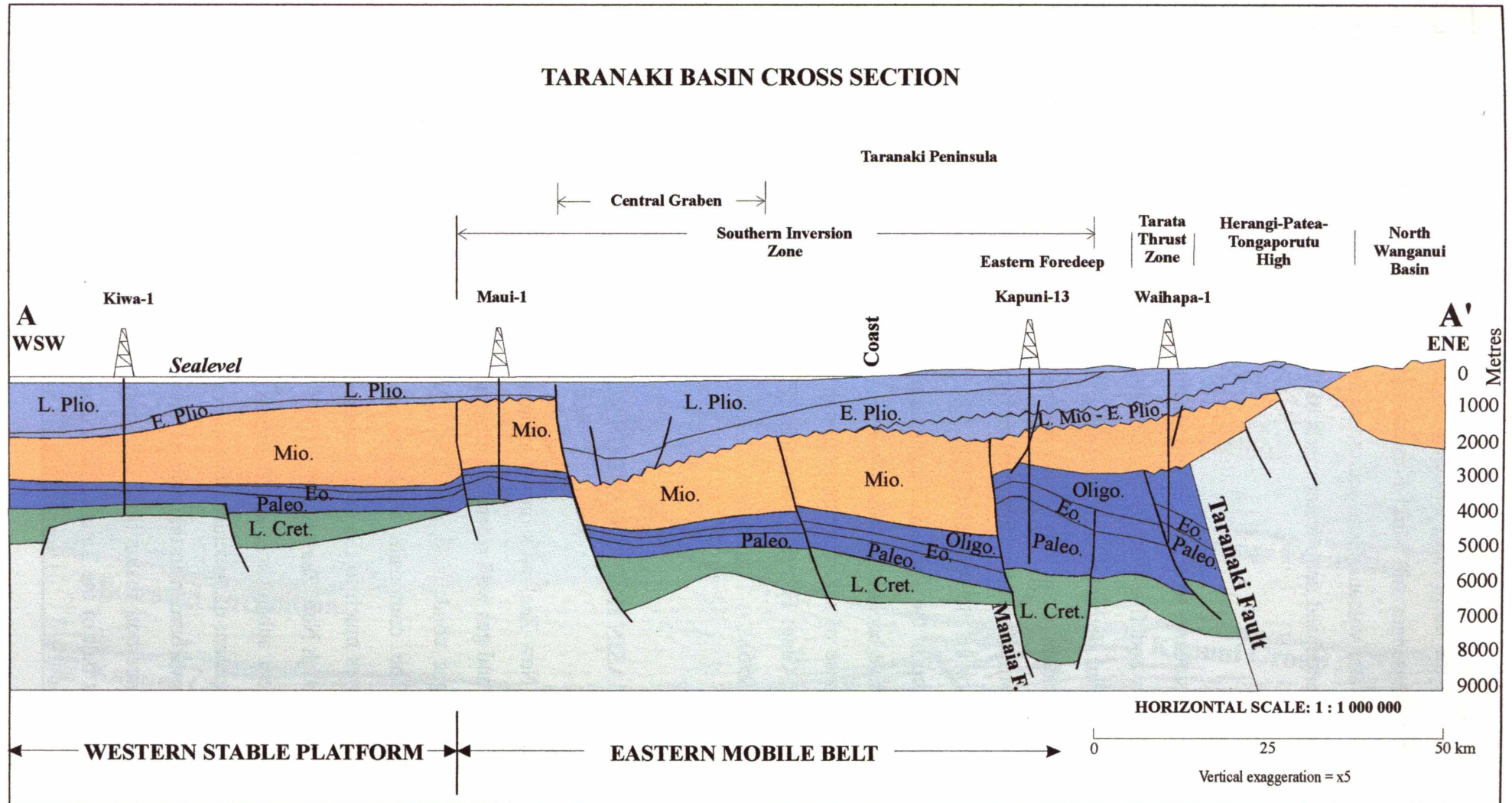


Fig. 1.8 Structural cross section of a transect running WSW - NE through offshore Maui-1 and onshore through the Waihapa-Ngaere Field, Tarata Thrust Zone, Taranaki Basin (see Fig. 1.7 for location of section). Shading: = late Neogene, = early Neogene, = Paleogene, = Late Cretaceous, = basement. E. Plio. = Early Pliocene; L. Plio. = Late Pliocene; Mio. = Miocene; Oligo. = Oligocene; Paleo. = Paleocene; L. Cret. = Late Cretaceous. Adapted from King & Thrasher (1996).

were deposited on the basin floor and base of slope across the centre of the basin, comprising Mt Messenger and Moki Formations (Fig. 1.2). Mohakatino Formation consists of deep-water volcanoclastic sediments deposited in the northeast (Nodder et al. 1990), while condensed deep-water marls of the Ariki Formation accumulated in the northwest.

The Pliocene-Pleistocene Rotokare Group (including base of slope sandstones of Mangaa Formation and fine-grained basin to shelf deposits in the north and west comprising the Giant Foresets Formation) (Fig. 1.2) marks an acceleration of basin infilling and progradation. Shelf, marginal marine, and terrestrial sequences form the Matemateaonga Formation which are overlain by fine-grained shelfal deposits of the Tangahoe Formation in the southeast (Fig. 1.2). In the Quaternary, increased plate convergence resulted in the Taranaki Peninsula region being uplifted and tilted with the initiation of active backarc andesitic volcanism through to the present. The long-lived regressive phase of sedimentation through the Neogene continues today with out-building of the Giant Foresets Formation (Fig. 1.2) (Palmer & Andrews 1993; King & Thrasher 1996).

1.4 TARANAKI BASIN HYDROCARBON SYSTEMS

Taranaki Basin is New Zealand's only commercially producing hydrocarbon basin producing both oil and gas with reserves estimated at 1213.3 BCF (billion cubic feet) gas, 210.3 BCF gas condensate, and 254.7 MMBOE recoverable oil (King & Thrasher 1996). The composite evolution of this active margin hydrocarbon producing basin owes much to the complex evolution of the Australia/Pacific plate boundary zone through New Zealand (Fig. 1.3, 1.5). Neogene tectonism, episodes of uplift and subsequent subsidence, and sediment burial have all been significant in terms of the development of structures and source rock maturity. Deposition of thick Miocene-Pliocene overburden in the eastern foredeep was instrumental in triggering or enhancing hydrocarbon maturation after trapping structures had formed in the Miocene fold/thrust belt of the Tarata Thrust Zone (King & Thrasher 1996). A high

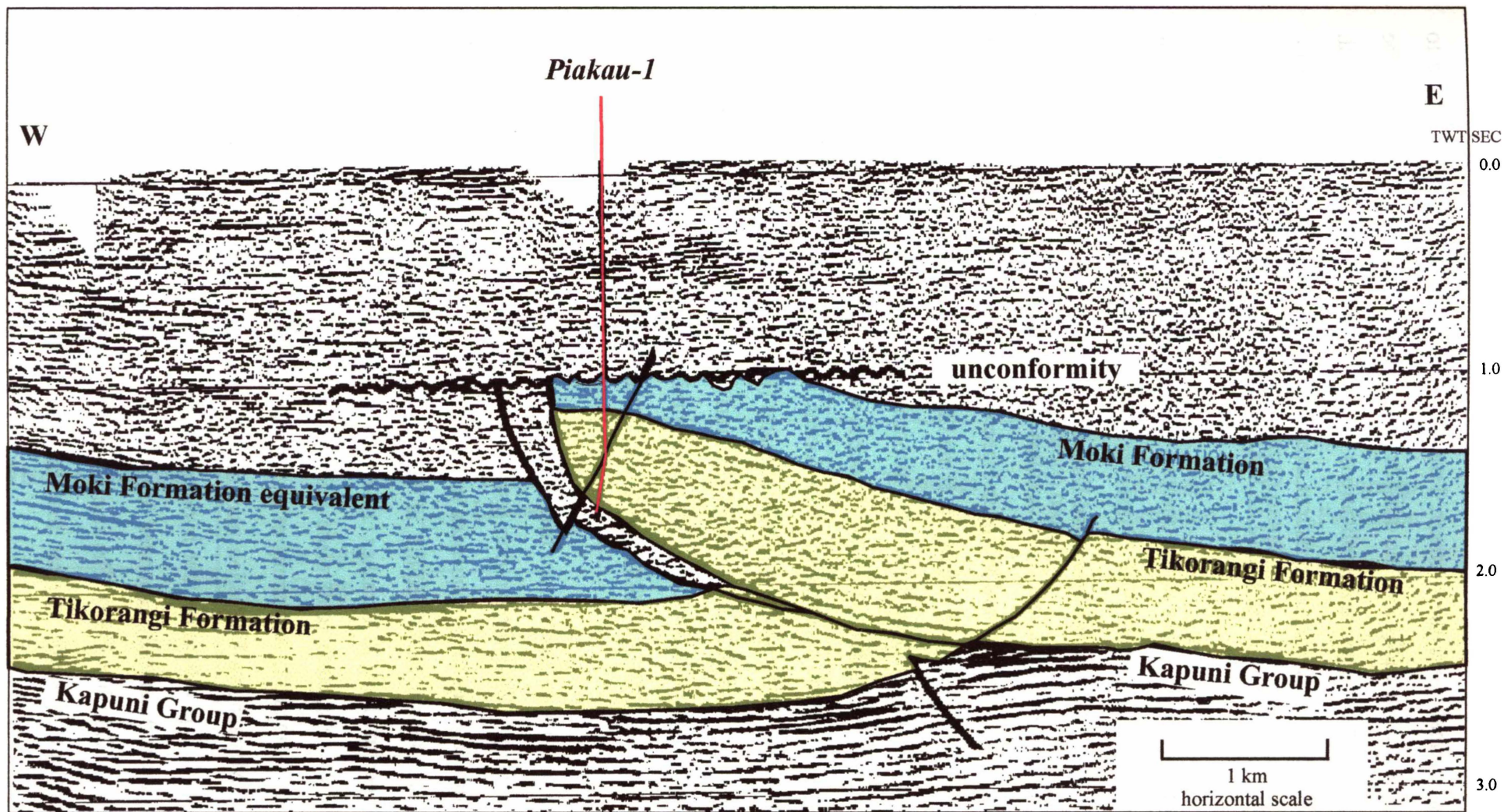


Fig. 1.9 Seismic section through the Piakau-1 well, Tarata Thrust Zone (see Fig. 1.7 for location map), showing timing of Tikorangi Formation thrusting is constrained to post-Moki Formation deposition (mid-late Miocene) as Moki Formation reflector is truncated by an unconformity. Adapted from Palmer & Andrews (1993).

heat flow anomaly over the northern Taranaki Peninsula, thought to be related to either magmatic intrusions into the crust or magmatic underplating at the base of the crust, may also have important implications for oil generation in the basin (Allis et al. 1995). The modern geothermal gradient averages 29°C/km over much of the basin, but ranges geographically from 22 to 33°C/km (Armstrong et al. 1994, 1996).

The majority of fields occur in the onshore Tarata Thrust Zone (Fig. 1.1B, 1.2), but these account for only about 30% of reserves. The major producing fields include the offshore Maui and onshore Kapuni and Kaimiro gas-condensate fields, and the major onshore McKee oil field, with five smaller oil fields of Kaimiro, Stratford, and TAWN (= Tariki, Ahuroa, and Waihapa-Ngaere). All major fields involve structural traps formed in the Neogene within, or on the flank of, the Eastern Mobile Belt. Most known reserves (Fig. 1.2) are hosted in Paleocene-Eocene shoreline and coastal plain sandstones, with younger reservoirs in Miocene slope and submarine fan sandstones, Miocene volcanoclastic sandstones, and Pliocene shelf sandstones, as well as in the earliest Miocene Tikorangi Formation carbonates (Fig. 1.2). Within the Tarata Thrust the reservoirs are located in near-crestal positions within allochthonous hanging wall blocks uplifted by thrust faulting. Cap rocks within the basin are generally marine, but sometimes terrestrial mudstones (King & Thrasher 1996).

Hydrocarbon source rocks for the Waihapa Field are Eocene (Mangahewa Formation) (Fig. 1.2) hydrogen-rich terrestrial coals and carbonaceous mudstones which accumulated in thick sequences in syn-rift/drift sub-basins (King & Thrasher 1996). These source rocks require at least 5 km of burial before hydrocarbon generation occurs. King & Thrasher (1996) contended that much of the hydrocarbon generation and migration took place relatively late in the basin's history, in the Pliocene. In Waihapa-1, Armstrong et al. (1996) suggested that the deepest parts of the Eocene Mangahewa Formation may have begun expelling hydrocarbons in the Late Miocene. It is estimated that hydrocarbon reserves discovered so far are less than 1% of those potentially generated from all source rocks in the eastern part of the basin (King & Thrasher 1996). The stacked nature of reservoirs and the complexity of the petroleum systems suggest that there is very good potential for further

Table 1.2 Some of the stratigraphic nomenclature applied to the Tikorangi Formation and accompanying Formations of the Ngatoro Group, Taranaki Basin.

van Rijen & van der Abeele (1963) Mangahewa-1 well Taranaki Basin	Kear & Schofield (1959) Te Kuiti Group South Auckland region	Pilaar & Wakefield (1978) Structure, evolution Taranaki Basin	Adams et al. (1980) Toko-1 well Taranaki Basin	Palmer (1985) Pre-Miocene strat. Taranaki Basin	King (1988a, b) Well summaries Onshore Taranaki Basin		King & Thrasher (1996) Geological synthesis Taranaki Basin	
Mahoenui Formation	Mahoenui Group	Mahoenui Formation	Upper Mahoenui Formation	Mahoenui Group	Ngatoro Group	Taimana Formation	Ngatoro Group	Taimana Formation
Tikorangi Member	Te Kuiti Group	Tikorangi Limestone	Tikorangi Limestone	Tikorangi Formation		Tikorangi Formation		Tikorangi Formation
Mahoenui Formation		Mahoenui Formation	Lower Mahoenui Formation	Otaraoa Formation		Otaraoa Formation		Otaraoa Formation

economic discoveries.

1.4.1 Waihapa-Ngaere structure

The Waihapa-Ngaere structure lies at the southern end of the Tarata Thrust Zone, a north-south trending chain of overthrust features (Fig. 1.1B, 1.8). The Waihapa structure is one of a number of successfully drilled structures with closure associated with anticlines, others including the Kapuni, Kaimiro, and Stratford structures (Hoolihan & Yang 1992). The Waihapa-Ngaere structure formed as a result of low-angle thrust faulting to produce an asymmetric north-south trending anticline with a steeply dipping western flank (35-40°), and an eastern flank dip of 15°.

The Waihapa-Ngaere structure culminates east of Ngaere-1 well, and plunges northward to a broad saddle located north of Ngaere-2 well. The western flank rises steeply towards Wharehuia-1 and may be discontinuous, while the eastern flank appears to continue northward into the Ahuroa area. Thinning of the Taimana and Manganui Formations onto the Waihapa anticline indicates that structuring occurred during the Early Miocene. Normal faulting, consistent with a north-south right-lateral transtensional regime, overlies the Miocene structure forming an en-echelon set of NNE-striking grabens in the Pliocene to Recent section (Hoolihan & Yang 1992). The Neogene normal faults link back with the Miocene thrusts. Thrusting is characteristic from Piakau-1 well (Fig. 1.9) to Urenui to the north, while further south in the Waihapa area, fault displacement of the Tikorangi Formation is minor and the structure at the level of the Tikorangi Formation is essentially a north-south elongated dome (Carter & Kelly 1989a).

Hoolihan & Yang (1992) suggested that compression, initiated during the Early Miocene resulted in a net crustal shortening of 2.5 km across the structure, an amount accepted by Sissons et al. (1994). While the climax of the compression was in the Early Miocene, compression continued through the mid-Late Miocene (Hoolihan & Yang 1992) resulting in about 1500 m of vertical offset in the Waihapa structure. In addition to thrusting, elevation of the Waihapa structure was probably partially due also to inversion (Sissons et al. 1994).

1.4.2 Development history of Waihapa-Ngaere Field

This section summarise the exploration and development history of the commercially producing Tikorangi Formation within the Waihapa-Ngaere oil field (Fig. 1.1B). Wells within this field provide the Tikorangi Formation core material used for this study (Fig. 1.4).

A structural high in the vicinity of Waihapa-1 (Fig. 1.4) was first mapped from seismic data in 1973 by New Zealand Aquitaine Petroleum. At this time the structure was thought to reach from Toko in the north to Eltham in the south. Subsequent seismic lines run by Petrocorp in 1978-79 allowed remapping of the structure to show two overthrust lobes emplaced from the east, namely the Toko and Toko South structures (Adams et al. 1980).

The discovery of these structures led to the spudding of Toko-1 in 1978 (Fig. 1.4), the first well to be drilled in the Waihapa-Ngaere Field. Toko-1, located at the southern onshore end of the overthrust belt, was drilled to target the Kapuni Group sandstones. While this well confirmed overthrust development, hydrocarbon results in the Kapuni sandstones were disappointing, although while drilling over the Tikorangi Formation interval unexpected mud losses, gas peaks, and oil shows were encountered. However, unstable hole conditions meant Toko-1 was plugged and abandoned without further testing (Adams et al. 1980).

In February 1985, Waihapa-1 (Fig. 1.4), the first of the Waihapa wells, was drilled to similarly target sandstones of the Kapuni Group. Surprisingly the non-target Tikorangi Formation interval again had oil shows and produced mud losses while drilling. Testing did not immediately follow drilling, and it was not until March/April 1988 that the Tikorangi Formation in Waihapa-1 was flow tested with unexpected and spectacular results of 2400 BOPD and 26 MMSCFD. Waihapa-1 was consequently completed as a production well and yielded 4350 BOPD and 4.9 MSCFD of gas by 1989. At this time the known Waihapa structure was interpreted as a stretched dome over the Waihapa and Toko areas (PEL 1995).

Waihapa-2 (Fig. 1.4) was the next well to be spudded in the field, in late July 1988, being sited as a step-out about 500 m west of the Waihapa-1 wellhead. Waihapa-2 was also completed as an oil producer in limestone. By 1989 it had achieved similar production rates to Waihapa-1 of 4000 BOPD, which stabilised at 3100 BOPD and 3 MSCFD gas over the Tikorangi Formation interval (Carter et al. 1988).

Waihapa-3 (Fig. 1.4), spudded later that year in October 1988, was a deviated appraisal-development well designed to evaluate the Tikorangi Formation's reservoir properties, and the oil-water contact in the southern part of the Waihapa Field. Waihapa-3 was drilled from the Waihapa-2 site, but was deviated SSE. Due to drilling difficulties the well was terminated in the Moki Formation above the drilling target. The well was plugged and abandoned (Carter & Kelly 1989b).

Drilling of Waihapa-4 and -5 followed (Fig. 1.4), both being completed in the early part of 1989. Waihapa-4 intersected the Tikorangi Formation near the northern boundary of the Waihapa licence as a crestal test of the Waihapa structure. The well was successfully tested with flow rates of 1600 BOPD and 1.8 MSCFD gas, and was subsequently completed as a producer. Waihapa-5 was drilled as a vertical well to test the southern flank of the Waihapa structure, after which it was drilled vertically to the unreached target of Waihapa-3. The well was again completed for production after giving oil flows of 1704 BOPD (Carter & Kelly 1989a; Young & Carter 1989).

Waihapa-6 and -6A (Fig. 1.4) were the last appraisal wells to be drilled in the extensive 1988/89 drilling programme. Waihapa-6 was drilled to evaluate the Tikorangi Formation and oil-water contact on the western side of the Waihapa structure, but was unsuccessful, no fractures being encountered within the formation. Waihapa 6A was side-tracked to intersect the structure updip NE of the original well, kicked off from the original Waihapa-6 at 990 m. The well flow tested at 3000 BOPD and 2.8 MSCFD gas and the well was completed as an oil producer (Carter & Kelly 1989b).

The last of the Waihapa drills to be spudded were Waihapa-7/7A and Waihapa-8

(Fig. 1.4). Due to the public unavailability of the corresponding Well Completion Reports, information is sparse. However, Spanninga G. *pers comm.* (1995) reported that during drilling in 1995, Waihapa-8 encountered major drilling difficulties due to a loss of circulation. King & Thrasher (1996) however report that oil was discovered in the younger Mt Messenger Formation in mid-1995.

Hu Rd-1/1A, south of the Waihapa-Ngaere Field *per se* (Fig. 1.4), was spudded in April 1991 with the primary objective of drilling the Tikorangi Formation play that was considered to be analogous to that in the adjacent oil-bearing Waihapa Field (NZ Oil & Gas 1992). Hu Rd-1/1A was a deviated well drilled towards the east from the original Hu Rd-1 bore in 1991 to test a combined fault and dip closure. Hu Rd-1/1A failed to produce hydrocarbons from the Tikorangi Formation, but did flow during testing at 5000 BWPD (barrels of water per day) (NZ Oil & Gas 1992). The well drilled into a thin-skinned imbricate structure between the Waihapa Field and the Taranaki Fault, where allochthonous slivers of Mesozoic basement are incorporated into the overthrust section. Hu Rd-1/1A thrusts involving both Tertiary sediments and imbricate slices of basement sets this well apart from others in the Tarata Thrust Zone which involve only Tertiary sediments (Hoolihan & Yang 1992). Hu Rd-1/1A represents an unsuccessful fault-closed structure along the Taranaki Fault, in contrast to closures associated with anticlines in the Waihapa-Ngaere Field which have been successful traps (Hoolihan & Yang 1992).

Ngaere-1 (Fig. 1.4), the first of the Ngaere wells, was spudded in February 1993 from the proposed Toko-B well site. The well was a deviated well drilled to evaluate the northern extent of the Waihapa structure. The well encountered large losses in the Tikorangi Formation due to extensive fracturing of the limestone. The well was completed as an oil producer after testing with an initial stabilised rate of 6000 BOPD (PEL 1995).

Ngaere-2 (Fig. 1.4), spudded in September 1993, was drilled at an angle of 40° through the Tikorangi Formation to optimise fracture intersection to test the productive potential of the limestone-dominated succession north of the successful

Ngaere-1 well. The well was expected to reduce the structural uncertainty in the area between the Waihapa-Ngaere and adjacent Ahuroa structures. High drilling fluid losses occurred indicating the presence of an open fracture network. Ngaere-2 was similarly completed as a oil producer (PEL 1995).

Ngaere-3 was spudded on the 14th of February 1994 in PML 38141 onshore Taranaki. The well is located approximately 7 km west of the township Stratford and 1.5 km south of the well Toko-1. Ngaere-3, a deviated appraisal/development well, was drilled to evaluate the Tikorangi Formation at the northern extent of the currently producing Waihapa/Ngaere structure and to evaluate the Mt Messenger and Urenui formations for their reservoir potential. Ngaere-3 penetrated the Tikorangi Formation at 3049 m AH, and large losses indicating the existence of an interconnected open fracture system occurred from this depth until TD (total depth). Ngaere-3 reached a total depth of 3259 m AHBKB on the 18th of March 1994 and the well was completed as an oil producer (PEL 1994).

Where it is fractured and encountered within the appropriate structural environment the Tikorangi Formation has continued to be a prime reservoir target in new prospecting areas away from the current producing fields. For example, in 1997 Fletcher Challenge Energy and Bligh Oil and Minerals NZ Ltd drilled the Piakau-1A exploration well, side-tracked from the Piakau-1 well (Fig. 1.7, 1.9) along the trend of the Waihapa-Ngaere oil field. The target depth of 2200 m was reached within the Tikorangi Formation and oil and gas shows were encountered with an initial rate of 1400 BOPD and 1.4 MMSCFD gas. The flow rate stabilised at about 700 BOPD day (Ministry of Commerce 1997).

Since then, Brisbane-based Bligh Oil and Minerals NL and its subsidiary Marabella Enterprises Ltd and partners drilled the Huinga-1 well in central onshore Taranaki during 1999, east of the Waihapa-Ngaere Field, primarily targeting the Tikorangi Formation interval. However, after problems with the well in mid-May 1999 when it encountered thicker than expected Triassic-Jurassic basement rock, which effectively removed the Tikorangi Formation interval from the deviated well bore, the well was

plugged (Ministry of Commerce 1999). Currently (mid-1999) the US oil exploration company Swift Energy New Zealand Ltd plan to spud Rimu-1, about 1.8 km southeast of Hawera, with the primary target being Eocene-age sands within the Kapuni Group, but an important secondary objective being the shallower fractured Tikorangi Formation (Ministry of Commerce 1999).

Maui-1 (Fig. 1.7), the only offshore well that provides some core material for the Tikorangi Formation, discovered the giant offshore Maui gas-condensate field in 1969 within the Kapuni Group (Shell BP Todd 1969; Palmer 1985).

1.5 TIKORANGI FORMATION

1.5.1 History of nomenclature

Many of the lithostratigraphic names used for the drilled sediments within Taranaki Basin were historically and inappropriately adopted from adjoining onshore areas, particularly the North Wanganui Basin (Fig. 1.1B), resulting in inconsistent and often uncertain stratigraphic nomenclature. Palmer (1985) was the first to address this problem and introduced new stratigraphic nomenclature for the Ngatoro Group, much of which is retained today. Table 1.2 provides some of the stratigraphic nomenclature applied to the Tikorangi Formation and accompanying formations of the Ngatoro Group.

The stratigraphic name Tikorangi, named after the north Taranaki township of Tikorangi, was first used by van Rijen and van der Abeele (1963) for earliest Miocene limestones encountered in Mangahewa-1 within the Mahoenui Formation (Fig. 1.6). It was informally named the Tikorangi Member of that Formation, while Tikorangi Limestone was later used by Pilaar & Wakefield (1978) (see Table 1.2). Van Rijen and van der Abeele (1963) recognised the similarity between the subsurface Tikorangi unit and the onland Te Kuiti Group limestones, but considered the Tikorangi limestone was a member of the Mahoenui Formation. Later, Adams et al. (1980) used the Tikorangi limestone for subdividing the Mahoenui Formation into

Upper (above) and Lower (below) portions. Palmer (1985) recognised that the Tikorangi unit is a correlative of the Te Kuiti Group limestones and is therefore overlain by Mahoenui Group. Glennie (1956) and Kear & Schofield (1959) had defined Mahoenui Group in outcrop as all those earliest Miocene calcareous mudstones, sandstones, siltstones, and limestones sitting above the Oligocene Te Kuiti (Group) Limestone or its lateral equivalent. Palmer (1985) therefore proposed the name Tikorangi Formation for the limestone, restricted the use of Mahoenui Group, as defined by to the overlying sequence, and the name Otaraoa Formation to the mudstone immediately underlying the Tikorangi Formation (Table 1.2).

The Otaraoa Formation, named after Otaraoa Rd in northeast Taranaki, was therefore defined by Palmer (1985) for a sequence of calcareous siltstones and sandstones named Lower Mahoenui Formation by Adams et al. (1980). The type section for the Otaraoa Formation occurs in Mangaheva-1 from 3250 to 3472 m depth and comprises Early Oligocene (Late Whaingaroan) to earliest Miocene (Waitakian) grey, very calcareous silty mudstone that is conformably overlain by Tikorangi Formation (Fig. 1.6). Otaraoa Formation is restricted to eastern Taranaki Basin, while the time equivalent on the Western Stable Platform is the Turi Formation, and the Abel Head Formation in onshore northwest Nelson (Palmer 1985).

The Ngatoro Group, named after Ngatoro Stream in central Taranaki Peninsula was defined by King (1988a, b) for rocks of Oligocene-earliest Miocene age with generally high calcium carbonate content. The Ngatoro Group includes the Otaraoa, Tikorangi, and Taimana Formations (Table 1.2). The Taimana Formation, named from Taimana-1 well, was introduced by King (1988a, b) for a calcareous interval between the Tikorangi Formation and the Wai-iti Group. Prior to this the beds were included within the Mahoenui Formation or Group as previously used by Glennie (1956), Kear & Schofield (1959), and Hay (1967, 1978) in the North Wanganui Basin. However, King & Thrasher (1996) restrict usage of the name Mahoenui to Early Miocene mudstones east of the Patea-Tongaporutu High, and not for Taranaki Basin strata.

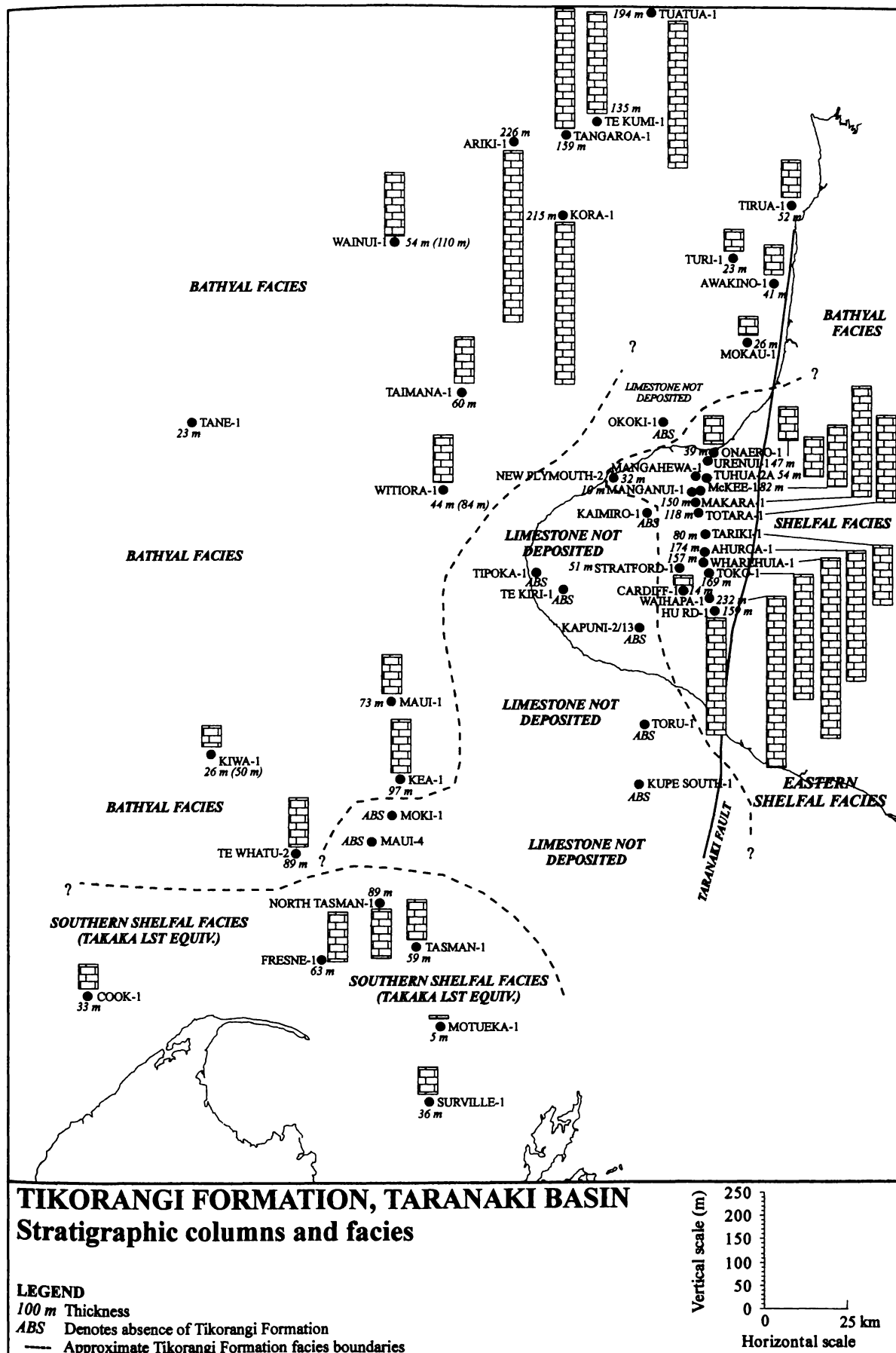


Fig. 1.10 Tikorangi Formation occurrence, thickness, and facies in selected wells, Taranaki Basin. Data compiled from Simpson 1992 and King & Thrasher 1996.

1.5.2 Type section

The type section of the Tikorangi Formation was designated by van Rijen & van der Abeele (1963) to be the 37 m-thick interval between 3213 m and 3250 m AHBKB (along hole below kelly bushing) in the Mangahewa-1 well drilled in 1960 (Fig. 1.6). They described the lower and upper boundaries of the formation as being conformable with the Otaraoa Formation and the Mahoenui Group (now Taimana Formation), respectively.

However, this type section is largely unsatisfactory due to a lack of any core material, the general descriptions for the unit coming from ditch cutting samples taken every 3 m. It is recommended here that the Waihapa-5 well becomes a designated reference section for the Tikorangi Formation because the availability of over 112 m of core material provides a much firmer basis for lithological analysis. Core material is available through the Ministry of Commerce, Wellington, located at their rock store, Lower Hutt. A stratigraphic (mud) log is available in Young & Carter (1989), publicly available report PR1851, housed in the Ministry of Commerce library, Wellington.

1.5.3 General lithology

The Tikorangi Formation was described by van Rijen & van der Abeele (1963) at the Mangahewa-1 type section (Fig. 1.6) as comprising 37 m of blue-grey sandy limestone, calcareous sandstone, and white crystalline limestone interbedded with calcareous mudstone. Palmer (1985) describes the Tikorangi Formation as a deep-water bioclastic limestone. King & Thrasher (1992, 1996) described the formation as ranging from both coarse-grained bioclastic limestone to fine-grained micritic limestone, with varying proportions of terrigenous material. Simpson (1992), King & Thrasher (1996), and others suggested the limestone often consists of reworked bioclastic material deposited at outer shelf to upper slope depths. In general, well completion reports give little descriptive detail for the unit, especially prior to the drilling of Waihapa-1 in 1985, since the Tikorangi Formation had not been considered a target. The formation commonly appears to grade into the more terrigenous deposits of the Otaraoa Formation below, while the contact with the

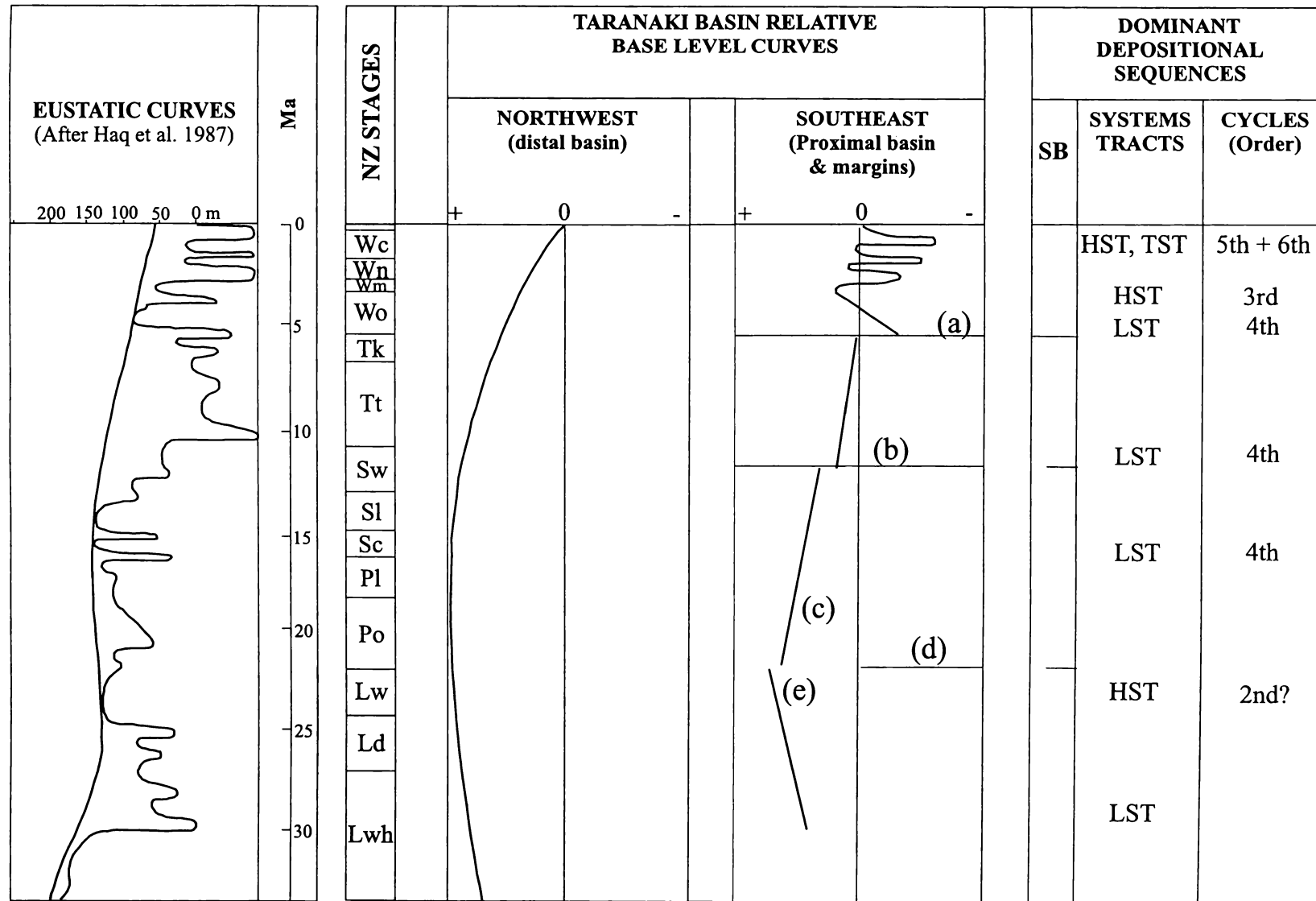


Fig. 1.11 Synthesis of depositional sequence cyclicity in Taranaki Basin. Curves represent changes in paleo-water depth through time with respect to present day shoreline. Notes (a) Type 1 angular unconformity; (b) tectonic unconformity on eastern margin; (c) maximum paleobathymetry in eastern foredeep; (d) eastern margin overthrust; (e) maximum regional onlap and siliciclastic starvation. SB = sequence boundary. Adapted from King & Thrasher (1996).

overlying Taimana is generally quite abrupt.

The Tikorangi Formation is typically a rather thin unit compared to others within Taranaki Basin, ranging in thickness from <50 m to >200 m at its thickest (Fig. 1.10). It corresponds to a condensed carbonate sequence capping a long-term (Late Cretaceous to Oligocene) transgressive cycle (Fig. 1.11). The Tikorangi Formation is underlain by Paleocene-Eocene passive margin sediments of the Kapuni Group and overlain by the Miocene Wai-iti Group sediments which record a significant influx of terrigenous clastics and the onset of regressive sedimentation (Fig. 1.2).

1.5.4 Facies

The Tikorangi Formation has been considered as a detrital temperate limestone deposited in shelfal to upper bathyal depths by reworking and basinward transport of shallow-water faunas (Johnston 1990; Simpson 1992; King & Thrasher 1996). It grades basinward into a fine-grained marl which in turn grades basinward into a foraminiferal ooze. The limestone was divided by Simpson (1992) and King & Thrasher (1996) into two broad facies, one consisting of a shelfal (Simpson 1992) or platform limestone (King & Thrasher 1996) with a high proportion of shallow-water fauna and terrigenous sediment, and the other as a deeper-water bathyal (Simpson 1992) or basinal facies (King & Thrasher 1996) (Fig. 1.10). The main differences between these two megafacies are summarised in Table 1.3. According to Simpson (1992), the shelfal limestone can be divided into two separate facies: a southern Taranaki Basin facies eastern Taranaki Basin facies of earliest Miocene (Waitakian = Lw) age (see Appendix 1.2 for New Zealand Oligocene-Miocene time scale). The bathyal Tikorangi Formation is found in the west and north of basin (Simpson 1992; King & Thrasher 1996).

1.5.5 Age

The Tikorangi Formation shows spatial variations in age among the two distinct megafacies (Fig. 1.12). It spans the Early Oligocene (Whaingaroan) to Early Miocene (Waitakian-Otaian) in the western and northern bathyal facies of the Western Stable Platform (King & Thrasher 1996) and in some onshore southern shelfal equivalents

Table 1.3 Comparative properties of Tikorangi Formation shelfal and bathyal facies. Amended from Simpson (1992).

Property	Shelfal Facies (<i>platform</i>)	Bathyal Facies (<i>basinal</i>)
<i>Colour</i>	Typically grey to buff to white, but occasionally olive to brown, rarely with green hues.	Generally white to light grey, rarely yellow brown.
<i>Classification</i>	Generally packstone grading to grainstone or wackestone.	Generally lime wackestone, but grading to lime packstone where foraminifera are especially abundant.
<i>Bedding</i>	Massive to well-bedded. Often interbedded with calcareous siltstone or mudstone and occasionally sandstone.	Massive to well bedded, occasionally interbedded with calcareous shales and siltstones.
<i>Nature</i>	Generally argillaceous.	Usually argillaceous.
<i>Calciclasts</i>	Planktic foraminifera, echinoids, bivalves, calcareous red algae, barnacles, bryozoans.	Rare shallow water fauna. Common to abundant planktic foraminifera, coccoliths.
<i>Siliciclasts</i>	Generally contains rounded fine quartz sand. Often containing lithic	Commonly silty and with traces of fine quartz sand.
<i>Authigenic/other</i>	Rarely contains pyrite and /or carbonaceous flecks. Often containing glauconite.	Rarely contains carbonaceous flecks and pyrite. Occasionally contains glauconite.
<i>Lithification</i>	Generally firm to hard, occasionally soft to very soft.	Generally moderately hard to hard, occasionally soft.
<i>Cementation</i>	Macro- to microcrystalline with occasional sparry calcite, often associated with fracturing. Occasionally sucrosic.	Micro- to cryptocrystalline. Occasionally sucrosic.

(Waitakian-Otaian) in the western and northern bathyal facies of the Western Stable Platform (King & Thrasher 1996) and in some onshore southern shelfal equivalents (Takaka Limestone) (Leask 1980), but appears to be restricted to an earliest Miocene (early Waitakian) onshore shelfal facies of the Eastern Mobile Belt (Palmer 1985; Simpson 1992; King & Thrasher 1996). The age of the southern shelfal facies wells (Cook-1, Fresne-1, Surville-1, Tasman-1, North Tasman-1) is not so definitive. King & Thrasher (1996) suggest an earliest Miocene (Waitakian) age akin to the onshore Taranaki shelfal facies. Palmer (1985) and Simpson (1992) suggest a broader Oligocene (Duntroonian) to Otaian age in keeping with the exposed onland South Island Takaka ages proposed by Leask (1980). Table 1.4 summarises dates from the Tikorangi Formation and underlying overlying Otaraoa and overlying Taimana Formations. Using foraminifera, Morgans (1985) dated the Tikorangi Formation in onshore Waihapa-1 as early Waitakian (early Lw), the reference age generally adopted in the other nearby Waihapa-Ngaere wells. At the onshore type section in Mangahehua-1 (Fig. 1.6), microfauna are indicative of the same Waitakian age (Palmer 1985).

1.5.6 Distribution and lateral equivalents

Stick columns have been constructed in Fig. 1.10 to show the presence or absence of Tikorangi Formation at well sites, and the thickness and general facies of the formation. The condensed, thin bathyal or basinal Tikorangi facies is widespread on the Western Platform, while the shelfal facies is restricted to easternmost and northernmost parts of the Taranaki Peninsula. The largely tectonically undisturbed bathyal facies shows a general thickening towards the northeast (Fig. 1.10) to reach 226 m at Ariki-1. In wells offshore, west of the shelfal facies, the limestone is generally less than 100 m thick, and thins offshore. The area immediately to the east of the bathyal facies is one where Tikorangi Formation is not recorded and appears not to have been deposited; it encompasses the region occupied by Maui-4, Moki-1, Kupe-South-4, Toru-1, Kapuni-2/13, Te Kiri-1, and Tipoka-1 wells (Fig. 1.10). The limestone is also absent further north at Kaimiro-1 and Okoki-1.

A thin (generally < 50 m) inner shelf lateral equivalent to the Tikorangi Formation,

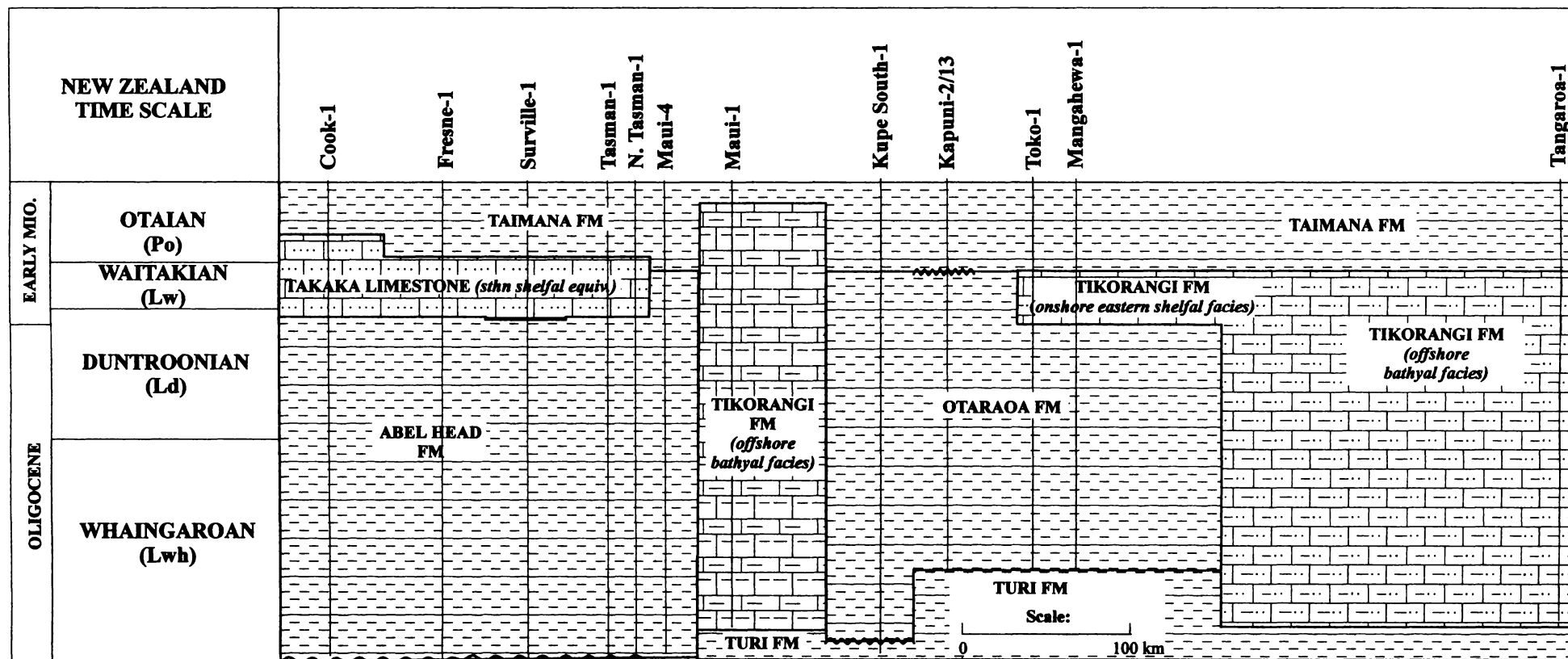


Fig. 1.12 Age comparison of the Tikorangi Formation in Taranaki Basin from the southern shelfal facies equivalent (Takaka Limestone) to the offshore bathyal facies, and onshore to the eastern shelfal facies, and again offshore to bathyal facies. Note the formation is absent south and north of the offshore bathyal facies at Maui-1 between the southern shelfal and onshore eastern shelfal facies. Wells are positioned from south (left) to north and to scale. Modified from Palmer (1985). Data compiled from Palmer (1985), Simpson (1982), and King & Thrasher (1996).

the Takaka Limestone, crops out in onland northwest Nelson, and is present in the subsurface of several wells immediately offshore (Fig. 1.10). The Takaka Limestone has been described by Leask (1980) as an inner to middle shelf deposit which is isolated from the Tikorangi Formation to the north as it grades into a deep-water calcareous mudstone. The offshore Takaka Limestone equivalent in the southern offshore wells (Cook-1, Fresne-1, Surville-1, Tasman-1, North Tasman-1) is generally thin, less than 60 m thick. Further to the north and offshore, in the Kea-1, Moki-1, and Maui-4 wells, the Takaka Limestone equivalent is absent. In the Maui well region, interbedded chalk and marl are well developed and have been described as a transitional facies by King & Thrasher (1996) between the southern/eastern shelfal facies and the western and northern true basinal facies.

The use of the term Cobden Limestone has in the past been used to describe the Tikorangi Formation offshore, particularly within petroleum company reports i.e., Simpson (1992). However the name is now restricted to a distinctive muddy limestone in the onland Paparoa Trough near Greymouth in the South Island (Nathan et al. 1986). Apart from a usually higher carbonate content (75-80%), the limestone is rather similar to the bathyal Tikorangi facies, being a highly bioturbated, light brown, muddy limestone (Nathan et al. 1986).

In contrast to the bathyal facies, the shelfal limestone occurring under much of eastern Taranaki Peninsula is structurally and stratigraphically complex (Fig. 1.8), involving a number of allochthonous overthrust sheets. Thrust sheets, divided by a series of faults, have generally been thrust westward to penetrate overlying mudstones (Fig. 1.9). Some northern wells may in fact have penetrated a number of stacked thrust sheets. Johnston (1980) has described the Tikorangi Formation encountered within the Waihapa, and Toko wells as being allochthonous. Correlation of the Tikorangi Formation between individual wells is consequently extremely difficult, and could necessitate an accurate reconstruction of pre-thrust positions.

The eastern shelfal facies tends to thicken southwards from Turi-1 (23 m) in the north of the basin to reach a maximum thickness in the Toko (169 m) and Waihapa

Table 1.4 Age control data for the Ngatoro Group, Taranaki Basin. Note: * denotes no specific dating undertaken - age inferred from nearby Waihapa-1. Data derived from well completion reports for individual wells unless specified. Foram = foraminifera; nanno = nannofossils. New Zealand stage ages contained in Appendix 1.2.

Well	<i>Taimana Fm & Equivalents</i>			<i>Tikorangi Fm</i>			<i>Otaraoa Fm</i>		
	Age (NZ stage)	Dated interval (m)	Method	Age (NZ stage)	Dated interval (m)	Method	Age (NZ stage)	Dated interval (m)	Method
<i>Waihapa-1</i>	Late Waitakian		foram	Early Waitakian		foram	Early Waitakian		foram
<i>Waihapa-2</i>	*Late Waitakian			*Early Waitakian			*Early Waitakian		
<i>Waihapa-4</i>	*Late Waitakian			*Early Waitakian			*Early Waitakian		
<i>Waihapa-5</i>	near top Waitakian to near base Otaian	2942-2951	nanno	near top Waitakian	upper 2/3	nanno			
<i>Waihapa-6</i>				-			near base Otaian	3207-3244	nanno
<i>Toko-1</i>	Altonian	2123-2200	foram	Otaian	2929-2974		Waitakian	3227-3476	foram
	Altonian	2200-2687	foram	Waitakian-Otaian	3974-3177		Duntroonian- Waitakian	3476-3742	foram
	Otaian	2687-2929	foram	Waitakian	3177-3227		Whaingaroan	3742-3802	foram
<i>Hu-Rd -1A</i>	n/a			Early Waitakian	2902, 2904.4, 2068	foram	n/a		
<i>Maui-1</i>	Late Miocene			Whaingaroan - Otaian			n/a		

areas (232 m), coinciding with the eastern side of the foredeep trough (Fig. 1.5), and then thins to the west (Fig. 1.10). Simpson (1992) suggested without explanation that the top of the Tikorangi Formation is missing from many eastern wells.

While the Tikorangi Formation was accumulating in Taranaki Basin, laterally extensive limestones (Orahiri and Otorohanga Limestones) of the Te Kuiti Group were forming in the adjacent North Wanganui Basin. These shelfal limestones are widespread throughout the South Auckland region and have been extensively studied by Nelson (1978), Nelson et al. (1988), and Nelson & Kamp (1994). The Orahiri Limestone has an Oligocene (Duntroonian) age while the younger Otorohanga Limestone, is like the Tikorangi Formation, Early Miocene (Waitakian) in age. The Orahiri Limestone is up to 60 m thick and comprises a variety of lithologies, ranging from sandy, glauconitic, and pebbly limestones, to pure limestones, some including distinctive oyster beds (Nelson 1978). The Otorohanga Limestone is typically a very pure limestone unit up to 60 m or more in thickness (Nelson 1978). These limestones have low reservoir potential because of their tight pressure-dissolved and highly cemented nature (Anastas et al. 1998).

1.6 CONCLUSIONS

This paper reviews the Tikorangi Formation in Taranaki Basin based on a variety of mainly unpublished and occasional published sources. The Tikorangi Formation reservoir, discovered while drilling other targets, has proved to be not only an interesting find, but also a prolific producer. Hosting the fifth largest hydrocarbon reserves in Taranaki Basin, the Tikorangi reservoir is unique because the host rock is essentially non-porous temperate limestone, not porous sandstone as is the typical situation in the basin, and production is exclusively from extensive networks of fractures within the limestone. The formation of these fractures is associated with Miocene compression and overthrusting along the Tarata Thrust Zone.

The Tikorangi Formation represents a condensed carbonate sequence at the top of a

regional transgressive cycle, deposited in shelfal to upper bathyal depths by reworking and basinward transport of shallow-water biota (shelfal facies). This facies grades basinward into a fine-grained marl (transition facies) and eventually into a bathyal ooze (bathyal facies). The Tikorangi Formation ranges in age from Early Oligocene to Early Miocene (Whaingaroan to Otaian) in the bathyal facies, but appears to be restricted to the earliest Miocene (Waitakian) in the shelfal deposits. The bathyal facies, largely tectonically undisturbed, is widespread on the Western Stable Platform, while the shelfal facies, restricted to easternmost and northernmost parts of the Taranaki Peninsula, mainly occurs in fractured allochthonous sheets thrust into less competent overlying mudrocks.

In the context of the projected decline of currently producing fields in New Zealand, there is an obvious need to establish new petroleum reserves. Clearly Taranaki Basin remains a focus of attention. An understanding of already discovered hydrocarbon systems will greatly aid in the identification and evaluation of new prospects within the basin. While the Tikorangi Formation must continue to be seen as an important potential hydrocarbon reservoir within Taranaki Basin, an improved understanding of its properties would aid in increasing its prospectivity. Unlike its onshore lateral equivalents in the Te Kuiti Group, the Tikorangi Formation is largely unknown and unstudied outside of petroleum circles, and there is a complete absence of any detailed information about the formation in the published scientific literature.

While the complex sedimentary and tectonic history of the Tikorangi Formation is broadly appreciated, much work remains to be able to better understand not only this hydrocarbon reservoir, but temperate-latitude carbonates more generally. The occurrence provides a rare opportunity to study limestone remaining within the subsurface burial environment, unlike its onshore lateral equivalents (Te Kuiti Group) which have been uplifted and exposed at the surface, and subjected to physical and chemical changes associated with that uplift.

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TOPIC 2:

A CARBONATE AND GEOPHYSICAL LOG-BASED LITHOSTRATIGRAPHY FOR THE SUBSURFACE MID-TERTIARY TIKORANGI FORMATION RESERVOIR, TARANAKI BASIN, NEW ZEALAND

2.1 ABSTRACT

This study presents a carbonate-based lithostratigraphy for the Oligocene-Early Miocene Tikorangi Formation, currently New Zealand's only carbonate and fracture-producing reservoir. The formation in eastern onshore Taranaki Basin consists of an earliest Miocene aged (Waitakian) foredeep facies of variably siliciclastic, muddy, typically fine to very fine sandy limestones containing mixed shelfal-slope skeletons interbedded with variably calcareous siliciclastites (claystones to siltstones). Offshore to the north and west the formation comprises basinal Oligocene-Early Miocene (Whaingaroan–Otaian) calcareous siliciclastites as condensed deeper water basinal equivalents. The totally subsurface nature of the Tikorangi Formation, absence of outcrop, and the lack of any complete core through the interval, necessitates the use of less traditional methods for lithostratigraphic discrimination.

Laboratory-determined data, derived from available core material for seven onshore wells (foredeep facies), and a single offshore well (basinal facies), have been pooled and correlated with a complete suite of geophysical log data. The resulting correlation(s) have been applied to Dt (sonic) and GR (gamma-ray) log data to derive interpretative carbonate logs for the entire thickness of the Tikorangi Formation. Four major facies have been defined: Facies A – calcareous siliciclastites (siliciclastic-dominated, slightly to moderately calcareous claystone to mudstone with <25% carbonate); Facies B – very calcareous siliciclastites (moderately to highly calcareous siliciclastic siltstone to fine sandstone with 25-

50% carbonate); Facies C – muddy limestones (muddy, very fine to fine sandy carbonates with 50-75% carbonate); and Facies D – sparry limestones (a purer, typically coarser fine sandy more sparry carbonate with >75% carbonate). These facies form the basic framework for identifying nine major lithostratigraphic units in the Tikorangi Formation which comprise either single or interbedded combinations of these four facies. A correlation panel for the eight wells in this study is presented.

The results highlight the utility of integrating geophysical log and laboratory data in stratigraphic analysis. Correlations derived in this study provide: a basis for the construction of a complete and detailed stratigraphy for the Tikorangi Formation, which was previously unavailable; the ability to identify more appropriate formational boundaries based on compositional changes; the possibility of extending this correlation to the many other wells penetrating this formation for which no core material is available; a potential aid in delineating and correlating those particular facies most likely to be the key ones for hosting hydrocarbon reserves; and a sound stratigraphic framework and foundation for further detailed studies of the formation.

Keywords carbonate; geophysical logs; lithostratigraphy; mid-Tertiary; Tikorangi Formation; hydrocarbons; fractured reservoir, Taranaki Basin, New Zealand

2.2 INTRODUCTION

The Ngatoro Group was named by King (1988a, b) for a succession of generally high-carbonate Oligocene-Early Miocene rocks within New Zealand's only commercially producing hydrocarbon basin, the Taranaki Basin (Fig. 2.1A-C). The Ngatoro Group comprises the Otaraoa, Tikorangi, and Taimana Formations, but is dominated by limestones of the Tikorangi Formation (Fig. 2.2). The Tikorangi Formation is of particular interest as it constitutes New Zealand's only

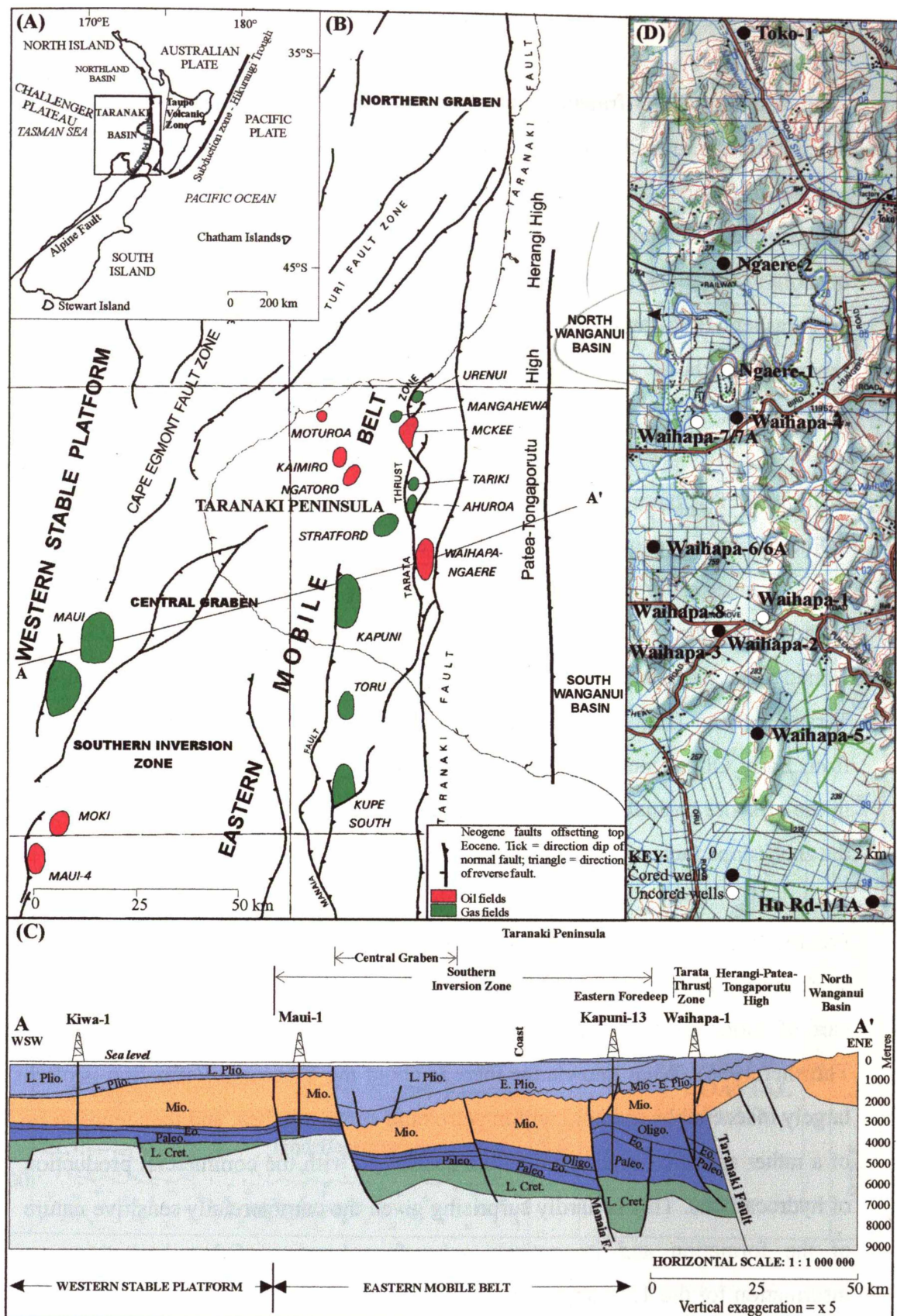


Fig. 2.1 (A) Location of Taranaki Basin in New Zealand. (B) Major structural and tectonic elements and main oil/condensate accumulations within Taranaki Basin. The Tikorangi Formation is dated as earliest Miocene in the east (Waihapa-1) and Oligocene-Early Miocene in the west (Maui-1). Adapted from King & Thrasher (1996). (C) Structural cross-section of a transect running WSW - NE through offshore Maui-1 and onshore through the Waihapa-Ngaere Field, Tarata Thrust Zone (see location in B). Adapted from King & Thrasher (1996). Shading: = late Neogene, = early Neogene, = Paleogene, = Late Cretaceous, = basement. E. Plio. = Early Pliocene; L. Plio. = Late Pliocene; Mio. = Miocene; Oligo. = Oligocene; Paleo. = Paleocene; L. Cret. = Late Cretaceous. E. Plio. = Early Pliocene; L. Plio. = Late Pliocene; Mio. = Miocene; Oligo. = Oligocene; Paleo. = Paleocene; L. Cret. = Late Cretaceous. (D) Location of the seven onshore wells (solid circles) providing core from the Tikorangi Formation within the Waihapa-Ngaere Field that form the basis for this study.

carbonate and wholly fracture-controlled reservoir. It lies between two calcareous siliciclastic-dominated units - the Otaraoa Formation below, comprising calcareous sandstones and siltstones, and the Taimana Formation above, consisting of calcareous mudstones and marls (Fig. 2.2). The Tikorangi Formation onshore in the subsurface beneath Taranaki Peninsula has been described by King & Thrasher (1996) as primarily a limestone consisting of varying proportions of reworked bioclastic and siliciclastic material deposited at outer shelf to upper slope depths.

Within the Tikorangi Formation two broad “mega-facies” have been previously delineated by Simpson (1992) and King & Thrasher (1996) (see Topic 1, Table 1.1). An outer shelf/slope facies typifies the eastern margins of the basin beneath onshore Taranaki, named here foredeep facies, and a deeper water bathyal facies, named here basinal facies, occurs in western and northern areas of offshore Taranaki Basin (Fig. 2.3). These end-member facies span different age ranges from Early Oligocene-Early Miocene (Whaingaroan-Otaian – see Appendix 1.2) in the offshore basinal facies, and principally earliest Miocene (Waitakian) only in the shelf/slope facies (see Fig. 1.12).

Previously published work on the Tikorangi Formation, and indeed any previous work outside of petroleum companies, is extremely limited and mainly included as part of more regional studies of Taranaki Basin (King 1990, 1994; King & Thrasher 1996). What knowledge there is about the Tikorangi Formation is often largely inaccessible and held within petroleum company files, and then tends to be of a rather specific or technical nature concerned with the commercial production of hydrocarbons. This is hardly surprising given the commercially sensitive nature of the formation and its entirely subsurface location. Other limitations on information for the Tikorangi Formation include the uneven spatial distribution of cored wells and the absence of any complete core coverage through the formation, so that only isolated “windows of opportunity” exist for studying the limestone.

Particular limitations in this study result from the scarcity of basinwide cored

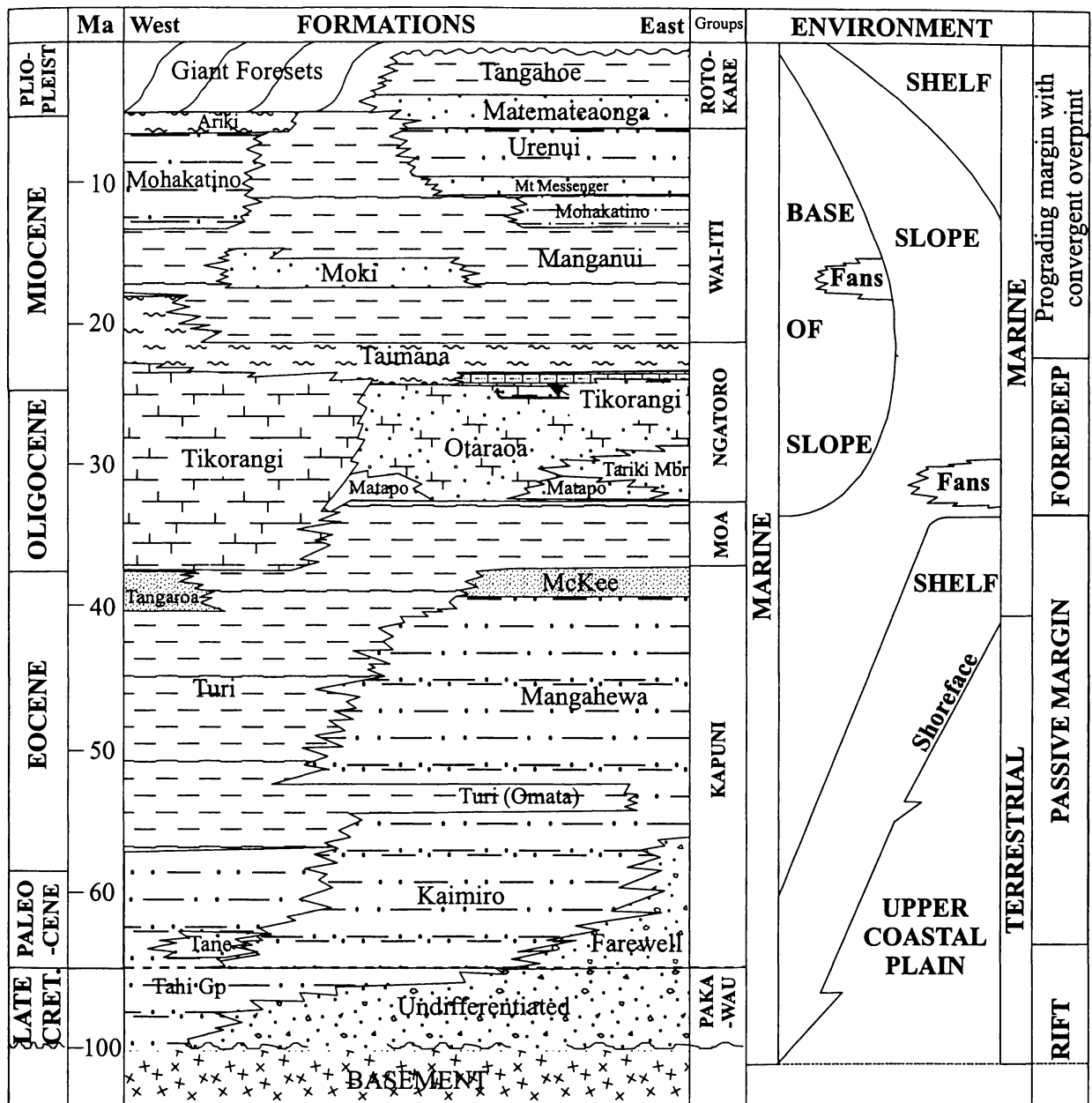


Fig. 2.2 Schematic lithostratigraphic, depositional, and tectonic framework for the Taranaki Basin. The carbonate-dominated Tikurangi Formation sits unique amongst otherwise siliciclastic-dominated facies. Adapted from King (1990).

material being available for only seven onshore wells (Fig. 2.1D) and a single offshore well, Maui-1 (Fig. 2.3). This is despite the comparatively large number of wells (80+) from onshore alone which penetrate the Tikorangi Formation (see Appendix 1.1). The high costs of coring mean that the formation has been drilled where the petroleum industry objectives have been to further geological information within already known economic targets. The focus of such petroleum exploration and development objectives within the Tikorangi Formation has been in the onshore oil-producing TAWN wells (Tariki, Ahuroa, Waihapa, Ngaere) otherwise forming the Waihapa-Ngaere Field (Fig. 2.1B, D), which has provided a disproportionately large amount of drill core material (Appendix 2.1) from a very localised area in relation to the known basinwide extent of the limestone (Fig. 2.3).

Given the above constraints, less traditional methods of stratigraphic evaluation have been necessarily employed in this study, namely an analysis of the extensive suite of geophysical or wireline logs available for each drill-hole. The integration of these geophysical logs and laboratory-derived data can provide a basis for unravelling an essentially complete and detailed lithostratigraphy, otherwise previously limited to very general and basic information provided by mudlog data.

The aim of this paper is to produce a complete and detailed, and as yet unavailable, lithostratigraphic framework for the Tikorangi Formation. The analysis will provide the foundation for other more specific studies of the limestone, including their petrography, diagenesis, geochemistry, and depositional history. Detailed study of the two end-member “megafacies” mentioned above will be made. Seven onshore eastern Taranaki wells (Toko-1, Ngaere-2, Waihapa-4, Waihapa-6, Waihapa-2, Waihapa-5, and Hu Rd-1) (Fig. 2.1D) will be used to represent the onshore shelf/slope facies, and a single offshore western Taranaki basin well, Maui-1, is used to represent the offshore basinal facies (Fig. 2.3). Background information relating to these wells is provided in Topic 1 as part of an overview of the general nature, distribution, and characteristics of the Tikorangi Formation. Other details about individual wells are contained within Appendices

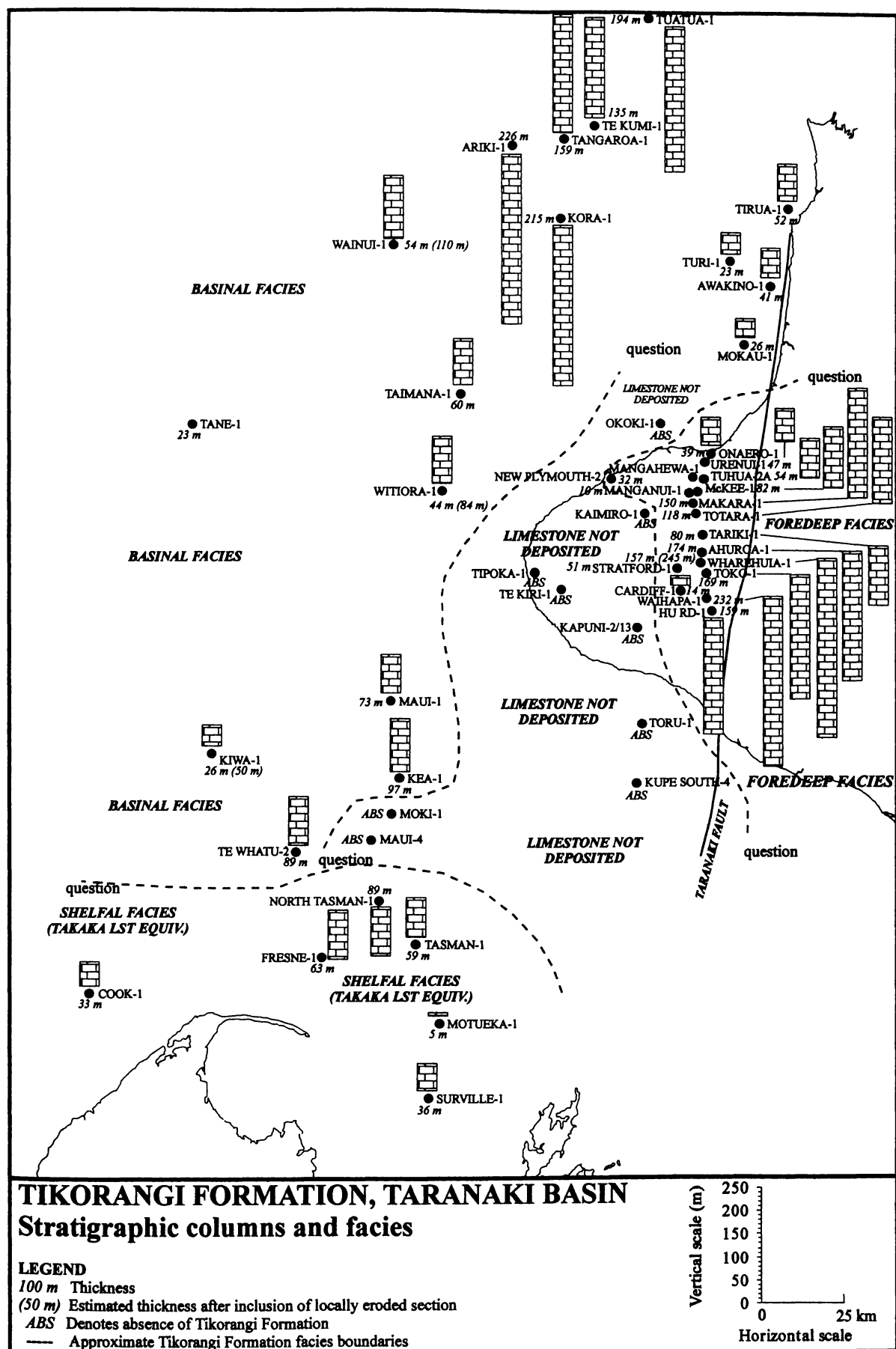


Fig. 2.3 Tikorangi Formation occurrence, thickness, and facies in selected wells, Taranaki Basin. Data compiled from Simpson (1992) and King & Thrasher (1996) and well completion reports.

and the Well Completion Reports (WCRs) of Waihapa-2 (Carter et al. 1988), Waihapa-4 (Carter & Kelly 1989a), Waihapa-6/6A (Carter & Kelly 1989b), Ngaere-2 (PEL 1995), Toko-1 (Adams et al. 1980), Hu Rd-1/1A (NZ Oil & Gas 1992), and Maui-1 (Shell BP & Todd 1969).

2.3 GEOLOGIC SETTING

Taranaki Basin, New Zealand's only commercial hydrocarbon basin (Fig. 2.1A), covers an area of about 100,000 km². The basin is essentially a subsurface feature, located mainly offshore, and is both composite and complex in nature (Fig. 2.1C). It contains a pile of sediment up to nine km thick, with a broadly transgressive record from the Late Cretaceous to Early Miocene, overlain by a regressive section that is still forming today (Fig. 2.2) (King & Thrasher 1996). Late Cretaceous sediments formed in fault-controlled sub-basins developed within an intra-continental rift transform system. Following rifting, the basin evolved throughout the Paleocene and Eocene into a passive margin. From Late Eocene, in association with the evolution of the Australia-Pacific plate boundary through New Zealand (see Topic 1, Fig. 1.3), fault-controlled sub-basins formed on the basin's southeastern margin.

From about the Early Oligocene, the basin underwent accelerated subsidence, which was most pronounced and rapid in the east, culminating in the development of a carbonate foredeep in which the shelfal/slope facies of Simpson (1992) and King & Thrasher (1996) accumulated. These deposits, renamed here the foredeep facies, included the thickest occurrences of the Tikorangi Formation (see Topic 1, Fig. 1.5). A change in plate boundary configuration in the Early Miocene saw overthrusting along the Taranaki Fault and formation of the Tarata Thrust Zone and associated structures within the Eastern Mobile Belt (Fig. 2.1B, C). The Waihapa-Ngaere structure (see Topic 1), formed during compression in the Tarata Thrust Zone as part of the Eastern Mobile Belt (Fig. 2.1B), is the setting for the

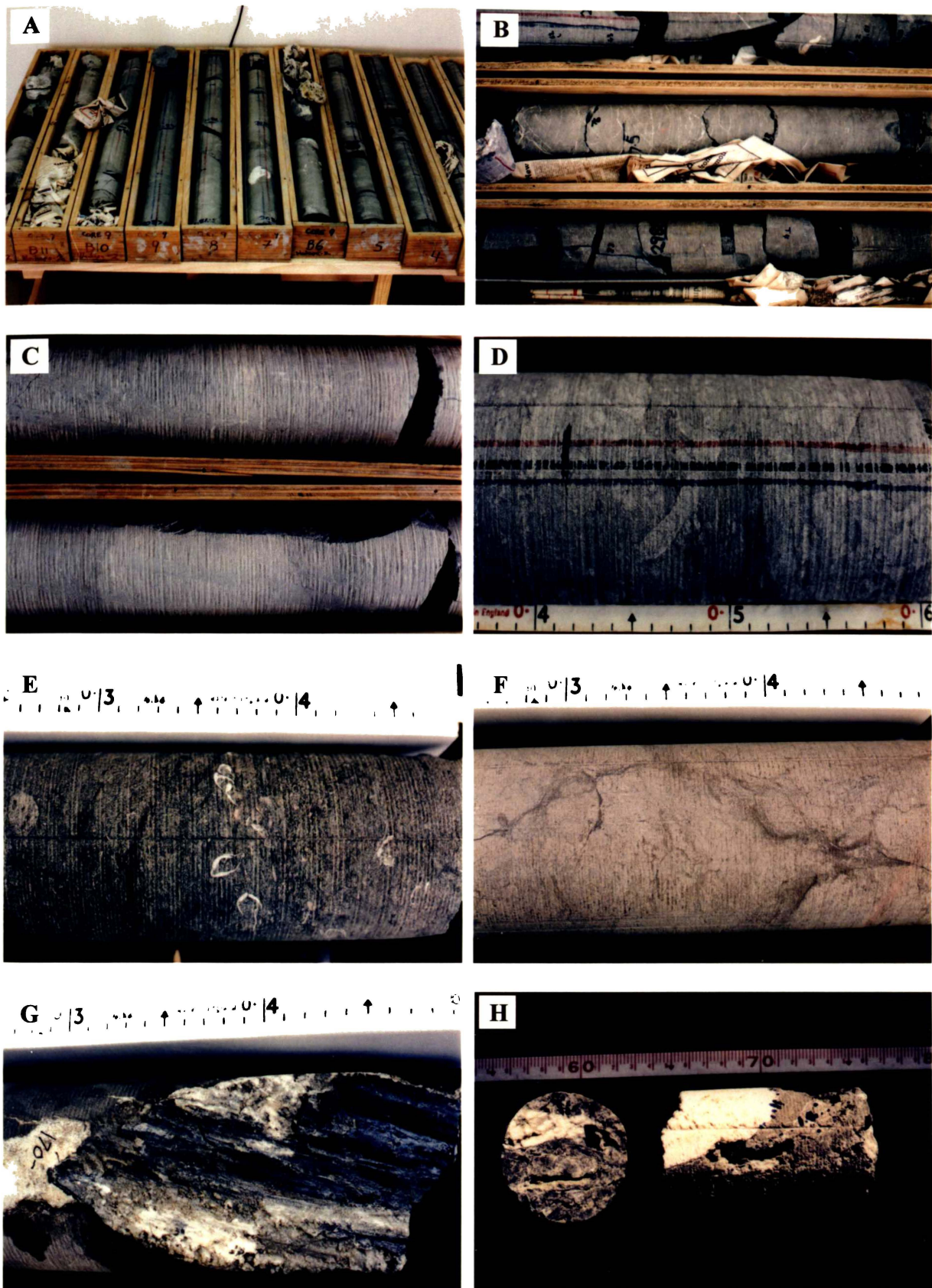


Plate 2.1 (A) Boxed 1 m lengths of core arranged stratigraphically for viewing and sampling (Waihapa-2, 100 mm-diameter core). (B) Natural- and drill-induced fractures in the Tikorangi Formation core (Waihapa-2, 100 mm-diameter core). (C) Core appears fine-grained and homogenous with concentrically ribbed outer surface as a result of drilling, and yields little sedimentary information (Waihapa-4, 100 mm-diameter core). (D) Intense bioturbation characterises much of the Tikorangi Formation core (Waihapa-4, 100 mm-diameter core). (E) Rarely macro-skeletal material is evident in cores (Waihapa-2, 100 mm-diameter core). (F) Dark-coloured commonly occurring horsetail stylolites at high-angles to bedding formed from tectonic compression. Pale grey colour is typical of the more carbonate-rich facies (Waihapa-2, 100 mm-diameter core). (G) Major fracture surface showing multiple phases of mineralisation and movement (Waihapa-2, 100 mm core). (H) Vein mineralisation occluding fracture porosity within the smaller diameter 70 mm core from Ngaere-2. Scale in (D) to (G) is in metres; H is in centimetres.

wells used in this study as representative of the fractured foredeep facies (Plate 2.1A-C, G). In contrast, western areas of the basin (Western Stable Platform) (Fig. 2.1B) have remained tectonically quiescent (King & Thrasher 1996) and provide the setting for the Maui-1 well, representative of the offshore deeper water basinal facies.

2.4 BACKGROUND INFORMATION FOR TIKORANGI FORMATION

In the eastern onshore region of Taranaki Basin the Tikorangi Formation reaches its maximum thickness of about 230 m in the vicinity of the Waihapa-Ngaere Field at Waihapa-1 (Fig. 2.3), and generally thins to the north and south from here. The formation is absent in a region directly west of onshore Taranaki Peninsula, but the offshore basinal facies occurs as condensed carbonates some 20-30 m thick further west, and becomes better developed and thicker (to >200 m) towards the north of the basin. In the southwest corner of the basin is the age equivalent shelf Takaka Limestone, usually <60 m thick (Fig. 2.3). This limestone is exposed onshore in the Nelson region of South Island (Leask 1980). Other exposed onland age equivalents (Te Kuiti Group limestones) are exposed in the adjacent North Island North Wanganui Basin (Fig. 2.1B) where they have been extensively studied by Nelson (1973, 1978), Nelson et al. (1988, 1994), and within the studies by Hood (1993) and Hood & Nelson (1996).

The Tikorangi foredeep carbonates, beneath Taranaki Peninsula, restricted to earliest Miocene (Waitakian) age, are often muddy and argillaceous (Plate 2.1A-E) and interbedded with calcareous sandstones, siltstones and claystones (Carter et al. 1988; Carter & Kelly 1989a, b; NZ Oil & Gas 1992; PEL 1995; Young & Carter 1989) (see Appendix 2.8 for general mudlog descriptions). On well-logs the base of the Tikorangi Formation is generally gradational over often tens of metres with the underlying Otaraoa Formation, which contrasts with the typically abrupt upper contact with the overlying Taimana Formation in which a marked increase

in sonic log (Dt) and Gamma-ray log (GR) values occurs over a few metres (see Section 2.7).

The Tikorangi Formation forms a major seismic reflector marker horizon in Taranaki Basin (see Topic 1, Fig. 1.9) whose upper surface lies some 1,500-3,400 m below the present land surface of Taranaki. Appendix 1.1 provides summary information for all onshore wells which have penetrated the Tikorangi Formation, including: formation top and base where penetrated in both AH (along hole) and TVSS (true vertical subsea); AHT (along hole thickness); mTV (metres true vertical); TST (true stratigraphic thickness); isocore thickness; and eastings and northings for the intersection of the top of the formation.

2.5 DRILL CORE

Drill core is rare for the Tikorangi Formation and is typically only available for the Waihapa-Ngaere fractured reservoir zones (Plate 2.1). The focus of core drilling has been in the onshore oil-producing TAWN wells (Tariki, Ahuroa, Waihapa, Ngaere) in the Waihapa-Ngaere Field. Five onshore wells (Waihapa-2, -4, -5, -6, and Ngaere-2) (refer Fig. 2.1B, D for location map) were cored discontinuously within the onshore Waihapa-Ngaere oil field, giving a total of about 368 m of drill core. This forms the sample basis for the present study (Appendix 2.1). Fig. 2.4 shows the disparity in thickness of the Tikorangi Formation in each of the cored wells versus the actual length of core drilled (see also Appendix 2.4 for individual well summary stratigraphic logs). The greatest percentage of cored formational thickness occurs in the Waihapa-Ngaere wells (Fig. 2.1D) and ranges from <20% in Waihapa-6 to >50% in Waihapa-5. In contrast, a paucity of drill core material exists away from this field. The only other core material available within the onshore foredeep facies of the Tikorangi Formation is from two wells located very near the Waihapa-Ngaere field wells, namely Hu Rd-1A and Toko-1 (Fig. 2.1D). These wells provide only eight metres (3% of formation thickness) and 2.2 m (<1% of formational thickness) of drill- core, respectively. For the offshore

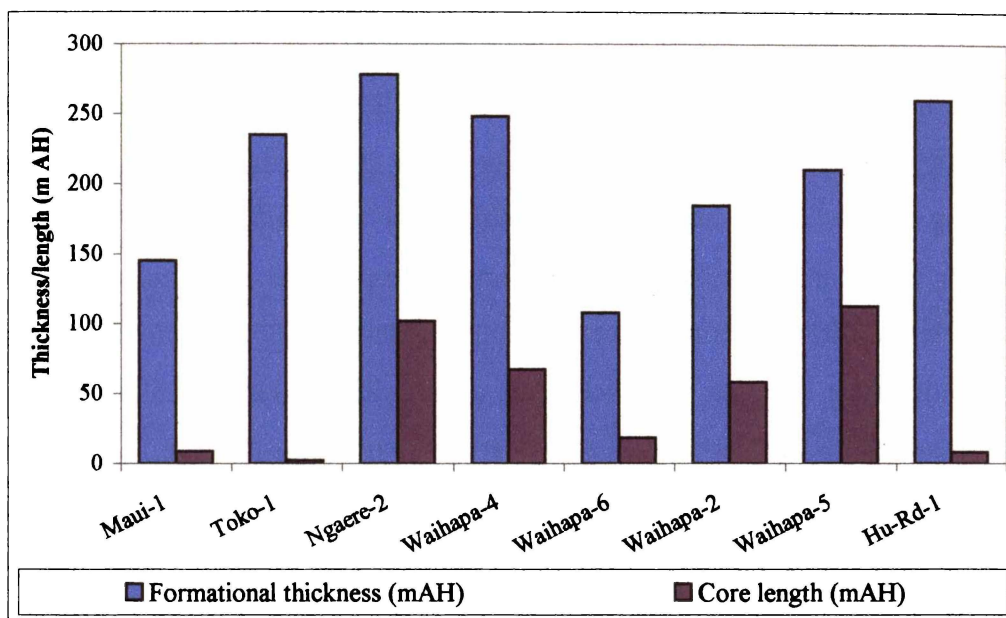


Fig. 2.4 Difference between the thickness of the Tikorangi Formation in each of the cored wells versus the actual core length drilled and available for sampling. mAH = metres along hole.

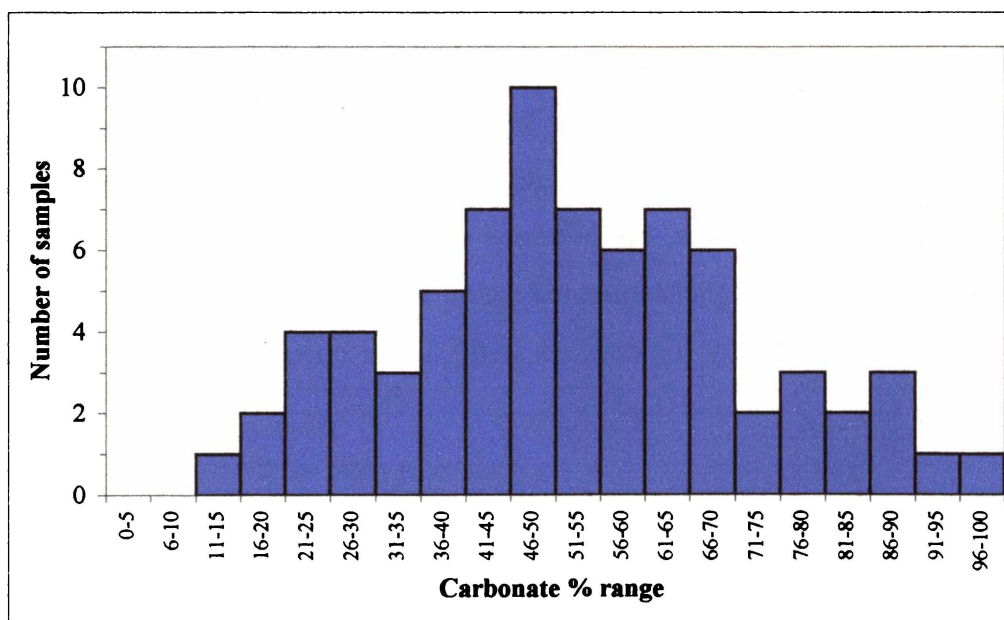


Fig. 2.5 Histogram showing distribution of Tikorangi Formation carbonate percentage data as determined from acid digestion.

basinal facies, about nine metres of drill core (Appendix 2.1) is available (6% of formational thickness) only from the offshore Maui-1 well (see Fig. 2.3 for location).

Cores are held in the Core Library, Gracefield, Wellington which is managed by the Ministry of Commerce (MOC). Core is boxed in 1m lengths and access is time consuming (Plate 2.1). The cores are whole, not slabbed, and provide little immediate opportunity for detailed inspection. Core material commonly contains natural (Plate 2.1G) or drilling-induced fractures (Plate 2.1C) and stylolites (Plate 2.1F), while some sections have been lost during drilling (Plate 2.1B). Natural fractures are commonly partially filled by carbonate minerals (Plate 2.1G, H) (see Topic 7). Protocol for sampling core dictates that no more than one third of any section be removed, and sampling is to be conducted by a MOC representative or technician. Core diameters differ between wells, ranging from large, heavy and cumbersome 100 mm diameter core in the Waihapa wells (Plate 2.1A-G) to a smaller 70 mm diameter core in the Ngaere-2 well (Plate 2.1H).

Difficulties were encountered in acquiring good lithological data from simply viewing the raw core material. In particular, often continuous concentric ribbing of the core surface (Plate 2.1C-E), produced during drilling, obscures definitive textural and compositional details that might otherwise be available in hand-specimen samples. When combined with the fact that MOC facilities prohibits slabbing the cores lengthwise, the presence of a coating of drilling mud about many cores, and the strongly bioturbated nature of the sediment (Plate 2.1D, E), there was little opportunity for detailed study of the cores at a hand-specimen level.

Information relating to drill core numbers, subsurface depths, percent recovery, and other core statistics are contained in Appendix 2.1. A sample catalogue for the 236 samples of Tikorangi Formation drill core collected for this study is given in Appendix 2.2.

Table 2.1 Summary rock property trends with increasing DT and GR. Arrows to right indicate increasing, to left indicate decreasing, while dash only denotes no discernable trend.

ROCK PROPERTY	As DT increases	As GR increases
<i>Whole rock composition</i>		
Carbonate %	→	←
Total matrix/cement %	←	→
Spar cement %	→	←
Micrite %	←	→
<i>Bioclastic composition</i>		
Total bioclast %	→	←
Bivalves %	→	←
Echinoderms %	→	←
Benthic forams %	→	←
Planktic forams %	→	←
Calcareous algae %	→	—
Spicules and spines %	—	←
<i>Siliciclastic composition</i>		
Total siliciclast %	←	→
Quartz %	←	→
Feldspar %	←	→
Glaucconite %	→	—
<i>Texture</i>		
Maximum skeletal grain size	→	←
Mean skeletal grain size	→	←
Maximum siliciclastic grain size	—	—
Mean siliciclastic grain size	→	←

2.6 CARBONATE CONTENT

Total carbonate percentage values were determined for a selection of 74 representative samples of Tikorangi Formation core (Appendix 2.3). These determinations were obtained during trace element analysis using the procedures outlined in Liddell (1993) and Winefield (1995). The carbonate represents the sum of calcite and/or dolomite in samples, and percentage data are summarised in Fig. 2.5. Values range from about 15-99%, with an average content of 53%. However, 57% of the samples contained less than 50% carbonate and therefore are not strictly limestones (Scoffin 1987). These samples are calcareous siliciclastic rocks.

Samples of the offshore facies from Maui-1 have carbonate values ranging from 32-41%, while samples from onshore Hu Rd-1 include the purest limestones, containing up to 99% carbonate. Waihapa, Ngaere, and Toko well cores show a wide range in carbonate values (15-86%) which can change rapidly over short distances. Despite the discontinuous nature of core samples, general up-core increases in carbonate content occur in Ngaere-2, and Waihapa-2 and -4, while Waihapa-5 shows an overall small up-core decrease.

2.7 GEOPHYSICAL LOGS

Very little detailed lithostratigraphic information is available for the Tikorangi Formation. While mudlogs provide some general sedimentological data based on the percentages of different lithologies occurring in cuttings, the information is much inferior to that provided by laboratory investigation of core material using carbonate analysis and standard petrographic techniques. In this study an attempt is made to use geophysical (electric) logs to provide some intraformational stratigraphic details for the Tikorangi Formation since they are the only near-complete data record available for the entire formation thickness.

Geophysical log data are contained on the disk (Appendix 2.5) accompanying this

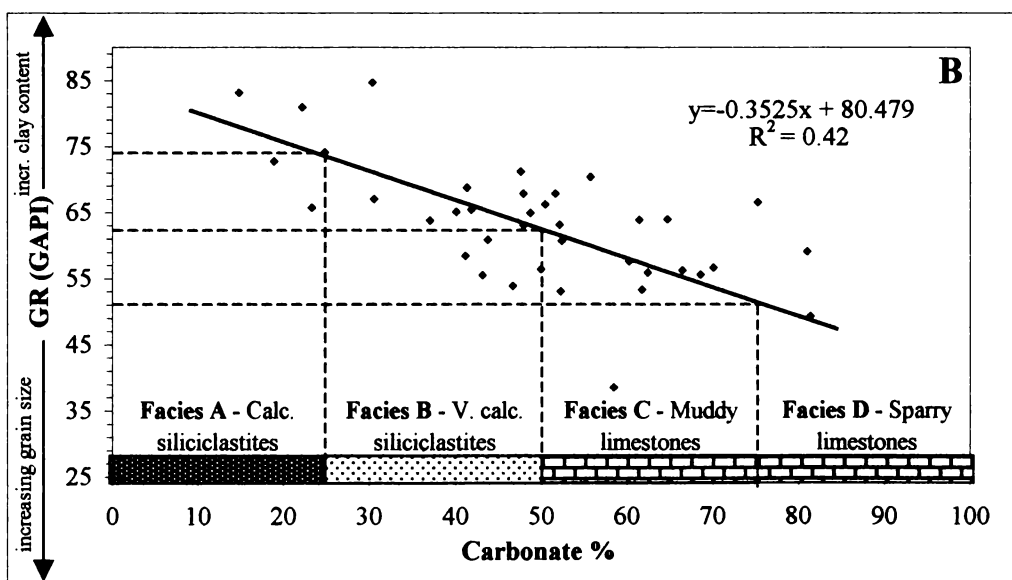
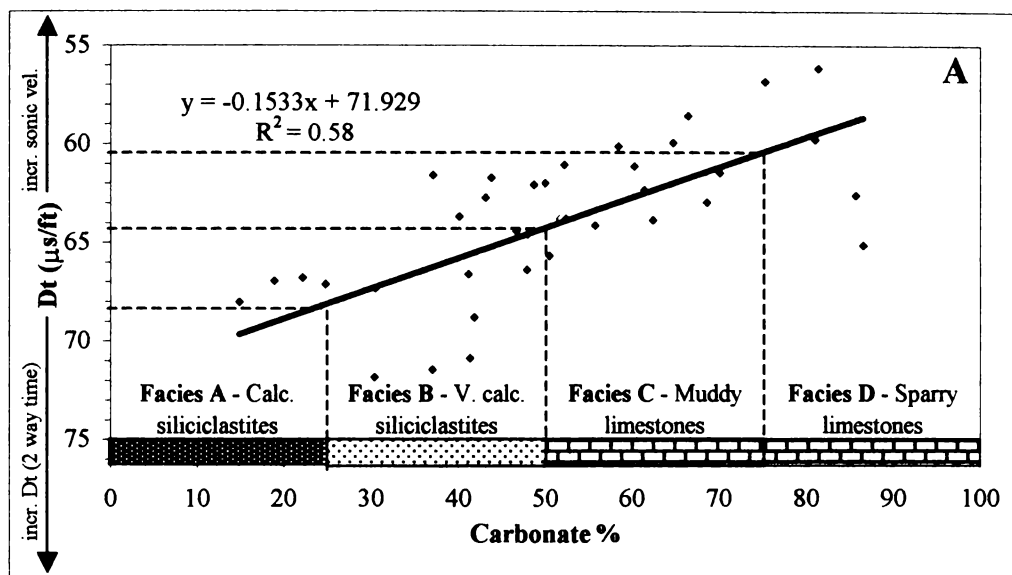


Fig. 2.6 Relationship diagrams between laboratory carbonate data and corresponding (A) sonic (Dt) and (B) gamma-ray (GR) values from geophysical logs. The correlation lines shown have been used to construct a complete carbonate lithostratigraphy for the entire Tikorangi Formation at each well site. Carbonate-based facies A to D are shown along the base of the diagrams.

thesis, and graphic logs of the same data are shown in the columns in Appendix 2.4. Dt (or sonic) logs were available for all wells except Hu Rd-1A, in which no Dt logs were run. The Dt value ($\mu\text{s}/\text{ft}$) is the two-way travel time, and the smaller this value the higher is the sonic velocity of the core sample. GR (gamma-ray) logs and a suite of resistivity logs (LLS – Laterolog shallow, LLD – Laterolog deep) were also available for all wells. A GR log for the sidetrack well Hu Rd-1 has been used as a surrogate for Hu Rd-1A.

2.7.1 Log defined Tikorangi Formation boundaries

The lower boundary of the Tikorangi Formation has previously been defined by electric log character and is placed at a noticeable increase in sonic velocity (decrease in Dt value) and resistivity (LLS, LLD), which is mirrored by a decrease in gamma-ray (GR) values. The responses reflect a generally gradational change from the argillaceous and silty nature of the underlying Otaraoa Formation (Palmer 1985; King & Thrasher 1996) to the limestone beds of the Tikorangi Formation (see summary logs in Appendix 2.4). The log appearance of the upper boundary of the Tikorangi Formation is usually more dramatic and corresponds with a sharp decrease in Dt and resistivity, and a corresponding increase in GR, upon entering the siltstones and fine sandstones of the Taimana Formation. In Waihapa-4 for example (see summary log - Appendix 2.4), the upper boundary of the Tikorangi Formation is very definite with both low Dt and GR values. The lower boundary is harder to place with the lower Tikorangi Formation calcareous siltstones merging down into the underlying siltstones/mudstones of the Otaraoa Formation (Carter & Kelly 1989a). Log correlation between Waihapa-4 and Waihapa-2 was described by Carter & Kelly (1989a) as extremely good over the upper part of the Tikorangi Formation.

2.8 CARBONATE FACIES

The carbonate percentage and petrographic database (see Topic 4) derived from scattered core samples provides only small and isolated windows into the nature

Facies	Name	Log characteristics		Carbonate %					Occurrence			Inferred textural characteristics			
		DT	GR	0	25	50	75	100	some	common	abundant	clay	silt	v.f. sand	f. sand
A	Calcareous siliciclastites	>68.0	>73.5	■					■			■			
B	Very calcareous siliciclastites	68-64.2	73.5-62.5		■					■		■	■		
C	Muddy limestones	64.2-60.4	62.5-51.0			■					■			■	■
D	Sparry limestones	<60.4	<51.0				■	■	■	■					■

Fig. 2.7 Summary characteristics of the four major carbonate facies in the Tikorangi Formation including: the corresponding limiting values of DT and GR; carbonate %; relative occurrence in cores; and inferred textural characteristics.

of the lithologies comprising the Tikorangi Formation. However, this laboratory-derived database takes on a new and heightened importance when it is correlated with the comprehensive suite of geophysical log data available for the entire Tikorangi Formation. Such a correlation provides the first opportunity for deriving a much fuller and detailed lithostratigraphy applicable to the entire Tikorangi Formation.

The derivation and application of this interpretative lithostratigraphic approach is discussed below for the eight wells represented in this study. No attempt is made here to extend this correlation to other wells for which no core sample material is available.

2.8.1 Correlation method

The suite of geophysical logs available for correlation with the laboratory-derived database are Dt, GR, and resistivity logs which typically provide measurements at 0.125 m AH intervals throughout the Tikorangi Formation. Initial groundwork investigations involved the correlation of geophysical log data for individual well samples with the laboratory-determined data from that well. This latter included carbonate %, siliciclast %, total bioclast %, matrix/cement %, micrite %, the proportions of particular skeletal grain types, the mean grainsize of skeletal and siliciclastic material, and the general rock classification. The degree of correlation between the two data sets was determined using R-squared values performed using a transformed regression model on linear trendlines within Microsoft Excel 97 for Windows.

2.8.2 Correlation results

Trends in Dt and GR values with changing rock properties are summarised in Table 2.1. The raw data correlation graphs for the entire sample database are reproduced in Appendix 2.6 and 2.7. Wells for which the longest core lengths and largest number of samples were available (Waihapa-2, -5 and Ngaere-2) individually provided some good correlations. However, the limited length of core and number of samples from some other wells, especially Maui-1 and Toko-1,

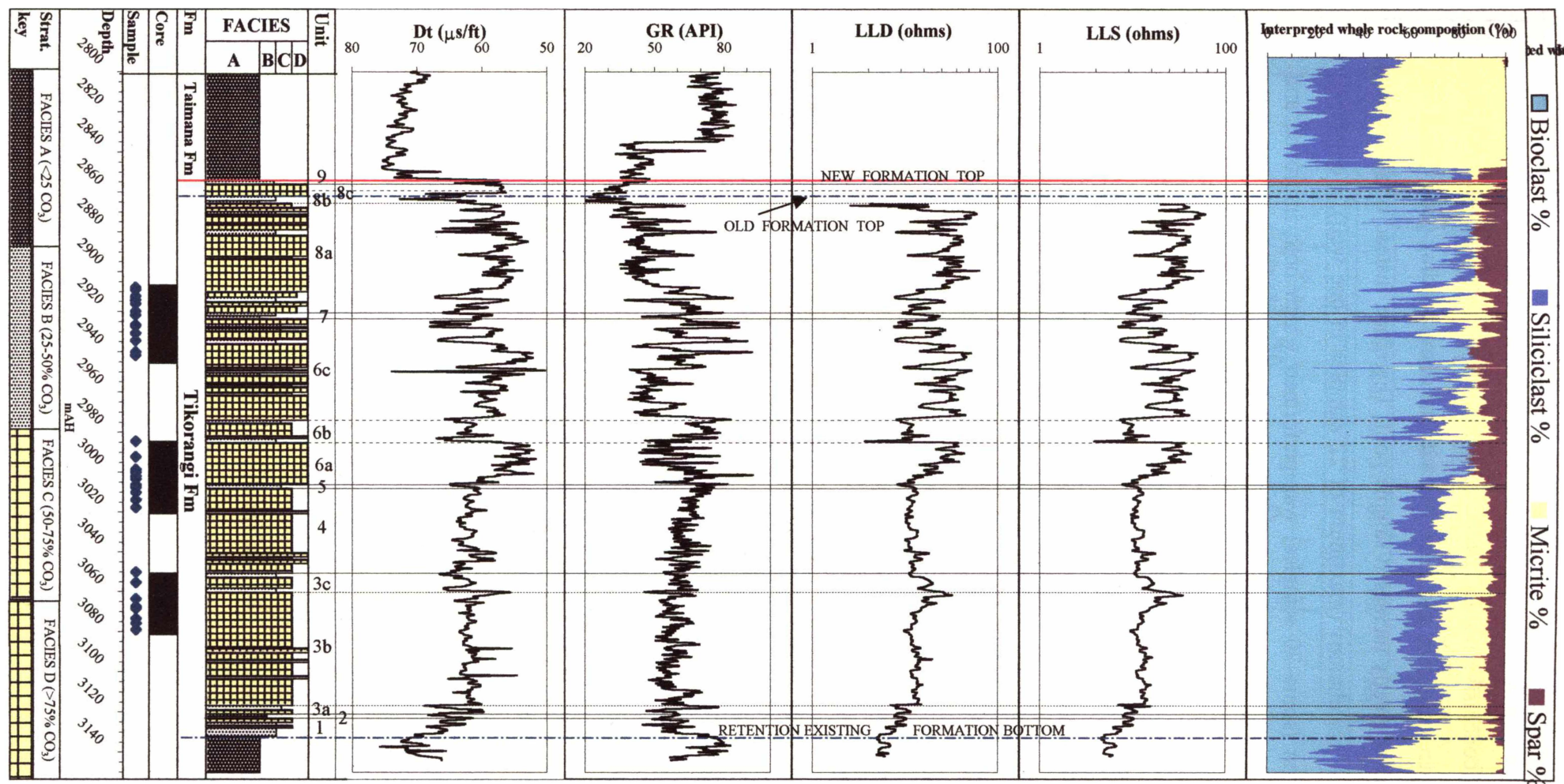


Fig. 2.8 Carbonate lithostratigraphy derived from correlations of geophysical well-log and carbonate % data for Ngaere-2 well. Key: Facies A - calcareous siliciclastites (0-25% carbonate); Facies B - very calcareous siliciclastites (25-50% carbonate). Facies C - muddy limestones (50-75% carbonate); Facies D - sparry limestones (>75% carbonate). Units are labelled and marked and drawn across log panels. Solid red line denotes changed upper and/or lower Tikorangi Formation boundary from those defined in Well Completion Report (PEL 1985). Dashed blue line denotes existing formation boundary. Core and sample locations and depths are shown. Interpreted whole rock compositions have been derived from correlating geophysical well log data and petrographic data. Dt = sonic log, GR = Gamma-ray log. LLD = Laterolog deep, LLS = Laterolog shallow (resistivity logs).

provided less conclusive results. Because of this, all the laboratory-derived data for all wells were combined and correlated with the corresponding geophysical log data to provide a greatly increased sample pool. Therefore, instead of attempting individual well correlations (maximum of 22 samples in one well), a combined pool correlation (some 70 samples) was performed which both improved and enhanced results.

With increasing sonic velocity (Dt), more competent and less porous rocks are correlated with a general linear increase in carbonate content, reflecting cleaner and generally coarser units having higher bioclast and spar cement contents, and lower siliciclastic and matrix/cement contents (Fig. 2.6A). Not surprisingly these trends are the opposite for GR results (Fig. 2.6B). As GR increases, or the shaliness increases, grain size generally decreases, with linearly increasing matrix (clay) and siliciclastic contents, and decreasing bioclast content. More specifically, the highest degrees of correlation were achieved for both Dt and GR versus carbonate %, which shows a clear increase with increasing sonic velocity (reducing Dt value) and corresponding decreasing GR (clay mineral content). These correlations were further improved by removing data from the offshore basinal Maui-1 well so as to enhance the onshore foredeep database. Removal of some of the Waihapa-4 had a similar enhancing affect, given a known miss-match of core sample and geophysical logging depths for parts of that well (G. Spanninga *pers. comm.* 1995). Gaps in the Dt data logs for Waihapa-2 and -5 also resulted in reducing the number of final samples for which carbonate data were available for correlation purposes to 42. The final correlations for carbonate % with Dt and GR are shown in Fig. 2.6. Not only did carbonate % correlations provide the best overall results, but the carbonate data also provides the most useful basis for establishing a meaningful carbonate-lithostratigraphy within a spectrum of carbonate-rich to carbonate-poor lithologies. To do this, lines delineating carbonate values of 25%, 50%, and 75% were drawn on both the Dt and GR plots so as to define four major carbonate facies: Facies A, <25% carbonate; Facies B, <25-50% carbonate; Facies C, 50-75% carbonate; and Facies D, >75% carbonate. The corresponding limiting values of Dt and GR for the four

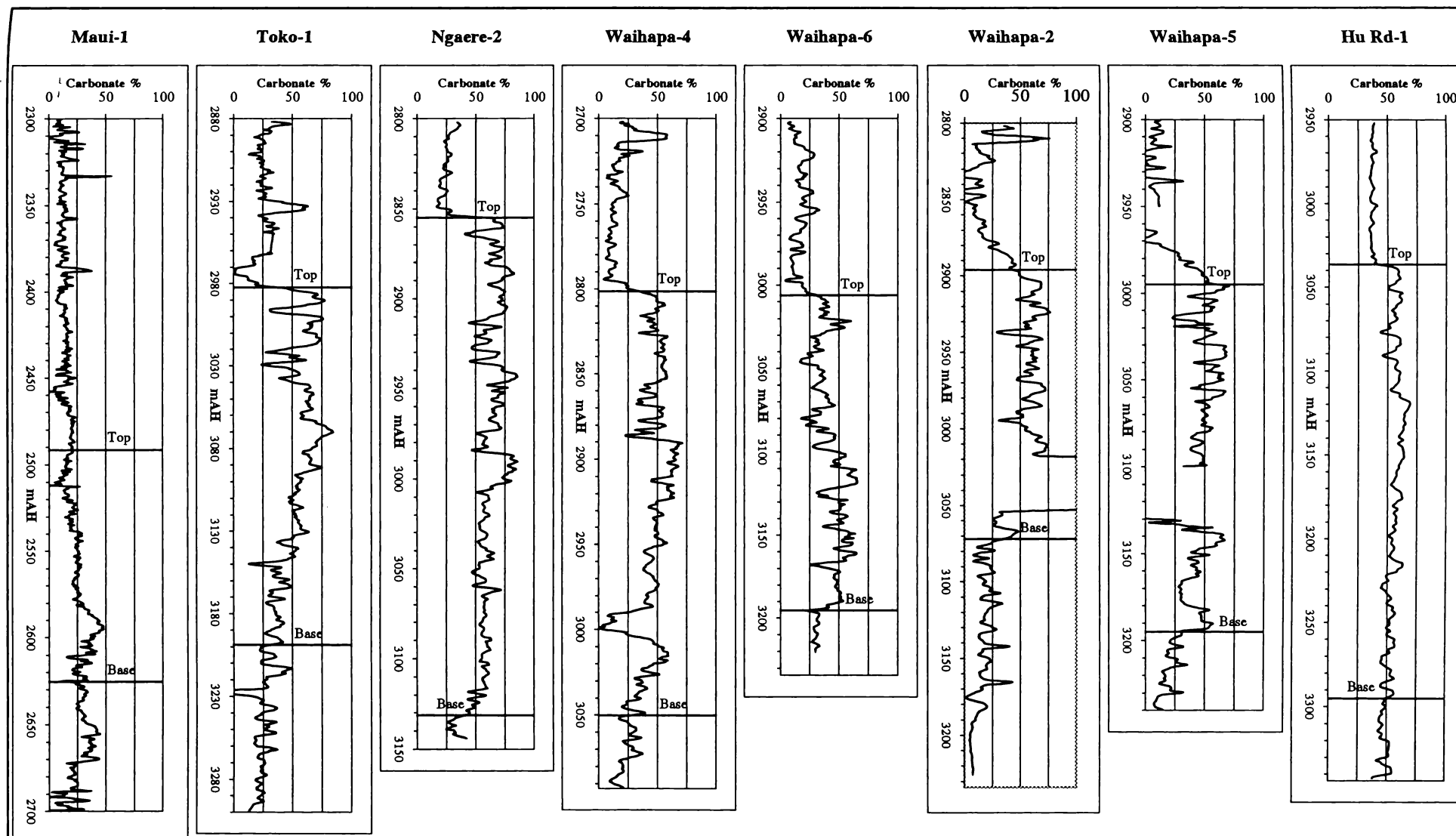


Fig. 2.9 Carbonate logs derived for the eight study wells using the well log data/carbonate data correlations in Fig. 2.6. Logs are drawn to the same scale with depth shown as mAH (metres along hole). Base and Top of the Tikorangi Formation shown are those suggested in this study (see Table 2.2). Logs are extended into the lower and upper Otaraoa and Taimana Formations to show the often marked change in carbonate composition between these formations and the Tikorangi Formation. As no samples of either the underlying or overlying formations were used in the data correlation method the accuracy of the values for these intervals is presently uncertain. Gaps in the carbonate log result from missing geophysical data log.

facies are shown in Fig. 2.7.

In order to keep the level of accuracy commensurate with scale used, instead of delineating the major carbonate facies in direct relation to Dt or GR, a moving average with a period of eight was used (data commonly at 0.125 m) to give an accuracy of scale of about 1 m, with the least resolvable thickness on the scale used being closer to 2 m. The resulting facies boundary lines could then simply be applied to the individual averaged well Dt logs in most cases, or the GR log in Hu Rd-1. An example full stratigraphic log is provided for the Ngaere-2 well in Fig. 2.8, and for all wells in Appendix 2.4. It is important to appreciate the scale to which the completed carbonate-based lithostratigraphy is shown, with 1 cm equivalent to >30 m. By using the correlation equations (Fig. 2.6), carbonate logs for the eight wells have been generated (Fig. 2.9).

2.8.2a Log versus laboratory-determined carbonate facies

As a test of the methodology outlined above, the geophysical log-determined facies for the 74 samples for which carbonate % data were available were correlated back to the facies determined solely from the laboratory carbonate data. Fig. 2.10A shows the % occurrences of the four facies from laboratory carbonate %, while Fig. 2.10B shows for the facies determined using the carbonate % Dt/GR correlation method. Results are consistently good across the four facies, with a significant 94% correlation between the two data sets. Small variation occurs in the number of log-determined Facies D (>75% carbonate), being slightly over-represented in the log compared to the laboratory analysis. Conversely, Facies B (25-50% carbonate) is slightly under-represented in the log-determined distribution. Facies A (0-25% carbonate) and C (50-75% carbonate) show direct correlation between the two data sets.

2.8.3 Carbonate facies definition

The geophysical logs are used to define four broad carbonate facies, A to D (Fig. 2.7). Because the logs do not necessarily record sedimentary detail, any sedimentological interpretations will tend to be rather generalised and rely heavily

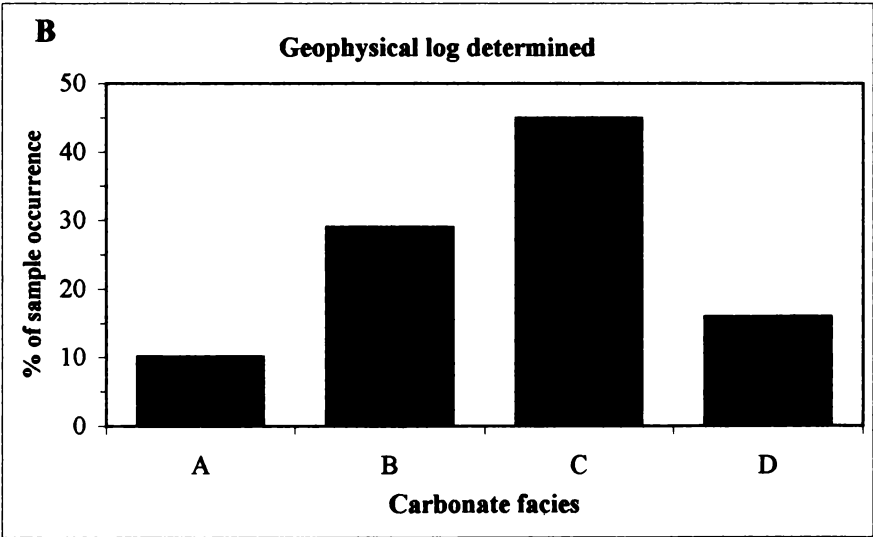
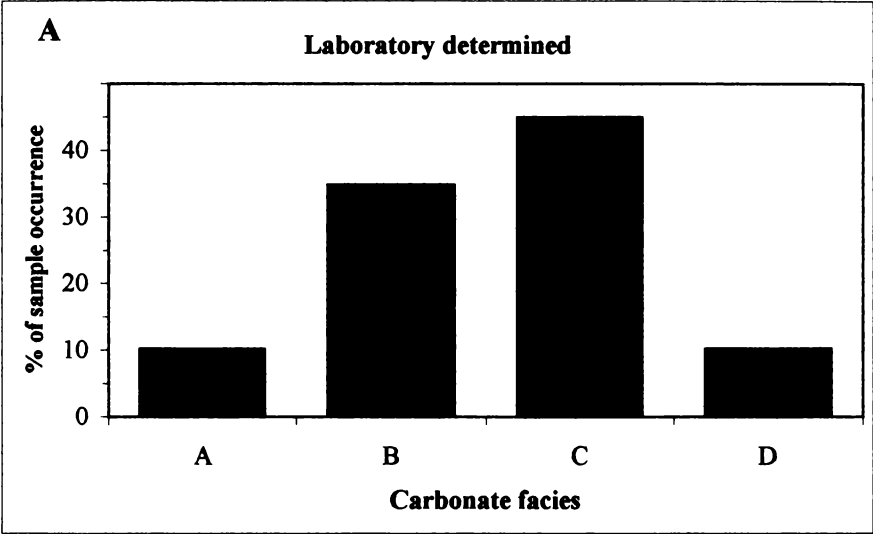


Fig. 2.10 (A) Carbonate facies distribution as determined from laboratory chemical analysis (see Appendix 2.3 for data). (B) Carbonate facies distribution for same samples as in (A) determined using geophysical well log data and carbonate % data correlations summarised in Fig. 2.6. The two data sets show good agreement pointing to the appropriateness of the correlation method.

on concept and for this reason facies names reflect this and have avoided the use of textural and petrographic terminology where possible.

2.8.3a Facies A (calcareous siliciclastites)

Facies A has carbonate contents of <25% and is a siliciclastic-dominated deposit, or siliciclastite. From the general relationships of Dt and GR these rocks are texturally the finest grained in the Tikorangi Formation and are grey to olive brown calcareous siliciclastic mudstones/claystones with a high portion of clay-sized material. Traces of very fine sand, glauconite, and skeletal material may occur. Facies A has the lowest bioclast content and the highest matrix and siliciclastic grain content in the Tikorangi Formation.

2.8.3b Facies B (very calcareous siliciclastites)

Facies B, defined by carbonate values of 25-50%, comprises very calcareous siliciclastic rocks. Texturally this facies is typically coarser than Facies A, and is dominated by siltstones and some fine sandstones with reduced matrix and clay contents, and increased amounts of bioclasts. Samples are moderately to very calcareous. These predominantly siltstone lithologies are generally olive grey, hard, argillaceous, and contain abundant disseminated carbonaceous material, visible skeletal material, traces of pyrite and glauconite, and scattered very fine quartz and lithic sand grains.

2.8.3c Facies C (muddy limestones)

Facies C samples have a carbonate content of 50-75%. They are impure, muddy, light grey to olive grey, firm to hard, limestones. Facies C rocks typically contain a variable mix of siliciclastic material, commonly fine quartz and lithic sand, and traces of glauconite and pyrite. Skeletal material dominates these rocks and is generally both fine grained and fragmented. Interparticle spaces are filled by muddy matrix and less common sparry cement.

2.8.3d Facies D (sparry limestones)

Facies D comprises relatively clean (i.e., less muddy), generally off-white to

Table 2.2 The abundance distribution of carbonate-based facies A to D in the Tikorangi Formation at each study well. Stratigraphic data compiled from Well Completion Reports for individual wells (see Section 2.2). mAH = metres along hole. TVSS = true vertical sub sea. TST = True stratigraphic thickness. * denotes well did not reach sufficient depth to confirm base of Tikorangi Formation. TD = total depth reached in well during drilling.

	<i>Maui-1</i>	<i>Toko-1</i>	<i>Ngaere-2</i>	<i>Waihapa-4</i>	<i>Waihapa-6</i>	<i>Waihapa-2</i>	<i>Waihapa-5</i>	<i>Hu Rd-1</i>
STRATIGRAPHIC DATA								
Tikorangi Formation top (mAH)	2510	2929	2861	2794	3012	2902	2994	3035
Tikorangi Formation top (mTVSS)	?	2772	2611	2567	2781	2655	2743	2782
Tikorangi Formation base (mAH)	2629	3227	3133	3051	3202	3094	3194	*3350TD
Tikorangi Formation base (mTVSS)	?	2941	2836	2823	2968	2846	2943	?
Thickness (mAH)	119	298	272	256	190	192	200	*315
Thickness (mTST)	?	298	227	257	153	168	199	?
Suggested limestone top (mAH)	2482	2982	2854	2802	3008	2888	2986	3035
Suggested limestone base (mAH)	2627	3217	3132	3050	3193	3072	3196	3295
Suggested total thickness (mAH)	145	235	278	248	185	184	210	260
FACIES								
Facies A								
Thickness (mAH)	28	58	6	53	16	28	30	51
% Total thickness	19	25	2	21	9	15	14	20
Range thickness (mAH)	2-8	<2-14	<2	2-20	2-4	<2-20	<2-16	2-14
Facies B								
Thickness (mAH)	117	54	36	79	40	55	64	63
% Total thickness	81	23	13	32	22	30	30	24
Range thickness (mAH)	1-37	<2-8	<2-4	2-22	<2-11	2-14	<2-10	2-18
Facies C								
Thickness (mAH)	0	54	113	96	40	53	88	94
% Total thickness	0	23	41	39	22	29	42	36
Range thickness (mAH)	-	<2-14	<2-28	2-16	<2-6	<2-11	2-14	2-14
Facies D								
Thickness (mAH)	0	69	123	20	12	48	28	52
% Total thickness	0	29	44	8	6	26	13	20
Range thickness (mAH)	-	2-20	<2-21	3-6	<2-5	<2-10	2-9	2-25

medium to light grey limestones whose carbonate contents are >75%. These limestones are usually very dense, hard, and finely crystalline, with high bioclast contents. They are commonly associated with increased amounts of spar cement, and generally have low matrix and siliciclastic contents.

2.8.4 Carbonate facies distribution

Appendix 2.9 documents the distribution of the various carbonate facies within the individual wells. By way of example, Fig. 2.8 shows the complete lithostratigraphy for a single well, Ngaere-2, plotted against well depth in m AH, along with revised formation boundaries, the geophysical logs used in the interpretation of the well stratigraphy, core and sample locations, interpretations of whole rock composition, and delineation of several units discussed in later sections. Complete stratigraphic interpretations for the other seven wells in this study are given in Appendix 2.4.

Table 2.2 shows the abundance distribution of each carbonate facies in the Tikorangi Formation at each well. Based on the distribution of these facies in relation to over- and underlying units, new positions for the tops and bottoms are suggested for the Tikorangi Formation in the eight wells. Until now, these boundaries have been defined solely on a change in geophysical log response rather than on a known facies change. Fig. 2.11 shows a cumulative facies distribution plot for the eight wells. Of note is the dominance of Facies B in offshore Maui-1, and the absence of any limestone Facies C or D. Conversely, Ngaere-2 not only contains the thickest Tikorangi Formation of the eight wells studied, but is the “cleanest” and most limestone-rich. Toko-1, Ngaere-2’s southern neighbour, also has a high proportion of both Facies C and D. Waihapa 6 is the least limestone-like of the onshore facies with a high proportion of siliciclastic Facies A and B. The other onshore wells have broadly similar facies distributions.

2.8.5 Interpreted whole rock compositions

Further correlations derived from the relationships between Dt versus the contents

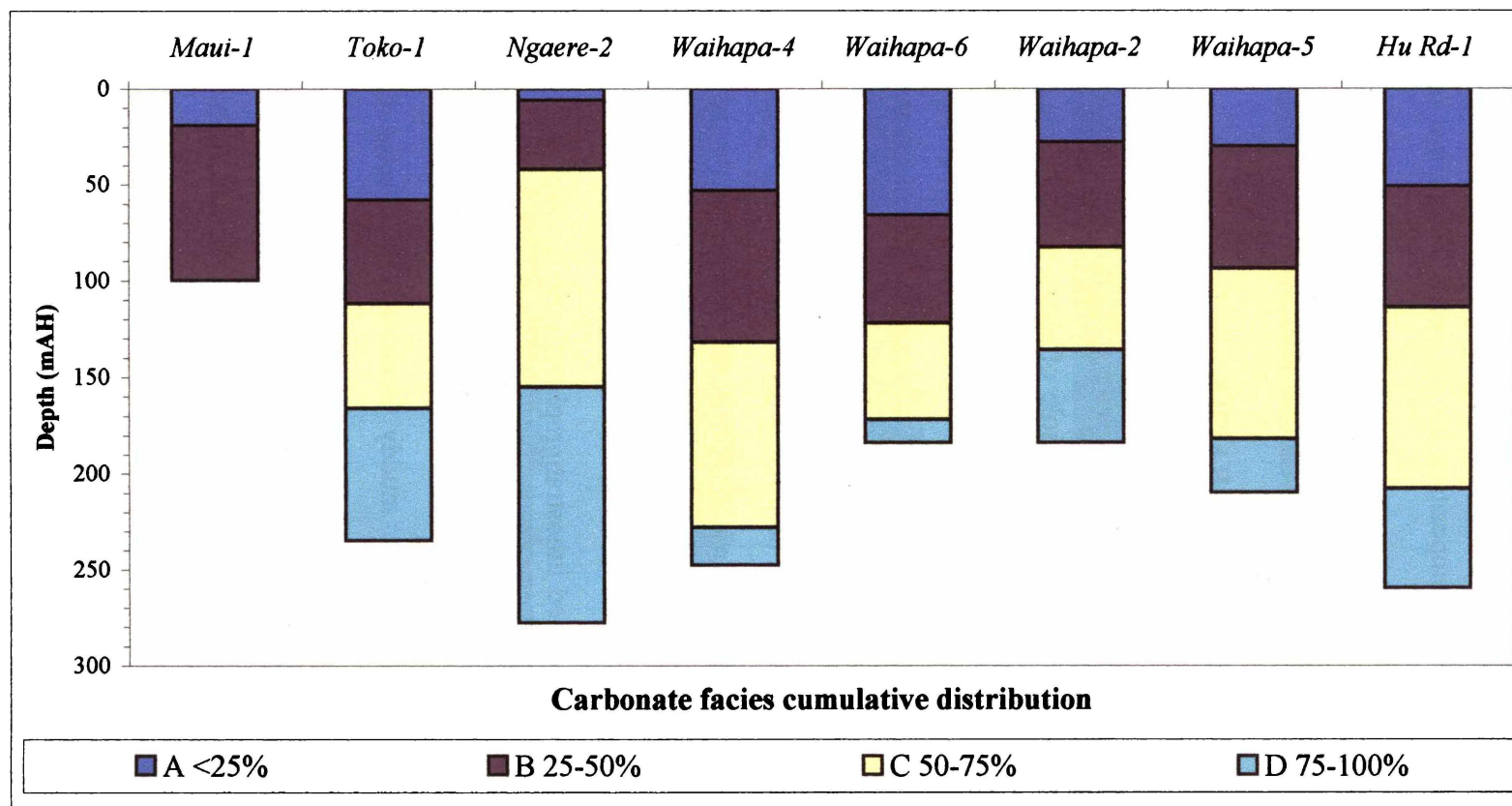


Fig. 2.11 Cumulative carbonate facies distribution plots for the eight study wells shown with the top of Tikorangi Formation as 0 datum and no stratigraphic position implied. mAH = metres along hole.

of total bioclasts, spar cement, matrix, and siliciclasts (Appendix 2.6, 2.7) enable more specific inferences to be drawn about whole rock composition in addition to the carbonate facies described above. An example for the Ngaere-2 well is shown on the right-side of Fig. 2.8 and for the other wells in Appendix 2.4, while notes on the trends in whole rock composition for all wells is contained in Appendix 2.10.

2.9 CARBONATE LITHOSTRATIGRAPHY

Fig. 2.12 is a panel diagram of the lithostratigraphy for the eight wells in this study. Maui-1, on the left, represents the sole offshore basinal facies, while the onshore foredeep facies wells are arranged from Toko-1 in the north to Hu Rd-1 in the south.

2.9.1 General observations

The basal Tikorangi Formation is commonly carbonate poor and grades from the underlying Otaraoa Formation through siliciclastic-dominated Facies A upward into a sequence of alternating mudstones and siltstones (Facies B) before, in most cases, thin limestone intervals (Facies C) are encountered. The base of the Tikorangi Formation is defined lithostratigraphically by an obvious change from Facies A dominance and geophysically by a correlatable marked decrease in Dt and GR values. Upon entering the lower carbonate units, carbonate content commonly increases from impure muddy limestones of Facies C (50-75% carbonate) to more sparry limestones of Facies D (>75% carbonate). In contrast to the lower boundary, the upper contact of the Tikorangi Formation with the overlying Taimana Formation is abrupt, and in all cases passes from more muddy Facies C or purer Facies D into a thin, very calcareous siliciclastite of Facies B. The low carbonate siliciclastic-dominated Facies A then marks the base of the overlying Taimana Formation.

Some major limestone units are present which may remain uninterrupted for

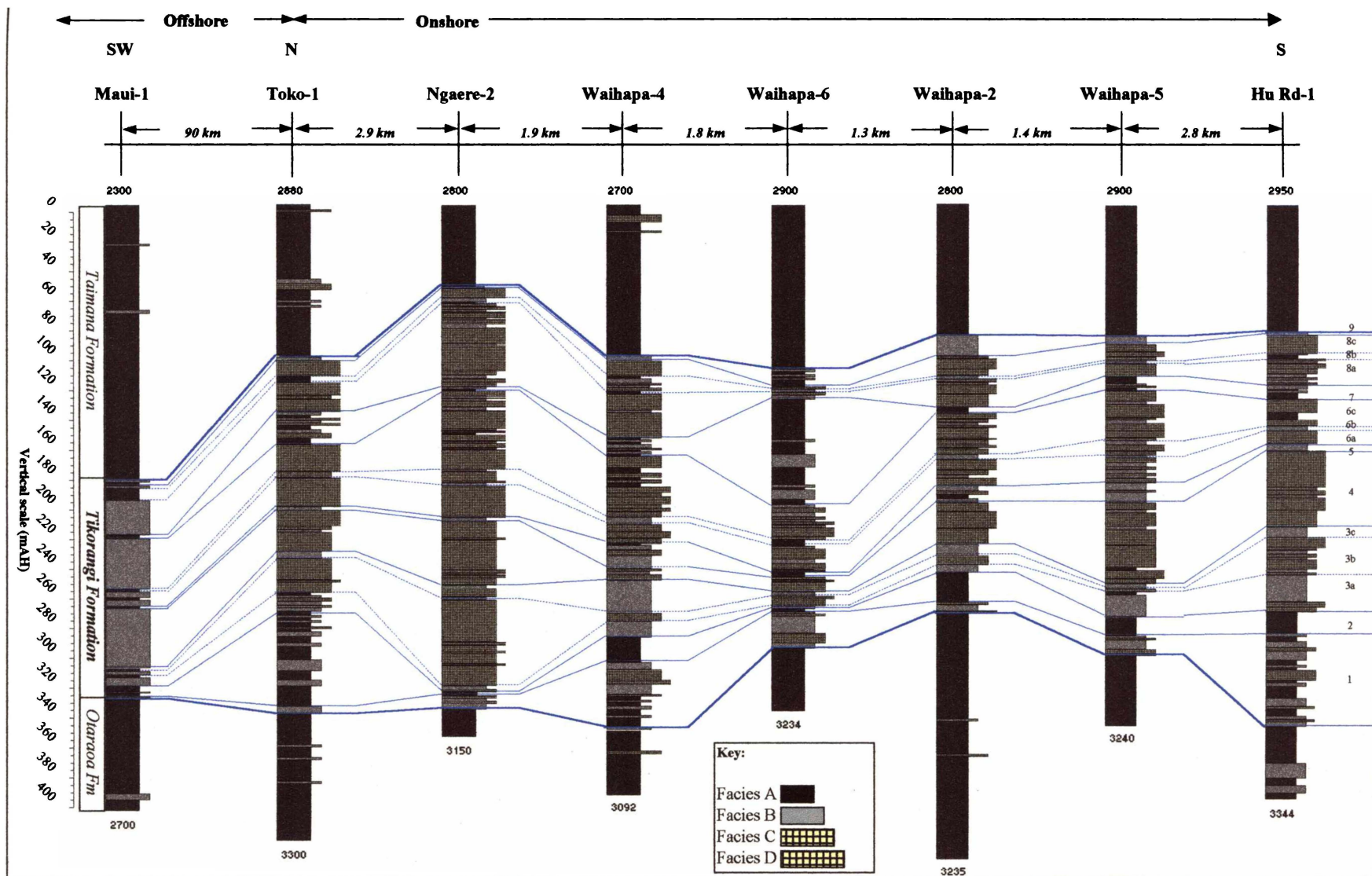


Fig. 2.12 Panel diagram showing the lithostratigraphy for the Tikorangi Formation interval. Wells are drawn from offshore Maui-1 to onshore Toko-1 and south to Hu Rd-1. Numbers at top and bottom of each column refer to depths in m AH (along hole). Lithostratigraphic subdivisions or units, defined by integrating geophysical well-log and carbonate percentage data, are numbered labelled on the right.

intervals up to 80 m thick. Thinner less-well developed limestone units are commonly separated by either single siltstone beds or, more commonly in the upper limestone, by either alternating siltstone-mudstone units or by solely mudstone facies.

The offshore Tikorangi Formation facies characterising the Maui-1 well comprises a much simpler lithologic succession than in the onshore wells because of the total dominance of siliciclastic-rich Facies A and B. The foredeep Waihapa-6 well shows some affinities with the Maui-1 well by being a more siliciclastic-dominated succession, with no development of the thick limestones occurring in the other onshore wells. Ngaere-2 is an especially limestone-rich well with a paucity of thin siliciclastic-rich facies.

Overall, the Tikorangi Formation is dominated by limestone facies with generally less common interbeds of siliciclastic-dominated facies that become more conspicuous in the lower part of the formation.

2.9.2 Lithostratigraphic units

Onshore wells are only 1-3 km apart, so that lithologic correlation of carbonate facies between wells should be possible. Tie lines have been suggested for facies between all the onshore wells, while correlation to the single offshore well is uncertain (Fig. 2.12). These litho-correlation lines effectively divide the Tikorangi Formation into nine major units, three of which have been further divided into sub-units (Fig. 2.12).

Table 2.3 summarises the stratigraphy of the nine major units in the eight wells. The offshore Maui-1 well has units which commonly comprise only one facies type, whereas most units in the onshore wells include a dominant, or occasionally co-dominant, facies, along with sub-dominant and minor facies associations. Fig. 2.12 shows the distribution and correlation of the units across all wells, while Table 2.4 summarises the facies makeup of the units for each of the offshore and onshore well sites. Some general comments follow about the individual units.

Table 2.3 Summary of lithostratigraphic unit data for the Tikorangi Formation in the eight study wells. mAH = metres along hole.

Tikorangi Formation	Maui-1	Toko-1	Ngaere-2	Waihapa-4	Waihapa-6	Waihapa-2	Waihapa-5	Hu Rd-1
Stratigraphy								
Total thickness	145	235	278	248	185	184	210	260
Unit 1								
Base unit (mAH)	2627	3217	3132	3050	3193	3072	3196	3295
Top unit (mAH)	2625	3212	3124	3005	3169	3065	3184	3234
Thickness (mAH)	2	5	8	45	24	7	12	61
% Total thickness	1	2	3	18	13	4	6	23
Unit 2								
Base unit (mAH)	2625	3212	3124	3005	3169	3065	3184	3234
Top unit (mAH)	2618	3151	3122	2989	3166	3045	3171	3221
Thickness (mAH)	7	61	2	16	3	20	13	13
% Total thickness	5	26	1	6	2	11	6	5
Unit 3								
3a								
Base unit (mAH)	2618	3151	3122	2989	3166	3045	3171	3221
Top unit (mAH)	2611	3137	3118	2979	3164	3040	3155	3195
Thickness (mAH)	7	14	4	10	2	5	16	26
% Total thickness	5	6	1	4	1	3	8	10
3b								
Base unit (mAH)	2611	3137	3118	2979	3164	3040	3155	3195
Top unit (mAH)	2609	3115	3061	2973	3157	3033	3152	3171
Thickness (mAH)	2	22	57	6	7	7	3	24
% Total thickness	1	9	21	2	4	4	1	9
3c								
Base unit (mAH)	2609	3115	3061	2973	3157	3033	3152	3171
Top unit (mAH)	2606	3110	3049	2952	3154	3026	3149	3164
Thickness (mAH)	3	5	12	21	3	7	3	7
% Total thickness	2	2	4	8	2	4	1	3
Unit 4								
Base unit (mAH)	2606	3110	3049	2952	3154	3026	3149	3164
Top unit (mAH)	2568	3083	3008	2943	3147	2998	3095	3113
Thickness (mAH)	38	27	41	9	7	28	54	51
% Total thickness	26	11	15	4	4	15	26	20
Unit 5								
Base unit (mAH)	2568	3083	3008	2943	3147	2998	3095	3113
Top unit (mAH)	2567	3081	3006	2927	3144	2988	3083	3108
Thickness (mAH)	1	2	2	16	3	10	12	5
% Total thickness	1	1	1	6	2	5	6	2
Unit 6								
6a								
Base unit (mAH)	2567	3081	3006	2927	3144	2988	3083	3108
Top unit (mAH)	2556	3061	2985	2914	3125	2970	3071	3100
Thickness (mAH)	11	20	21	13	19	18	12	8
% Total thickness	8	9	8	5	10	10	6	3

2.9.2a Unit 1

Unit 1 forms the base of the Tikorangi Formation and marks a gradational change from invariably siliciclastic-dominated Facies A of the underlying Otaraoa Formation into a very calcareous siliciclastite of Facies B. This unit may contain interbeds of Facies A with Facies B, and in some wells the unit may change to limestones of Facies C and D. In these wells (Hu Rd-1 and Waihapa-4) (Fig. 2.12) this basal unit reaches thicknesses of 61 and 45 m, respectively (Table 2.3). In other wells the thickness of the basal unit is typically less than 10 m.

2.9.2b Unit 2

This unit is invariably dominated by calcareous siliciclastites of Facies A in the onshore wells, which are correlated with dominantly Facies A deposits in the offshore Maui-1 well. In Toko-1 (Fig. 2.12), however, units of Facies A, thinning upward, are interbedded with very calcareous siliciclastites - Facies B, producing the thickest occurrence for unit 2 of 61 m (Table 2.3). In other wells unit 2 is usually less than 20 m thick, with particularly poor development in the limestone-rich Ngaere-2 well, and limestone-poor Waihapa-6 well.

2.9.2c Unit 3 (a/b/c)

Unit 3 has been divided into three sub-units. The lower unit 3a is dominated by Facies B, which may contain a thin limestone at the base, at Hu Rd-1, where the unit is thickest at 26 m, and at Ngaere-2 (Fig. 2.12). In other wells unit 3a is less than 16 m thick (Table 2.3). In Toko-1 Facies B is interbedded with thin limestones, which sees a change back to Facies A at the top of the unit, occurring also in Waihapa-5. Unit 3a is poorly developed in Waihapa-6. The equivalent unit in Maui-1 is again dominated by Facies B, with a thin overlying siliciclastic bed of Facies A.

Unit 3b is invariably composed of limestones of Facies C and some Facies D. Thin interbeds of Facies B occur in Hu Rd-1. Both Hu Rd-1 and Waihapa-6 grade upwards to purer limestones of Facies D (Fig. 2.12). Thin interbeds of Facies D limestones occur within a very thick (57 m) unit 3b in Ngaere-2. In all other wells

Table 2.3 cont. Summary of lithostratigraphic unit data for the Tikorangi Formation in the eight study wells. mAH = metres along hole.

Tikorangi Formation	Maui-1	Toko-1	Ngaere-2	Waihapa-4	Waihapa-6	Waihapa-2	Waihapa-5	Hu Rd-1
6b								
Base unit (mAH)	2556	3061	2985	2914	3125	2970	3071	3100
Top unit (mAH)	2554	3057	2975	2910	3122	2967	3055	3097
Thickness (mAH)	2	4	10	4	3	3	16	3
% Total thickness	1	2	4	2	2	2	8	1
6c								
Base unit (mAH)	2554	3057	2975	2910	3122	2967	3055	3097
Top unit (mAH)	2521	3039	2924	2869	3098	2939	3022	3079
Thickness (mAH)	33	18	51	41	24	28	33	18
% Total thickness	23	8	18	17	13	15	16	7
Unit 7								
Base unit (mAH)	2521	3039	2924	2869	3098	2939	3022	3079
Top unit (mAH)	2519	3017	2922	2857	3029	2936	3013	3070
Thickness (mAH)	2	22	2	12	69	3	9	9
% Total thickness	1	9	1	5	37	2	4	3
Unit 8								
8a								
Base unit (mAH)	2519	3017	2922	2857	3029	2936	3013	3070
Top unit (mAH)	2496	2998	2867	2828	3024	2917	3005	3053
Thickness (mAH)	23	19	55	29	5	19	8	17
% Total thickness	16	8	20	12	3	10	4	7
8b								
Base unit (mAH)	2496	2998	2867	2828	3024	2917	3005	3053
Top unit (mAH)	2488	2995	2863	2817	3022	2915	3002	3049
Thickness (mAH)	8	3	4	11	2	2	3	4
% Total thickness	6	1	1	4	1	1	1	2
8c								
Base unit (mAH)	2488	2995	2863	2817	3022	2915	3002	3049
Top unit (mAH)	2486	2985	2856	2806	3019	2902	2990	3037
Thickness (mAH)	2	10	7	11	3	13	12	12
% Total thickness	1	4	3	4	2	7	6	5
Unit 9								
Base unit (mAH)	2486	2985	2856	2806	3019	2902	2990	3037
Top unit (mAH)	2482	2982	2854	2802	3008	2888	2986	3035
Thickness (mAH)	4	3	2	4	11	14	4	2
% Total thickness	3	1	1	2	6	8	2	1

unit 3b is less than 24 m thick, and commonly less than 10 m, with poorest development at Waihapa-5. The unit is again represented by Facies B in Maui-1.

Unit 3c consists solely of very calcareous siliciclastites of Facies B, except at Ngaere-2 which contains a central dominant limestone bed of Facies C (Fig. 2.12). Unit 3c is thickest (21 m) in Waihapa-4, but is usually less than 12 m thick in all other wells (Table 2.3). The unit is represented by a thin siliciclastite in Maui-1.

2.9.2d Unit 4

In most wells unit 4 comprises a major limestone involving both Facies C and D, and is best developed in the southern Waihapa-5 and Hu Rd-1 wells, with thicknesses of up to 54 m (Fig. 2.12). The unit is relatively poorly developed in the central Waihapa-6 and Waihapa-4 wells where thicknesses are less than 10 m (Table 2.3). Toko-1 and Waihapa-4 contain a single thin Facies B bed within the limestone, while Waihapa-5 includes several interbeds of Facies B and rarely Facies A. The unit comprises Facies B in Maui-1.

2.9.2e Unit 5

Unit 5 is dominated by Facies B which contains a thin limestone unit in Waihapa-2, -4, and -5 (Fig. 2.12). The unit is at maximum thickness (16 m) in Waihapa-4, but is usually 6 m or less thick in other wells (Table 2.3). Waihapa-2 also contains a thin Facies A interbed at about mid-section, which is the only facies forming this unit in the siliciclastic-dominated Waihapa-6 and Maui-1 wells. Unit 5, not unlike many of the other siliciclastic-rich facies, is poorly developed in Ngaere-2 and Toko-1.

2.9.2f Unit 6 (a/b/c)

Unit 6a is a Facies C and D limestone-dominated unit, best developed and purest in the northern onshore wells of Ngaere-2 and Toko-1 where the purer Facies D limestones comprise the entire up to 21 m-thick unit (Fig. 2.12). The unit is, however, generally well represented in all wells. In Waihapa -6, -2, and -5 the limestone contains a single or multiple thin interbeds of Facies B.

Table 2.4 Summary of the facies makeup (A to D) for the nine stratigraphic units in both the seven onshore foredeep and single offshore basinal well.

Tikorangi Formation Stratigraphic Units															
Foredeep facies <i>Onshore wells</i>	1	2	3a	3b	3c	4	5	6a	6b	6c	7	8a	8b	8c	9
Range thickness (m)	5-61	2-61	2-26	3-57	3-21	7-54	2-16	8-21	3-16	18-51	2-69	5-55	2-11	3-13	2-14
Average thickness (m)	23	18	11	18	8	31	7	16	6	30	18	22	4	10	6
Dominant facies	B	A	B	C	B	C/D	B	C/D	B	C/D	A	C/D	B	C	B
Subdominant facies	A/C	-	-	D	-	-	-	-	C/D	A	B/C	-	A	D	-
Minor facies	D	B/C	A/C/D	B	C	A/B	A/C	B	-	B	D	A/B	C	-	A
Basinal facies <i>Offshore well</i>	1	2	3a	3b	3c	4	5	6a	6b	6c	7	8a	8b	8c	9
Thickness (m)	2	7	7	2	3	38	1	11	2	33	2	23	8	2	4
Dominant facies	B	A	B	B	A	B	A	B	A	B	A	B	A	B	A/B
Minor facies	-	B	A	-	-	-	-	A	-	-	-	-	-	-	-

Unit 6b is typically a thin, poorly developed very calcareous siliciclastite (Facies B) with a limited range of thicknesses, typically less than 5 m in most wells (Table 2.3). Ngaere-2 and Waihapa 5 wells contain a single limestone interbed, while Toko-1 is represented solely by Facies C limestone as the unit clearly becomes more carbonate-rich northwards (Fig. 2.12). The unit is represented by a thin Facies A in Maui-1.

Unit 6c is a co-dominated Facies C and D limestone unit which is particularly well developed in Ngaere-2 and Waihapa-4 with thicknesses of 51 m and 41 m, respectively (Fig. 2.12; Table 2.3). This unit well developed carbonate unit tends to be purest in the southern wells where Facies D limestones become dominant. The unit can contain thin unit(s) of Facies A or B, and is least developed in Toko-1 and Hu Rd-1 with thicknesses of 18 m.

2.9.2g Unit 7

Unit 7 is dominated by Facies A calcareous siliciclastites and is usually less than 10 m thick, but is uncharacteristically well developed in Waihapa-6 with a thickness of 69 m (Fig. 2.12; Table 2.3). In many wells unit 7 comprises interbeds of very calcareous siliciclastites of Facies B and limestones of Facies C, and rarely of Facies D. In Ngaere-2 and Waihapa-2 the unit consists solely of Facies A, and likewise at Maui-1.

2.9.2h Unit 8 (a/b/c)

Unit 8a is a high carbonate unit which is best developed in the northern wells and reaches its maximum thickness (55 m) at Ngaere-2 (Fig. 2.12). In other wells the unit is generally less than 30 m thick (Table 2.3). In Ngaere-2, Waihapa-4, and Hu Rd-1 the unit contains rare thin interbed(s) of Facies B.

Unit 8b is typically a thin Facies B-dominated unit which is thickest (11 m) in Waihapa-4, but is less than 5 m in most other wells. The unit is less pure to the south where it is represented solely by Facies A in Toko-1 and offshore Maui-1 (Fig. 2.12; Table 2.3). Waihapa-4 contains thin interbeds of Facies B and C set in

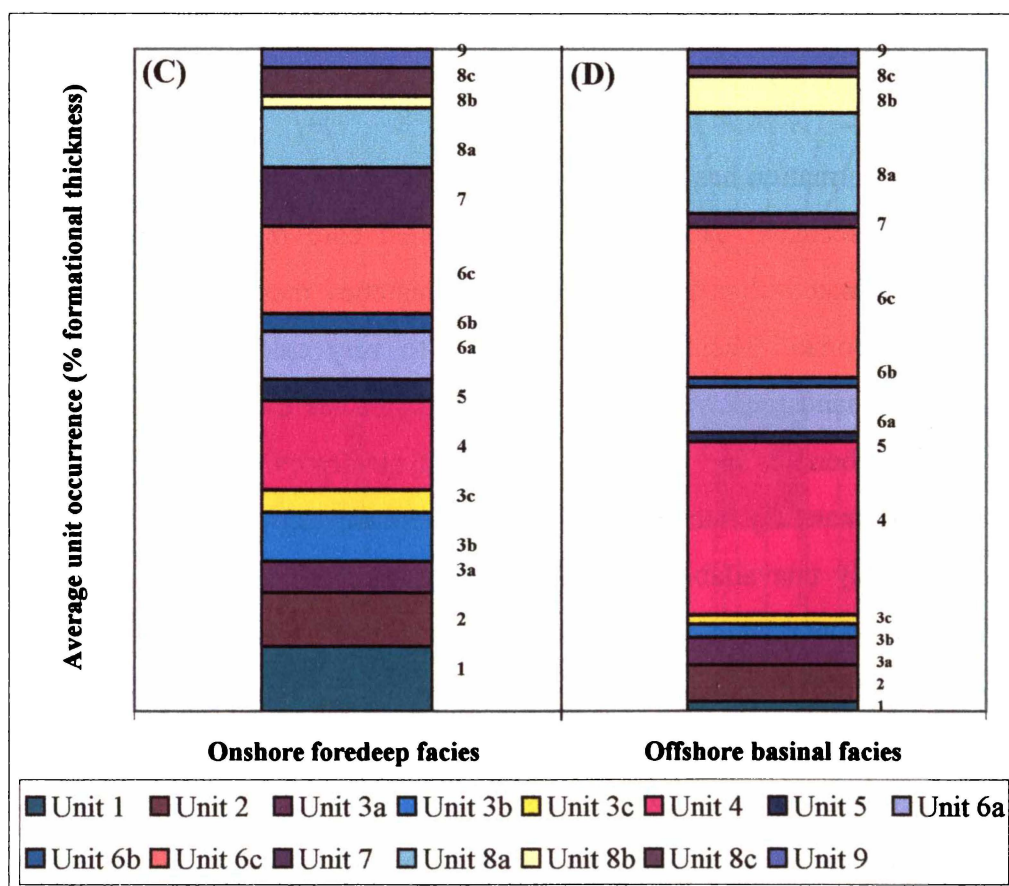
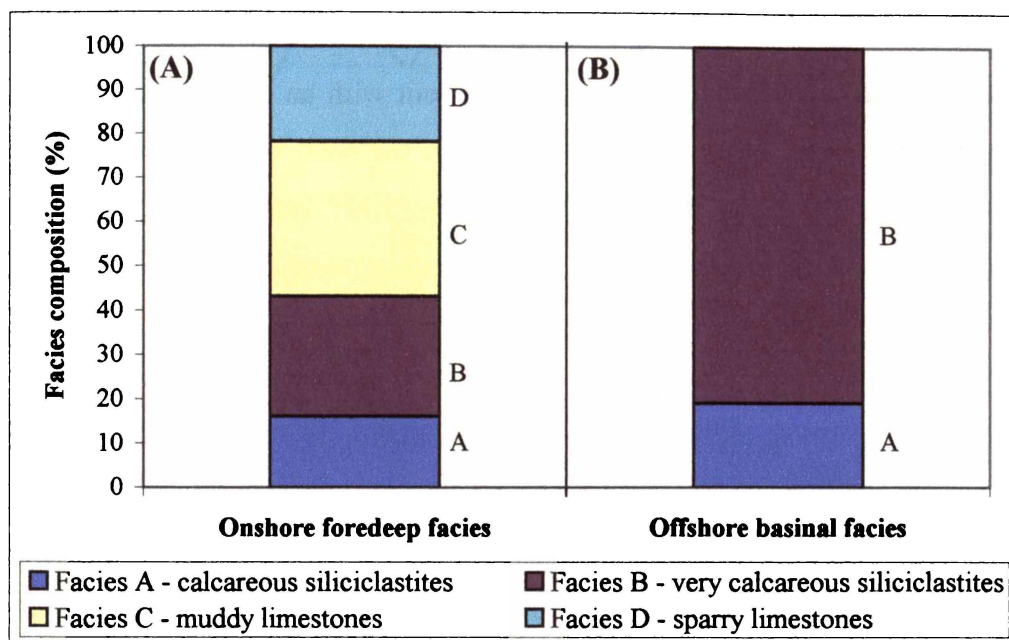


Fig. 2.13 Carbonate facies occurrence as % of formational thickness within the onshore foredeep megafacies (A) and offshore basinal megafacies (B). Stratigraphic unit occurrence as % of average formational thickness for onshore foredeep megafacies (C), and offshore basinal megafacies (D).

Facies A.

Unit 8c is the uppermost and purest carbonate unit with an absence of any non-carbonate facies. The unit tends to be thicker in the southern wells, reaching a maximum thickness of 13 m in Waihapa-2 (Fig. 2.12; Table 2.3). It is poorly developed in Waihapa-6. A thin Facies B is representative of the unit in Maui-1.

2.9.2i Unit 9

Unit 9 is the uppermost unit of the Tikorangi Formation and is dominantly a thin Facies B unit. In Waihapa-2 this unit is best developed with a thickness of 14 m, while in other wells the unit is commonly less than 5 m thick (Fig. 2.12; Table 2.3). Unit 9 passes abruptly into low-carbonate siliciclastic-dominated facies of the overlying Taimana Formation.

2.10 DISCUSSION

The Tikorangi Formation has been divided into four major carbonate facies based on carbonate percentage data derived from limited core material: Facies A - siliciclastic-dominated slightly to moderately calcareous mudstone to claystone with <25% carbonate; Facies B - moderately to very calcareous siliciclastic siltstone to fine sandstone with 25-50% carbonate; Facies C - muddy limestone with 50-75% carbonate; and Facies D - a purer, typically more sparry limestone with >75% carbonate. By integrating this carbonate database with geophysical log data, a previously unavailable carbonate lithostratigraphy based on these four facies has been constructed for both the onshore foredeep and offshore basinal “megafacies” of the Tikorangi Formation.

Siliciclastites of Facies A are the least abundant facies, accounting for about 16% of the formation in onshore wells, and 19% in the offshore Maui-1 well (Fig. 2.13A, B). Highly calcareous siltstones to fine sandstones of Facies B account for slightly more than one quarter of the formation onshore and the remaining 81% of

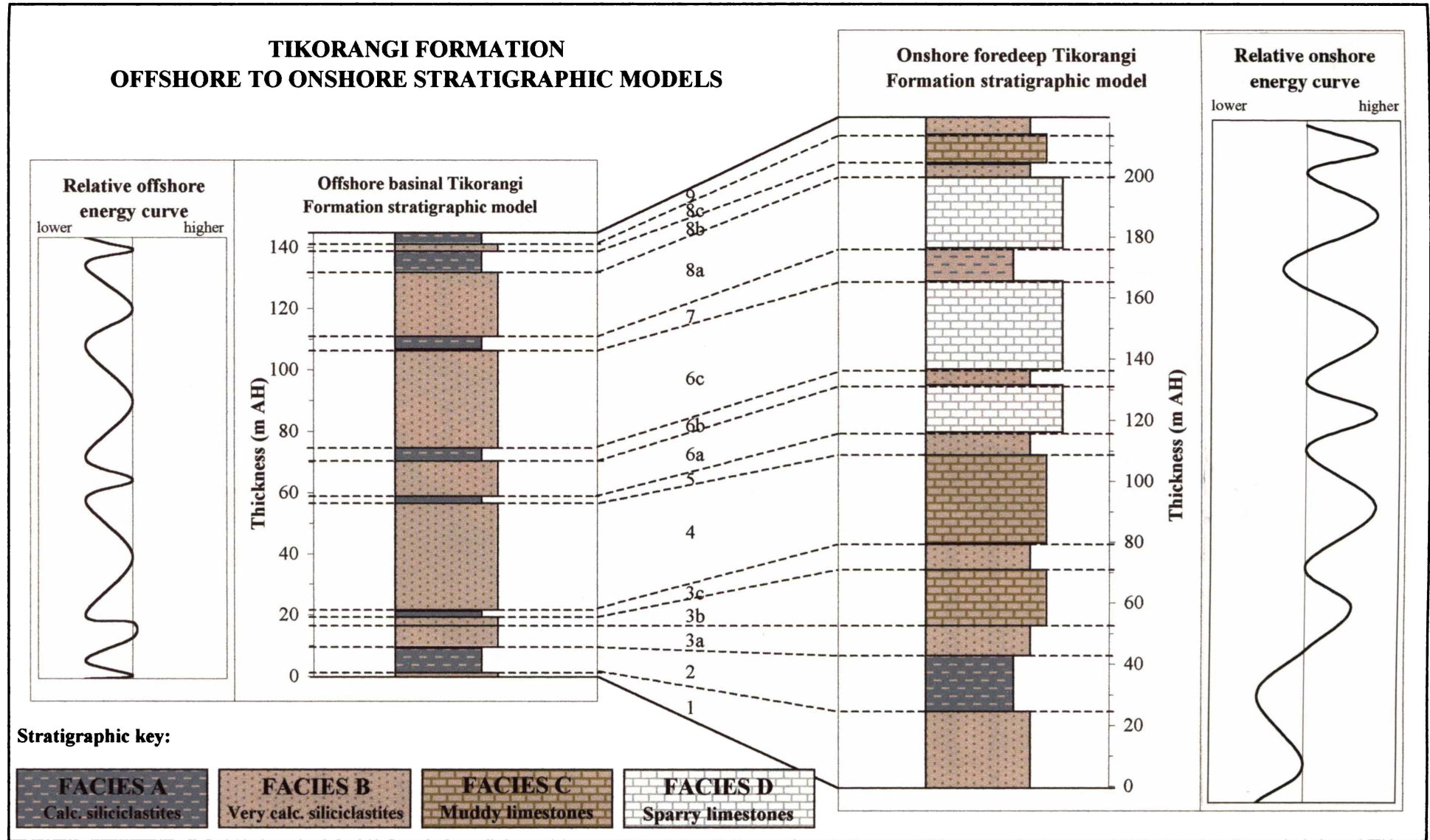


Fig. 2.14 Simplified lithostratigraphic models for the onshore foredeep and offshore basinal megafacies of the Tikorangi Formation showing associated relative changes in inferred depositional energy. Higher energy units in foredeep facies represent significant input from mass-emplacement events sourced from shallower shelfal depths.

the formation offshore (Fig. 2.13A, B). The two high-carbonate facies, C and D, respectively represented by muddy fine limestones (50-75% carbonate) and purer, coarse sparry limestones (>75% carbonate), occur solely with the onshore foredeep facies, and together account for 57% of the Tikorangi Formation (Fig. 2.13A).

The differing distribution and bedding interrelationships of the four carbonate facies has enabled the definition of nine major correlatable units within the Tikorangi Formation. Fig. 2.13C, D shows the average relative abundance of these units in the formation. These nine units can be simplified by representing each unit by its dominant carbonate facies type to produce a summary graphic log for each well, and in turn a simplified lithostratigraphic model for the foredeep to offshore basinal megafacies of the Tikorangi Formation (Fig. 2.14).

The onshore foredeep megafacies column (Fig. 2.14) emphasises the predominance of muddy and sparry limestones of Facies C and D. Six major limestone units are identified which are particularly well developed in the middle- and upper-portions of the formation. These limestones are separated by generally thinner, moderately to highly calcareous siliciclastites of Facies B, which tend to decrease in thickness upwards as the overall carbonate content increases. In all cases the Facies B units are less than eight metres thick, while the limestone units are at least twice, and commonly three times, this thickness. The basal Tikorangi Formation is unequivocally marked by an increase in carbonate content and the appearance of the first moderately calcareous unit comprising Facies B. But overall the lower part of the formation is typically carbonate-poor and includes an interval of Facies A calcareous siliciclastites (unit 2) before passing up into more carbonate-rich facies.

The summary model for the offshore basinal facies (Fig. 2.14) similarly depicts nine major identifiable units, which possibly could be lateral correlatives of those onshore. Limestones are absent here and are replaced by moderately to highly calcareous siliciclastites (mudstones) of Facies B, with thin interbeds of slightly to

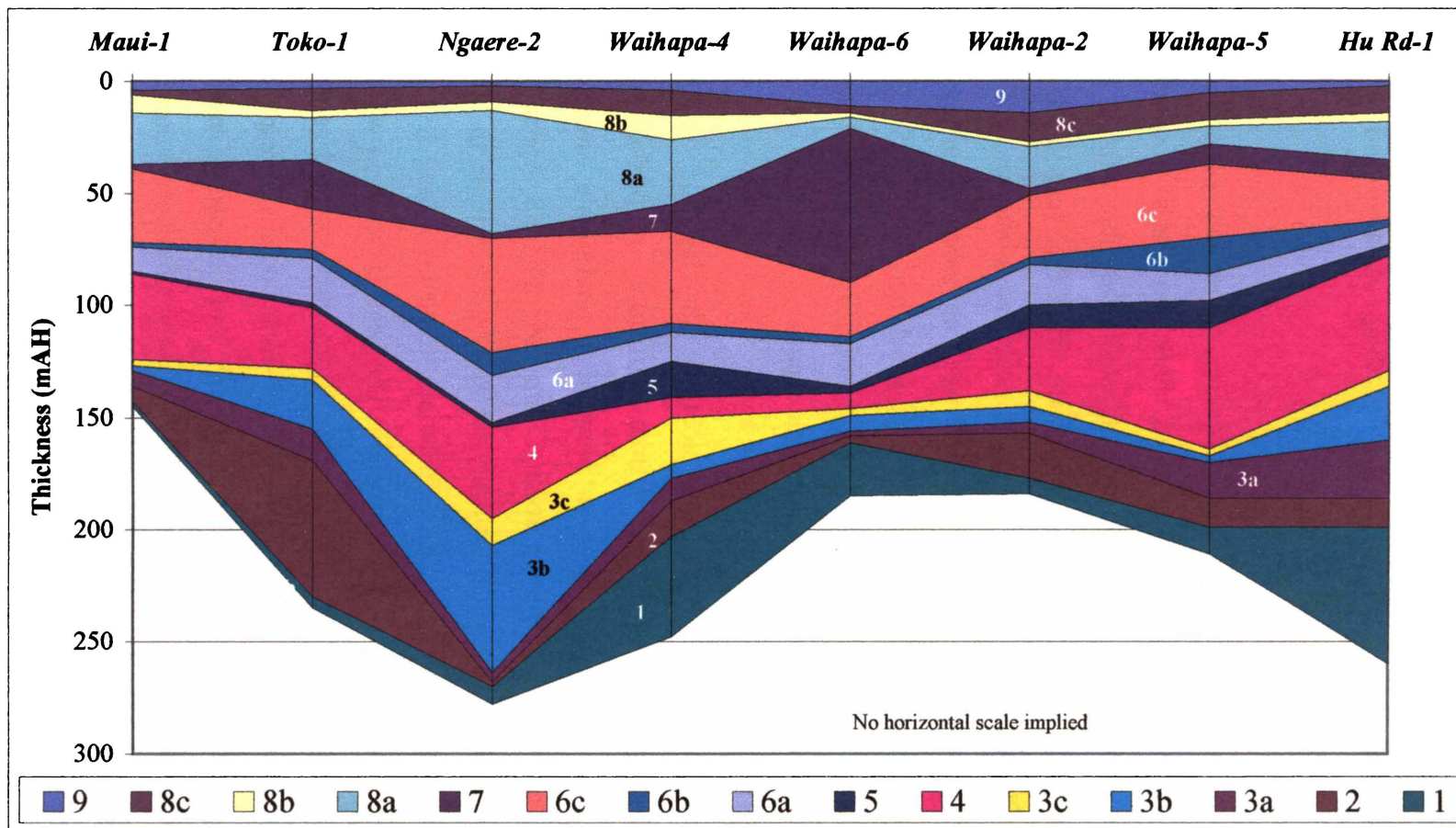


Fig. 2.15A Basic lithostratigraphy of the Tikorangi Formation within the study wells showing correlation of units with top Tikorangi Formation as datum. mAH = metres along hole.

moderately calcareous siliciclastites (Facies A). The absence of limestone Facies C and D in Maui-1 points to a depositional site sufficiently distal from a shelf source area that shelf carbonate material has not been redeposited en masse to this locality. Meanwhile, siliciclastic input has remained sufficiently high to dilute any carbonate accumulating from the pelagic settling of dominantly planktic foraminifera and coccoliths.

The lithology of the Tikorangi Formation at Maui-1 has previously been described by King & Thrasher (1996) as interbedded chalk and marls. This could be somewhat misleading given that the term chalk usually describes a rather soft and friable, deep-water limestone, which contrasts with the very hard, dense, calcareous mudstone evident in core sample. The calcareous mudstones of Maui-1 therefore represent a transition between the foredeep facies occurring in the onshore wells and a true basinal carbonate ooze which may be found in the more distal western and northwestern extents of the basin (Simpson 1992), far away from the influence of any significant siliciclastic input.

Whole rock compositions (proportions of bioclasts, siliciclasts, matrix, and spar cement in samples) have been derived from correlations of petrographic and geophysical log data to provide a previously unavailable interpretative compositional record for the entire Tikorangi Formation (Fig. 2.8; Appendix 2.4). The basal Tikorangi Formation is typically marked by an increase in bioclastic detritus at the expense of siliciclastic material, so distinguishing it from the underlying less calcareous Otaraoa Formation. The general trends in whole rock composition reinforce those already established from carbonate and geophysical log analysis, with an overall upcore increase in carbonate content corresponding to increasing amounts of bioclasts and spar cement, and decreasing amounts of siliciclastic and micrite/matrix material. This implies there has been a diminishing siliciclastic input throughout the time of deposition of the Tikorangi Formation, and/or a corresponding increase in carbonate production. The top of the formation is defined by a return to low-carbonate siliciclastites of Facies A upon entering the overlying Taimana Formation.

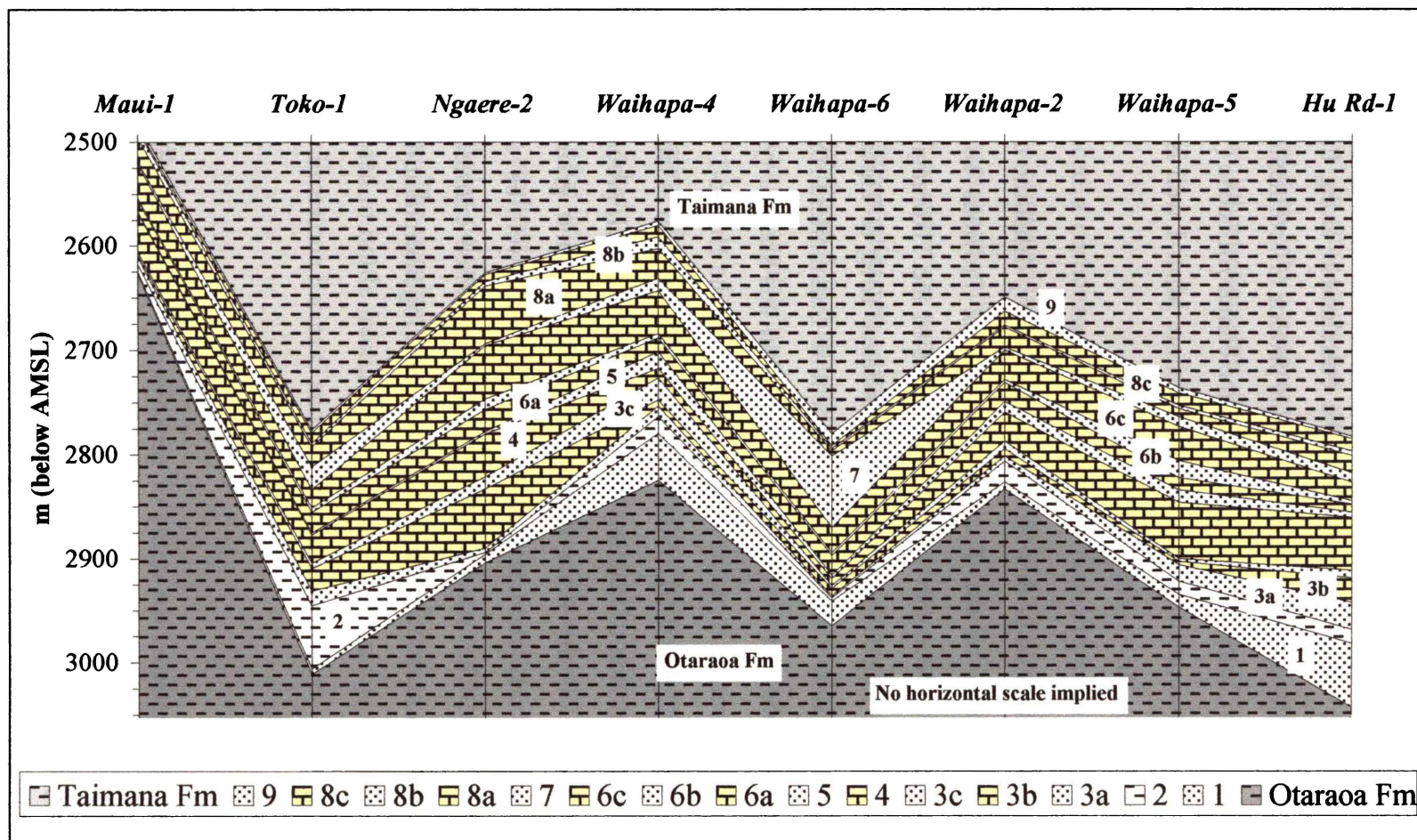


Fig. 2.15B Complete lithostratigraphy for the Tikorangi Formation within the study wells showing units in current stratigraphic position, and the dominant lithologic facies within each unit. mAMSL = metres above mean sea-level.

Subdivision of the Tikorangi Formation into nine major units, each comprising either a single, or some combination of the four, carbonate facies, has provided an opportunity for suggesting lithostratigraphic correlations between the eight wells in this study (Fig. 2.15A, B). Given the short distance of spacing between the seven onshore wells, these units appear to be correlatable along their general north-south trend. This implies a broadly similar pattern of sedimentation in the vicinity of the eastern Taranaki Basin margin in the earliest Miocene (Waitakian). Correlation between the onshore wells and the offshore Maui-1 well is suggested, but is much more speculative (Fig. 2.14, 2.15A, B).

It has not been the intention of this topic to address in any detail the depositional mechanisms and setting of the Tikorangi Formation. Previous authors (e.g., Simpson 1992; King & Thrasher 1996) have suggested the Tikorangi Formation was formed from the redeposition of shelf carbonates. King & Thrasher (1996) suggested that the common occurrence of the benthic foraminifera *Amphistegina* is indicative of redeposition from shallow waters, but this skeletal type was not observed in any core material in this study apart from in the Hu Rd-1 well. Other evidence for a mass-emplaced origin for the Tikorangi Formation is hard to gauge because of the general lack of bedding features in core material, probably due to strong bioturbation. On the other hand, the often very fine grain size and fragmental nature of skeletal material in samples may well be a result of reworking downslope. The topic will be re-addressed when considering other information derived from petrographic and geophysical log interpretations.

2.11 CONCLUSIONS

This study has demonstrated the utility of geophysical logs in subsurface studies where a limited and incomplete core record negates the opportunity for more traditional study using sedimentological methods. The integration of core-derived laboratory data and geophysical log data can provide a means by which invaluable, complete, and relatively detailed lithostratigraphic interpretations can

be made for an entire formation where none were previously possible due to the limitations imposed by incomplete core. However, this kind of interpretative lithostratigraphic reconstruction and correlation must be kept at a level which is commensurate with the quality and resolution of available data. The type of integration used in this study has provided a basis for the subdivision of the Tikorangi Formation into a number of readily identifiable and correlatable units which form a lithostratigraphic framework for further evaluating formation characteristics.

Having produced a carbonate-content based lithostratigraphy for the Tikorangi Formation, it is suggested that the lower and upper boundaries of the formation be redefined in accordance with those presented in this study. It is also suggested that assignment of a new type section is appropriate because of the lack of core material and lithostratigraphic data for the present Mangahewa-1 type section. Accordingly, Waihapa-5 is nominated as the new type section for the Tikorangi Formation due to the availability of over 112 m of core material (Appendix 2.4.7).

Further application of the correlations derived in this study could be extended to other wells in which geophysical logs have been recorded through the Tikorangi Formation and for which no core material exists. This would provide additional impetus to the study of the Tikorangi Formation as an oil-producing reservoir by allowing the fuller delineation and correlation of units throughout the eastern Taranaki Basin. The optimum units for fracture development would probably be those predisposed to brittle fracture, namely the denser and purer carbonate units represented by limestone Facies C and D in this study.

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TOPIC 3:

WELL-LOG TRENDS AND DEPOSITIONAL HISTORY OF THE MID-TERTIARY TIKORANGI FORMATION RESERVOIR, TARANAKI BASIN, NEW ZEALAND

3.1 ABSTRACT

The Oligocene-Early Miocene Tikorangi Formation, an important fracture-controlled reservoir, is a redeposited, mixed carbonate-siliciclastic sequence within the Ngatoro Group, Taranaki Basin, New Zealand. The Tikorangi Formation developed during a period of major tectonic subsidence and a basinwide marine transgression which were fundamentally responsible for controlling the creation of foredeep trough accommodation, the rate and type of sediment supply into the foredeep, and the relative position of sea level. The complex interplay of these factors has produced both a vertically and laterally varied, and lithostratigraphically complex, carbonate-dominated sequence.

Carbonate supply basinward has been by periodic mass emplacement events, formed by highstand shedding from topographic highs and fringing shelf areas. Storms and tectonic disturbances may have been important periodic triggers. Mass emplacement has displaced shallow-water biota (e.g., coralline red algae, *Amphistigena*) basinward to be variably intermixed with pelagic deeper-water bathyal biota. Proximal parts of the transgressive and highstand carbonate facies tracts were deposited in deep shelfal depths, but distal facies were deposited at bathyal depths.

Geophysical well-log characterisation has enabled a “sequence stratigraphy type approach” that has provided a surrogate chronostratigraphic framework within which five major geophysical log sequences, representative of sedimentary phases within the Tikorangi Formation, have been identified and correlated. Phase I -

base of TST, comprising retrogradational siliciclastic-dominated redeposited units associated with foredeep subsidence. Phase II - continuation of Phase I retrogradation but with increased mass redeposited carbonate influx during accelerated foredeep subsidence and sea-level rise, the top marking the maximum flooding surface. Phase III - base of HST, a progradational sequence comprising relatively pure redeposited carbonate units associated with declining subsidence rates and minimal siliciclastic input, with movement of facies belts basinward. Phase IV - prograding aggradation dominated by often thick, periodically mass-emplaced, carbonate-rich units separated by thin background siliciclastic shale-like units. Facies belts remained essentially static. Phase V - top of HST and retrogradational sequence marks the reintroduction of siliciclastic material into the basin following uplift of Mesozoic basement associated with accelerated compressional tectonics along the Australia-Pacific plate boundary, initially diluting and ultimately extinguishing carbonate production factories. The top of the Tikorangi Formation marks a return to siliciclastic-dominated sedimentation and the start of a major tectonically-controlled regressive phase which is still continuing.

Keywords carbonate; geophysical logs; depositional history; mid-Tertiary; Tikorangi Formation; hydrocarbons; fractured reservoir, Taranaki Basin, New Zealand

3.2 INTRODUCTION

The Oligocene to Early Miocene carbonate-rich Tikorangi Formation is an important economic fracture-controlled reservoir within the subsurface of Taranaki Basin, North Island, New Zealand (Fig. 3.1). The formation belongs in the Ngatoro Group, together with the calcareous, siliciclastic-dominated units of the underlying Otaraoa Formation and the overlying Taimana Formation (Fig. 3.2). The Ngatoro Group is part of an up to about 8 km thick sedimentary succession filling Taranaki Basin (King & Thrasher 1996) (Fig. 3.1C). The

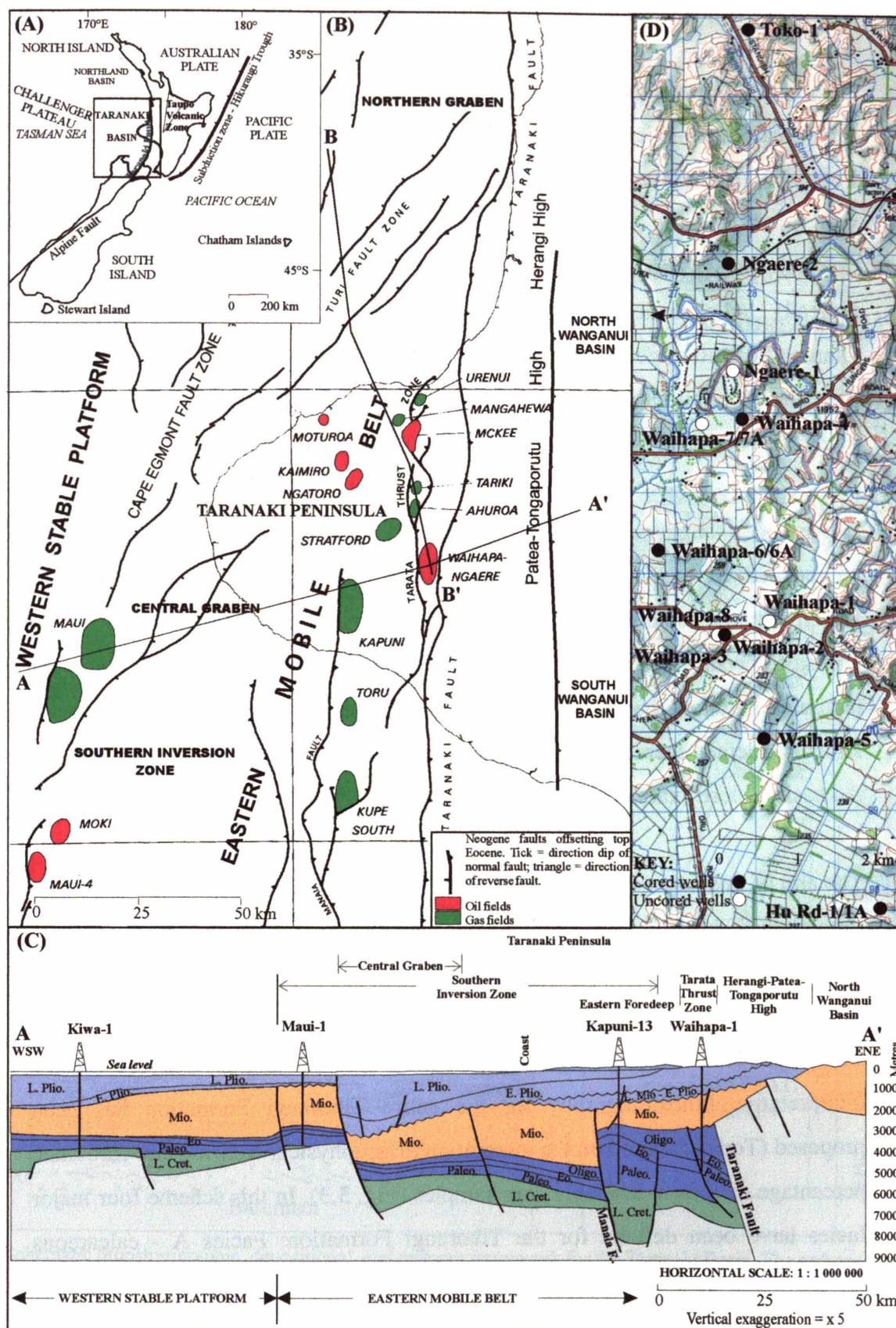


Fig. 3.1 (A) Location of Taranaki Basin in New Zealand. (B) Major structural and tectonic elements and main oil/condensate accumulations within Taranaki Basin. The Tikonangi Formation is dated as earliest Miocene in the east (Waihapā-1) and Oligocene-Early Miocene in the west (Maui-1). Adapted from King & Thrasher (1996). (C) Structural cross-section of a transect running WSW - NE through offshore Maui-1 and onshore through the Waihapā-Ngaere Field, Tarata Thrust Zone (see location in B). Adapted from King & Thrasher (1996). Shading: ■ = late Neogene, ■ = early Neogene, ■ = Paleogene, ■ = Late Cretaceous, ■ = basement. E. Plio. = Early Pliocene; L. Plio. = Late Pliocene; Mio. = Miocene; Oligo. = Oligocene; Paleo. = Paleocene; L. Cret. = Late Cretaceous. E. Plio. = Early Pliocene; L. Plio. = Late Pliocene; Mio. = Miocene; Oligo. = Oligocene; Paleo. = Paleocene; L. Cret. = Late Cretaceous. (D) Location of the seven onshore wells (solid circles) providing core from the Tikonangi Formation within the Waihapā-Ngaere Field that form the basis for this study.

Tikorangi Formation is the most distinctive unit in the Ngatoro Group, comprising mixed carbonate-siliciclastic deposits. In onshore wells (foredeep facies – see Topic 2) these are typically muddy to sometimes sparry limestones, interbedded with fine calcareous sandstones, siltstones and claystones, while in offshore wells (basinal facies) the Tikorangi Formation consists of highly calcareous, but typically siliciclastic-dominated condensed deeper-water equivalents. The Otaraoa Formation consists of siltstones and sandstones (Palmer 1985), while the Taimana Formation is predominantly a siltstone with some fine sandstone, mudstone, and thin limestone development (King & Thrasher 1996).

It has been suggested that the Tikorangi Formation sediments have been redeposited from shallower depths (Simpson 1992; King & Thrasher 1996), principally because of the occurrence of some shallow-water benthic foraminifera amongst deeper outer shelf/slope biota. However, due to the strongly bioturbated nature of much of the sediment which has obscured textural, compositional and structural details there is little evidence for inferring a history of redeposition on the basis of core examination alone.

The aim of this paper is to identify and interpret the geophysical well-log patterns through the Tikorangi Formation in wells from the onshore Waihapa-Ngaere Field and the offshore Maui-1 site (Fig. 3.1) as a basis for unravelling a broad-scale depositional history of the deposits. Despite the wholly subsurface nature of the Tikorangi Formation and the lack of continuous core through the formation, a new interpretative lithostratigraphy for the entire Tikorangi Formation has been proposed (Topic 2) based on the integration of geophysical well-log and carbonate percentage data from available core samples (Fig. 3.3). In this scheme four major facies have been defined for the Tikorangi Formation: Facies A - calcareous siliciclastites (typically claystones to mudstones with <25% carbonate); Facies B – very calcareous siliciclastites (typically siltstones to fine sandstones with 25-50% carbonate); Facies C - muddy limestones with 50-75% carbonate; Facies D - sparry limestones with >75% carbonate. The work has enabled subdivision of the Tikorangi Formation into a number of readily identifiable and correlatable units

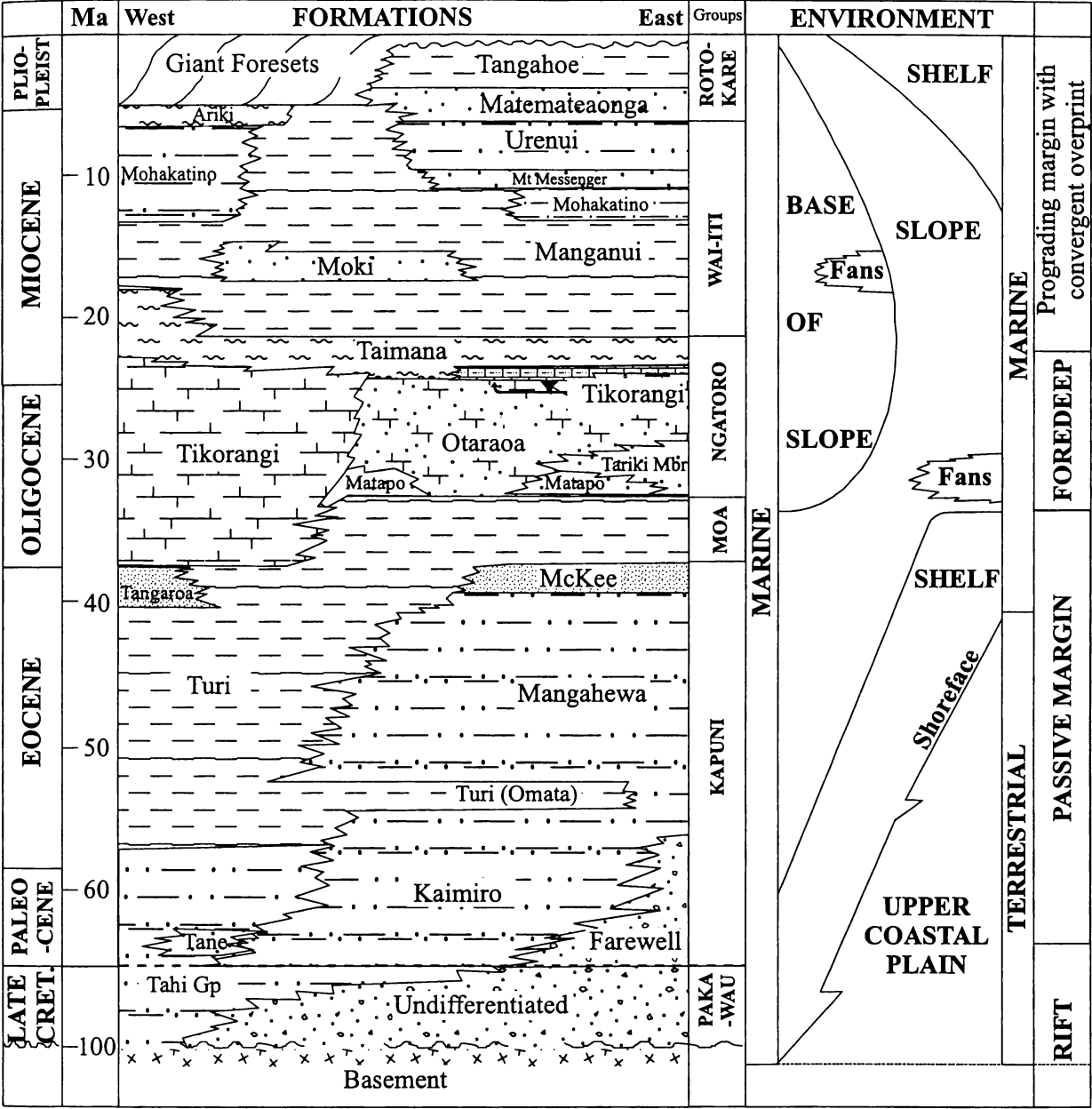


Fig. 3.2 Schematic lithostratigraphic, depositional, and tectonic framework for the Taranaki Basin. The carbonate-dominated Tikorangi Formation sits unique amongst otherwsie siliciclastic-dominated facies. Adapted from King (1990).

which form the lithostratigraphic framework for this paper. However, by themselves lithostratigraphic studies provide no real chronostratigraphic base as correlations are often diachronous (Emery & Myers 1996). The use of well-log characterisation as a correlation tool affords more of a “sequence stratigraphy type approach” that should provide a surrogate chronostratigraphic framework for the deposits.

This "sequence stratigraphy type approach" relies upon the identification and correlation of "like" geophysical-log patterns that will be shown to correspond to a limited number of sedimentary stages or phases within the Tikorangi Formation. These sedimentary phases provide a basis for establishing the formation's depositional history. The relationships and timing of the phases to the nine major lithostratigraphic units within the Tikorangi Formation (Fig. 3.3) will be examined to provide an insight into the relative timing of their formation between the wells. In turn this allows some general inferences to be drawn about possible depositional controls and mechanisms. Waihapa-5 well (Fig. 3.1D, 3.3) will be used as a case example.

3.3 GEOLOGIC SETTING

The Tikorangi Formation was deposited in a foreland basin setting within Taranaki Basin (Fig. 3.4) (Stern & Davey 1990; Stern & Holt 1994; King & Thrasher 1996), adjacent to the Australian-Pacific Plate boundary (Fig. 1.1A). The Patea-Tongaporutu-Herangi High, a buried upthrust basement block east of the Taranaki Fault, separates the Taranaki Basin from the Late Paleogene-Quaternary sediments in North and South Wanganui Basins to the east (Fig. 3.1B) (Palmer & Andrews 1993; King & Thrasher 1996). Although carbonate sedimentation usually occurs during periods of tectonic quiescence and minimal siliciclastic input (e.g., Nelson & Hume 1987; Smosna & Patchen 1991; James 1997), the Tikorangi Formation formed during a major tectonic change at the onset of Pacific Plate subduction beneath the Australian Plate. Comparisons can

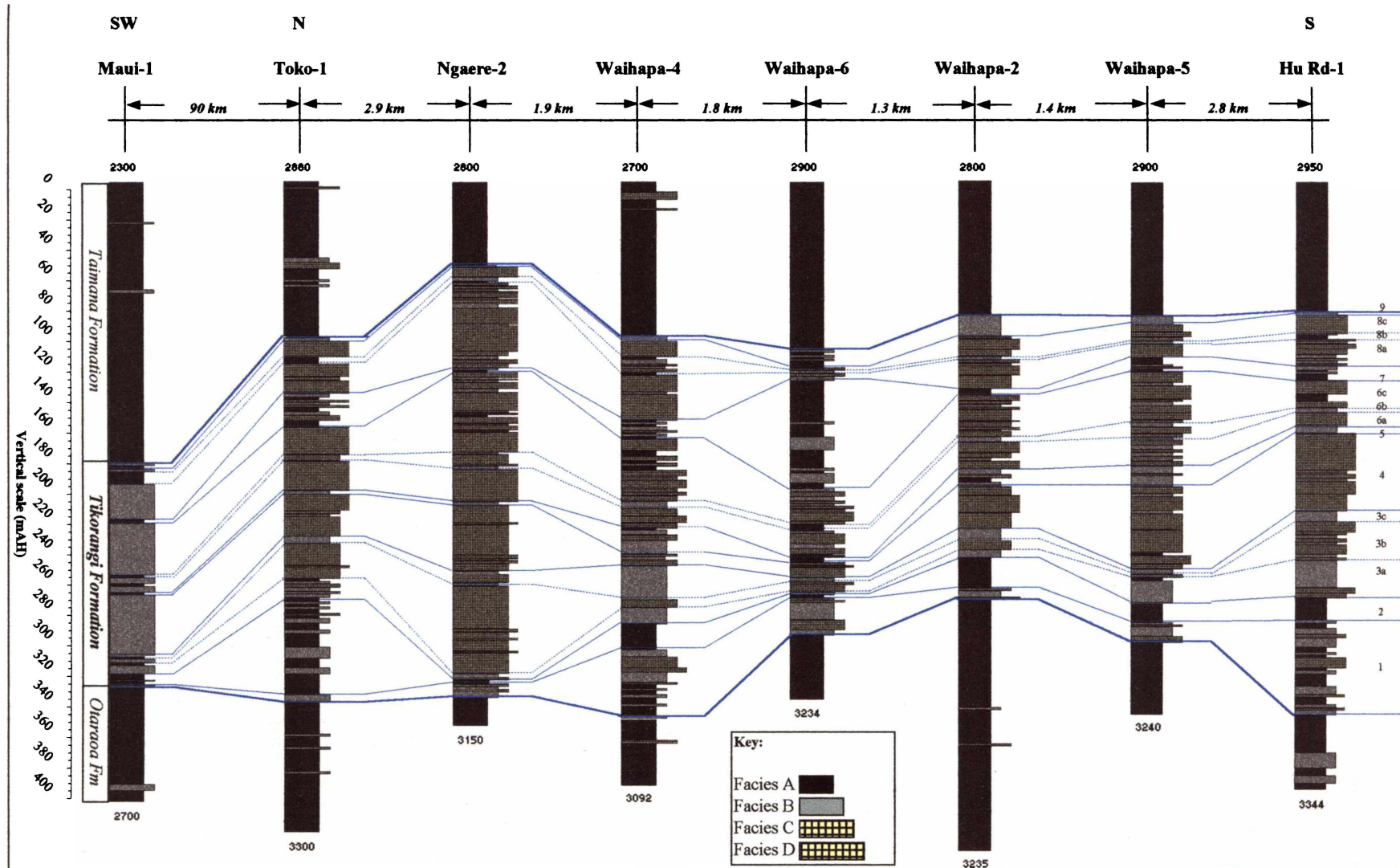


Fig. 3.3 Panel diagram showing the lithostratigraphy for the Tikorangi Formation interval. Wells are drawn from offshore Maui-1 to onshore Toko-1 and south to Hu Rd-1. Numbers at top and bottom of each column refer to depths in m AH (along hole). Lithostratigraphic subdivisions or units, defined by integrating geophysical well-log and carbonate percentage data (see Topic 2), are numbered labelled on the right.

be made with Ordovician limestone in the central Appalachian Basin which similarly formed during an active phase of plate collision. Taranaki Basin foundering in the Oligocene and the initiation of a basinwide marine transgression, caused by foreland thrust loading (Fig. 3.5) (Stern & Holt 1994), initiated deposition of the Tikorangi Formation within a foreland basin. The geometry of the foredeep trough (Fig. 3.4) produced a wedge-shaped deposit that is thickest in the east towards the Taranaki Fault. The Haq et al. (1987) sea-level curve suggests there was little eustatic influence during deposition of the earliest Miocene (Waitakian) foredeep facies, while several fluctuations are indicated during deposition of the Oligocene-Early Miocene (Whaingaroan – Otaian) basinal facies occurring in the offshore Maui-1 well (Fig. 3.5B).

From the Early Miocene, the onset of significant horizontal compression resulted in the Taranaki Fault and associated Tarata Thrust Zone (Fig. 3.1B, C) becoming the mobile western edge of a large area of contraction that formed in the foreland behind the propagating subduction zone (King & Thrasher 1996). The associated series of overthrust systems and structures, in which the onshore wells used in this study are sited, have been instrumental in the formation of the fractured Tikorangi Formation reservoir.

3.4 GEOPHYSICAL WELL-LOG CHARACTERISATION

3.4.1 Basic concepts

While sequence analysis is concerned with the inference of depositional controls on sedimentary successions, the identification of such controls is based here on geophysical well-log characterisation, or vertical log profiling, from which inferred changes in depositional energy and patterns of sedimentary infill are made. The main concept in vertical log profiling is that a decrease in the gamma-ray (GR) log reflects an increase in grain size (decrease in clay content) and therefore an increase in environmental energy to which a relative lowering of sea-level may be implied (Rider 1986; Emery & Myers 1996). The converse applies

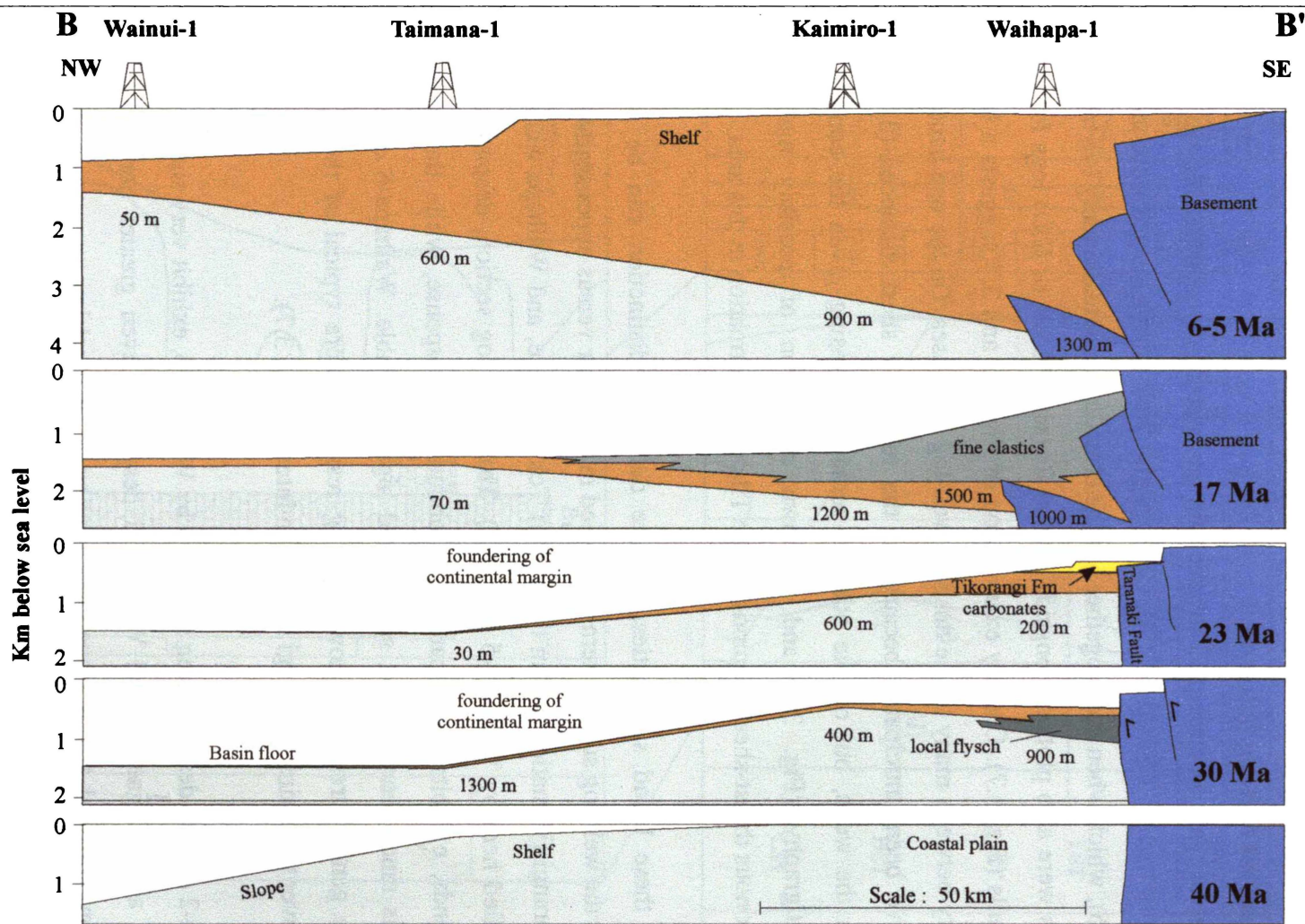


Fig. 3.4 Cross sections through Taranaki Basin showing the magnitude and distribution of incremental Oligocene-Miocene subsidence (in metres), and progressive deformation of the Oligocene-Eocene boundary shown by base of brown colouring. Early Miocene subsidence in the east (17 Ma) was the result of foreland loading by overthrust basement (blue). See Fig. 3.1 for approximate cross section location. Adapted from King & Thrasher (1996).

for an increasing GR log. Resistivity logs (Rt) (either ILD - induction log deep or LLD – laterolog deep) typically mirror (oppose) GR trends because resistivity increases as the clay content decreases. Sonic velocity (Dt) generally increases (Dt values decrease as is a measure of two-way travel time) with decreasing GR.

3.4.2 General well-log patterns

Initial investigations attempted to ascertain any potentially correlatable well-log patterns or trends. To achieve this, GR logs and their mirror images were plotted (Fig. 3.6), which when seen together has the effect of accentuating any log trends. GR logs were also plotted alongside Dt and Rt (either LLD or ILD) logs for the eight wells (Fig. 3.7). cursory examination of Fig. 3.6 and 3.7 suggests a broad similarity between many of the onshore well-log responses. On the one hand this may have been anticipated because of the relatively short distances (3 km) between the wells, but on the other is perhaps surprising given the complex lithostratigraphy (Fig. 3.3) and unknown correlation of possibly multiple allochthonous thrust-sheets comprising the Tikorangi Formation in this area.

Despite these broad similarities, a more definitive distinction can be made between the well-log suite patterns identified in the lower versus upper sections of the Tikorangi Formation within the onland Toko, Ngaere, and Waihapa wells, as exemplified here by Waihapa-5 (Fig. 3.8). The lower log section, despite some clear trends, exhibits a comparatively subdued log response, while the upper section is much more erratic, spiked, and highly variable. Waihapa-6 deviates from the general trend by showing a log response more typical of the upper section over the entire Tikorangi Formation interval (Fig. 3.7).

Waihapa-2 and -4, despite being separated by Waihapa-6, exhibit very similar log patterns, as do Ngaere-2 and Waihapa-5 despite an even greater north-south separation. Hu Rd-1 stands alone as presenting an atypical log response to those of the other onshore wells, although some similarities can be seen with Toko-1 (Fig. 3.6, 3.7). Maui-1 has a distinctively different log character, being some 90

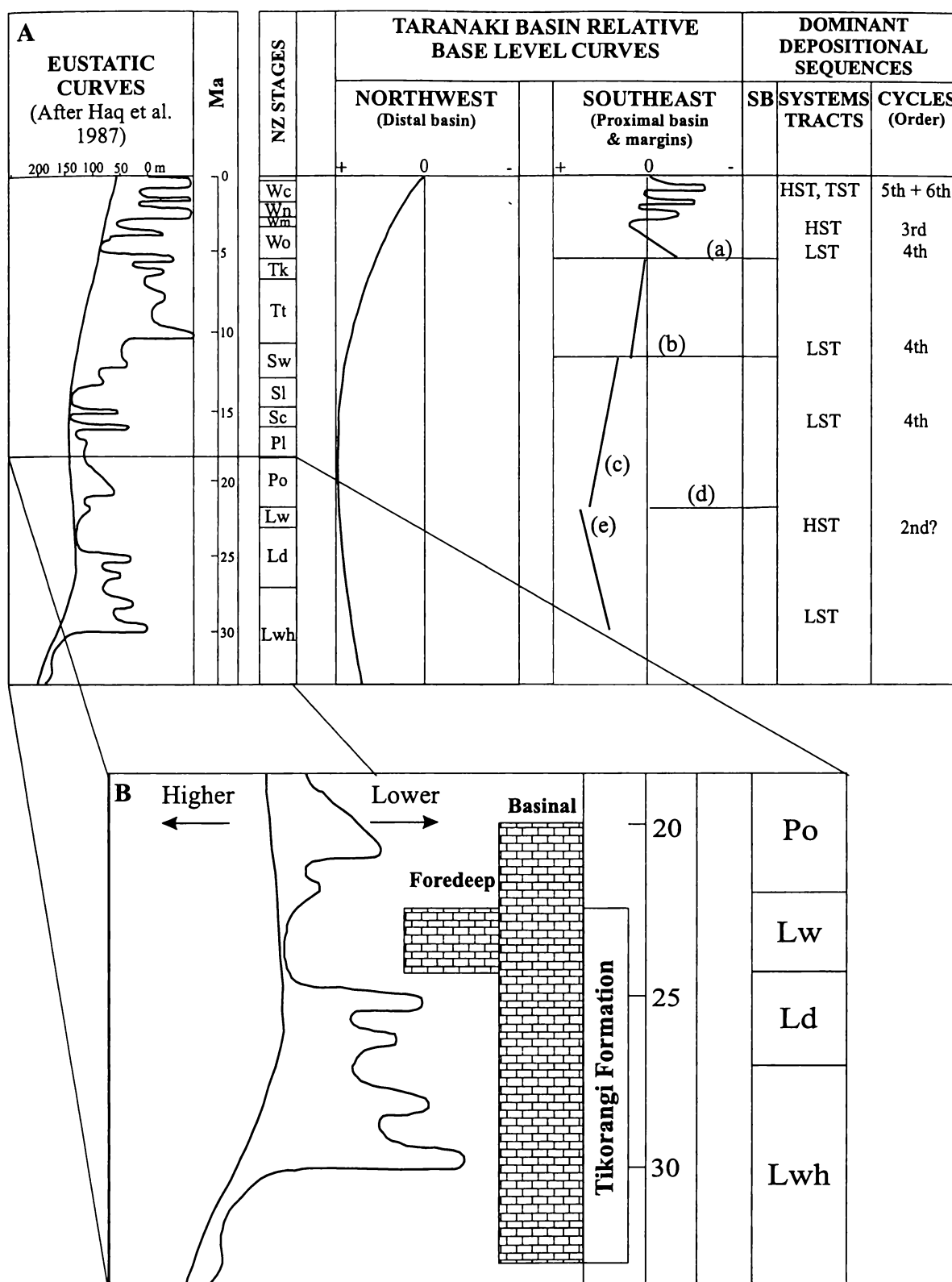


Fig. 3.5 (A) Synthesis of depositional sequence cyclicity in Taranaki Basin. Curves represent changes in paleo-water depth through time with respect to present day shoreline. Notes (a) Type 1 angular unconformity; (b) tectonic unconformity on eastern margin; (c) maximum paleobathymetry in eastern foredeep; (d) eastern margin overthrust; (e) maximum regional onlap and siliciclastic starvation. (B) Enlargement of Lwh-Po sea-level curve showing timing of deposition of the Tikorangi Formation "megafacies": foredeep (in onshore Waihapa-Ngaere field wells) and basinal (in offshore Maui-1 well). SB = sequence boundary. Adapted from King & Thrasher (1996).

km away from the onshore wells and representing a condensed deep-water lithological equivalent.

These rudimentary initial findings form a basis for the correlation of “like” well-log patterns. The broad division into lower and upper log sections (Fig. 3.7) generally equates with initially increasing GR values (decreasing Dt values) followed in the mid- to upper-mid-part of the formation to a change to a generally decreasing GR (increasing Dt) pattern. The basic trend shown by the Rt suite of logs is similar to that shown by Dt, both generally mirroring (opposing) the GR trend.

Given these broadly identifiable patterns, the actual values of GR, Rt, and Dt provide a means of comparatively quantifying a wells geophysical log characteristics, of which maximum, minimum, and average values are shown in Table 3.1. GR minimum (GR min) values (coarsest lithologies with lowest clay mineral contents) show two groupings. The first exhibits the lowest GR min values (20-21) and includes Toko-1, Ngaere-2, Waihapa-4, and offshore Maui-1. The second grouping shows much higher GR min values (31-43), those at Waihapa-5 and -6 being greater than at Waihapa-2 and Hu Rd-1. GR maximum (GR max) values (finest lithologies with highest clay mineral contents) are significantly lower in Waihapa-4 (55) and rather lower in Toko-1 (73) in comparison to other onshore wells (79-98). Waihapa-5 and Hu Rd-1 exhibit the highest onshore GR max values, while offshore Maui-1 has the highest GR max overall (108). Average GR values range from a low of 35 in Waihapa-4 to a high of 64 in Waihapa-5. Overall GR average values, analysed using simple trendline analysis, show an increase from the northern to the southern wells, indicative of relatively cleaner, clay poor, and coarser lithologies to the north.

Rt minimum (Rt min) values (highest clay contents, least resistive) are consistent among all wells, ranging from 4-10, while Rt maximum (Rt max) values (lowest clay contents, most resistive) range from a low of 20 in Maui-1 to a high of 339 in Toko-1. Rt average values range from a low of 10 in Maui-1 to a maximum of 50

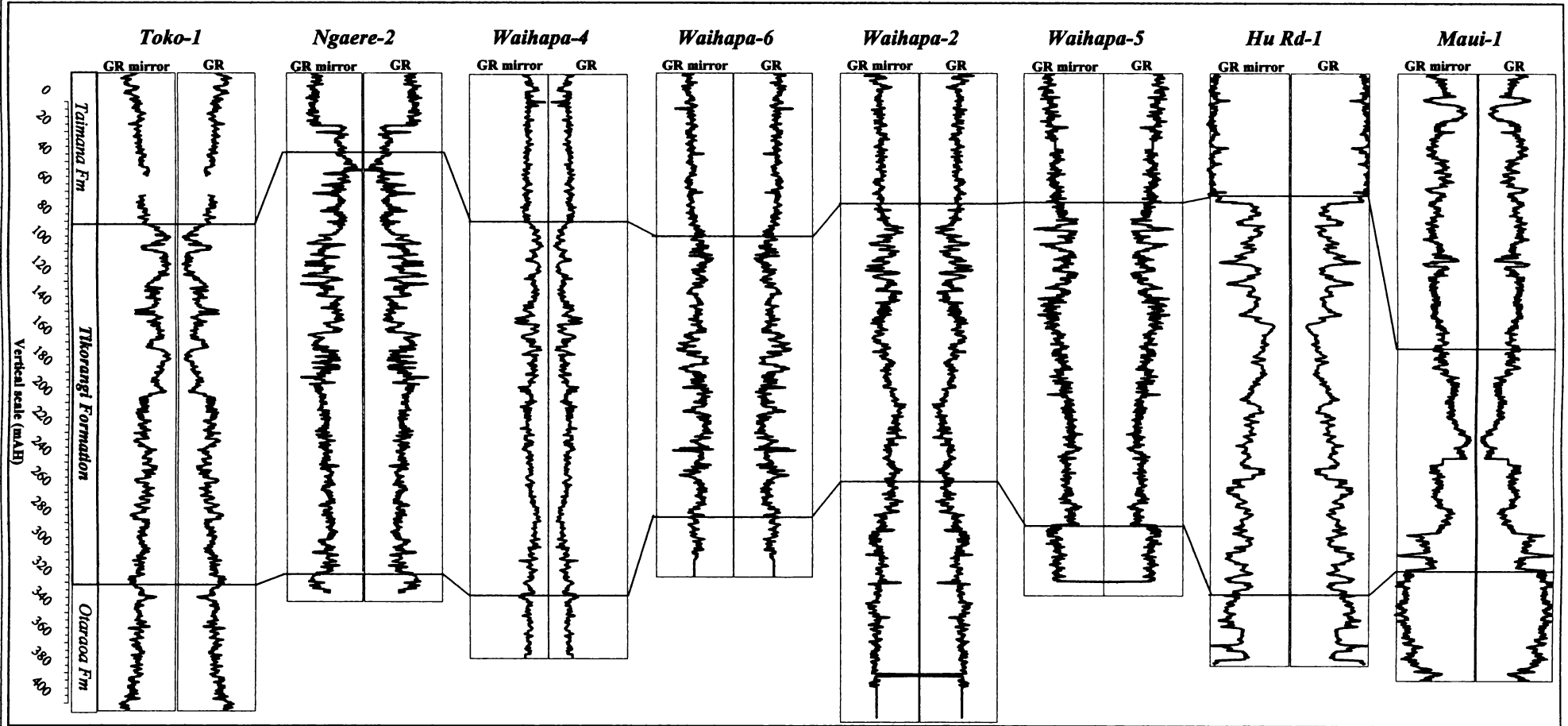


Fig. 3.6 GR logs and their mirror images depicting log patterns within the TIKORANGI FORMATION. The onshore wells are arranged north-south, while the bottom and top of the TIKORANGI FORMATION (black lines) are those defined in Topic 2. No horizontal scale implied in relation to well positions. mAH = metres along hole.

in Hu Rd-1 (Table 3.1).

Dt minimum (Dt min) values (highest sonic velocities, most competent lithologies with relatively low porosities) are the lowest in Ngaere-2 at 50 $\mu\text{s}/\text{ft}$ (Table 3.1), while Waihapa-6, uncharacteristic of the other onshore well responses, has a Dt (min) value of 66, greater than that of the offshore Maui-1 at 64 $\mu\text{s}/\text{ft}$. Dt maximum (Dt max) values (lowest sonic velocities, least competent lithologies with relatively higher porosities) are lowest (74-73 $\mu\text{s}/\text{ft}$) in Waihapa-5 and Ngaere-2 and highest (88-89 $\mu\text{s}/\text{ft}$) in Waihapa-6 and offshore Maui-1. Hu Rd-1 is not included due to the absence of a sonic log. Dt average values range from a low of 56 $\mu\text{s}/\text{ft}$ in Waihapa-2 to an onshore maximum average value of 66 $\mu\text{s}/\text{ft}$ in Waihapa-4 and Waihapa-5. The highest Dt average value of 74 $\mu\text{s}/\text{ft}$ occurs in offshore Maui-1. Dt average, minimum and maximum values show increasing, minimally decreasing, and decreasing values respectively from north to south, indicative of overall cleaner (less clay-rich), more porous lithologies in the northern wells.

From the above general trends in log values and the initial recognition of similarities in well-log patterns in the Tikorangi Formation, the GR logs have been divided into three major up-column patterns, as exemplified in Waihapa-5 (Fig. 3.8). These are: Type (A) = an overall linear increase upwards in GR values (or a corresponding upwards decrease in sonic velocity (increasing Dt values)); Type (B) = an overall decreasing upwards in GR values (or a corresponding upwards increase in sonic velocity (decreasing Dt values)); and Type (C) = neither an overall increase or decrease upwards in GR values, but an irregular pattern with a fixed medial line position (similarly seen in corresponding Dt log). Typically Type (A) and (B) trends show corresponding linear up-column increasing and decreasing in GR respectively, but less commonly may show exponential growth or decay trends, particularly noticeable in the basal portions of Waihapa-5, Toko-1, and Waihapa-4 (Fig. 3.6-3.8).

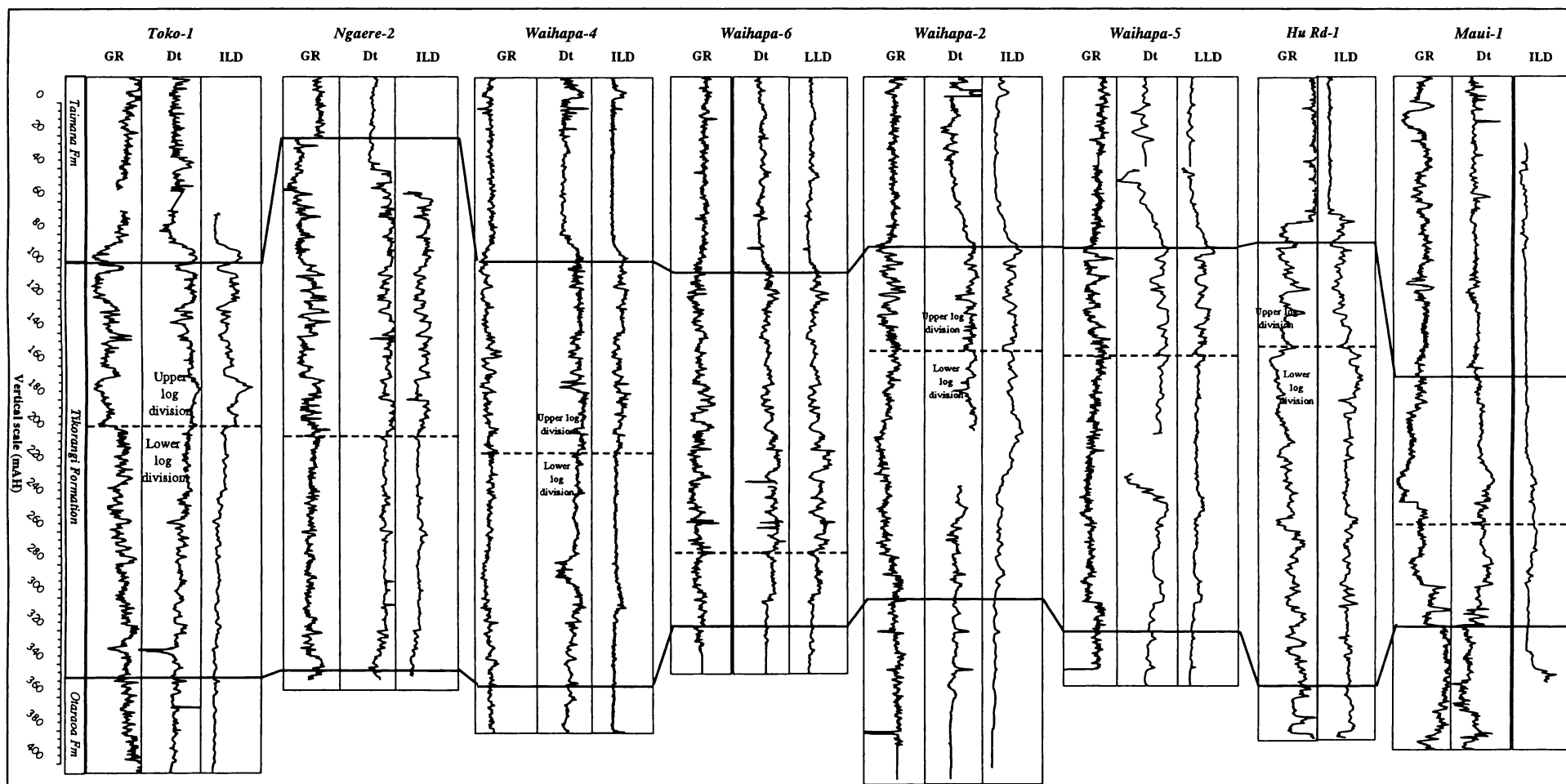


Fig. 3.7 Geophysical logs shown for the Tikorangi Formation in the eight study wells. Top and base of the Tikorangi Formation are shown (see Topic 2). GR=Gamma-ray log (API); Dt=sonic log (ms/ft); ILD=resistivity log (ohms). Dashed line separates generally more subdued lower log sections and upper more erratic, often spiky log sections. Note that the ILD logs in Toko-1 and Ngaere-2 are incomplete in the upper Tikorangi and lower Taimana Formations. Note also gaps in Dt logs in Waihapa-2 and -5. All logs are drawn to scale in MAH (metres along hole). No horizontal scale is implied in relation to well hole positions.

3.4.3 Well-log phases

The identification and division of GR logs into up-column patterns of Type (A), (B), or (C) forms the primary basis for correlation of like GR responses between wells, supported also by the Dt and Rt log values, and carbonate lithostratigraphy (Fig. 3.3). Waihapa-5 is used as a key well for establishing a reference geophysical well-log signature because of its simple and clearly identifiable log patterns; here five characteristic well-log divisions or phases are identified within the Tikorangi Formation (Fig. 3.8). For a brief discussion of other individual study well-log patterns see Appendix 3.1.

The base of the initial Phase I is denoted by an abrupt jump from a higher to lower GR value that corresponds to the lithostratigraphic base of the Tikorangi Formation. Phase I is characterised by a linearly increasing GR Type (A) pattern until a sudden GR decrease at its top that marks the base of the dominant Phase II, another Type (A) pattern that shows an initial high rate of increase that decays exponentially. The top of Phase II is distinguished by a GR maxima that marks the beginning of a Type (B) or decreasing GR pattern corresponding to Phase III, and a more general change from a lower more subdued to an upper more active and highly variable log response (Fig. 3.8). The Phase III/IV boundary is marked by a significant drop in GR to begin a Type (C) pattern in which the GR log is highly irregular. The Phase IV/V body is at a GR minima and marks a change to another Type (A) pattern. The top of Phase V marks the boundary of this short-lived Type (A) trend and coincides with the placement of the upper boundary of the Tikorangi Formation (see Topic 2). A general increase in GR occurs in the lower section of the overlying Taimana Formation.

3.4.3 Distribution and correlation of well-log phases

The five log phases identified in the Waihapa-5 reference well-log (Fig. 3.8) have been recognised within the other onshore wells, although some uncertainty surrounds the phase boundary positioning in Hu Rd-1 due to its unusual GR log response, and in the offshore Maui-1 well. Data pertaining to each of the five phases in the eight wells are summarised in Table 3.2, and the distribution of the

WAIHAPA-5 - INTERPRETED GR LOG PATTERNS FOR THE TIKORANGI FORMATION

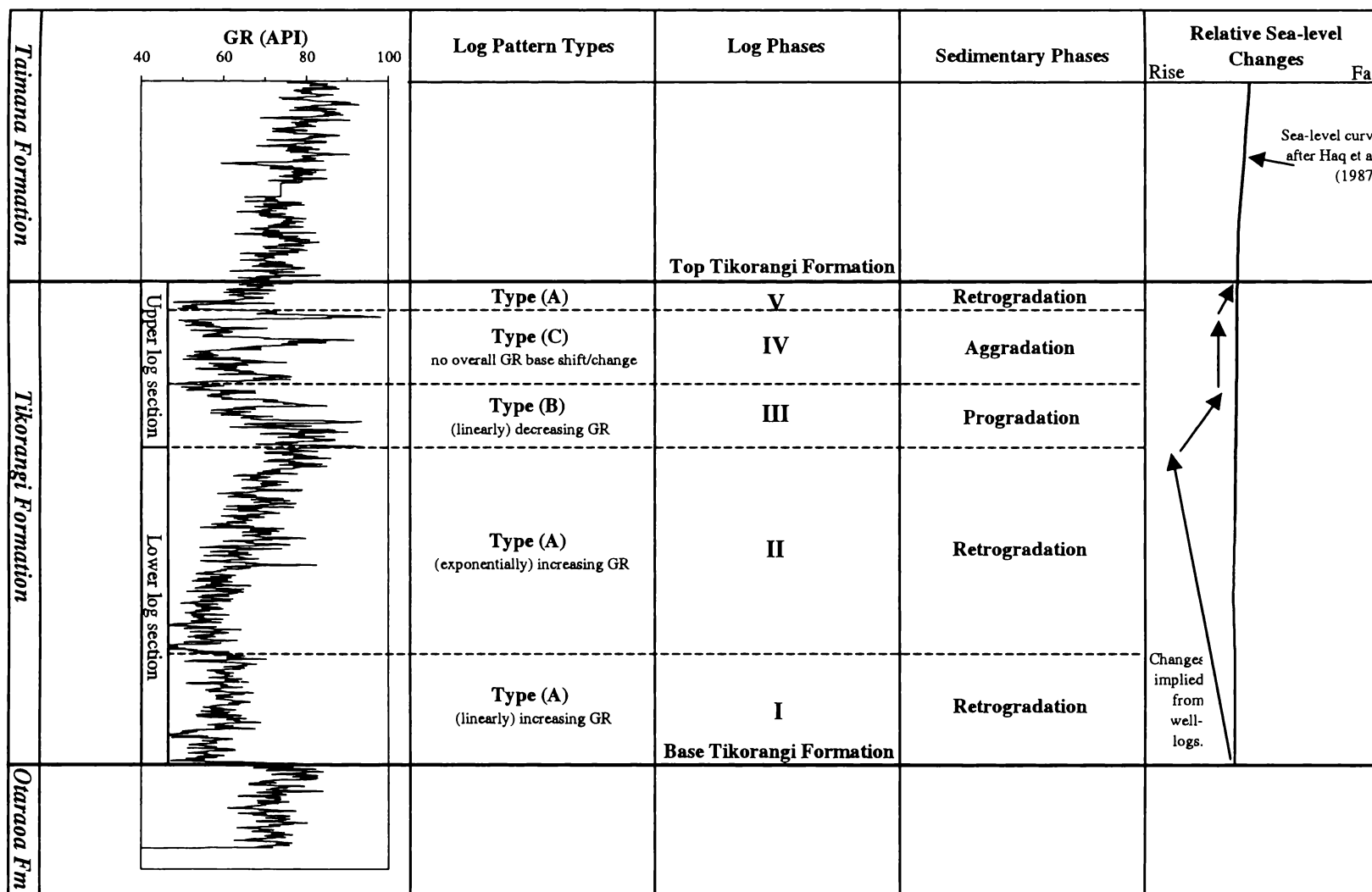


Fig. 3.8 GR plot for Waihapa-5 showing an upward change from a more regular subdued log response in the lower two-thirds of the Tikorangi Formation to a more erratic, spiky log response in the top third. Also shown are major log pattern types and phases, interpreted sedimentation patterns, and relative sea-level changes.

five log phases in the wells is depicted in Fig. 3.9.

Phase I is particularly thin in Waihapa-6 (4 m), but very well developed at Toko-1 (68 m) and Hu Rd-1 (76 m) where it accounts for nearly one third of the formation thickness. Phase II is considerably thicker than the initial phase, with the exception of Toko-1, and is the longest lived of any phase in most other wells. It ranges in thickness from a minimum of 25 m in Waihapa-6 to a maximum of 106 m in Hu Rd-1. As a percentage of total well thickness Toko-1 is low at 22%, while in several wells Phase II accounts for 40% or more of formational development. Phase III ranges from a thickness of 25 m in Waihapa-5 to 81 m in Waihapa-6, accounting for 12 and 44% respectively of total well thickness. Typically Phase III accounts for one fifth of the formation's thickness. Phase IV is very similar in thickness to Phase III, ranging from 20 m in Maui-1 to 68 m in Ngaere-2. As a percentage of total well depth Phase IV is under-represented in a number of wells, but again typically accounts for about 20% of the formation's thickness. The final Phase V is the least well developed, and shows the least variability in thickness, ranging from 8 m in Toko-1 to 20 m in Waihapa-2. Typically Phase V accounts for only about 6% of total formation thickness.

The delineation of these five log phases enables a geophysical log-based correlation between all wells, and one in which the correlation lines may be considered to closely approximate time lines (Fig. 3.10).

3.4.4 Relation of well-log phases to stratigraphic units

The relationship of the previously identified nine major lithostratigraphic units in the Tikorangi Formation (Fig. 3.3) to the five well-log phases is shown in Fig. 3.11, and the data for phase positioning are summarised in Table 3.3. Fig. 3.12 superposes the phase boundary or surrogate time lines on the established lithostratigraphic units (see Topic 2) for the study wells.

The lower boundary of Phase I in all wells (Fig. 3.11) marks a change from the underlying Otaraoa Formation up into the Tikorangi Formation corresponding to a

Table 3.1 Summary geophysical log data statistics for the Tikorangi Formation in the eight study wells.

Geophysical log values	<i>Toko-1</i>	<i>Ngaere-2</i>	<i>Waihapa-4</i>	<i>Waihapa-6</i>	<i>Waihapa-2</i>	<i>Waihapa-5</i>	<i>Hu Rd-1</i>	<i>Maui-1</i>
GR (GAPI)								
Minimum value	21	20	21	41	31	43	33	20
Maximum value	73	92	55	90	79	98	98	108
Average value	46	57	35	57	53	64	63	53
Rt (LLD or ILD) (ohms)								
Minimum value	4	4	10	5	5	6	7	4
Maximum value	339	63	78	39	103	106	224	20
Average value	25	18	21	14	31	14	50	10
Dt (μs/ft)								
Minimum value	53	50	56	66	*54	*57	n/a	64
Maximum value	86	74	84	88	*82	*73	n/a	89
Average value	64	60	66	64	*56	*66	n/a	74

GR = Gamma-ray log; Rt = resistivity log; Dt = sonic log; * denotes missing log section for part of the Tikorangi Formation in these wells. No Dt log run in Hu Rd-1.

change from Facies A (typically claystones to mudstones with <25% carbonate) to Facies B (moderately to highly calcareous siliciclastites - typically siltstones to fine sandstones with 25-50% carbonate). In all cases the lower boundary of Phase I coincides with the base of the lowermost lithostratigraphic Unit 1 (Table 3.3). The upper boundary of Phase I in all cases (Fig. 3.11, Table 3.3) sees an increase in carbonate content from most commonly Facies A, in six wells, to either Facies B or Facies C (muddy limestones with 50-75% carbonate). Two wells show a facies change from Facies B to Facies C. The upper Phase I boundary commonly occurs at the boundary between lithostratigraphic Units 2 and 3a (Table 3.3), although it sits much lower in the middle of Unit 1 in Waihapa-4. The contact appears higher in Ngaere-2 (Table 3.3), occurring between Units 3b/3c, and similarly occurs at the 3c/4 contact in both Waihapa-5 and Hu Rd-1.

The Phase I/II boundary in all wells except Hu Rd-1 (Fig. 3.11, Table 3.3) corresponds to a change from a lower to higher carbonate facies, from either Facies A, or Facies B, to typically Facies C. In the case of Ngaere-2 this represents a change to Facies D (sparry limestones with >75% carbonate). The Phase II/III boundary occurs stratigraphically low in the northernmost wells, in mid Unit 4 in Toko-1 and mid Unit 5 in Ngaere-2 (Fig. 3.11, Table 3.3). Adjacent to Ngaere-2, in Waihapa-4, this phase boundary is at the contact between Units 5 and 6a, while in Waihapa-6,-2, and -5, the boundary is higher, between Units 6b and 6c. At the southernmost well, Hu Rd-1, the II/III boundary is similar in position to the northern wells, between Units 5 and 6 (Fig. 3.11, Table 3.3).

Unlike the underlying two phase boundaries, the Phase III/IV boundary (Fig. 3.11, Table 3.3) in all wells corresponds to a shift to lower carbonate facies. Commonly this facies change is from Facies D to either B or A, or less commonly from Facies C or B to Facies A. In six of the eight wells, this boundary marks a change to Facies A (claystones to mudstones with <25% carbonate) (Fig. 3.11, Table 3.3). The position of Phase III/IV boundary usually occurs at the contact of lithostratigraphic Units 6c and 7, although in Ngaere-2 and Waihapa-5 the boundary occurs slightly lower, within upper Unit 6c (Fig. 3.11, Table 3.3). The

Table 3.2 Data pertaining to definition of Log Phases (e.g. see Fig. 3.8) in the Tikorangi Formation study wells.

Log Phase	Toko-1	Ngaere-2	Waihapa-4	Waihapa-6	Waihapa-2	Waihapa-5	Hu Rd-1	Maui-1
I								
Well log trend type	(B) _L	(A) _L	(B) _L	(A) _L	(A) _L	(A) _L	(A) _E	(A) _L
GR description	decr.(lin)	incr.(lin)	decr.(lin)	incr.(lin)	incr.(lin)	incr.(lin)	decr.(exp)	incr.(lin)
Phase length (mAH)	68	15	30	4	28	48	76	21
Phase % of formation	29	5	12	2	15	23	29	14
II								
Well log trend type	(A) _E	(A) _E	(B) _L /(A) _E	(B) _E /(A) _E	(B) _L /(A) _L	(A) _E	(B) _L	(B) _L /(A) _L
GR description	incr.(exp)	incr.(exp)	decr.(lin)/incr.(exp)	decr.(exp)/incr.(exp)	decr.(lin)/incr.(lin)	incr.(exp)	decr.(lin)	decr.(lin)/incr.(lin)
Phase length (mAH)	52	111	94	25	76	94	106	41
Phase % of formation	22	40	38	14	41	45	41	28
III								
Well log trend type	(B) _L /(C)	(B) _L /(C)	(B) _L	(B) _E /(A) _E	(B) _L	(B) _L	(C)/(B) _L	(B) _L /(A) _E
GR description	decr.(lin)/no shift	decr.(lin)/no shift	decr.(lin)	decr.(exp)/inc.(exp)	decr.(lin)	decr.(lin)	no shift/decr.(lin)	decr.(lin)/incr.(exp)
Phase length (mAH)	57	77	56	81	29	25	35	43
Phase % of formation	24	28	23	44	16	12	13	30
IV								
Well log trend type	(B) _L /(C)	(B) _L /(C)	B _E /C	(B) _L /(C)	(C)	(C)	(B) _L /(C)	(C)/(B) _L
GR description	decr.(lin)/no shift	decr.(lin)/no shift	decr.(exp)/no shift	decr.(lin)/no shift	no base shift	no base shift	decr.(lin)/no shift	no shift/decr.(lin)
Phase length (mAH)	50	68	58	61	31	31	33	20
Phase % of formation	21	24	23	33	17	15	13	14
V								
Well log trend type	(A) _L	(A) _L	(A) _L	(A) _E	(A) _E	(A) _L	(A) _L	(A) _E
GR description	decr.(lin)	decr.(lin)	decr.(lin)	decr.(exp)	decr.(exp)	decr.(lin)	decr.(lin)	decr.(exp)
Phase length (mAH)	8	7	10	14	20	12	10	20
Phase % of formation	3	3	4	8	11	6	4	14

Type (A) = increasing GR trend; Type (B) = decreasing GR trend; Type (C) = no GR base-line shift; decr. = decreasing; incr. = increasing; L = linearly; E = exponentially.

Phase IV/V boundary, unlike the other phase boundaries, does not occur at a carbonate facies transition but amid either Facies B, C, or D. The positioning of this phase boundary in relation to the lithostratigraphy is consistent across all wells, occurring within Unit 8 (Fig. 3.11, Table 3.3). The upper boundary of Phase V (Fig. 3.11, Table 3.3) in all cases represents a change from Facies B to Facies A and corresponds to the change of the Tikorangi Formation into the overlying Taimana Formation at the top of lithostratigraphic Unit 9.

3.5 INTERPRETATION OF WELL-LOG PHASES

3.5.1 General principles

The five well-log phases in the Tikorangi Formation, with their included well-log patterns (Types (A) - increasing upwards GR values; Type (B) - decreasing upwards GR values; and Type (C) - no overall upwards GR baseline shift), enables identification of periods corresponding to relative basin-margin progradation, retrogradation, or aggradation. In turn this allows inferences to be drawn concerning variations in relative sea-level (Emery & Myers 1996). Waihapa-5 is used as the primary example (Fig. 3.8), while Table 3.4 summarises the log trend interpretations for all eight wells.

3.5.1a Type (A) = retrogradational trend

In a Type (A) trend GR values increase upwards because of decreasing grain size (fining up), and a gradual increase in clay/silt mineral content. Type (A) retrogradational trends can result from an increase in fines or alternatively from an upward thinning of sandier clay-poor beds in an otherwise shaley sequence that commonly occurs in deep-marine settings, and so may record the waning of a depositional system. Type (A) could also represent an increase in siliciclastic input and/or a decrease in bioclastic content. Such “dirtying upwards” develops a retrogradational sequence, a trend characteristic of Phases I, II, and V in Waihapa-5 (Fig. 3.8) and in the majority of the other wells (Table 3.4). Retrogradational trends imply significant deepening that occurs when sediment supply is less than

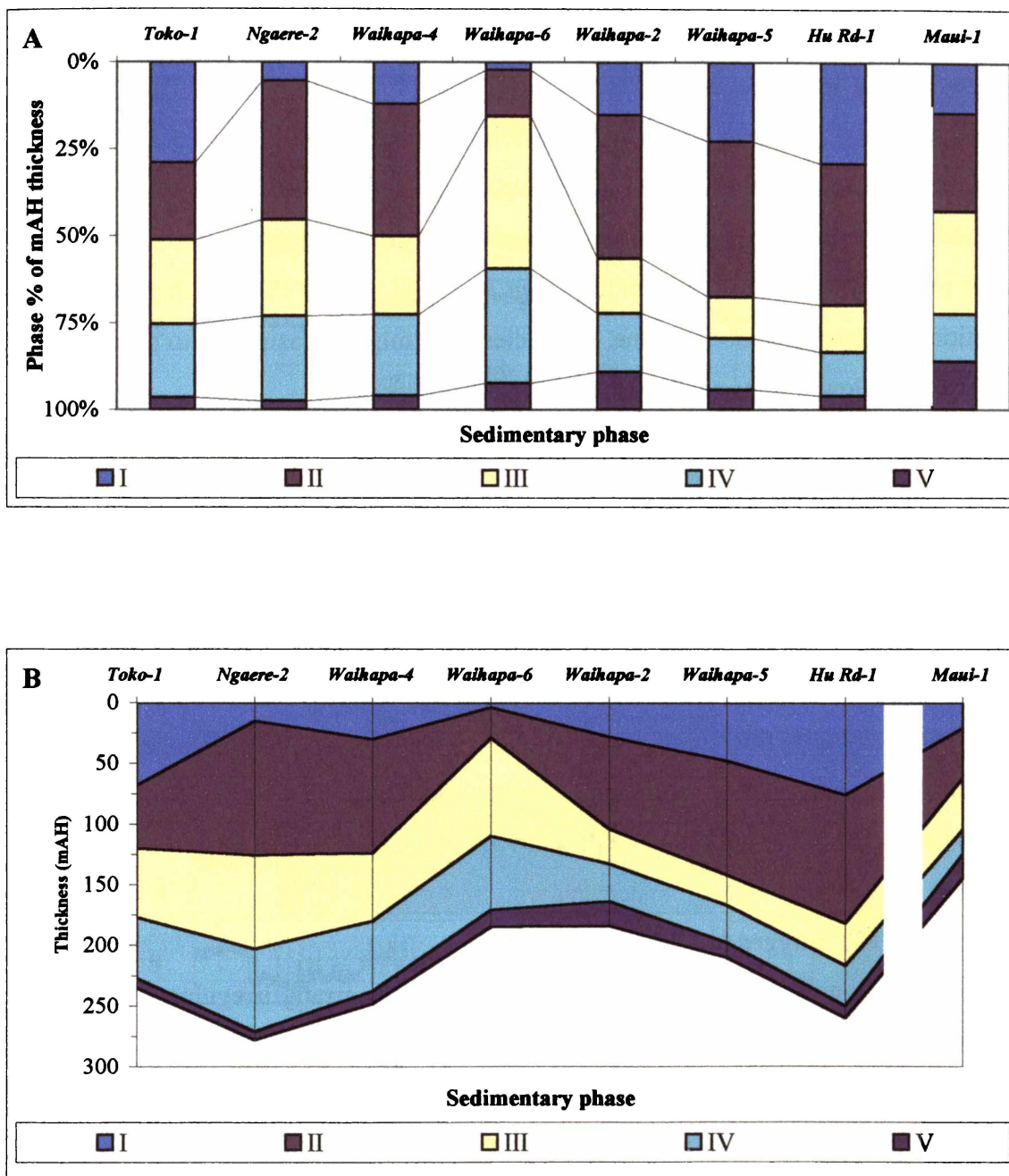


Fig. 3.9 (A) Columns showing distribution of sedimentary phases I - V as a percentage of the Tikorangi Formation thickness for each study well. (B) "Panel diagram" showing phase thickness in mAH (metres along hole) for each study well.

the rate of creation of accommodation volume (Mitchum et al. 1993).

3.5.1b Type (B) = progradational trend

The Type (B) log trend of an upward decreasing GR is usually associated with “cleaning upwards”, an increasing grain size (coarsening-up trend), or a progradational sequence due to a gradual decrease in clay/silt content. This trend is characteristic of Phase III in Waihapa-5 and the other wells (Fig. 3.8, Table 3.4). It suggests that the relative rate of subsidence decreased to less than that of the sediment influx, so that the basin tended to prograde (Mitchum et al. 1993). Such progradational geometry occurs when sediment supply exceeds the rate of creation of accommodation volume, and facies belts migrate basinward to produce a relative shallowing-upwards or regressive sequence.

The Type (B) progradational trend can also reflect a progressive change in lithology or a gradual change in the proportions of thinly bedded units from shale-rich to shale-free. In deep-marine settings the cleaning up is seen as part of a more symmetrical bow trend related to an increase in the sand percentage of thinly bedded turbidites, as may be the case for example in Phase III in Waihapa-6 (Fig. 3.10). Occasionally this trend may be the result of a gradual change from siliciclastic to carbonate deposition and need not necessarily be related to upward-shallowing or to progradation of the depositional system.

3.5.1c Type (C) = aggradational trend

A Type (C) or aggradational trend characterises a very erratic irregular GR log response with no overall progradational or retrogradational trend. This type of trend occurs when the sediment supply and rate of volume creation are roughly balanced, resulting in a vertical stacking of facies belts. An aggradational trend characterises Phase IV in Waihapa-5 and in the majority of other wells (Fig. 3.8, Table 3.4).

3.5.2 Phase I

An abrupt change from high to much lower GR values marks the base of the

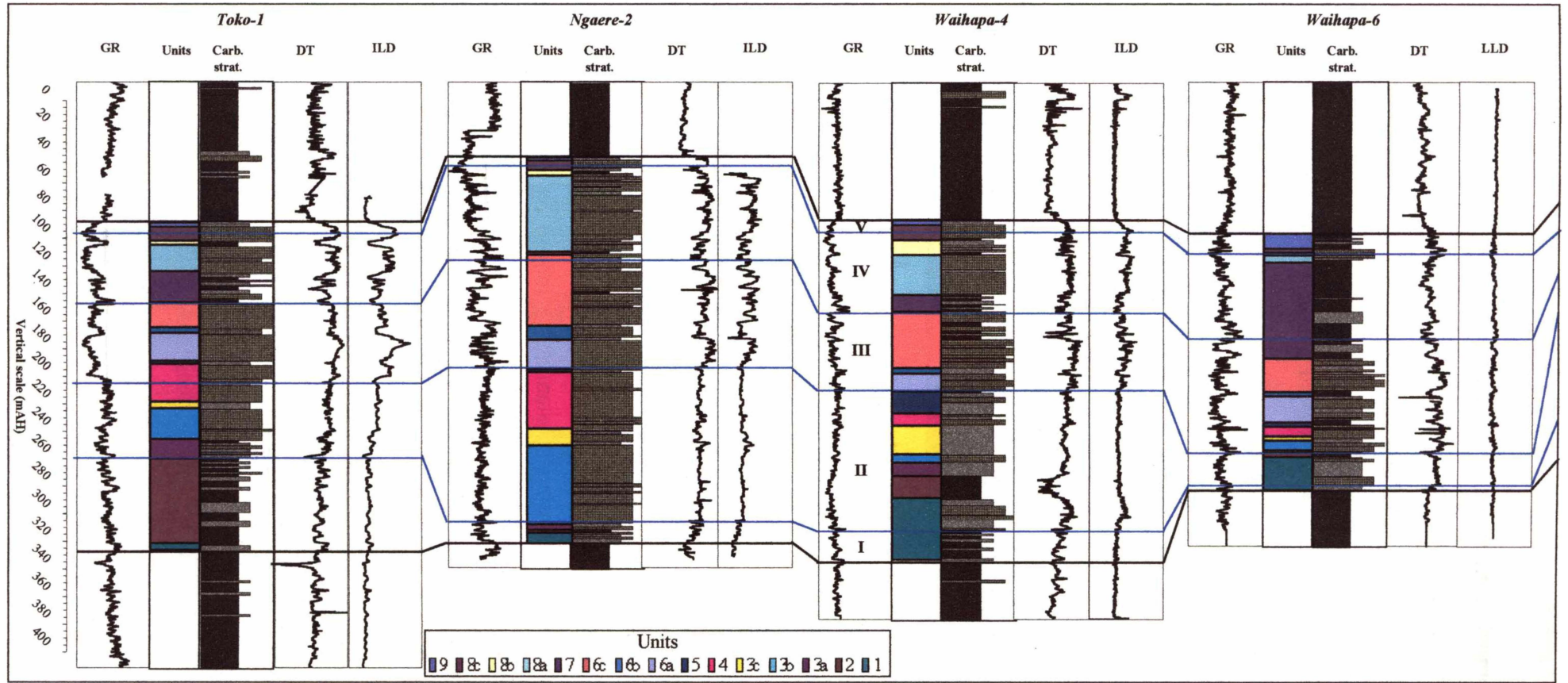


Fig. 3.10 Geophysical logs and carbonate-based lithostratigraphy and units in relation to the five Log Phases I-V in the Tikorangi Formation at the eight study wells.

Tikorangi Formation and sedimentary Phase I (Fig. 3.8, 3.10, 3.13). The change is considered to be time surface 1. Across this surface depositional conditions change sharply from the lower energy, more clay-rich, finer-grained Facies A, (typically claystones to mudstones with <25% carbonate) of the underlying upper Otaraoa Formation, to the overlying cleaner, coarser-grained, moderately to highly calcareous siliciclastites of Facies B (typically siltstones to fine sandstones with 25-50% carbonate) of the lower Tikorangi Formation. This basal Phase I contact probably corresponds to a sequence boundary and the start of a transgressive systems tract (TST) (Fig. 3.13) which is characterised by retrogradational parasequence sets comprising fining-up packets which decrease in thickness upwards (Fig. 3.8, 3.13). The formation of the TST coincided with rapid sea-level rise as the foredeep trough began to descend from shelfal to bathyal depths (King & Thrasher 1996).

The base of sedimentary Phase I marks the base of Unit 1 of the Tikorangi Formation. In the majority of onshore wells studied here, and in the offshore Maui-1 well, Phase I typically shows a slight retrogradational trend (Fig. 3.8, 3.13; Table 3.2, 3.4). This mildly dirtying-up sequence is probably indicative of increasing water depths, often reflected by a change from the basal more carbonate-rich beds of Facies B and C back to a Facies A-dominated phase. This is unlikely to be due to an increased siliciclastic supply in the lower Tikorangi Formation as source areas were substantially removed by this time with the rapidly progressing transgression. Retrogradation is therefore thought to reflect continued foredeep subsidence resulting in some landward movement of facies belts.

With minimal siliciclastic input, shallow-water carbonate production factories established themselves upon topographic highs and shelfal areas fringing the foredeep trough. From these sites mass depositional events reworked and redeposited carbonate material to the deeper outer shelfal areas in which the onshore wells in this study were likely to have been sited at this time. Mass redepositional mechanisms were limited to occasional and random events as

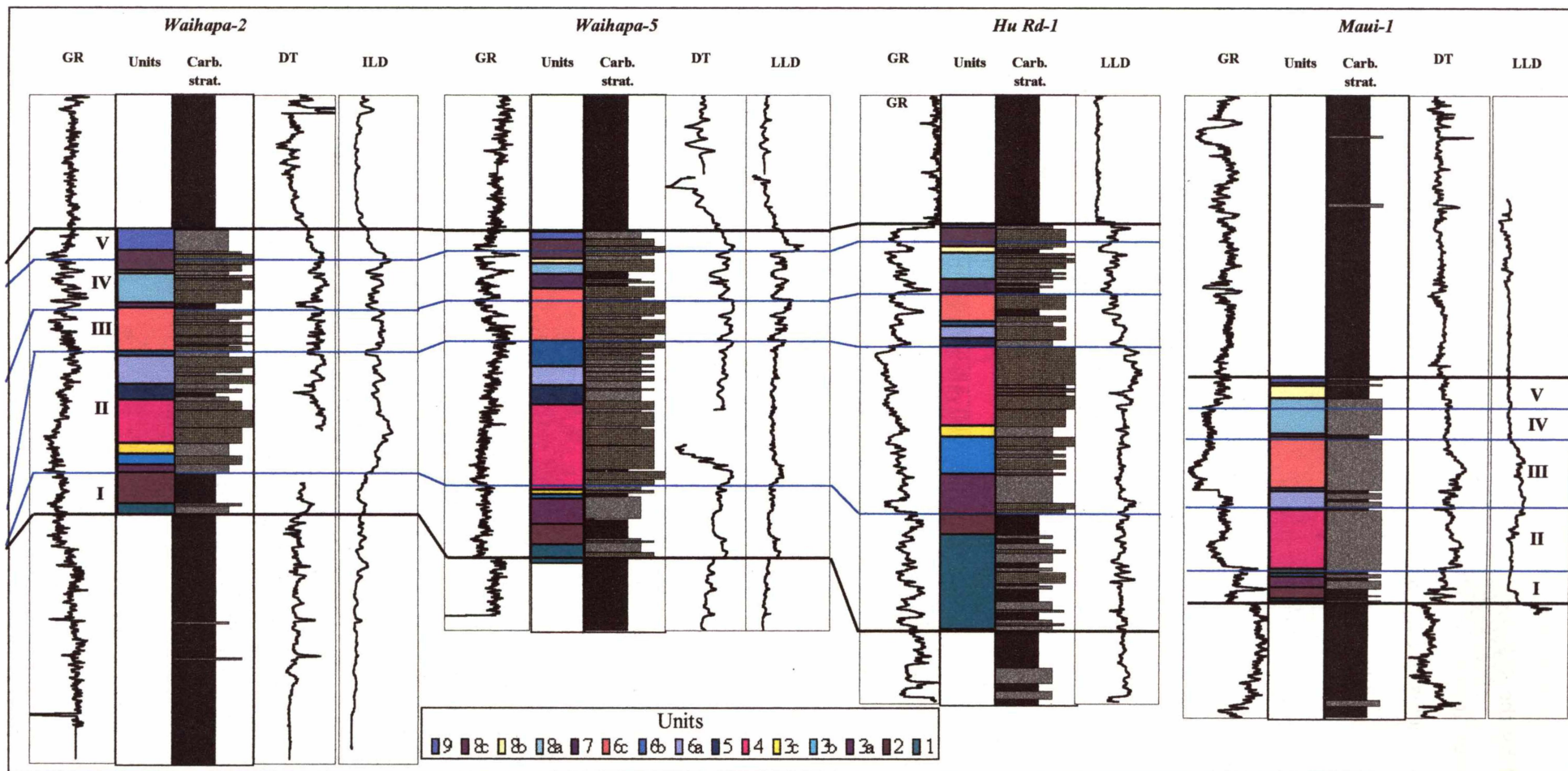


Fig. 3.10 (contin.)

evidenced by the still generally siliciclastic-dominated (<50% carbonate) nature of the lower formation. Dilution of carbonate material by mixing with more siliciclastic facies during emplacement could have been a factor in early events (Fig. 3.8, 3.13; Table 3.2).

About 17% of the Tikorangi Formation thickness is associated with this mildly retrogradational Phase I, or on average a 38 mAH (along hole) thickness. During this phase, Units 1 and 2 were mainly deposited, while stratigraphically higher Units 3a and 3b also formed at Ngaere-2 and Waihapa-5, respectively, at this time. The apparent diachroneity of the upper Phase 1 boundary can be explained by the complex and variable supply and timing of supply of both reworked and redeposited carbonate and siliciclastic sediment, and the resulting variability in stratigraphic unit thickness. Trendline analysis shows that Phase I was longer lived, or produced generally slightly thicker deposits, in the southern wells, particularly in Waihapa-5 and Hu Rd-1 (Table 3.2, 3.4; Fig 3.10). These sites may have been more proximal at this time to siliciclastic source areas compared to the more northern wells.

In the two northern wells, Toko-1 and Waihapa-4, the Phase I trend is progradational rather than retrogradational (Table 3.2, 3.4). This may be the result of a decreasing siliciclastic supply and a change from Facies A to cleaner, relatively clay-poor and coarser, more carbonate-rich Facies B, and eventually Facies C units (Fig. 3.10). These wells may have also been sites more proximal to carbonate source areas, and therefore experienced greater carbonate input than experienced in other wells during this time.

Any correlation of the onshore Phase 1 out into the offshore Maui-1 well is extremely uncertain. Nevertheless, a similar retrogradational sequence can be identified in the lower Tikorangi Formation section, but is known to have begun forming at a much earlier age in the Oligocene (Whaingaroan).

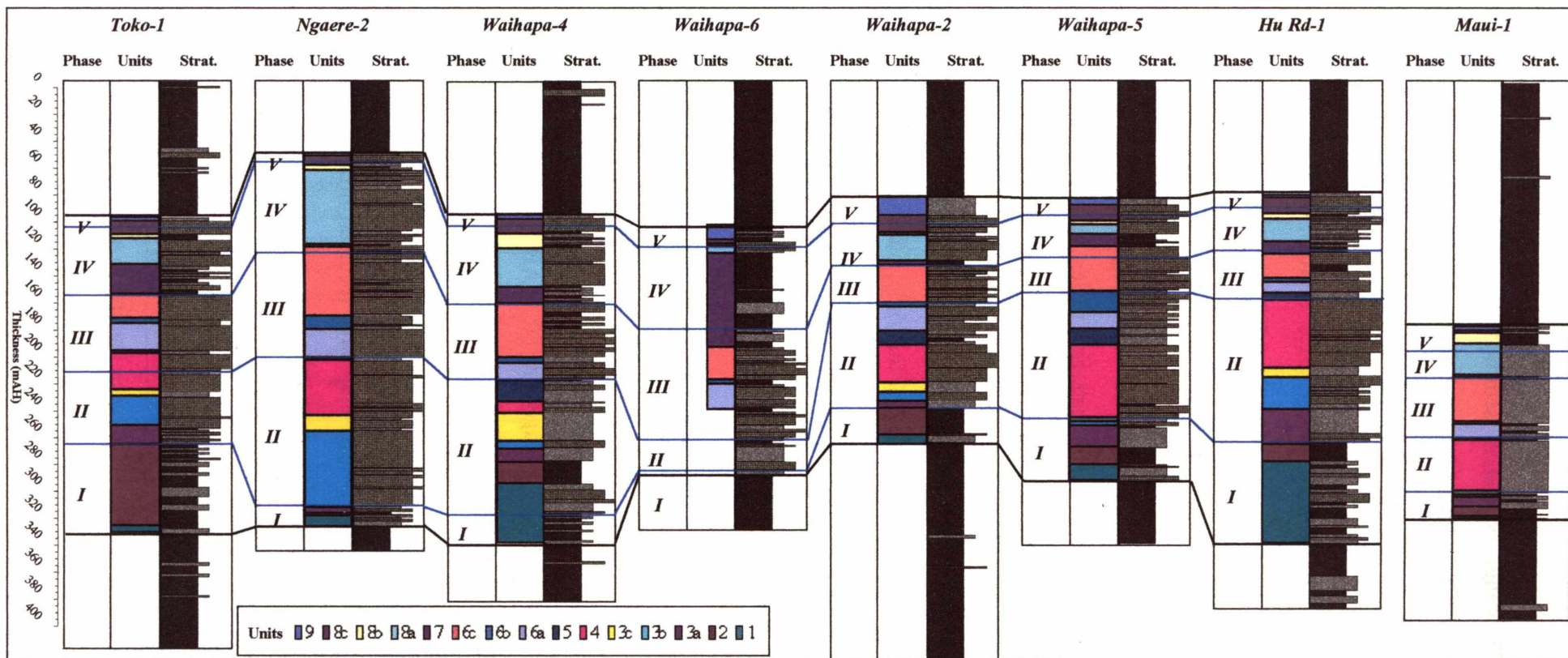


Fig. 3.11 Relationship of Log (Sedimentary) Phases I-V to stratigraphy for the Tikorangi Formation in the eight study wells.

3.5.3 Phase II

Phase II of Tikorangi Formation sedimentation represents in many wells a continuation of the initial Phase I retrogradation, but is often more pronounced, or changes from a linearly increasing to exponentially increasing GR, particularly evident in Waihapa-5 (Fig. 3.13, Table 3.3). Phase II in more northern wells, especially Toko-1 and Waihapa-4 (Fig. 3.13, Table 3.3), sees a change from an atypical progradational trend in Phase 1 to a retrogradational one characteristic of Phase II.

The lower Phase II boundary, or time surface 2 (Fig. 3.10, 3.11, 3.13; Table 3.3), is marked by a change to more carbonate-rich facies, either Facies B or C (muddy limestones with 50-75% carbonate), as carbonate deposition began to dominate as siliciclastic source areas were rapidly diminishing. A range of Tikorangi Formation lithostratigraphic units was formed during this retrogradational phase. Upper Unit 1 developed in Waihapa-4 at this time, but more commonly Units 3a, 3b, 4 at the Toko-1 and Hu Rd-1 sites (Fig. 3.10, 3.11; Table 3.3), while progressively farther south the stratigraphically higher retrogradational units range from Units 5 to 6c.

Phase II, unlike Phase I, is associated with generally thicker sediments (as seen in trendline analysis) in the northern wells (Fig. 3.9, Table 3.2). On average Phase II is the longest lived of all five phases, comprising about 34% of the Tikorangi Formation thickness, or on average an 80 mAH thickness. This phase is particularly long-lived in Ngaere-2, but short-lived in Waihapa-6. The generally more carbonate-rich nature of Ngaere-2 suggests a preferential or proximal carbonate supply, whereas Waihapa-6, perhaps as a result of topographic elevation or more distal positioning, may have received little carbonate material during this time due to by-passing of mass flows.

Phase II, in some instances having an exponentially increasing GR, may be suggestive of accelerating relative sea-level rise (Fig. 3.10, 3.13). Carbonate sedimentation was outpaced by subsidence leading to an overall deepening and, as

Table 3.3 Summary data defining the boundary conditions between the five Log Phases (I-V) in the Tikorangi Formation.

Sedimentary Phase	Phase boundary	Toko-1	Ngaere-2	Waihapa-4	Waihapa-6	Waihapa-2	Waihapa-5	Hu Rd-1	Maui-1
I	<i>Lower boundary</i>								
	Lithostratigraphic unit	b1	b1	b1	b1	b1	b1	b1	b1
	Carbonate facies	A/B	A/B	A/B	A/B	A/B	A/B	A/B	A/B
	<i>Upper boundary</i>								
	Lithostratigraphic unit	2/3a	3b/3c	m1	2/3a	2/3a	3c/4	2/3a	3c/4
II	Carbonate facies	A/B	B/C	A/C	A/B	A/B	B/C	A/C	A/B
	<i>Lower boundary</i>								
	Lithostratigraphic unit	2/3a	3b/3c	m1	2/3a	2/3a	3c/4	2/3a	3c/4
	Carbonate facies	A/B	B/C	A/C	A/B	A/B	B/C	A/C	A/B
	<i>Upper boundary</i>								
III	Lithostratigraphic unit	m4	m5	5/6a	6b/6c	6b/6c	6b/6c	4/5	5/6a
	Carbonate facies	B/C	B/D	A/C	A/C	B/C	B/C	D/B	A/B
	<i>Lower boundary</i>								
	Lithostratigraphic unit	6c/7	u6c	6c/7	17	6c/7	u6c	6c/7	6c/7
	Carbonate facies	D/A	D/B	C/A	B/A	D/A	D/B	C/A	B/A
IV	<i>Upper boundary</i>								
	Lithostratigraphic unit	6c/7	u6c	6c/7	17	6c/7	u6c	6c/7	6c/7
	Carbonate facies	D/A	D/B	C/A	C/B	D/A	D/B	C/A	B/A
	<i>Lower boundary</i>								
	Lithostratigraphic unit	m8c	u8b	u8b	m8b	m8c	m8c	l8c	l8a
V	Carbonate facies	D	B	B	C	D	D	C	B
	<i>Upper boundary</i>								
	Lithostratigraphic unit	m8c	u8b	u8b	m8b	m8c	m8c	l8c	l8a
	Carbonate facies	D	B	B	C	D	D	C	B
	<i>Lower boundary</i>								
V	Lithostratigraphic unit	t9	t9	t9	t9	t9	t9	t9	t9
	Carbonate facies	B/A	B/A	B/A	B/A	B/A	B/A	B/A	B/A
	<i>Upper boundary</i>								
	Lithostratigraphic unit	t9	t9	t9	t9	t9	t9	t9	t9
	Carbonate facies	B/A	B/A	B/A	B/A	B/A	B/A	B/A	B/A

b = base; l = lower; m = middle; u = upper; t = top; / = boundary; A = calcareous siliciclastites (<25% carbonate); B = very calcareous siliciclastites (25-50% carbonate); C = muddy limestones (50-75% carbonate); D = sparry limestones (>75% carbonate).

in Phase I, continued movement of facies belts landward. This possibly coincided with substantially accelerated deepening of the Taranaki Basin foredeep trough during this time (King & Thrasher 1996). Carbonate production can often keep pace with sea-level rise except where the rise is very rapid and results in changes in environmental parameters, which was probably the situation during Phase II. However, shallow factory sites continued to supply periodic mass flows during this phase. In Waihapa-5 particularly, a number of small-scale stacked parasequences forming the more general retrogradational trend (Fig. 3.8) may have resulted from the cyclic filling by mass-emplaced sediments over time during this accelerated relative sea-level rise (e.g., Emery & Myers 1996).

This retrogradational sequence is indicative of an overall TST, commonly characterised by a set of parasequences, each of which becomes finer-grained upwards, as is evident in Waihapa-5 (Fig. 3.13), until the maximum flooding surface is reached. This is marked on well-logs by the maximum GR value and the most shale-rich resistivity, and generally corresponds to the Phase II/III boundary.

The only exception to a retrogradational Phase II is in Hu Rd-1 (Table 3.2, 3.3; Fig. 3.10) where a thick progradational stack may be a result of decreasing siliciclastic contents and therefore largely submerged basement source rocks during this period of rapid marine transgression. Hu Rd-1, with its uncharacteristically much coarser nature and very shallow water skeletons (see Topic 4), may represent a more near *situ* Tikorangi Formation facies formed on shallow topographic highs and shelf areas. Subsequently, during periods of highstand shedding, these highs provided likely source areas for the other onshore wells in this study. Such highs would likely be bypassed by any siliciclastic material and would account for the progradational trend seen at Hu Rd-1.

In offshore Maui-1, Phase II shows a progradational and later aggradational trend, which may also be related to dwindling siliciclastic supply.

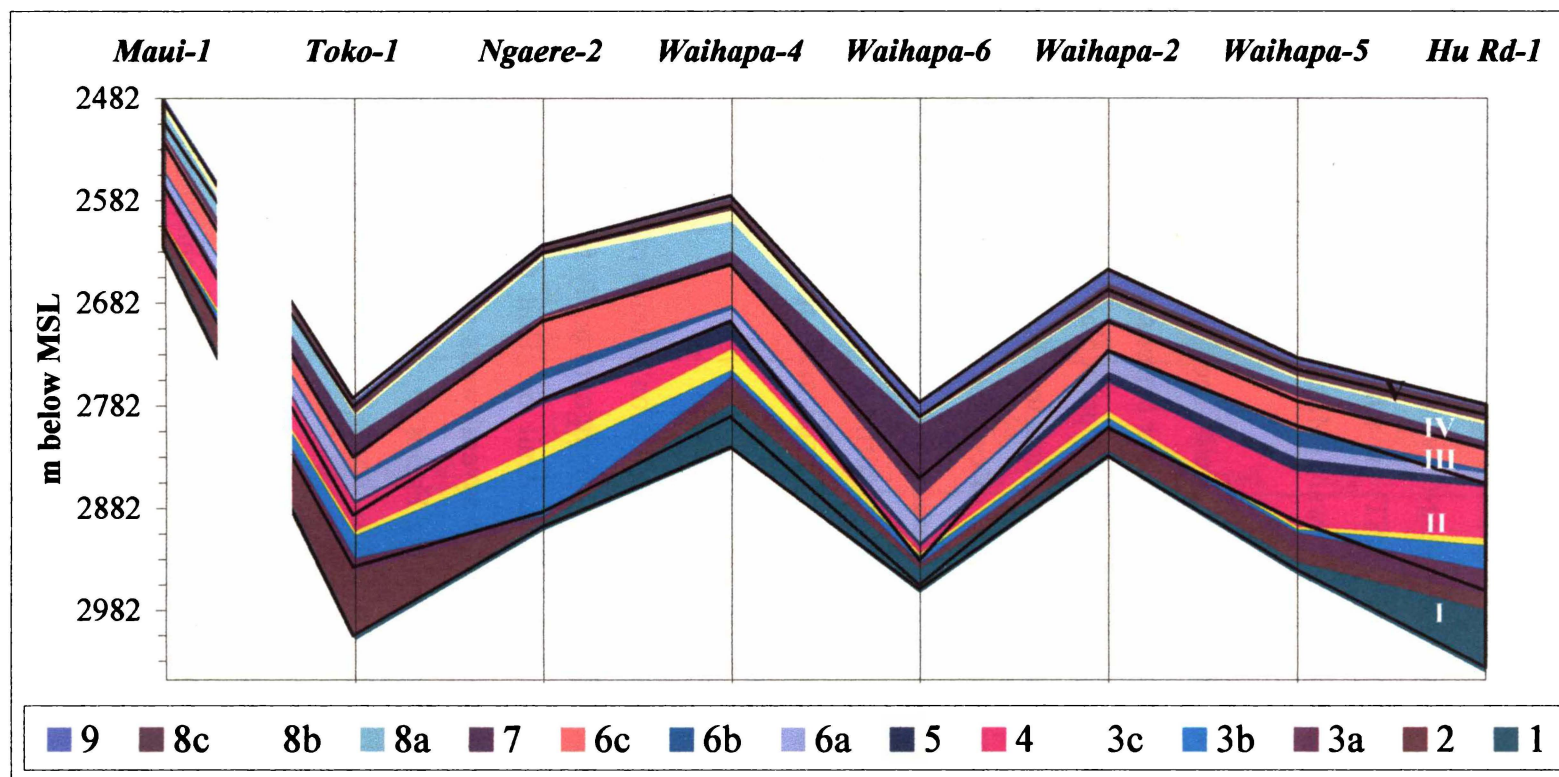


Fig. 3.12 Sedimentary Phases I-V for the Tikorangi Formation in relation to lithostratigraphy (Units 1 - 9) for the eight study wells. MSL = mean sealevel. Note: distances between well locations are not drawn to scale.

3.5.4 Phase III

The base of Phase III is marked by the maximum flooding surface for the Tikorangi Formation, and a change to carbonate-rich Facies C. Phase III is characterised by a relatively short-lived progradational phase in Waihapa-5 (Fig. 3.13), which tends to be more prograding aggradation in the more northern wells (Fig. 3.10; Table 3.4). The coarsening-upward trend of Phase III is characteristic of the highstand systems tract (HST) in which well-logs indicate coarsening upward stacks that are building basinward (Mitchum et al. 1993).

A feature of Phase III in the northern wells, seen in Toko-1 and Ngaere-2 (Fig. 3.10), is the thick, often box car, crescent, or barrel shape of GR units, suggestive of mass emplacement. Barrel-type units are particularly prominent in Waihapa-6. This is typical of submarine fan deposition in which sandy parts of the leveed channels have a consistently rounded or crescent-shaped pattern (Mitchum et al. 1993). Where present in the more southern wells, such mass emplaced units are on a smaller scale and are much more difficult to identify (Waihapa-2 and -5), possibly because they represent more distal sites from those areas supplying carbonate material at the time.

Phase III has been responsible for the deposition of units ranging from upper Unit 4 in the northernmost well (Toko-1), or more commonly from the top of Unit 6b, to near or at the upper boundary to Unit 6c. Unit 6c is the dominant unit characteristic of this phase, which in several wells sees the first introduction of abundant carbonate material forming Facies D, with carbonate contents greater than 75%.

A decrease in basinal subsidence to a rate relatively less than that of sediment influx is thought to have occurred during this period, so that the foredeep tended to fill. The carbonate system would have tended to prograde during such a decrease in the rate of sea-level rise, and may be a result of highstand shedding (Driscoll et al. 1991) occurring when shoals on topographic highs and shallow shelfal areas build up when siliciclastic input is reduced. This progradation

Table 3.4 Summary of GR log trends and their sedimentary interpretation for the five Log Phases (I-V) in the Tikorangi Formation.

Log Phase	Toko-1	Ngaere-2	Waihapa-4	Waihapa-6	Waihapa-2	Waihapa-5	Hu Rd-1	Maui-1
I								
Well log trend type	(B) _L	(A) _L	(B) _L	(A) _L	(A) _L	(A) _L	(A) _E	(A) _L
Sed. interpretation	prograd.	retrograd.	prograd.	retrograd.	retrograd.	retrograd.	retrograd.	retrograd.
II								
Well log trend type	(A) _E	(A) _E	B _L A _E	B _E /A _E	B _L /A _L	(A) _E	(B) _L	(B) _L /(A) _L
Sed. interpretation	retrograd.	retrograd.	prograd./retrograd.	prograd./retrograd.	prograd./retrograd.	retrograd.	prograd.	prograd./retrograd.
III								
Well log trend type	(B) _L (C)	(B) _L (C)	(B) _L	(B) _E /(A) _E	(B) _L	(B) _L	(C)/(B) _L	(B) _L (A) _E
Sed. interpretation	prograd./aggrad.	prograd./aggrad.	prograd.	prograd./retrograd.	prograd.	prograd.	aggrad./prograd.	prograd./retrograd.
IV								
Well log trend type	(B) _L (C)	(B) _L (C)	(B) _E /(C)	(B) _L (C)	(C)	(C)	(B) _L (C)	(C)/(B) _L
Sed. interpretation	prograd./aggrad.	prograd./aggrad.	prograd./aggrad.	prograd./aggrad.	aggrad.	aggrad.	prograd./aggrad.	aggrad./prograd.
V								
Well log trend type	(A) _L	(A) _L	(A) _L	(A) _E	(A) _E	(A) _L	(A) _L	(A) _E
Sed. interpretation	retrograd.	retrograd.	retrograd.	retrograd.	retrograd.	retrograd.	retrograd.	retrograd.

Type (A) = increasing GR upward trend; Type (B) = decreasing GR upward trend; Type (C) = no GR base shift; L = linearly increasing or decreasing; E = exponentially increasing or decreasing. Prograd. = progradational trend; retrograd. = retrogradational; aggrad. = aggradational; Sed = sedimentary.

occurred when the surrounding shallow platform sediment during the highstand from the platform to the slope and basinward. Depositional slopes at the basin margin may have been steepened to the point that mass gravity sediment flows were probably effective in transporting shallow-water carbonate lithologies basinward. Storms may also have been a significant factor in initiating down-slope transport from shallower water settings (Foreman et al. 1991).

Phase III is generally better developed with thicker sediments in the northern wells, the maximum thickness occurring at Waihapa-6. On average, this phase forms 23% of the thickness of the Tikorangi Formation, which averages 51 mAH thickness.

The positioning of Phase III in offshore Maui-1 is uncertain due to its considerably more basinal position and possible influences from additional siliciclastic sources to the south rendering log pattern correlation extremely subjective.

3.5.5 Phase IV

Phase IV is a generally aggradational to prograding aggradational phase in which often no overall GR base line shift occurs. The base of Phase IV is generally marked by a downgrade in carbonate content from either the high carbonate Facies C or D, to typically Facies A. This phase marks an increase in the availability of siliciclastic material and effectively ends deposition of the carbonate-rich Facies C and D in Waihapa-6. In other wells only thin periodic influxes of siliciclastic-rich material have occurred, with the majority of Phase IV dominated by pure limestones of Facies D in the northern wells, and more muddy limestones of Facies C in the southern wells.

During Phase IV the rate of sediment supply and the rate of volume creation were roughly balanced, resulting in the vertical stack of facies belts (Fig. 3.10). This phase, like Phases II and III, has produced generally slightly thicker deposits in the northern wells (Fig. 3.9, Table 3.2). Box car or barrel-shaped GR patterns are

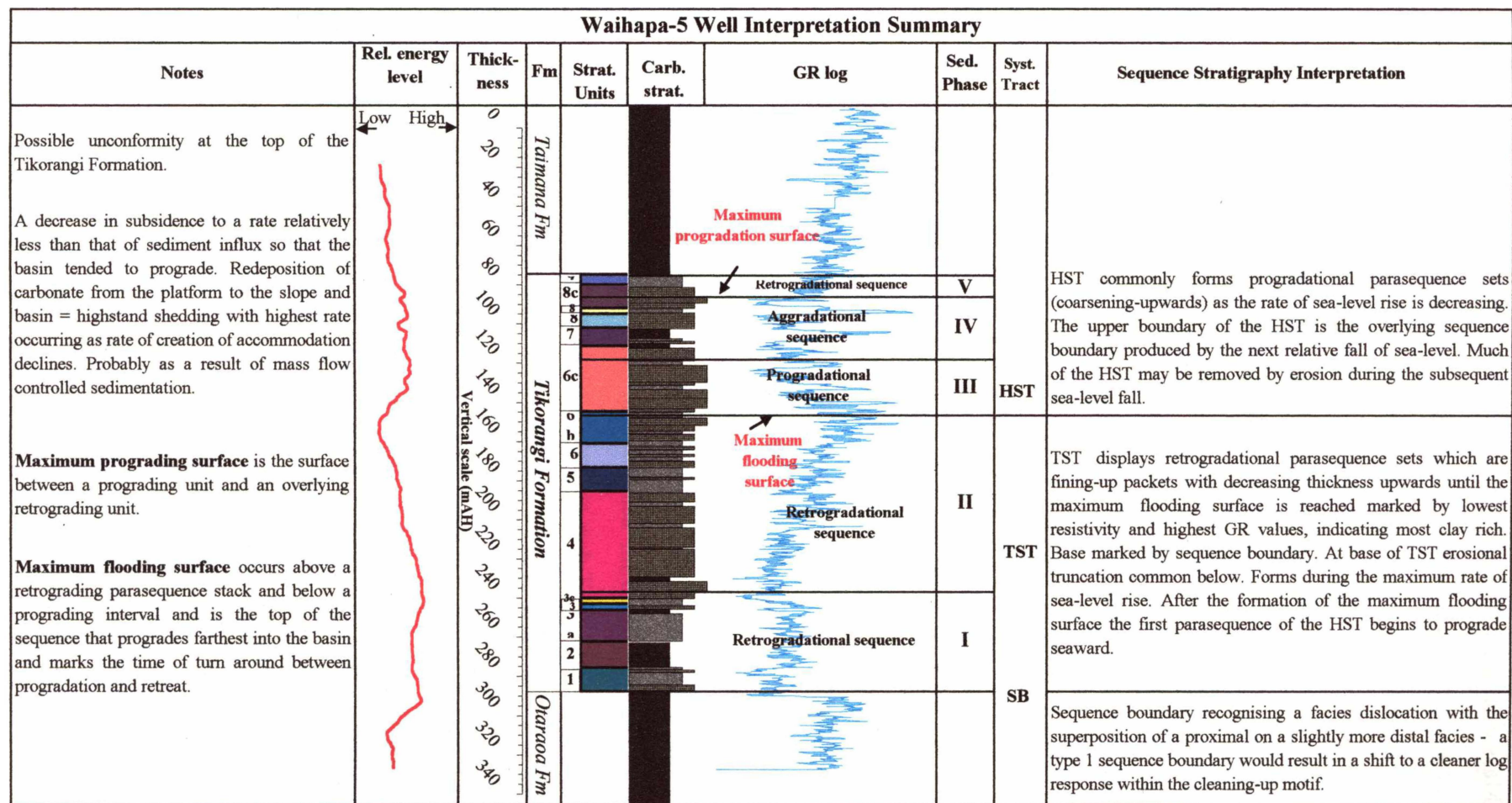


Fig. 3.13 Sedimentary history of the Tikorangi Formation as seen in the onshore Waihapa-5 well. mAH = metres along hole. SB = sequence boundary.

probably again indicative of mass emplacement, a feature of the northern wells in Phase IV. Mass-emplaced units are not so obvious in the more southern wells and, if present, are further from source.

The upper boundary of Phase IV marks the maximum progradation surface. Here GR values are at a minimum and the surface bounds prograding and an overlying retrograding unit. A feature of Phase IV is the erratic GR log character in which very high GR peaks may represent sonic spikes or markers corresponding to background pelagic sedimentation. These markers are usually thin, fine-grained, siliciclastic-rich units, or shales, that have high GR response, low resistivity and low sonic velocity, and probably represent condensed intervals. GR spikes correspond with pauses in highstand carbonate shedding with very little siliciclastic input at the peak of the transgression.

Phase IV on average forms 21% of the Tikorangi Formation thickness, which equates to an average 47 mAH thickness. As in the previous Phase III, Waihapa-6 has the thickest units. Phase IV has been responsible for the deposition of stratigraphic units ranging from the uppermost of Unit 6c to commonly mid Unit 8. This may be lower Unit 8 in the southernmost onshore well (Hu Rd-1) and upper Unit 8 in the more northern wells (Ngaere-2 and Waihapa-4).

Phase IV in offshore Maui-1 has also been correlated with a similar aggradational to slightly progradational trend.

3.5.6 Phase V

The base of Phase V occurs onshore in either Unit 8b or 8c (Fig. 3.10; Table 3.3) and represents a short-lived retrogradational phase in which carbonate production from factory sites declined as siliciclastic sedimentation increased. Uplift of siliciclastic source areas occurred and eventually siliciclastic influxes drowned the carbonate production factories and brought to an end the deposition of carbonate-rich sediments, effectively ending deposition of the Tikorangi Formation.

Phase V is slightly better developed or longer-lived in the southern wells, pointing to a more proximal siliciclastic source area in this direction. On average, Phase V accounts for the least thickness in the Tikorangi Formation, only 12%, or a 5 m AH thickness. The phase is dominated by Units 8c and 9 (Table 3.3).

The top of Phase V marks the top of lithostratigraphic Unit 9, in all cases a relatively thin Facies B unit which changes to Facies A once in the overlying Taimana Formation. After this time only occasional thin limestones occur within the Taimana Formation, ending the previous dominance of carbonate sedimentation.

3.6 CONCLUSIONS

The redeposited foredeep facies of the Tikorangi Formation beneath onshore Taranaki formed during the earliest Miocene (Waitakian) during a period of major tectonic activity and a basinwide marine transgression with little influence from eustatic sea-level change. With increased rates of submergence about 27 Ma (King & Thrasher 1996), and near drowning of eastern Mesozoic basement siliciclastic source areas, the resulting decreased influx of siliciclastic material into the basin enabled formation of the carbonate-rich Tikorangi Formation whose deposition marks the maximum flooding of the onshore part of the basin.

Formation of the Tikorangi deposits was fundamentally controlled by tectonism directly influencing the creation of foredeep trough accommodation, the rate and type of sediment supply into the foredeep, and relative position of sealevel. The interplay amongst these factors has produced a mixed siliciclastic-carbonate succession which often displays both complex vertical and lateral lithological variation over relatively short distances of a few kilometres.

Carbonate supply into the basin has been controlled by periodic mass-emplacement events, particularly evident in the upper parts of the formation, that

probably formed by highstand shedding from topographic highs and fringing shelf areas. These areas are inferred to have developed carbonate build-ups, possibly as shoals or banks, during a long-term period of sea-level rise. Over-steepening or slumping of carbonate sediment from these banks, and storms, were probably important trigger events causing mass sediment movement downslope (Foreman et al. 1991). Once initiated, these mass flows may have been channelled in some instances, with feeder channels preferentially supplying certain sites and not others. Carbonate resedimentation is generally thought to be more common during highstands due to overproduction in shallow water resulting in overloading and steepening of the slope and instability leading to failure and the generation of sediment gravity flows (Tucker & Wright 1990).

Episodic mass emplacement has produced fine fragmental skeletal material and has displaced certain shallow-water biota (e.g., coralline red algae, *Amphistigena*) basinward (see Topic 4). Background lower-volume carbonate input was also supplied more continuously by planktic foraminifera and nannofossils. Hu Rd-1 is sedimentologically unique, being much coarser-grained, more carbonate-rich, and containing an abundance of shallow-water skeletons, especially *Amphistegina*. This well appears to represent a much shallower, possibly near *situ* facies which may have formed on a topographic basement high.

Wells throughout different parts of the depositional system(s) show both differences and similarities in geophysical log response. The complexities probably relate to sites receiving variable quantities of both carbonate and siliciclastic material at different times, and are suggestive of multi-point source regions and inter-facies mixing during sediment reworking and redeposition. Consequently, some wells (Ngaere-2) are more carbonate-rich, while others (Waihapa-6) are more siliciclastic-rich. Most typically in the northern wells, thick (to 20 m or more) carbonate-rich facies are inferred to be mass-emplaced from the barrel- and block-shaped signatures seen in their GR geophysical logs. These log characteristics are suggestive of a more proximal carbonate source in the north.

Five major correlatable geophysical log sequences have been established, representative of major depositional phases within the Tikorangi Formation. Phase I is characterised by retrogradation and continued foredeep subsidence. Phase II continues the Phase I retrogradational trend, but with accelerated foredeep subsidence and sea-level rise. Together, Phases I and II form an overall TST with the sequence boundary placed at the base of the Tikorangi Formation, and its top marking the maximum flooding surface. More generally, these lower two phases show rather subdued log responses, after which a major change in depositional mechanisms is likely. Phase III shows a progradational trend associated with declining subsidence rates and movement of carbonate facies basinward. Phase IV is a prograding aggradational sequence dominated, like Phase III, by often thick, periodically mass-emplaced carbonate-rich units separated by thin, shale-like units representing sonic spikes and background siliciclastic sedimentation. Phase V marks a return to retrogradational conditions and the reintroduction of siliciclastic material following uplift of basement associated with a period of increased convergence at the Australian/Pacific plate boundary. Phases III to V correspond to sedimentation during a HST. Proximal parts of the transgressive and highstand carbonate facies tracts have been deposited in deep shelf settings, but distal facies accumulated at bathyal depths.

The offshore Oligocene to Early Miocene (Whaingaroan to Otaian) basinal Tikorangi Formation facies is atypical of more landward deposits and represents a condensed, deeper-water equivalent to the onshore wells. Offshore the formation is mainly a variably calcareous siliciclastite formed from the hemipelagic settling of dominantly fine quartz and feldspar, and the pelagic fallout of planktic foraminifera and nannofossils (coccoliths). It was sufficiently removed from the foredeep trough that it was not to be influenced to any significant extent by those factors controlling sedimentation at the more landward well sites.

Renewed tectonism on the basin's eastern margin towards the end of the earliest Miocene was associated with further basement thrusting westwards which provided an uplifted siliciclastic source which effectively diluted and eventually

suppressed carbonate production. This ended carbonate-dominated deposition of the Tikorangi Formation and marked a change from an overall transgressive to a major regressive phase, which continues today.

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PETROGENESIS OF SHELF TO BASIN MEGAFACIES IN THE MID-TERTIARY MIXED CARBONATE-SILICICLASTIC TIKORANGI FORMATION RESERVOIR, TARANAKI BASIN, NEW ZEALAND

4.1 ABSTRACT

Detailed petrography of the mixed carbonate-siliciclastic Tikorangi Formation reservoir rock in Taranaki Basin has delineated five petrographic facies: I - mudstones; II – wackestones; III – packstones; IV - poorly washed grainstones; V - sparry grainstones. Skeletal varieties within these petrofacies have aided in the identification of three texturally and compositionally unique megafacies for the Tikorangi Formation.

Megafacies 1, an earliest Miocene (Waitakian), near-situ, shallow-shelfal limestone defined by, and limited to, Hu Rd-1A well, the southern- and easternmost well of the onshore Tarata Thrust Zone of the Eastern Mobile Belt, is characterised by very coarse sand-sized, poorly washed and very pure grainstones (80-99% carbonate) dominated by relatively shallow-water high energy taxa (including larger foraminifera, calcareous red algae, barnacles, and bryozoan debris) indicative of a photic, shallow-marine environment. Interbedded siliciclastic-rich layers comprise subrounded to rounded greywacke lithic fragments which, together with rare angular brecciated blocks of greywacke, place this megafacies on or very near variably exposed Mesozoic basement associated with the Patea-Tongaporutu-Herangi High.

Megafacies 2 occurs further west and north in the Tarata Thrust Zone (Ngaere-2, Toko-1, and Waihapa-2, -4, -5, -6 wells associated with the Waihapa/Ngaere oil field), as an earliest Miocene (Waitakian) foredeep megafacies comprising a spectrum of variably siliciclastic, generally carbonate-dominated rocks ranging from rare mudstones to grainstones, but dominated by wackestones, packstones, and poorly washed grainstones, including a prominent component of reworked

and redeposited siliciclastics and shelfal bioclasts (bivalves, echinoderms, calcareous red algae, benthic foraminifera). Mass-emplacement into the Taranaki foredeep (foreland basin) resulted in: basinward displacement of shallow-water biota; production of highly fragmented fine sand-sized shelfal material; intermixing of shelfal skeletons with background slope microfauna (pelagic foraminifera) and microflora (coccoliths); generation of a spectrum of limestones that are mainly compositionally and texturally distinctive from age-equivalent deposits (Te Kuiti Group) exposed onland.

Megafacies 3 occurs in more distal offshore basinal settings, as at Maui-1 on the Western Stable Platform, basinward, and is an Oligocene-Early Miocene (Whaingaroan-Otaian) deeper-water equivalent comprising very calcareous wackestones (up to 41% carbonate). Skeletal types are predominantly pelagically settled planktic foraminifera and coccoliths, while the siliciclastic fraction is dominated by but are mainly dominated by clay- to fine silt-sized quartz and feldspar derived from Patea-Tongaporutu-Herangi High and South Island basement, and windblown Australian sources.

Depositional settings for the three contrasting megafacies existed in relatively close proximity, each with an individual set of environmental parameters controlled largely by the interplay of the evolving and complex plate tectonic setting, including sudden development of a carbonate foredeep, changes in relative sealevel within an overall transgressive regime, and the changing availability and sources of siliciclastic supply. Tikorangi Formation megafacies capture a shelf-to-basinal perspective of New Zealand's only hydrocarbon-producing limestone reservoir, at a time when many other New Zealand basins were also accumulating non-producing carbonate-dominated deposits.

Keywords petrogenesis; carbonate; shelf-to-basin facies; Tikorangi Formation; Oligocene-Miocene; Taranaki Basin; hydrocarbons; fractured reservoir; limestone

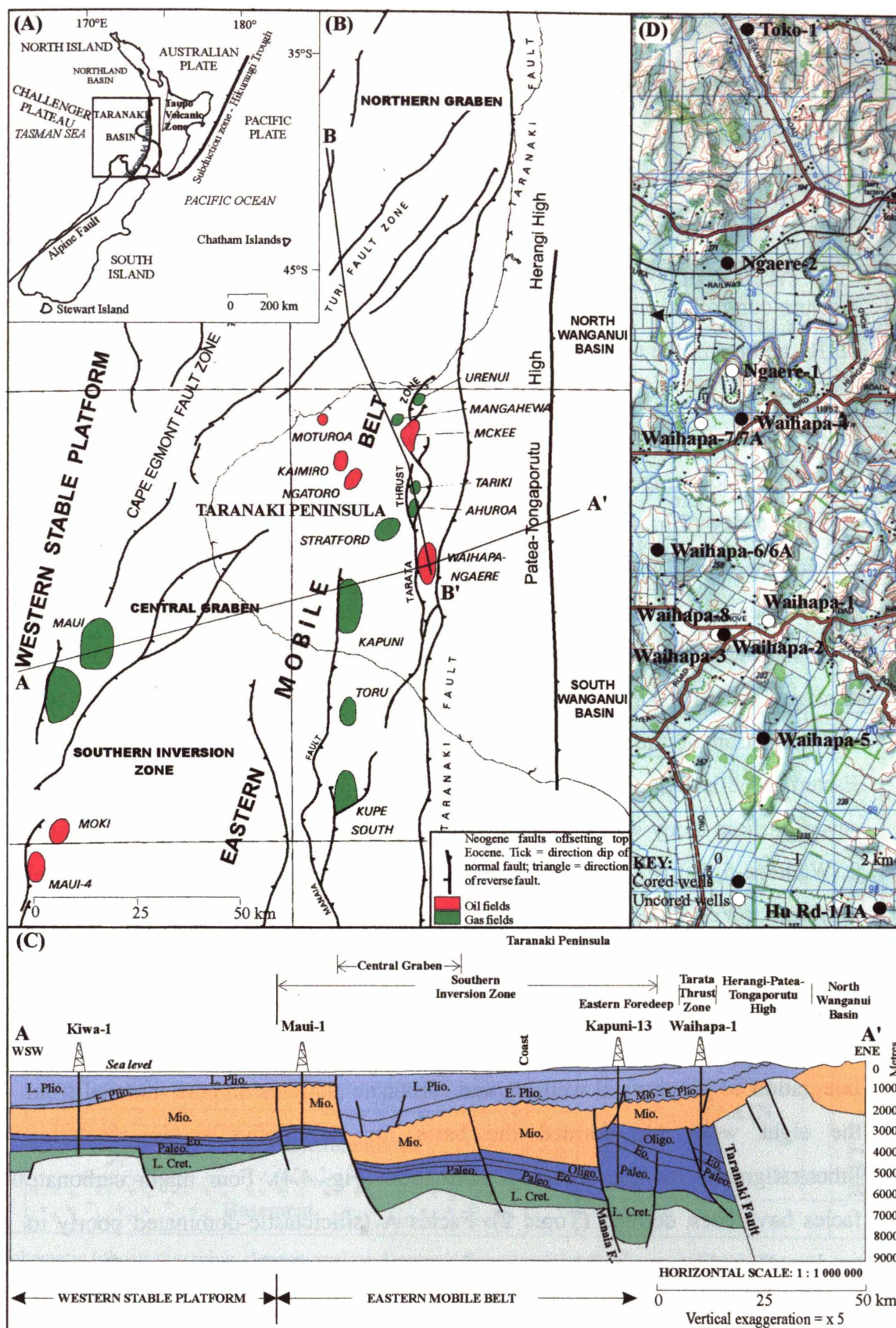


Fig. 4.1 (A) Location of Taranaki Basin in New Zealand. (B) Major structural and tectonic elements and main oil/condensate accumulations within Taranaki Basin. The Tikorangi Formation is dated as earliest Miocene in the east (Waihapā-1) and Oligocene-Early Miocene in the west (Maui-1). Adapted from King & Thrasher (1996). (C) Structural cross-section of a transect running WSW - NE through offshore Maui-1 and onshore through the Waihapā-Ngaere Field, Tarata Thrust Zone (see location in B). Adapted from King & Thrasher (1996). Shading: = late Neogene, = early Neogene, = Paleogene, = Late Cretaceous, = basement. E. Plio. = Early Pliocene; L. Plio. = Late Pliocene; Mio. = Miocene; Oligo. = Oligocene; Paleo. = Paleocene; L. Cret. = Late Cretaceous. E. Plio. = Early Pliocene; L. Plio. = Late Pliocene; Mio. = Miocene; Oligo. = Oligocene; Paleo. = Paleocene; L. Cret. = Late Cretaceous. (D) Location of the seven onshore wells (solid circles) providing core from the Tikorangi Formation within the Waihapā-Ngaere Field that form the basis for this study.

4.2 INTRODUCTION

The Tikorangi Formation is an Oligocene to Early Miocene mixed carbonate-siliciclastic sequence in Taranaki Basin (Fig. 4.1A), currently New Zealand's only commercial hydrocarbon basin. The formation is an important highly-productive fracture-controlled oil reservoir within the onshore Waihapa-Ngaere Field (Fig. 4.1B), and forms the only carbonate-dominated host within Taranaki Basin.

The basin contains a broadly transgressive sedimentary record of Late Cretaceous to Early Miocene age overlain by a very thick regressive section which is still forming today (Fig. 4.2). From mid-Oligocene the basin underwent accelerated subsidence which was most pronounced and rapid in the east, resulting in the development of a carbonate foredeep into which the bulk of the Tikorangi Formation was deposited (Fig. 4.3, 30-23 Ma panels). A change in plate boundary configuration in the Early Miocene saw overthrusting along the Taranaki Fault and formation of the Tarata Thrust Zone and associated structures within the Eastern Mobile Belt (Fig. 4.1B, C). It is within the Tarata Thrust Zone that the seven onshore study wells (Toko-1, Ngaere-2, Waihapa-4, Waihapa-6, Waihapa-2, Waihapa-5, Hu Rd-1/1A) are located (Fig. 4.1D). In contrast, western areas of the basin (Western Stable Platform) have remained comparatively tectonically quiescent and provide the setting for the offshore Maui-1 well (Fig. 4.1C) (King 1994; King & Thrasher 1996).

Integration of geophysical well-log and carbonate analyses on core material from the eight wells has formed the basis for developing a high-resolution lithostratigraphy for the Tikorangi Formation (Fig. 4.4). Four major carbonate facies have been defined (Topic 2): Facies A (siliciclastic-dominated poorly to moderately calcareous mudstone to claystone with <25% carbonate); Facies B (mixed, moderately to strongly calcareous siliciclastic siltstone to fine sandstone-carbonate with 25-50% carbonate); Facies C (impure muddy carbonate with 50-75% carbonate); and Facies D (purer, typically more sparry carbonate with >75% carbonate).

The intention of this topic is to examine in more detail the compositional and

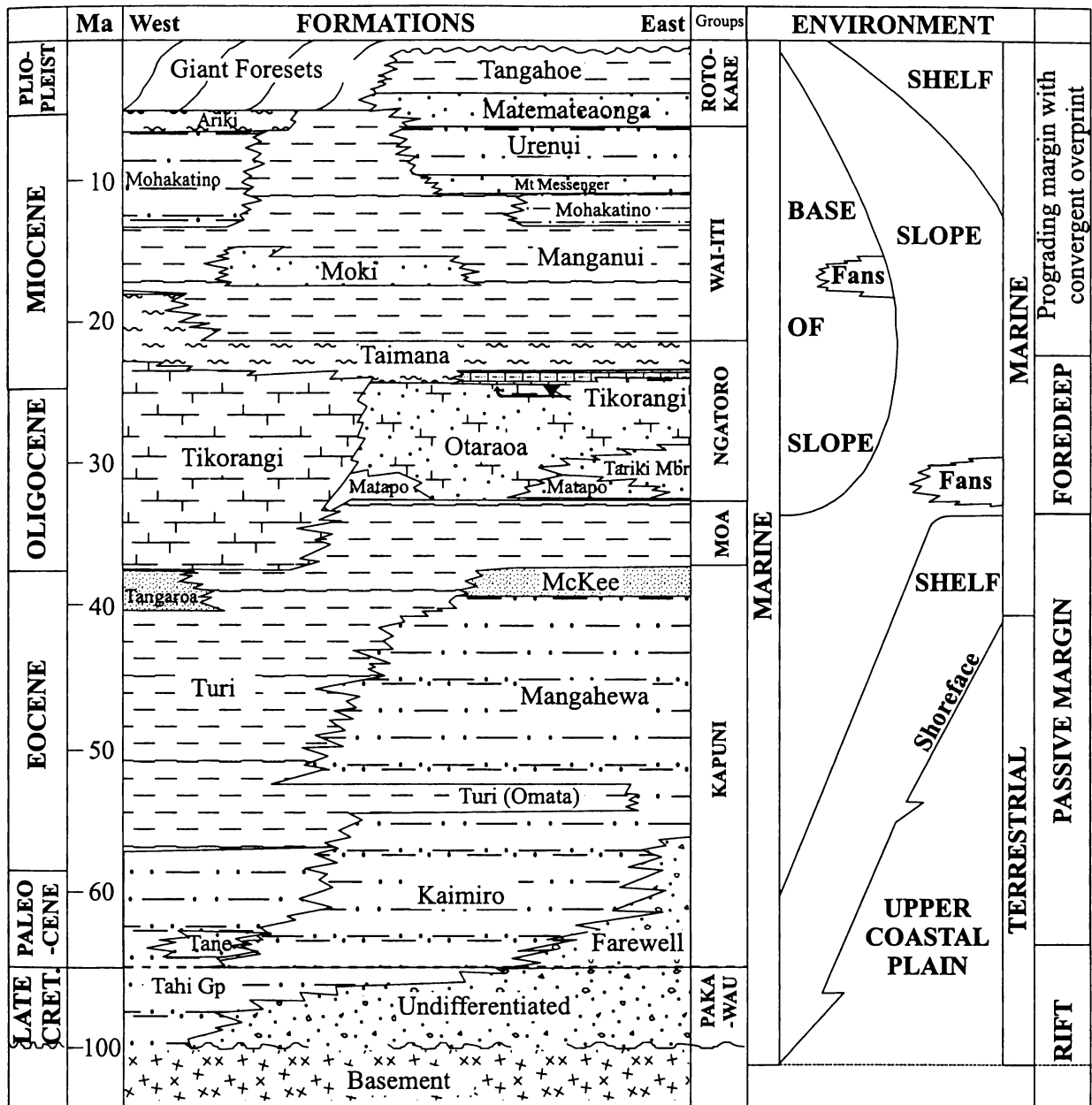


Fig. 4.2 Schematic lithostratigraphic, depositional, and tectonic framework for the Taranaki Basin. The carbonate-dominated Tikorangi Formation sits unique amongst otherwise siliciclastic-dominated facies. Adapted from King (1990).

textural character of the Tikorangi calcareous rocks using standard petrographic techniques. Petrography is discussed initially in general terms for the above four carbonate-geophysical log facies, before then establishing a finite number of more specific texturally and compositionally defined petrographic facies for the formation. The inter-relationships amongst these petrofacies will be examined, as will any discernible upcore trends in the study wells. Finally, the petrography of the Tikorangi Formation will be summarised within the framework of three Tikorangi Formation megafacies for which paleoenvironments, interpretative whole rock compositions, and depositional settings will be discussed.

4.3 PETROGRAPHY

4.3.1 Mineralogy

Skeletons within the Tikorangi Formation are solely LMC (low-Mg calcite <4 mol% MgCO_3), typical of nontropical carbonates generally (Hood & Nelson 1996). Prior to undergoing stabilisation reactions these skeletons were a mix of aragonite, HMC (high-Mg calcite, >12 mol% MgCO_3), IMC (intermediate-Mg calcite, 4-12 mol% MgCO_3) and LMC forms. Occasionally thin-shelled former aragonitic infaunal bivalves, and rarely gastropods, were initially preserved within the fine-grained muddy sediments to later undergo neomorphic transformation to LMC forms. Early neomorphic stabilisation to LMC via incongruent dissolution (e.g., Hood & Nelson 1996) has also occurred of originally HMC (echinoderms, calcareous red algae) and IMC (bryozoans, benthic foraminifera) skeletons. Primary LMC skeletons (e.g., epifaunal bivalves, planktic foraminifera, coccoliths, barnacles, and some bryozoans) remain apparently unaltered.

4.3.2 Geophysically-defined carbonate Facies A to D

Samples obtained from the Tikorangi Formation (Appendix 2.2) for this petrographic study are fundamentally controlled by the stratigraphic positioning of drill core material (Appendix 2.1 for core). The distribution of these samples in relation to the geophysically-defined facies is summarised in Fig. 4.5A. Facies C samples dominate the collection, with lesser but similar numbers of Facies B and D samples, and only a few examples of Facies A material.

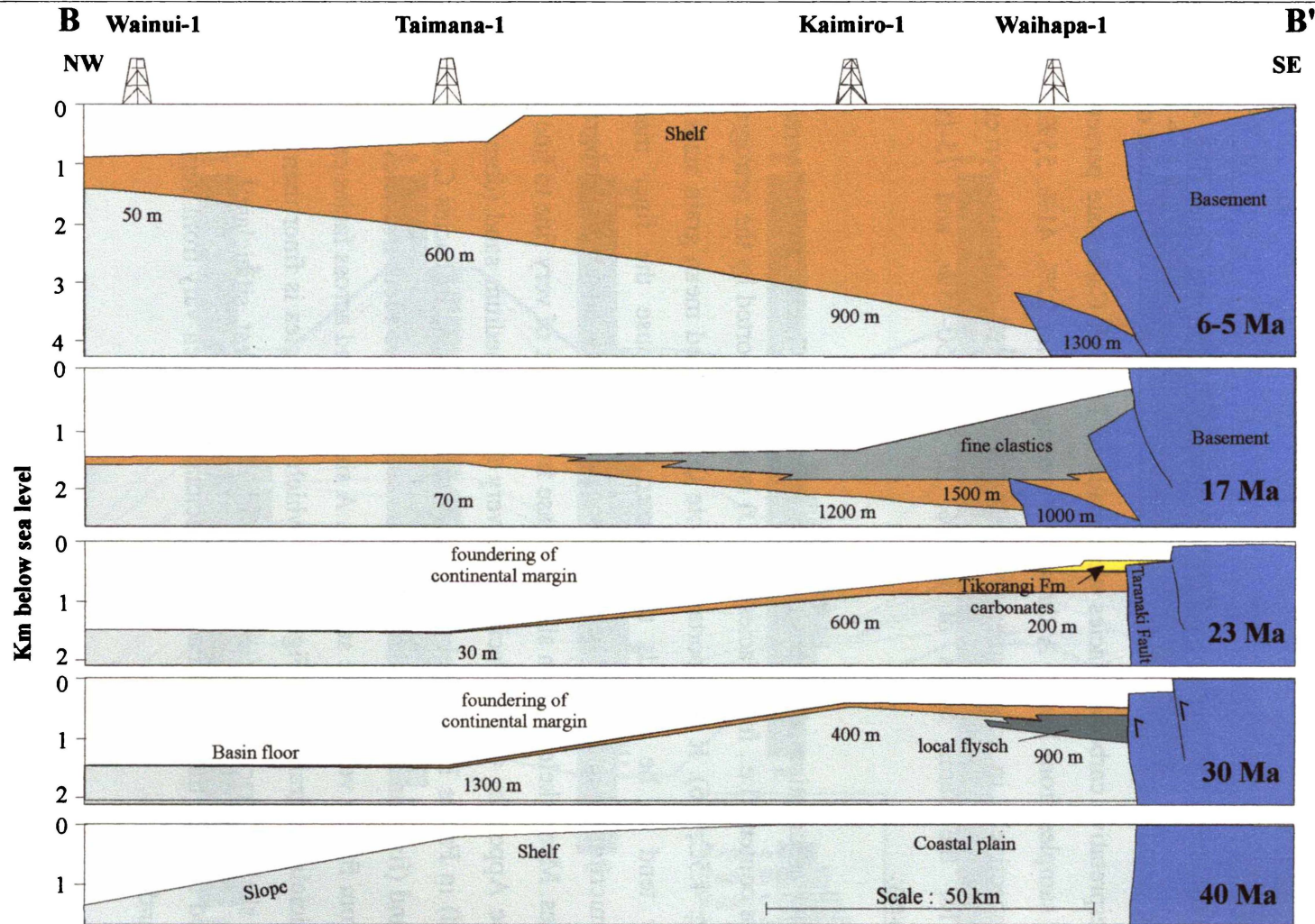


Fig. 4.3 Cross sections through Taranaki Basin showing the magnitude and distribution of incremental Oligocene-Miocene subsidence (in metres), and formation of the carbonate foredeep into which the thickest sediments of the Tikorangi Formation were deposited. The base of the brown colouring denotes the Oligocene-Eocene boundary. See Fig. 4.1 for approximate cross section location. Adapted from King & Thrasher (1996).

Petrographic data for core samples are documented in Appendix 4.1 and summarised for the four carbonate facies in Fig. 4.5. Petrographic percentage data were derived by taking the mid-point of the percentage range recorded in Appendix 4.1 and recalculating this value as that part of the whole rock composition (Appendix 4.2).

Average measured carbonate percentages for the four carbonate facies (Fig. 4.5B) show the sound basis upon which the initial identification and distribution of the four interpretative carbonate facies were made in Topic 2. Carbonate percentage data for samples from Facies A through D average about 22%, 41%, 55%, and 75%, respectively, in good agreement with the interpreted carbonate percentage ranges for the same facies of 0-25%, 25-50%, 50-75%, and 75-100%, respectively.

The earlier assumption of increasing grain size (Topics 2 and 3) with increasing carbonate content (i.e., from Facies A to D) is also supported by the petrographic data (Fig. 4.5C, 4.6). It is important to note that reported mean grain sizes here probably tend to be towards the coarser end because the finer material (matrix/micrite) is unable to be easily measured using standard petrographic techniques. Mean skeletal grain sizes increase from a mix of very fine to fine sand sizes (see Appendix 4.7) in Facies A to very fine to medium sand (dominantly fine sand) in Facies B. Skeletal grain sizes further increase in Facies C to reach coarse sand (fine sand-dominated), while the coarsest sizes occur in Facies D with ranges from fine to very coarse sand grade. A similar trend across facies exists for mean siliciclastic grain size (Fig. 4.5C), which in all facies is finer than the co-existing skeletal fraction. Facies A comprises the finest siliciclastic fraction, dominated by silts, through to Facies D siliciclastics which vary from very fine to coarse sand.

Average whole rock compositions show a progression of increasing bioclastic and spar cement contents with increasing carbonate content (Fig. 4.5D). Thus Facies A has the least bioclastic content and Facies D the highest. Conversely, siliciclastic grain and matrix/micrite contents are highest in Facies A and decrease progressively across the facies to be lowest in Facies D.

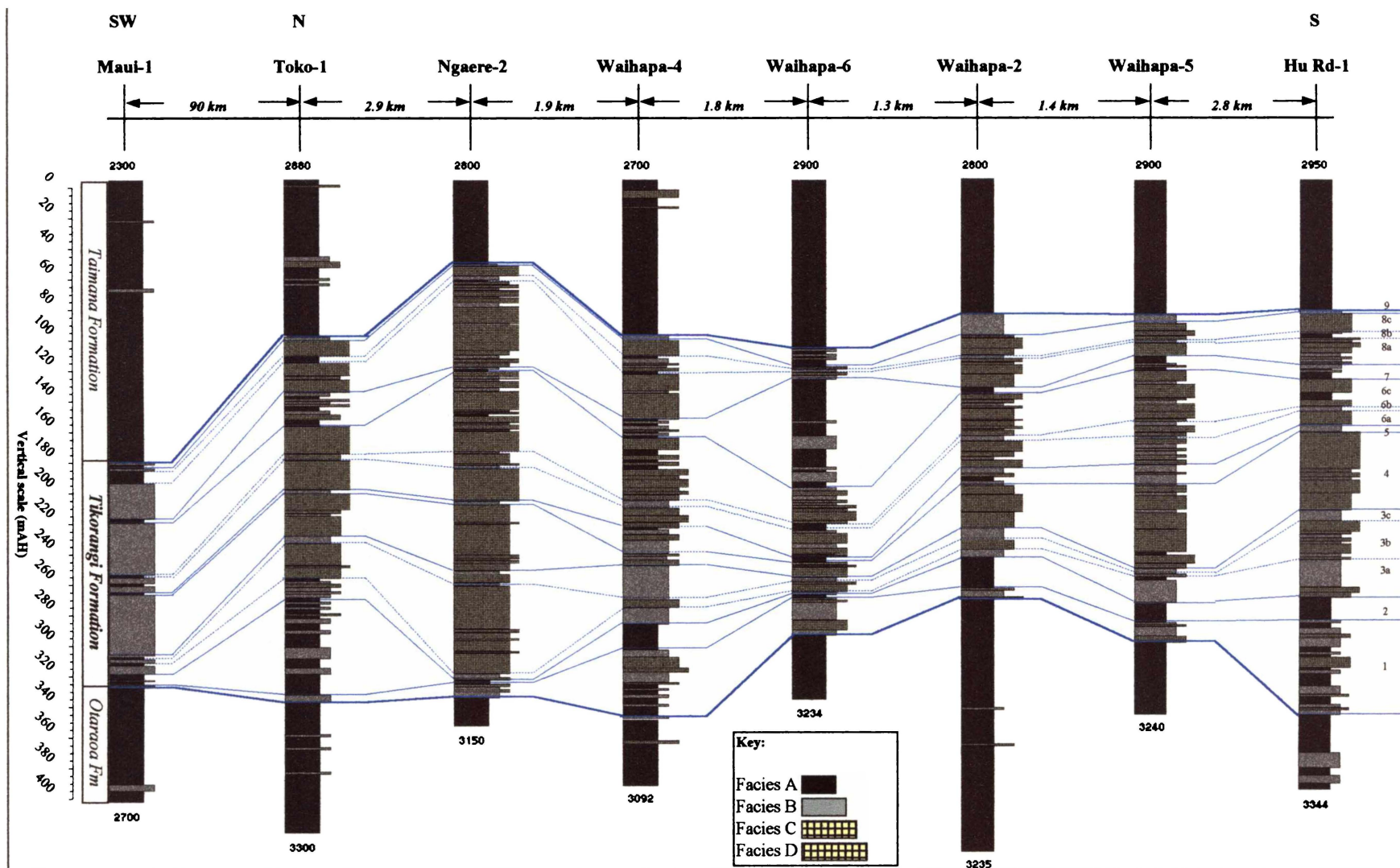


Fig. 4.4 Panel diagram showing the lithostratigraphy for the Tikorangi Formation interval. Wells are drawn from offshore Maui-1 to onshore Toko-1 and south to Hu Rd-1. Numbers at top and bottom of each column refer to depths in m AH (along hole). Lithostratigraphic subdivisions or units, defined by integrating geophysical well-log and carbonate percentage data (see Topic 2), are numbered labelled on the right.

Skeletal compositional trends (Fig. 4.5E) show a general decrease in planktic foraminifera from Facies A to D, while slightly higher contents of bivalves and echinoderms occur in Facies C and D. Calcareous red algae are rare overall, but become important contributors in Facies D along with barnacles and bryozoans. Siliciclastic composition is broadly similar across all facies (Fig. 4.5F), although quartz and feldspar contents show a relative decrease at the expense of rock fragments in the higher carbonate facies.

4.4 PETROFACIES

Having examined the general petrography of the lithostratigraphically defined carbonate facies, a number of texturally and compositionally defined petrofacies have been identified within the Tikorangi Formation. The textural classification employed is that devised by Dunham (1962) for carbonate rocks, a scheme widely used in the petroleum industry. The typically fine-grained nature of Tikorangi samples has necessitated their texture being determined petrographically.

Five main petrofacies occur in the Tikorangi Formation (summarised in Table 4.1) (Plate 4.1A-F), namely mudstones (Petrofacies I), wackestones (Petrofacies II), packstones (Petrofacies III) through poorly washed grainstones (Petrofacies IV), and sparry grainstones (Petrofacies V).

4.4.1 Relationship of carbonate facies and petrofacies

The link between the five petrofacies and the originally defined carbonate facies is shown in Fig. 4.7. The general relationship of decreasing matrix and increasing grains (includes both bioclastic and siliciclastic grains) with increasing carbonate content from Facies A to D is evident. Carbonate Facies A is the only one to contain Petrofacies I mudstones, while only carbonate Facies D includes true Petrofacies V grainstones.

4.4.2 Relative occurrence of petrofacies

Before examining in detail the five petrofacies, their relative occurrence amongst the analysed samples from the Tikorangi Formation is noted in Fig. 4.8.

Carbonate facies Petrographic Summary

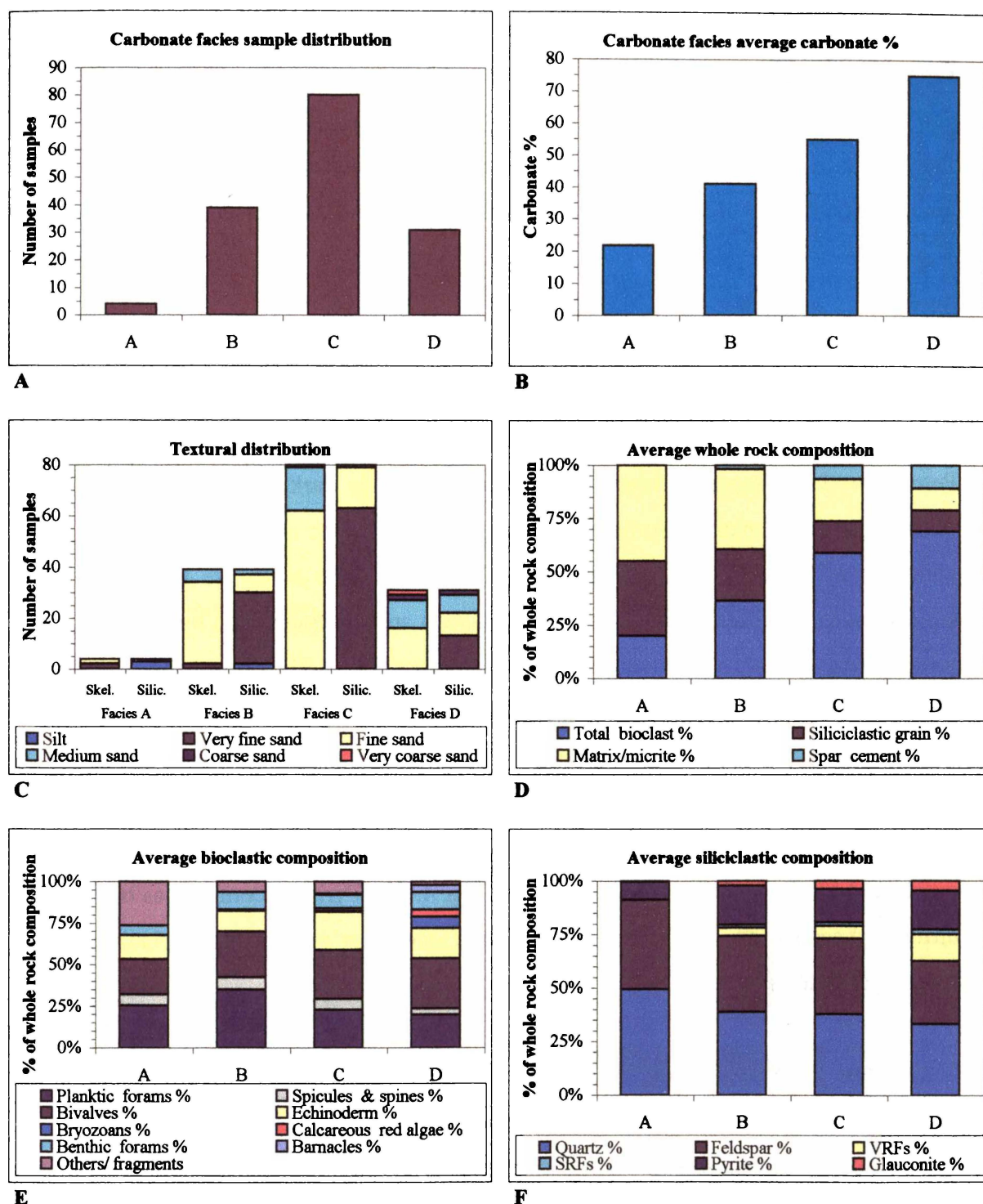


Fig. 4.5 Summary petrography data for the four Tikorangi Formation carbonate facies A-D. (A) Number of samples, (B) average carbonate content, (C) textural characteristics, (D) average whole rock composition, (E) average bioclastic composition, and (F) average siliciclastic composition for individual carbonate facies. Facies A = calcareous siliciclastites (<25% carbonate). Facies B = very calcareous siliciclastites (25-50% carbonate). Facies C = muddy limestones (50-75% carbonate). Facies D = sparry limestones (>75% carbonate).

Packstones account for 35% of samples collected, while wackestones and poorly washed grainstones for 29% and 27%, respectively. Together these three petrofacies account for more than 90% of the sampled Tikorangi Formation. Grainstones form only 8% of samples, and mudstones are rare at 1% of the total sample database.

Petrographic data pertaining to individual petrofacies and their respective compositional skeletal varieties are summarised in Table 4.2 and discussed below.

4.5 PETROFACIES I - MUDSTONES

Defined by <10% identifiable bioclasts and having mud-supported fabrics, these Petrofacies I mudstones (Plate 4.1A) are dominated by dark, very fine-grained (clay to fine silt) matrix/micrite accounting for 50% of the average whole rock composition (Table 4.1, 4.2) (Fig. 4.9A). Texturally these rocks are lutites, or equivalent to fossiliferous micrites of Folk (1962) and are dominated by planktic foraminifera and calcareous nannofossils (coccoliths) (Fig. 4.9B; Plate 4.1H), with occasional fragments of echinoderms, spicules and spines, benthic foraminifera and bivalves. Skeletal grain size is largely controlled by the average foraminiferal test size (0.1 mm), although other biota represent fine abraded and generally variably sorted fragments (Fig. 4.9D). Siliciclasts are dominated by subangular quartz and feldspar of silt to fine sand size (Fig. 4.9C). Pyrite is common as both infills and scattered grains, while glauconite is rare. Spar cement infills planktic foraminiferal tests.

Petrofacies I rocks occur solely within carbonate Facies A (Fig. 4.9E) (siliciclastic-dominated, poorly to moderately calcareous, mudstone to claystone with <25% carbonate). Laboratory determined carbonate contents for these samples range from 15 to 30% (Fig. 4.9F) and average 22% carbonate. This suggests that a large proportion of the matrix is clay to silt sized siliciclastic material and not carbonate mud or micrite. This is further evident from x-ray diffraction analysis which detected clay mineral contents of only a few percent

Carbonate facies - textural composition summary

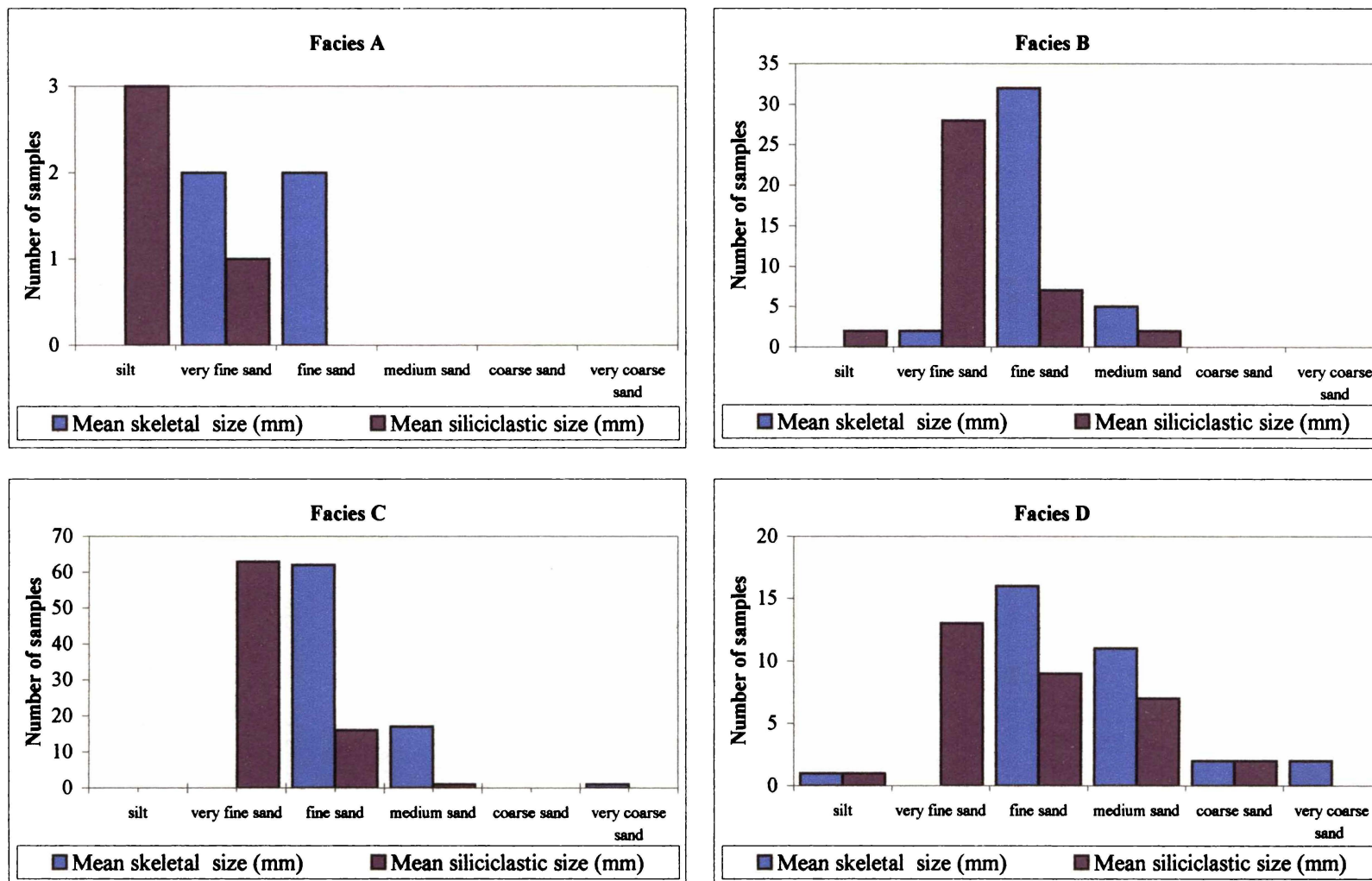


Fig. 4.6 Summary of the textural characteristics of the four carbonate facies within the Tikorangi Formation. Facies A = calcareous siliciclastites (<25% carbonate). Facies B = very calcareous siliciclastites (25-50% carbonate). Facies C = muddy limestones (50-75% carbonate). Facies D = sparry limestones (>75% carbonate).

(see Topic 6) and is supported by more general findings reported in Simpson (1992).

4.6 PETROFACIES II - WACKESTONES

Petrofacies II comprises wackestones, defined as containing >10% bioclasts and having mud/matrix-supported fabrics (Table 4.1, 4.2) (Plate 4.1B). Matrix averages 41% of the whole rock composition (Fig. 4.10A) and the rocks are analogous to the sparse biomicrites of Folk (1962). Bioclasts dominate over siliciclasts and on average account for one third of the whole rock composition. Bioclasts are variously dominated by one or other of planktic foraminifera (av. 34%), bivalve (av. 25%), and occasionally echinoderm fragments (Fig. 4.10B) (see Appendix 4.3 for more detailed descriptions). Maximum skeletal grain size commonly reaches 0.75 mm and rarely exceeds 2.5 mm, although long thin fragments of occasional bivalves or echinoderms may reach up to 9 mm (Plate 4.1G, H). Other important groups include benthic foraminifera. Skeletal grains are highly abraded and fragmented, typically fine sand-sized (Fig. 4.10D) (av. 0.18 mm), and generally moderately to well sorted.

Siliciclasts account on average for about one quarter of Petrofacies II and typically comprise very fine sand-sized (Fig. 4.10D) (range silt to medium sand, av. 0.1 mm), commonly subangular, well to very well sorted sub-equal quantities of quartz and feldspar (Fig. 4.10C). Together these minerals form about 80% of the average siliciclastic composition. Pyrite is an important authigenic mineral appearing as scattered clusters and infills. Glauconite, rock fragments, and intergranular spar cement are rare.

Petrofacies II rocks commonly occur within carbonate Facies B (Fig. 4.10E), with occasional examples in Facies A and C. Based on the geophysical correlations (Topic 2) these Tikorangi Formation wackestones dominantly have carbonate contents from 25-50%. Laboratory determined carbonate data yield values from 30-50% (Fig. 4.10F), with an average of 38%.

Table 4.1 Summary characteristics of the five petrofacies identified within the Tikorangi Formation.

Petrofacies	Name	Rock classification (After Dunham 1962)	Bioclast content (%)	Fabrics	Occurrence (sampled)	Carbonate facies	Carbonate content	Skeletal types
I	calcareous lutites	mudstones	<10	mud/matrix supported	rare	A	15 -30 (av. 22)	Planktic foraminifera, nannofossils
II	calcareous very sandy lutite	wackestones	30	mud/matrix supported	common	B (rarely A, C)	30-50 (av.38)	Planktic foraminifera, bivalves, +/- benthic foraminifera, echinoderms
III	fine muddy calcareenites	packstones	65	grain supported	very common	C (rare B, D)	29-86 (av.53)	Bivalves, planktic foraminifera, echinoderms, +/- benthic foraminifera, spicules/spines, algae
IV	impure fine muddy calcareenites to sparry medium calcareenites	poorly washed grainstones	60	grain supported	common	C (some D)	60-70 (av. 61)	Bivalves, planktic foraminifera, echinoderms, +/- benthic foraminifera, algae, spicules/spines, bryozoans, barnacles
V	fine to very coarse pure sparry calcareenites	sparry grainstones	80	grain supported	some	D	75-99 (av.85)	Echinoderms, bivalves, bryozoans, barnacles, benthic foraminifera, algae

4.7 PETROFACIES III - PACKSTONES

Packstones assigned to Petrofacies III, defined by >5% mud matrix in a grain-supported fabric, account for 53 rocks sampled within the Tikorangi Formation and represent the most commonly occurring petrofacies (Table 4.1, 4.2). These packstones are analogous to Folk's (1962) biomicrite. Bioclasts av. 65% of the whole rock composition (Fig. 4.11A) and are dominantly fragmental and fine sand-sized (av. 0.2 mm) (Fig. 4.11D) (Plate 4.1C). Skeletal grains are strongly abraded, and are usually moderately to well sorted. The wackestones are variously dominated by one or other of bivalve (av. 32%; Fig. 4.11B), planktic foraminifera (av. 26%), and echinoderm fragments (av. 20%) (see Appendix 4.3 for more detailed descriptions). Fragments of benthic foraminifera, spicules and spines which may become locally important, and calcareous red algae, occur rarely.

Matrix/micrite is the second most abundant component (av. 18%) of these packstones. Siliciclasts are relatively few and are generally angular to subangular and well to very well sorted. They are dominated by very fine sand-sized quartz and feldspar (Fig. 4.11C) (overall av. 0.1 mm). Glauconite is present in minor quantities with rare volcanic rock fragments. Spar cement contents increase in relation to the other matrix-rich petrofacies, but still only av. 4%.

Petrofacies III packstones dominantly occur in carbonate Facies C (Fig. 4.11E), a few within Facies B and D. This would imply a dominance of carbonate contents in the range of 50-75%, while actual laboratory determined values across all packstone samples vary from 29-86% carbonate (Fig. 4.11F), with an av. of 53%.

4.8 PETROFACIES IV - POORLY WASHED GRAINSTONES

Poorly washed grainstones of Petrofacies IV total 44 samples (Table 4.1, 4.2) and are defined by having sub-equal quantities of mud matrix and spar cement, analogous to biomic sparites of Folk (1962). Rocks are skeletal-rich limestones (Plate 4.1E) av. 60% bioclasts (Fig. 4.12A) variously dominated by one or other of bivalve fragments (av. 31%), planktic foraminifera (av. 22%), echinoderm

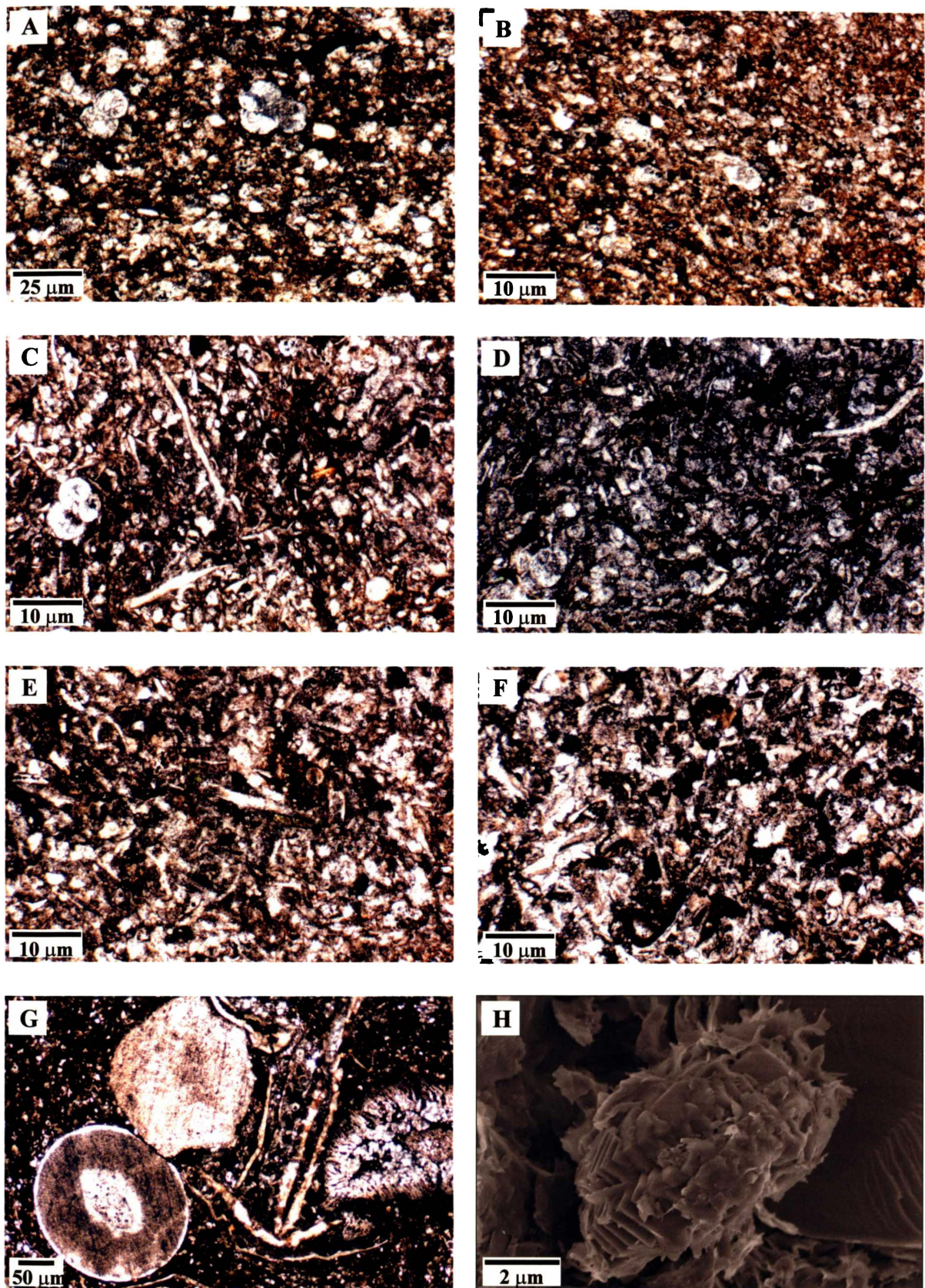


Plate 4.1 Photomicrographs of representative samples of the five petrofacies occurring within the Tikorangi Formation (A-H). (A) Petrofacies I; planktic foraminiferal-rich mudstone (sample NG2.3.2). (B) Petrofacies II; planktic foraminiferal-rich wackestone (sample W6.4.2). (C) Petrofacies III; bivalve-rich/echinoderm/planktic foraminiferal packstone (sample W5.2.5). (D) Petrofacies IV; planktic foraminiferal/bivalve-rich packstone (sample NG2.1.10). (E) Petrofacies IV bivalve-rich/benthic/planktic foraminiferal poorly washed grainstone (sample W5.6.1B). (F) Petrofacies V; echinoderm-rich/bivalve/benthic/planktic foraminiferal grainstone (sample W4.6.16). (G) Petrofacies II; rare wackestone consisting of large echinoderm, sponge, and infaunal, formerly aragonitic, bivalve fragments set in the more typical matrix of fine skeletal debris (sample W5.4.21). (H) Petrofacies I; SEM view showing cement coated fragmental coccolith (nannofossil) material which in thin section contributes significantly to the micrite/matrix (sample Mau3). See Appendix 2.2 for sample details.

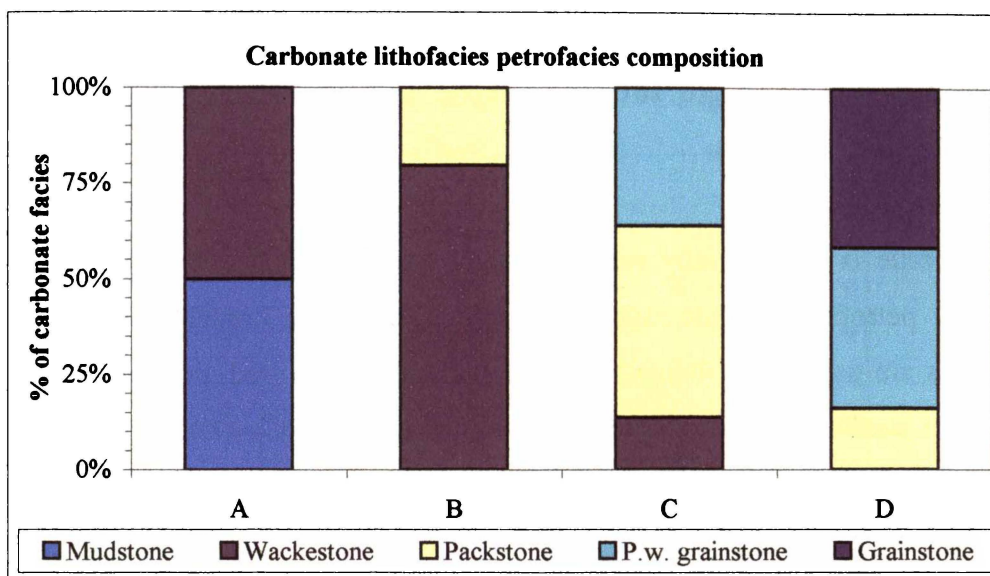


Fig. 4.7 Petrofacies distribution within the four carbonate facies defined within the Tikorangi Formation. Facies A = calcareous siliciclastites (<25% carbonate), Facies B = very calcareous siliciclastites (25-50% carbonate), Facies C = muddy limestones (50-75% carbonate), and Facies D = sparry limestones (>75% carbonate). P.w. = poorly washed.

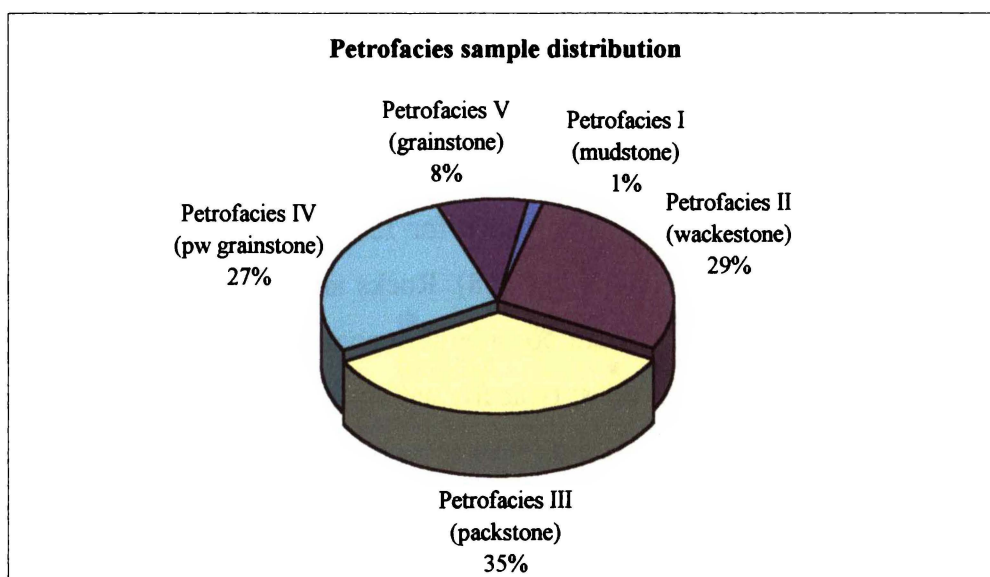


Fig. 4.8 Petrofacies type distribution of samples of Tikorangi Formation that form the basis of this study. pw = poorly washed.

fragments, and occasionally barnacle debris (av. 21%) (Fig. 4.12B) (see Appendix 4.3 for more detailed descriptions). Benthic foraminifera, calcareous red algae, and spicules and spines are minor, as are bryozoan and barnacle grains. Skeletal material is commonly fine to medium sand-sized (av. 0.24 mm), rarely coarser (Fig. 4.12D). Skeletons are strongly abraded and are mainly moderately to moderately well sorted.

Matrix/micrite is substantially reduced (av. 14%) in comparison to previously discussed petrofacies while spar cement increases in content (av. 12%). Siliciclasts are generally subangular to subrounded, well sorted, dominantly very fine to fine sand-sized quartz and feldspar grains (Fig. 4.12C). Other components include rare volcanic and sedimentary rock fragments and some pyrite and glauconite.

Poorly washed grainstones are most characteristic of carbonate Facies C, with several also in Facies D (Fig. 4.12E). Carbonate values are predominantly in the 60-70% range (Fig. 4.12F).

4.9 PETROFACIES V - GRAINSTONES

Defined as having <5% mud matrix, these grain-supported, clean spar cemented Petrofacies V grainstones (Plate 4.1F) account for 13 of the analysed samples of Tikorangi Formation (Table 4.1, 4.2; Fig. 4.8). Rocks are notably bioclastic-rich (av. 78%) (Fig. 4.13A). Bioclasts are considerably coarser grained (Hu Rd-1A) (av. 0.5 mm) than in other petrofacies; typically within the medium to very coarse sand-sized fraction (Fig. 4.13D). Grainstones are variously dominated by one or other of echinoderm (av. 25%), bivalve (av. 22%) (Fig. 4.13B) fragments and less commonly by bryozoan and barnacle debris) (see Appendix 4.3 for more detailed descriptions). Benthic foraminifera and calcareous red algae grains, previously unimportant in any petrofacies, together form 41% of the bioclastic composition. Planktic foraminifera av. only 10%. Skeletal grains are generally moderately to moderately well sorted and moderately abraded.

Table 4.2 Tikorangi Formation petrographic summary table. Grainsize scale is contained in Appendix 4.7.

TIKORANGI FORMATION	CO ₂	Mega	Carbonate facies				Mean petrofacies grain sizes						Mean bioclastic abundances						Mean siliciclastic abundances						Matrix/ cement												
	%	Facies	A	B	C	D	Bioclasts			Siliciclasts			% of whole rock composition						% of whole rock composition																		
	Average CO ₂ %	% of Megafacies	% of Petrofacies	Calc. mudstones	Very calc. vf ssts.	Muddy limestones	Sparry limestones	Silt	Very fine sand	Fine sand	Medium sand	Coarse sand	Very coarse sand	Silt	Very fine sand	Fine sand	Medium sand	Coarse sand	Very coarse sand	Planktic forams	Spicules/spines	Bivalves	Echinoderms	Bryozoans		Red algae	Benthic forams	Barnacles	Others/fragments	Quartz	Feldspars	VRFs	SRFs	Pyrite	Glauconite	Matrix/micrite	Spar cement
MEGAFACIES																																					
BASINAL (PELAGIC)																																					
MUDSTONES																																					
Planktic foraminiferal/nannofossil	●	●	●		●					●				●						●									●	●					●		
FOREDEEP (REDEPOSITED)																																					
MUDSTONES																																					
Planktic foraminiferal/nannofossil (2)	●	●	●	●						●				●						●	●	●	●			●		●	●					●	●		
WACKESTONES																																					
Bivalve (22)	●	●	●	●	●	●				●	●			●	●	●				●	●	●	●		●			●	●	●	●	●	●	●	●	●	
Planktic foraminiferal (17)	●	●	●	●	●	●				●	●	●		●	●	●	●			●	●	●	●	●		●			●	●	●	●	●	●	●	●	
Echinoderm (2)	●	●	●	●	●	●				●	●	●		●	●	●	●			●	●	●	●	●		●			●	●	●	●	●	●	●	●	
PACKSTONES																																					
Bivalve (23)	●	●	●	●	●	●	●		●	●	●	●		●	●	●	●	●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
Echinoderm (16)	●	●	●	●	●	●	●		●	●	●	●		●	●	●	●	●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
Planktic foraminiferal (14)	●	●	●	●	●	●	●		●	●	●	●		●	●	●	●	●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
POORLY WASHED GRAINSTONES																																					
Bivalve (18)	●	●	●	●	●	●	●		●	●	●	●		●	●	●	●	●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
Echinoderm (17)	●	●	●	●	●	●	●		●	●	●	●		●	●	●	●	●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
Planktic foraminiferal (6)	●	●	●	●	●	●	●		●	●	●	●		●	●	●	●	●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
GRAINSTONES																																					
Bivalve (5)	●	●	●	●	●	●	●		●	●	●	●		●	●	●	●	●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
Echinoderm (4)	●	●	●	●	●	●	●		●	●	●	●		●	●	●	●	●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
SHALLOW-SHELFAL (NEAR SITU)																																					
POORLY WASHED GRAINSTONES																																					
Barnacle (1)	●	●	●		●							●					●			●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		
GRAINSTONES																																					
Barnacle (2)	●	●	●		●	●					●	●					●	●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		
Bryozoan (2)	●	●	●		●	●					●	●					●	●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		

Key: ● = very common ● = common ● = some ● = rare

Spar cement is the second most important component of the whole rock composition, av. 11% but reaching as high as 20% in some rocks. In contrast to other petrofacies matrix/micrite is rare, av. only 3%, while siliciclastics are similarly the lowest of all petrofacies at only 8%. Subangular to subrounded, well sorted, dominantly very fine to coarse sand-sized quartz and feldspar grains dominate the siliciclastics, along with common volcanic rock fragments (Fig. 4.13C) (reworked out of basement greywackes). Pyrite, sedimentary rock fragments and glauconite are rare. Grainstones are solely found within the purest carbonate Facies D (Fig. 4.13E) with all samples having carbonate contents greater than 75% and reaching as high as 99% (Fig. 4.13F).

4.10 PETROFACIES INTER-RELATIONSHIPS

Having described details of the five petrofacies in the Tikorangi Formation and their respective skeletal varieties it is relevant to overview the textural and compositional inter-relationships existing between them (Fig. 4.14A-F), with a simplified summary shown in Fig. 4.15.

4.10.1 Whole rock composition (Fig. 4.14A)

The general trend in average whole rock composition is one of increasing bioclastic content and spar cement with corresponding decreasing matrix/micrite and siliciclastic content from Petrofacies I to V. The matrix/micrite and siliciclastic-dominated rocks of Petrofacies I contain few identifiable bioclasts. Petrofacies II rocks remain dominated by a reduced amount of matrix/micrite and siliciclastics and a corresponding increase in bioclastic content. Spar cement is rare. Rocks of Petrofacies III see a change from siliciclastic to carbonate grain domination, with decreasing matrix/micrite and siliciclastics and the appearance of some spar cement. Petrofacies IV rocks record a further important increase in spar cement, which becomes sub-equal in content with matrix/micrite; bioclastic content is slightly less than in Petrofacies III. Petrofacies V has a further increase in bioclastic content with a corresponding decrease in matrix/micrite and siliciclastics, and are bioclastic-dominated rocks with moderate quantities of intergranular spar cement.

Petrofacies I - mudstones

Petrographic Summary

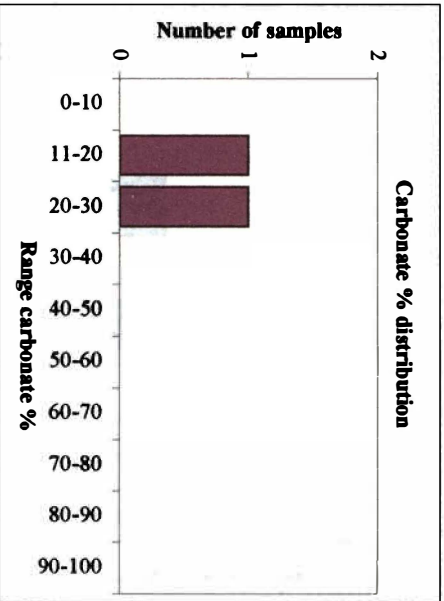
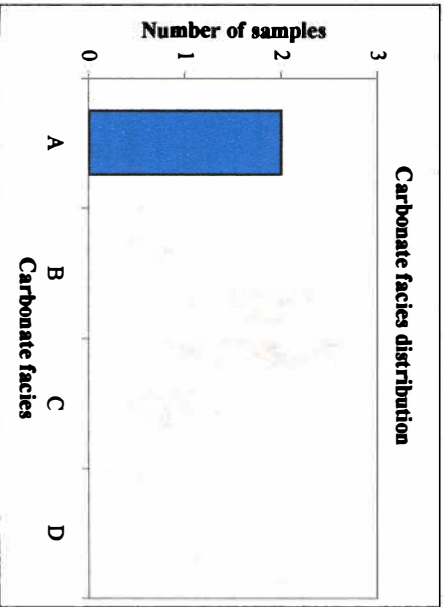
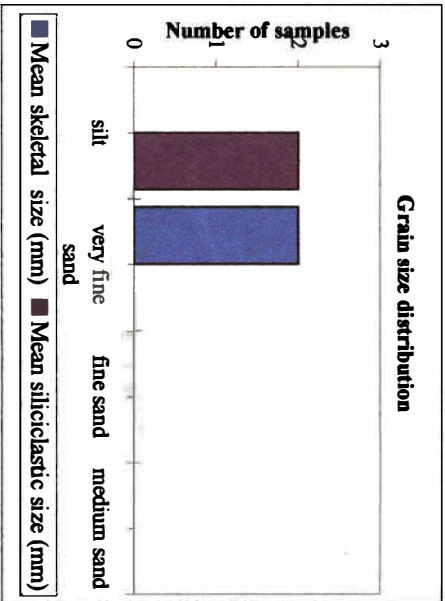
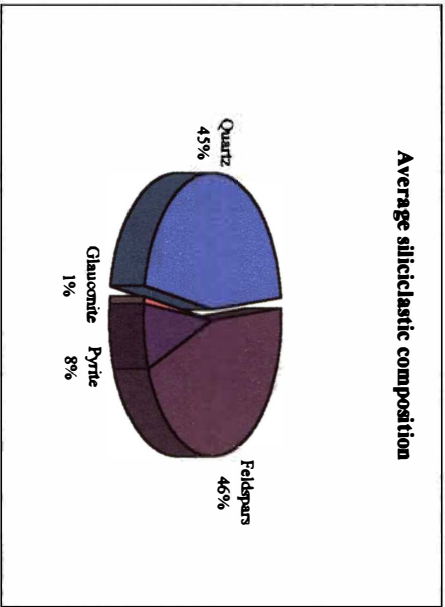
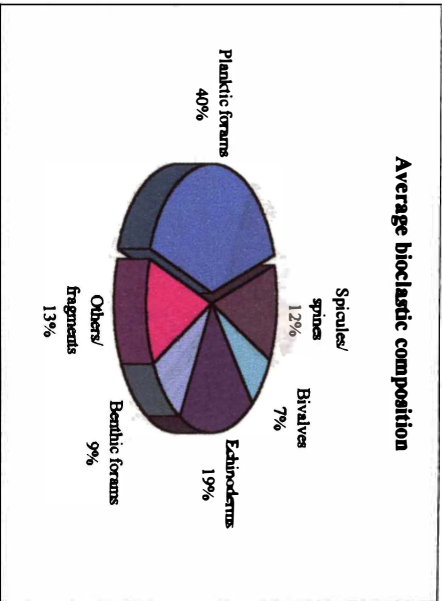
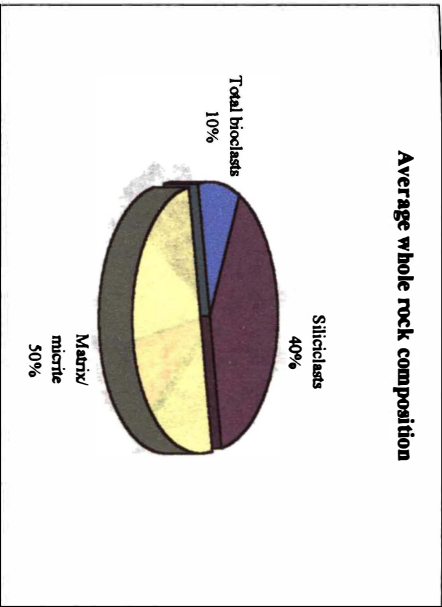


Fig. 4.9 Petrographic summary of Tikorangi Formation Petrofacies I mudstones. Average (A) whole rock, (B) bioclastic, and (C) siliciclastic compositions. (D) Grainsize, (E) carbonate facies, and (F) carbonate percent distributions. Facies A = calcareous siliciclastites (<25% carbonate), Facies B = very calcareous siliciclastites (25-50% carbonate), Facies C = muddy limestones (50-75% carbonate), and Facies D = sparry limestones (>75% carbonate).

Petrofacies II - wackestones

Petrographic Summary

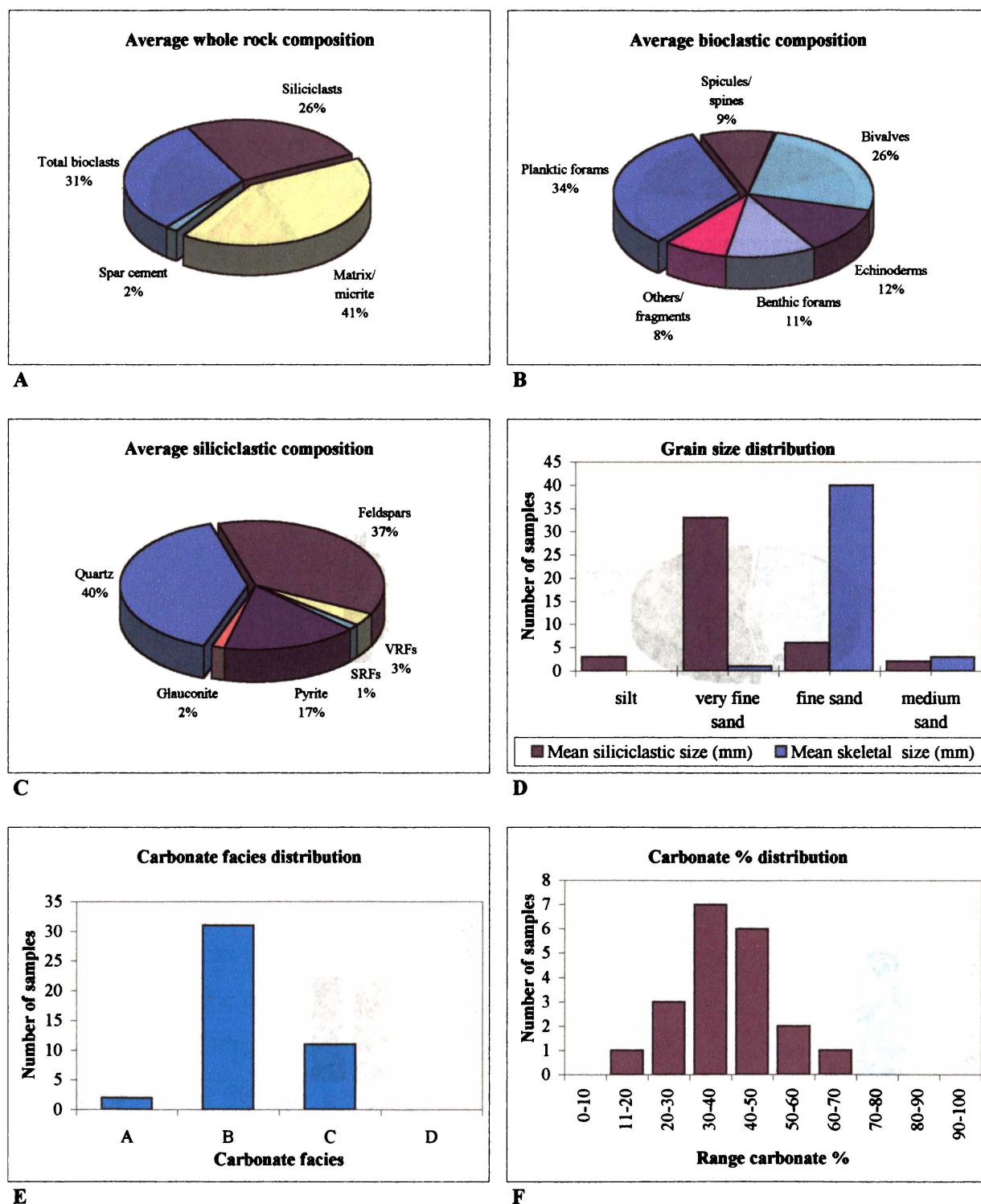


Fig. 4.10 Petrographic summary of Tikorangi Formation Petrofacies II wackestones. Average (A) whole rock, (B) bioclastic, and (C) siliciclastic compositions. (D) Grainsize, (E) carbonate facies, and (F) carbonate percent distributions. Facies A = calcareous siliciclastites (<25% carbonate), Facies B = very calcareous siliciclastites (25-50% carbonate), Facies C = muddy limestones (50-75% carbonate), and Facies D = sparry limestones (>75% carbonate).

Petrofacies III - packstones

Petrographic Summary

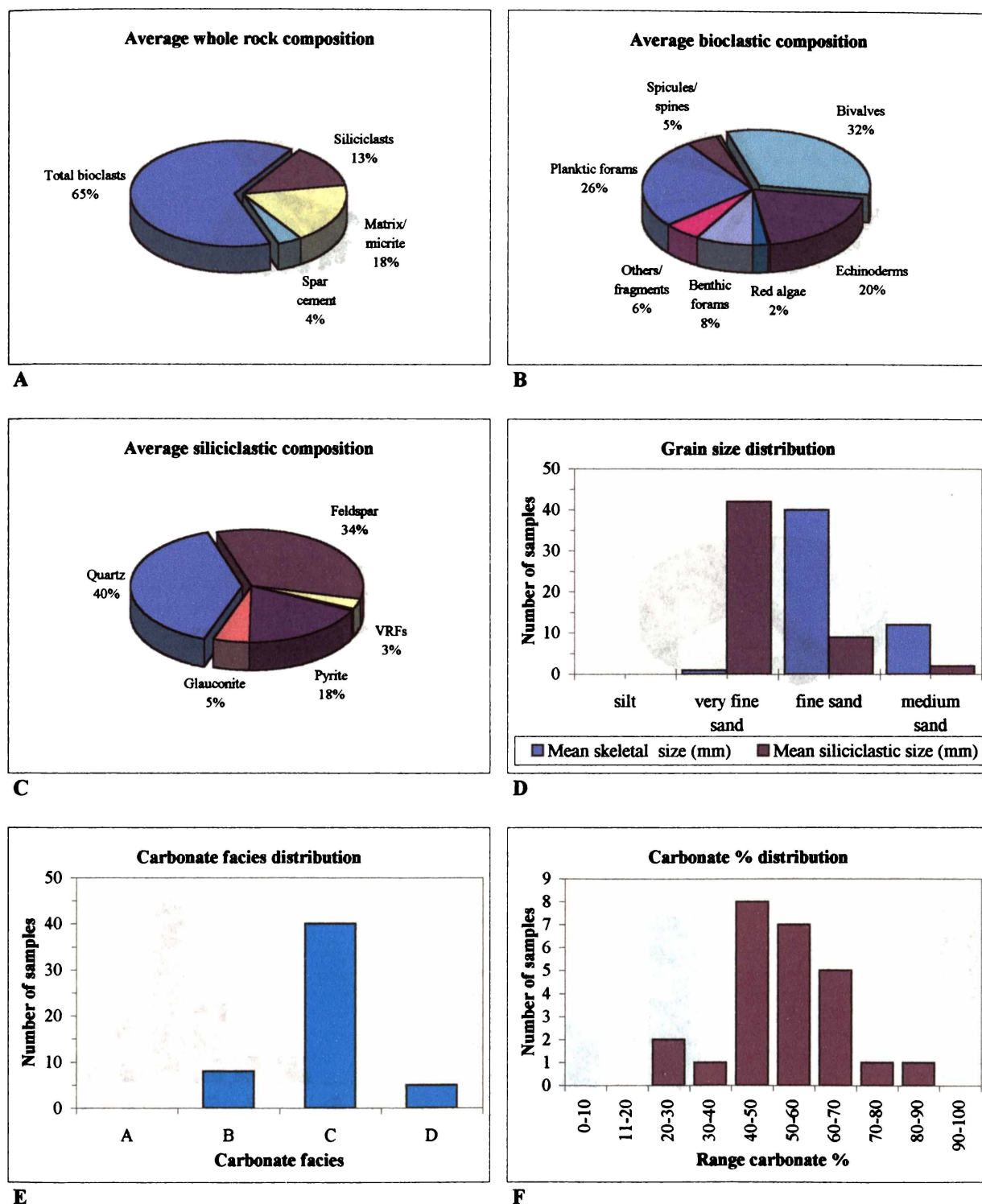


Fig. 4.11 Petrographic summary of Tikorangi Formation Petrofacies III packstones. Average (A) whole rock, (B) bioclastic, and (C) siliciclastic compositions. (D) Grainsize, (E) carbonate facies, and (F) carbonate percent distributions. Facies A = calcareous siliciclastites (<25% carbonate), Facies B = very calcareous siliciclastites (25-50% carbonate), Facies C = muddy limestones (50-75% carbonate), and Facies D = sparry limestones (>75% carbonate).

Petrofacies IV - poorly washed grainstones Petrographic Summary

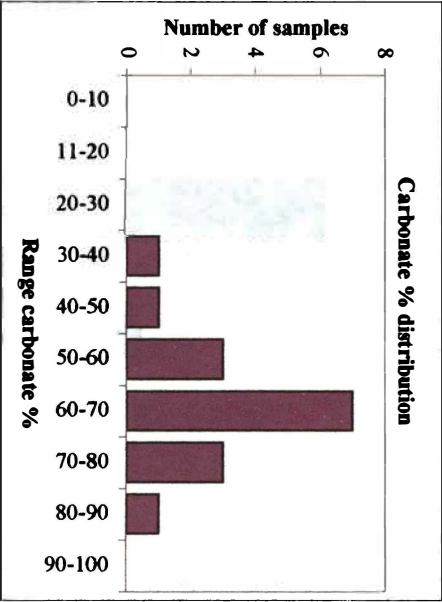
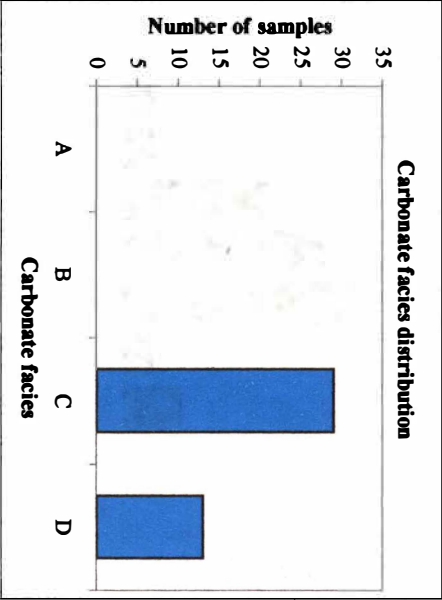
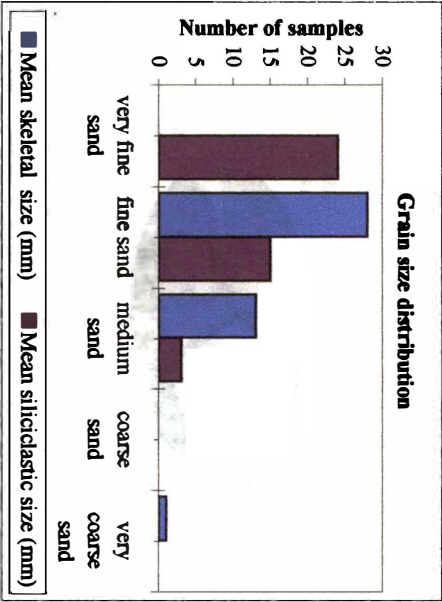
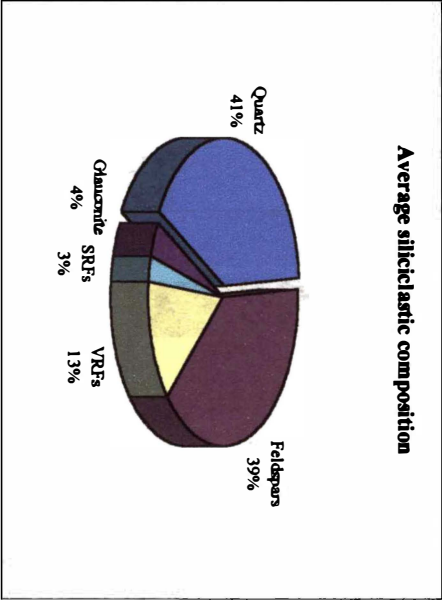
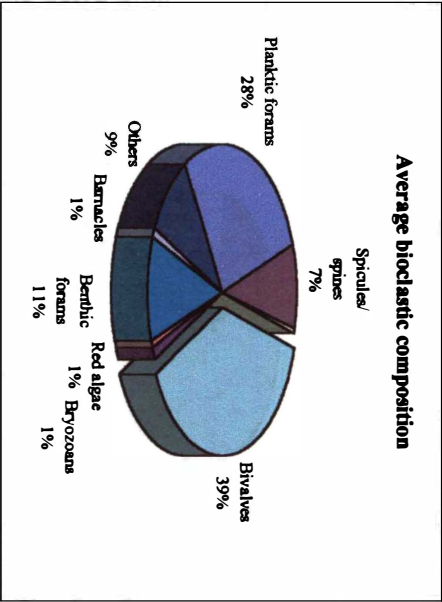
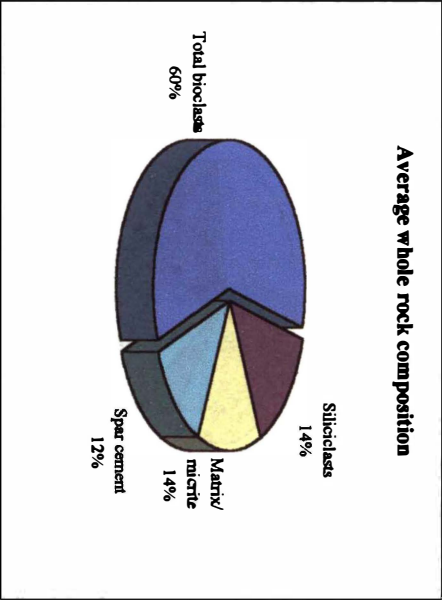


Fig. 4.12 Petrographic summary of Tikorangi Formation Petrofacies IV poorly-washed grainstones. Average (A) whole rock, (B) bioclastic, and (C) siliciclastic compositions. (D) Grainsize, (E) carbonate facies, and (F) carbonate percent distributions. Facies A = calcareous siliciclastites (<25% carbonate), Facies B = very calcareous siliciclastites (25-50% carbonate), Facies C = muddy limestones (50-75% carbonate), and Facies D = sparry limestones (>75% carbonate).

Petrofacies V - grainstones **Petrographic Summary**

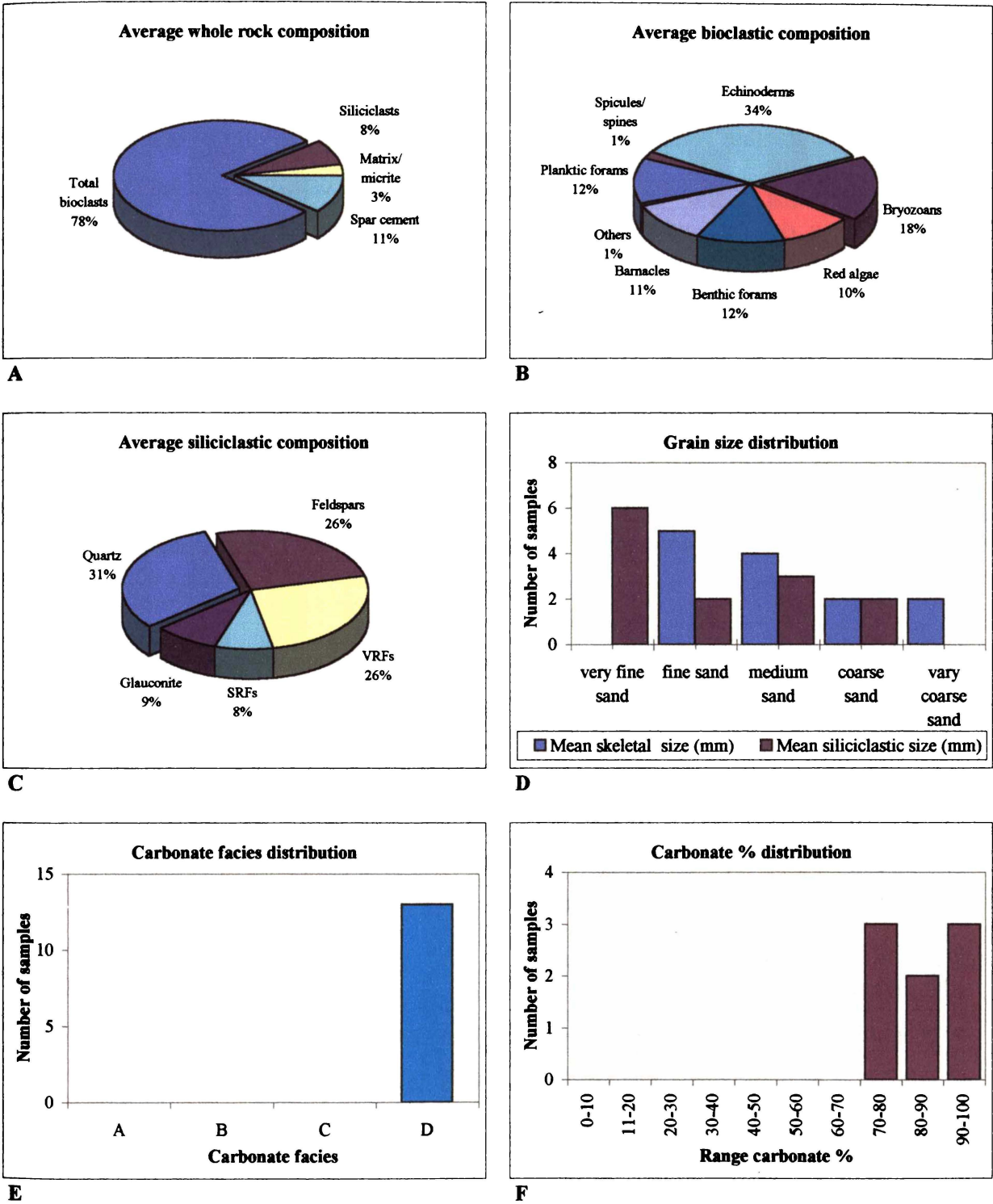


Fig. 4.13 Petrographic summary of Tikorangi Formation Petrofacies V grainstones. Average (A) whole rock, (B) bioclastic, and (C) siliciclastic compositions. (D) Grainsize, (E) carbonate facies, and (F) carbonate percent distributions. Facies A = calcareous siliciclastites (<25% carbonate), Facies B = very calcareous siliciclastites (25-50% carbonate), Facies C = muddy limestones (50-75% carbonate), and Facies D = sparry limestones (>75% carbonate).

4.10.2 Bioclastic composition (Fig. 4.14B)

Planktic foraminiferal and spicules and spine content decreases from Petrofacies I to V. Bivalve fragments increase in abundance from Petrofacies I to III but decline in Petrofacies IV and V. Echinoderms overall tend to be slightly more common in the higher order petrofacies, while calcareous red algae first appear rarely in Petrofacies III and increase to become significant components in Petrofacies V. Benthic foraminifera show little variation across all petrofacies, while fragments of other rare groups such as brachiopod, ostracod, and sponge debris show a decrease with increasing order of petrofacies. Bryozoans and barnacles are limited to Petrofacies III to V, being significant components in the latter.

4.10.3 Siliciclastic composition (Fig. 4.14C)

Siliciclasts comprise mainly quartz, feldspar, rock fragments, pyrite and glauconite. The content of quartz and feldspar decreases from Petrofacies I to V at the expense of increasing amounts of rock fragments and pyrite in particular, and also glauconite.

4.10.4 Texture (Fig. 4.14D)

From Petrofacies I to IV there is a gradual increase in mean skeletal grain size from very fine to fine sand grade, which then suddenly jumps to medium/coarse sand size in Petrofacies V. A similar increasing trend occurs in mean siliciclastic grain size, but mainly in the silt to very fine sand over Petrofacies I to IV, increasing to medium sand in Petrofacies V.

4.10.5 Carbonate content (Fig. 4.14E)

A general linear trend of increasing average carbonate content occurs from Petrofacies I to V, involving mixed carbonate siliciclastic-dominated rocks in Petrofacies I and II, and carbonate-dominated limestones in Petrofacies III to V.

4.10.6 Carbonate facies distribution (Fig. 4.14F)

Petrofacies I corresponds solely with carbonate Facies A while Petrofacies II is dominated by carbonate Facies B with some Facies C and rare A. Petrofacies III comprises mainly carbonate Facies C with some Facies B and D. Petrofacies IV is

Petrofacies

Petrographic Summary

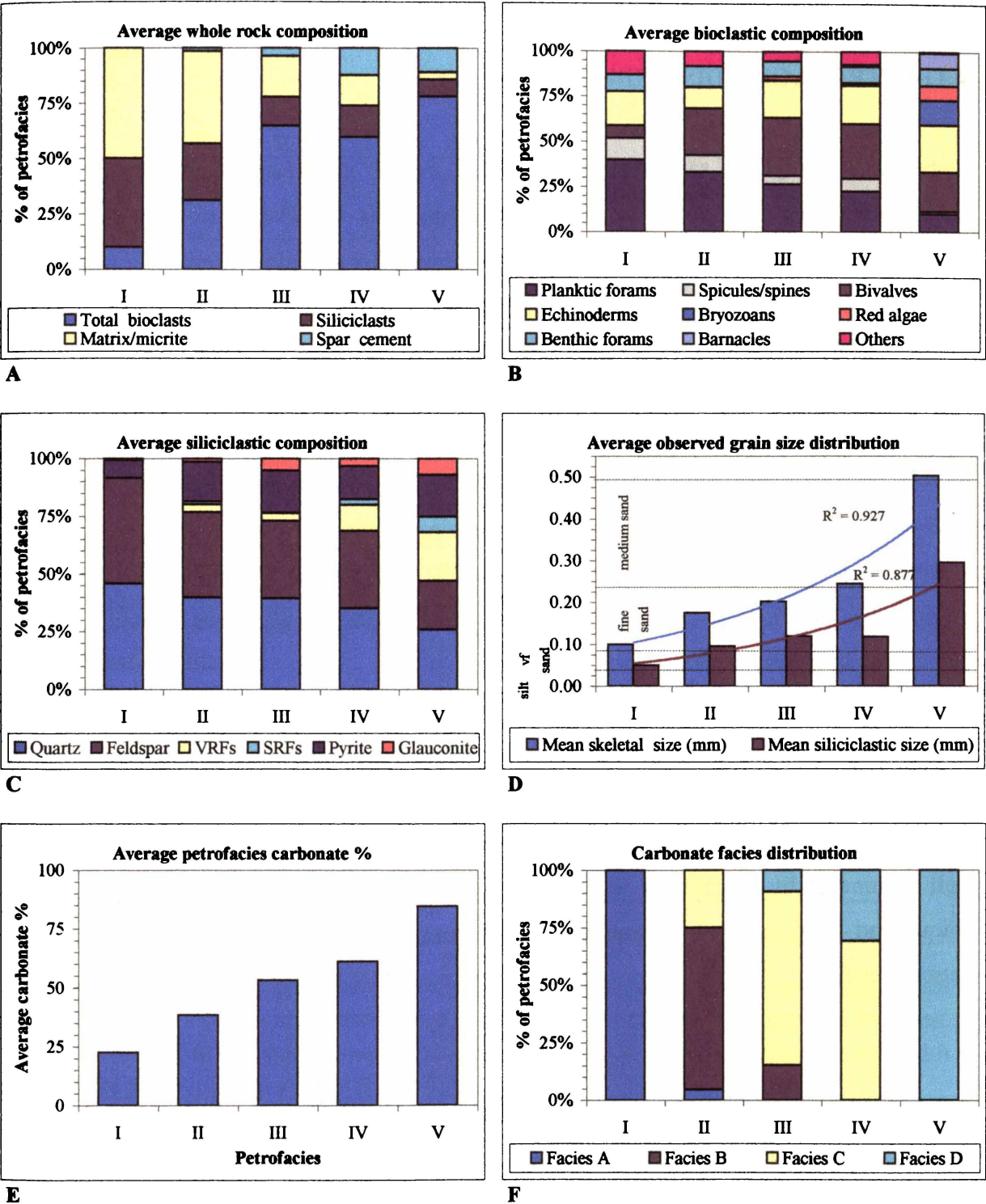


Fig. 4.14 Petrographic summary of five petrofacies within the Tikorangi Formation. Average (A) whole rock, (B) bioclastic, and (C) siliciclastic compositions. Average (D) observed grainsize, (E) carbonate percent, and (F) carbonate facies distributions. Petrofacies I = mudstones, II = wackestones, III = packstones, IV = poorly washed grainstones, V = grainstones. Facies A = calcareous siliciclastites (<25% carbonate), Facies B = very calcareous siliciclastites (25-50% carbonate), Facies C = muddy limestones (50-75% carbonate), and Facies D = sparry limestones (>75% carbonate).

also dominated by carbonate Facies C units with significant amounts of Facies D. Petrofacies V is limited to carbonate Facies D.

4.11 PETROFACIES DISTRIBUTION IN WELLS

Detailed petrography of samples from individual wells is graphically summarised in Appendix 4.4 based on raw data contained in Appendix 4.1. The distribution of petrofacies amongst the study wells, shown in Fig. 4.16 and simplified in Fig. 4.17, emphasises the complex and varied textural and compositional make-up of the Tikorangi Formation. Petrofacies I rocks are scarce and sampled only in Ngaere-2 and Waihapa-5. Petrofacies II is much more widespread, occurring in Ngaere-2 and in all Waihapa wells (Waihapa-2, -4, -5, -6) and is the sole petrofacies in offshore Maui-1. Petrofacies III is similarly widespread, dominating in Ngaere-2 and occurring in all Waihapa wells. Petrofacies IV is sole petrofacies sampled and occurs Ngaere-2, all Waihapa wells, and Hu Rd-1A, but is most conspicuous in Waihapa-4, -5, and -6. Petrofacies V dominates and has limited occurrence in Ngaere-2, Waihapa-2, -4, and -5.

A general trend of increasing dominance of higher order limestone petrofacies (III-V) occurs from the southern to the northern Waihapa wells (Fig. 4.17). Hu Rd-1A, unlike the Waihapa and Ngaere-2 wells, is very much a pure limestone well dominated by Petrofacies V, with a few Petrofacies IV rocks. Maui-1 is unique and from the limited sample database comprises solely wackestones of Petrofacies II.

4.12 MEGAFACIES OF THE TIKORANGI FORMATION

Having examined the petrography of the Tikorangi Formation and identified five petrofacies and their corresponding skeletal varieties, three major petrographic associations or "megafacies" can be identified based on their textural and compositional characteristics (Table 4.3) (Plate 4.2A-C). These are discussed below.

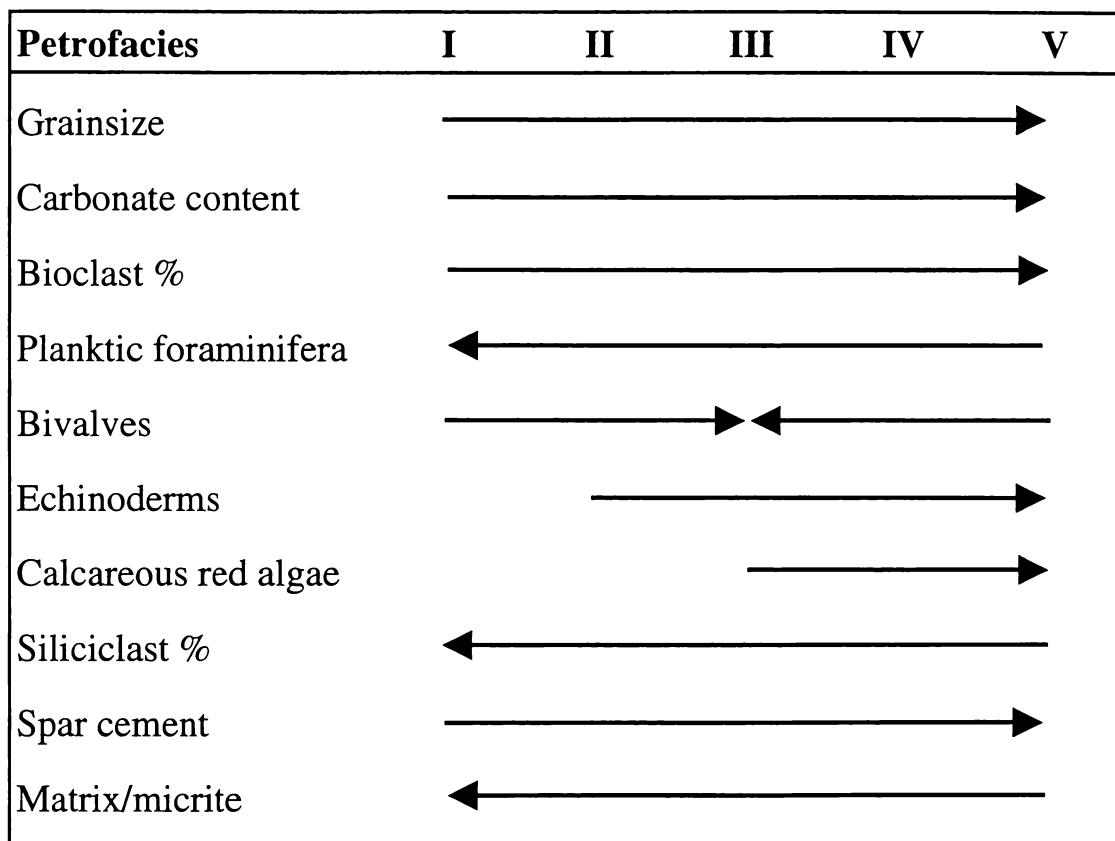


Fig. 4.15 Summary petrofacies inter-relationships/trends with increasing petrofacies order from Petrofacies I mudstones through to Petrofacies V sparry grainstones. Direction of arrow denotes increase in that direction i.e. arrow to left = increase with decreasing petrofacies order from V to I.

4.12.1 Megafacies 1 - bryozoans/barnacles/calcareous red algae/benthic foraminifera

This megafacies is characterised by pure limestones with unique textural and compositional properties (Fig. 4.18). Texturally they are coarse-grained, from medium to very coarse sand-sized (Plate 4.2A). Compositionally they are bioclast-dominated, with a prevalence of spar cement and only rare matrix/micrite. Skeletal components include shallow-water biota atypical of any other rocks sampled within the Tikorangi Formation. These biota include co-dominant bryozoans and barnacles with important contributions from calcareous red algae and large benthic foraminifera (*Amphistegina* and *Lepidocyclina*). Siliciclastic laminae show a predominance of rock fragments, both sedimentary and volcanic, unseen in other megafacies. Their high carbonate values (up to 99%) result in a dominance of carbonate Facies D and Petrofacies V grainstones, with rare poorly washed grainstones of Petrofacies IV. This megafacies is limited in occurrence to core sampled from the southernmost well in this study, at Hu Rd-1A.

4.12.2 Megafacies 2 - bivalves/echinoderms/planktic foraminifera

The second megafacies identified within the Tikorangi Formation typifies the other onshore wells in this study, namely Toko-1, Ngaere-2, and Waihapā-2, -4, -5, and -6. This megafacies comprises a spectrum of siliciclastic-carbonate mixtures having highly variable textures and compositions. However, three main skeletal types persist throughout, namely bivalves, planktic foraminifera, and echinoderms, typically in that order of decreasing abundance (Fig. 4.19). The rocks are mainly fine sand-sized skeletal sandstones to limestones with variable quantities of very fine sand-sized siliciclastics (Plate 4.2B).

Limestones (>50% carbonate) form 73% of this megafacies, 56% being Facies C muddy limestones and 17% purer Facies D sparry limestones. Facies B rocks account for 23% of the megafacies, with only 3% attributed to Facies A. The average whole rock composition is 53% bioclasts, 23% matrix/micrite, 6% spar cement, and 17% siliciclastics. Overall carbonate contents average 53%.

In terms of petrofacies distribution within Megafacies 2, 28% of rocks are

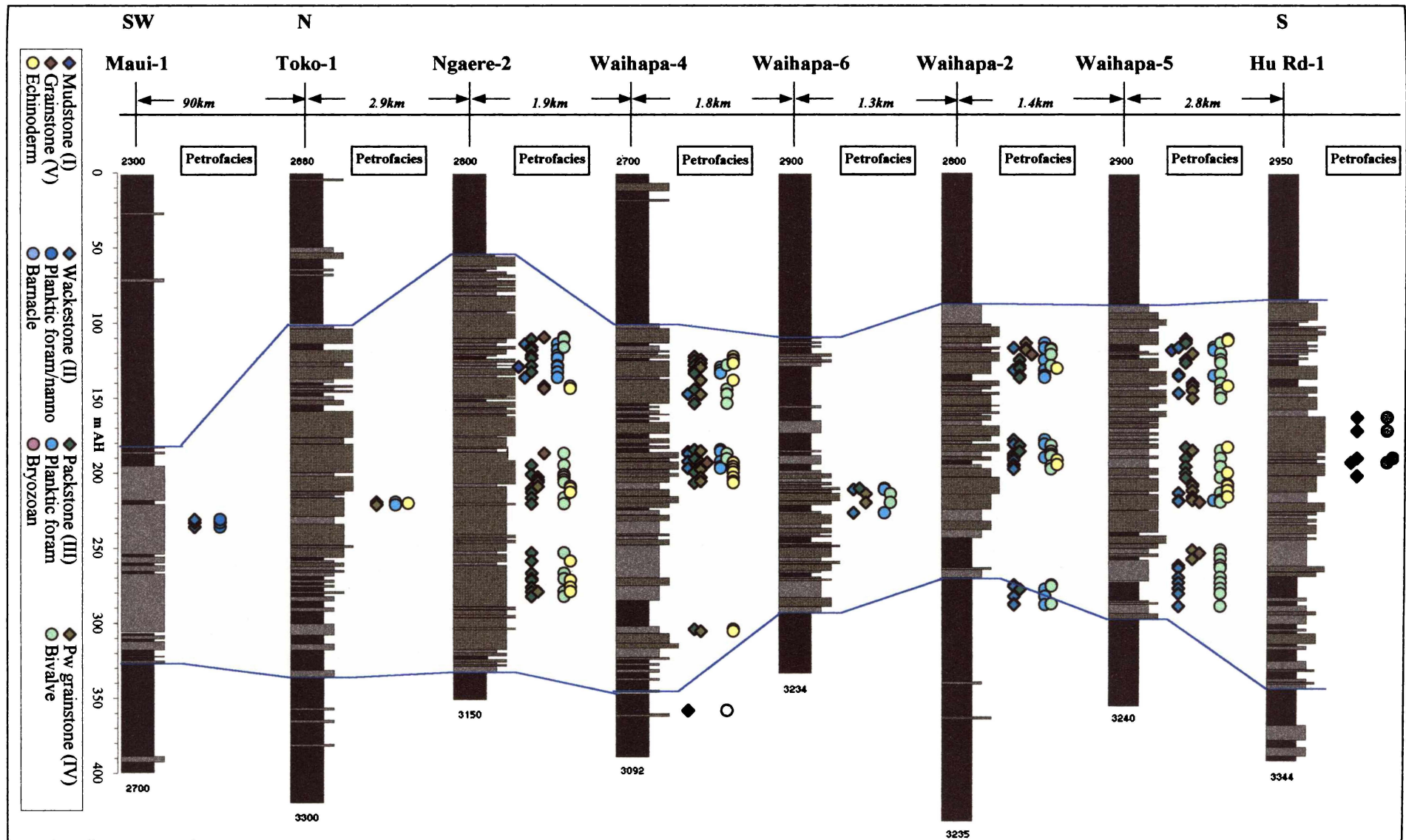


Fig. 4.16 Lithostratigraphy for the eight study wells showing textural and skeletal compositional changes over short distances in the Tikorangi Formation. Pw grainstone = poorly washed grainstone. Number top and bottom of columns are depths in metres along hole in each well.

Petrofacies II wackestones with only 1% Petrofacies I mudstones. Petrofacies III packstones comprise 37% of rocks, while 28% are Petrofacies IV poorly washed grainstones. Some 6% are Petrofacies V grainstones.

4.12.3 Megafacies 3 - planktic foraminifera/nannofossils (coccoliths)

The offshore Maui-1 well provides the third example of a unique Tikorangi Formation megafacies. It is characterised by mudstones or calcilutites having a high matrix/micrite content, and less than one third of the average whole rock composition comprises recognisable sand/silt-sized bioclasts (Fig. 4.20). There are typically fine sand-sized planktic foraminifera and nannofossils (coccoliths) (Plate 4.2C). In the irresolvable mud fraction, calcareous nannofossils (coccoliths) are abundant (Plate 4.1H). Observable siliciclastics are rare and of silt size. Carbonate values range from about 30-40%. XRD analysis (see Topic 6) suggests the majority of the matrix/micrite comprises silt- and clay-sized siliciclastic material, but apparently not common clay minerals. Intergranular spar cement is not evident. Rocks in this megafacies are assigned to mainly carbonate Facies B and are wackestones of Petrofacies II.

4.13 PETROGRAPHIC TRENDS

Using correlations between petrographic and geophysical log data (see Topic 2) it has been possible to construct complete compositional logs for the entire Tikorangi Formation interval for individual wells in this study, despite a paucity of core sample in most wells. Acknowledging the often variable petrographic make-up of the formation, the aim of this interpretative petrography is to attempt to discern general upcore trends to assist with general paleoenvironmental interpretations. These interpretative compositional logs accentuate the general trends shown by core sample data and filter the less significant or sample specific data. Complete logs are shown and discussed for the three identified megafacies. Hu Rd-1/1A is used as a reference for Megafacies 1; Waihapa-5 is used as a reference for the other onland Waihapa/Ngaere-2 and Toko-1 wells for representing Megafacies 2; and Maui-1 is the reference for Megafacies 3.

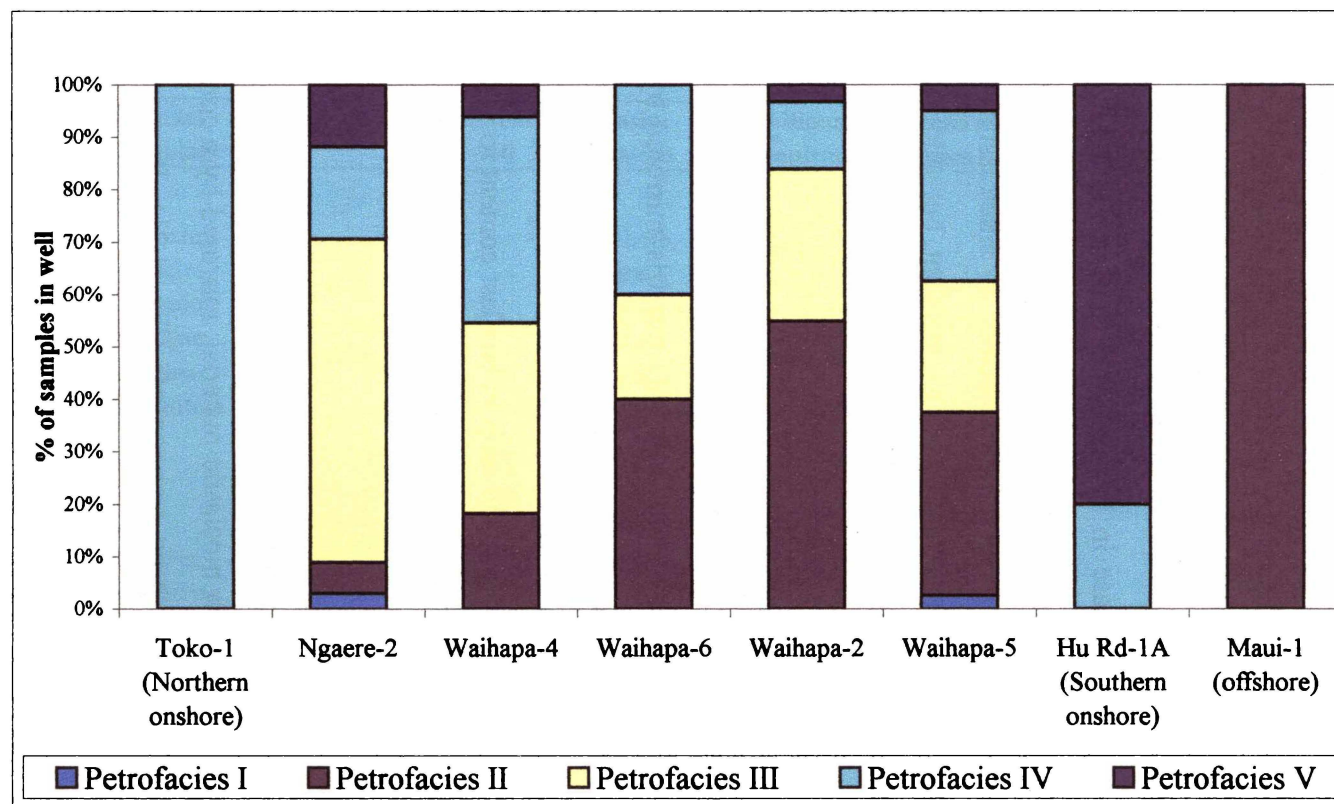


Fig. 4.17 Distribution of the five petrofacies within the eight study wells. Petrofacies I = mudstones, II = wackestones, III = packstones, IV = poorly washed grainstones, V = grainstones.

Whole rock compositions have been derived for all three megafacies by integrating both GR (gamma-ray) and DT (sonic) logs with bioclastic, siliciclastic, matrix and spar cement percentage values obtained from core sample petrography (Fig. 4.21). Interpreted bioclastic and siliciclastic compositions have been determined only for Megafacies 2 (Fig. 4.22) due to the paucity of core from the other megafacies and the lack of any geophysical log for Hu Rd-1A.

4.13.1 Megafacies 1 (*Hu Rd-1A*)

The barnacle/bryozoan/calcareous red algal/benthic foraminiferal megafacies shows a general upcore increase in bioclastic content reaching a maximum of about 85% some two-thirds upsection (Fig. 4.21). The increasing bioclastic content is matched by a corresponding decrease in siliciclastic and matrix contents. The upper third of the formation has a consistent, but reduced, bioclastic content punctuated by more siliciclastic-rich units.

Siliciclastic contents are as high as 40% in the lower section and less than 5% at its purest levels. Matrix comprises up to 50% in the lower formation and then gradually decreases in abundance upwards. This trend is mirrored by a gradual increase in spar cement which rises from generally <5% in the basal sections to reach nearly 15% in the upper sections. Across the upper boundary of the Tikorangi Formation there is a dramatic drop in bioclast content to virtually zero, and a substantial increase in siliciclastic components and matrix (Fig. 4.21).

4.13.2 Megafacies 2 (*Waihapa-5*)

The base of the bivalve/echinoderm/planktic foraminiferal megafacies is marked by a sharp increase (to 55%) in bioclastic material, mirrored by a corresponding decrease in matrix and siliciclastic components (Fig. 4.21). Bioclasts reach a maximum of about 70% in the upper part of the formation before a sharp decline at the top. For siliciclasts, the upcore trend drops from 30% in the lower sections to 10% or less in the upper formation, with matrix content showing a similar trend declining from 50% in lower to 10% in upper sections (Fig. 4.21). Spar cement is present throughout most of the formation, but generally forms less than 10% of the whole rock composition.

Table 4.3 Major properties of the three Tikorangi Formation megafacies identified within onshore and offshore Taranaki Basin. Petrofacies types: I - mudstones (calcareous lutites); II - wackestones (moderately to strongly calcareous fine arenites); III - packstones (fine muddy calcarenites); IV - poorly washed grainstones (impure fine muddy calcarenites to sparry medium calcarenites); V - sparry grainstones (fine to very coarse pure sparry calcarenites). Carbonate facies: Facies A – calcareous siliciclastites (siliciclastic-dominated, slightly-moderately calcareous claystone-mudstone, <25% carbonate); Facies B – very calcareous siliciclastites (moderately-highly calcareous siliciclastic siltstone-fine sandstone, 25-50% carbonate); Facies C – muddy limestones (muddy, very fine-fine sandy carbonates, 50-75% carbonate); and Facies D – sparry limestones (pure, typically very coarse sand-sized carbonate, >75% carbonate).

Megafacies	Description/ setting	Skeletal assemblage	Age	Reference well	Basin location	Depositional mechanisms	Petrofacies types	Carbonate facies	Texture	Environmental parameters	Hydro- carbons
1	Shallow-inner shelfal - proximal basement	Bryozoans, barnacles, calcareous red algae, benthic foraminifera	Earliest Miocene (Waitakian)	Hu Rd-1A	Onshore, Tarata Thrust Zone, Eastern Mobile Belt	Near situ	V>IV	D	Very coarse sand	Photic, shallow, mod.-high energy, topographic highs, rocky substrate	Non- producing
2	Foredeep (mixed carbonate- siliciclastites) shelfal/bathyal biota	Bivalves, echinoderms, planktic foraminifera	Earliest Miocene (Waitakian)	Waihapa-5	Onshore, Tarata Thrust Zone, Eastern Mobile Belt	Redeposited shelfal component intermixed with background bathyal-biota	III>II/IV>>V >>I	C>B>D>A	Very fine to fine sand	High energy mass flows into low energy pelagic bathyal foredeep	Producing
3	Basinal (bathyal calcareous siliciclastites)	Planktic foraminifera, nannofossils (coccoliths)	Oligocene-Early Miocene (Whaingaroan- Otaian)	Maui-1	Offshore, Western Stable Platform	Pelagic settling	II>>I	B>>A	Clay to very fine sand	Deep-water, low energy	Non- producing

Planktic foraminifera decrease in abundance from the underlying Otaraoa Formation into the Tikorangi Formation and then show an overall increase upcore, reaching a maximum in the upper sections where bioclastic contents are low (Fig. 4.22). More siliciclastic/matrix-rich beds are enriched in planktic foraminifera. Echinoderms generally follow a reverse trend to the planktic foraminifera, decreasing upcore and being more abundant in the bioclastic-rich upper beds (Fig. 4.22). A similar trend occurs for bivalves and benthic foraminifera, and possibly also calcareous red algae. Spicules and spines remain persistent minor components throughout the formation. Unidentified skeletal fragments tend to follow the planktic foraminiferal trend, increasing upcore and being more prevalent in the siliciclastic-matrix-rich units.

Interpreted siliciclastic compositions for Waihapa-5 show no major variation upcore, although a decrease in quartz and feldspar content and an increase in pyrite occurs on entering the basal Tikorangi Formation (Fig. 4.22). Pyrite appears to be more prevalent in the bioclastic-rich units.

4.13.3 Megafacies 3 (*Maui-1*)

Compositionally, Maui-1 is a siliciclastic/matrix-dominated succession containing two major planktic foraminiferal-coccolith-rich units towards the lower and middle portions of the formation (Fig. 4.21). These carbonate-enriched units are both about 20 m thick and have observable bioclastic contents up to 45%; otherwise contents less than 10% characterise much of the formation (Fig. 4.21). Conspicuous intergranular spar cements are evident (to 5%) only in the two calcareous-rich intervals. Bioclastic contents marginally increase upcore, reflected in decreased matrix contents. Observable siliciclastic contents range from 15% to 40% and matrix from 30% to 65%.

4.14. DISCUSSION

Taranaki Basin underwent accelerated subsidence from 30-22 Ma (Late Oligocene to earliest Miocene), particularly in the eastern areas adjacent to Taranaki Fault (King & Thrasher 1996). Subsidence in the Oligocene was related ultimately to

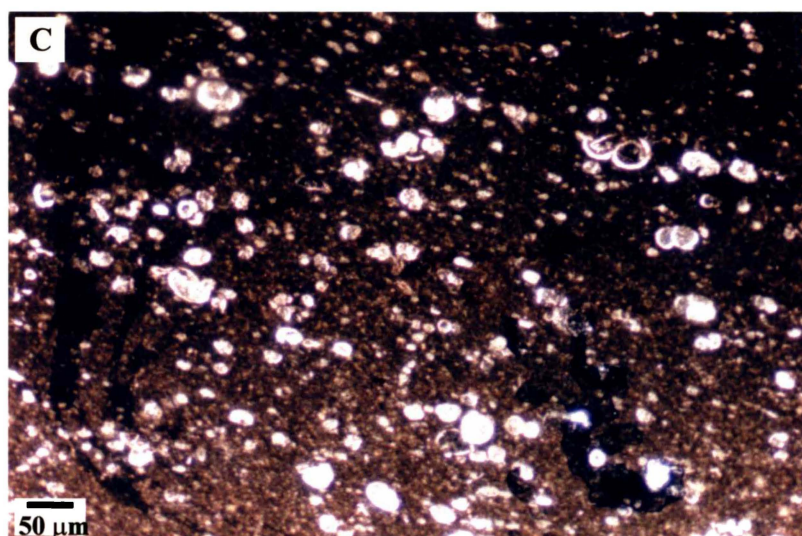
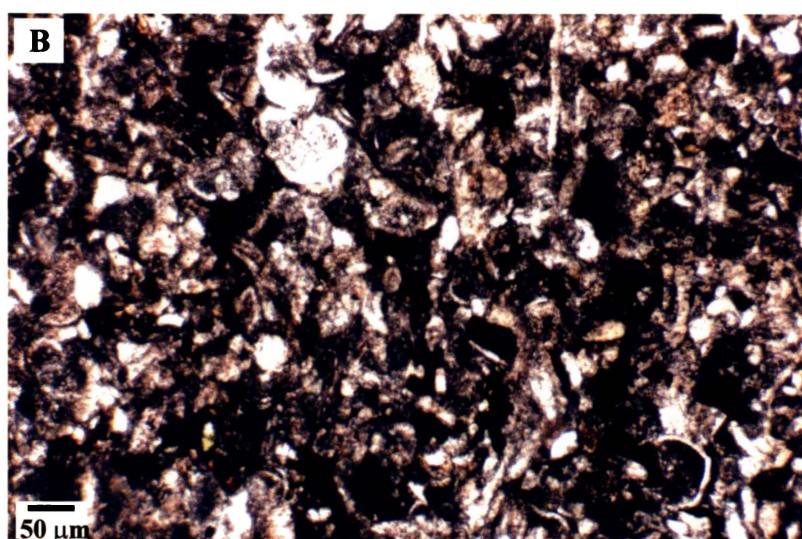
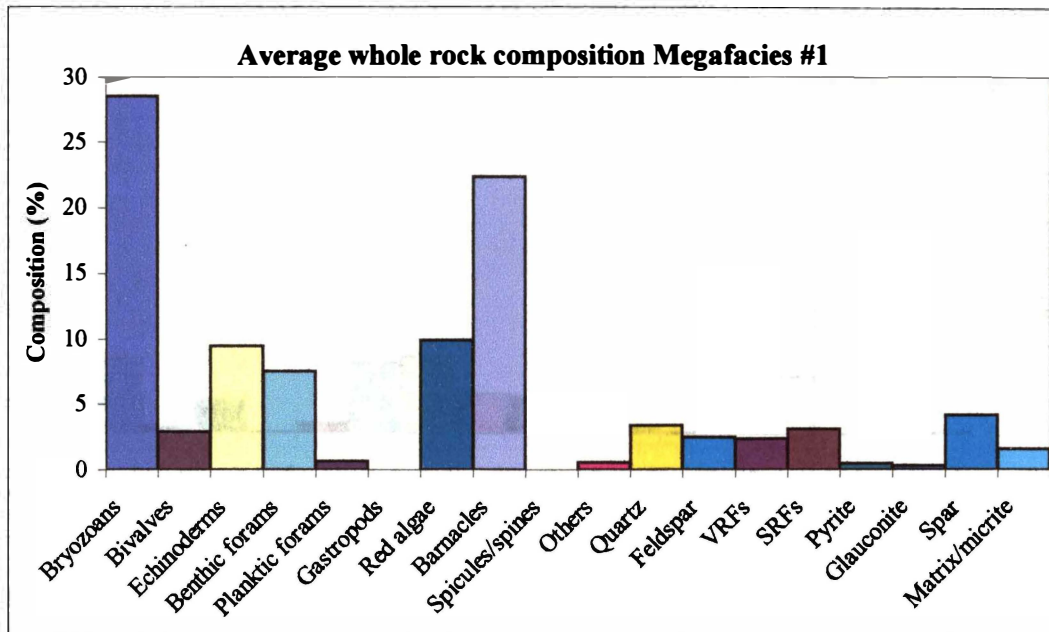


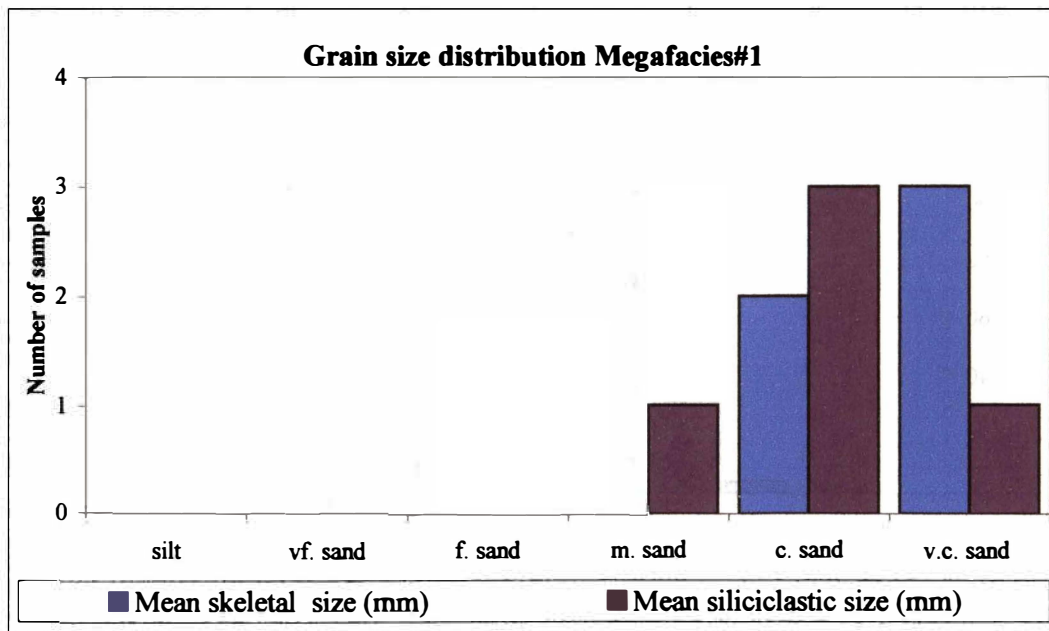
Plate 4.2 Photomicrographs of thin sections representative of the three Tikorangi Formation megafacies. (A) The onshore shallow-shelfal Megafacies #1 bryozoan/barnacle/calcareous red algae/benthic foraminifera assemblage occurring in a grainstone (sample Hu2.1A). (B) The onshore foredeep Megafacies #2 bivalve/echinoderm/planktic foraminifera assemblage occurring in a grainstone. This sample also contains conspicuous amounts of calcareous red algae viewed as evidence of redeposition from shelfal areas (sample NG2.3.14). (C) The offshore basinal Megafacies #3 planktic foraminifera/coccolith assemblage occurring in a wackestone (sample Mau-1). See Appendix 2.2 for sample details.

Megafacies #1

Bryozoan/barnacle/calcareous red algae/benthic foraminifera



A

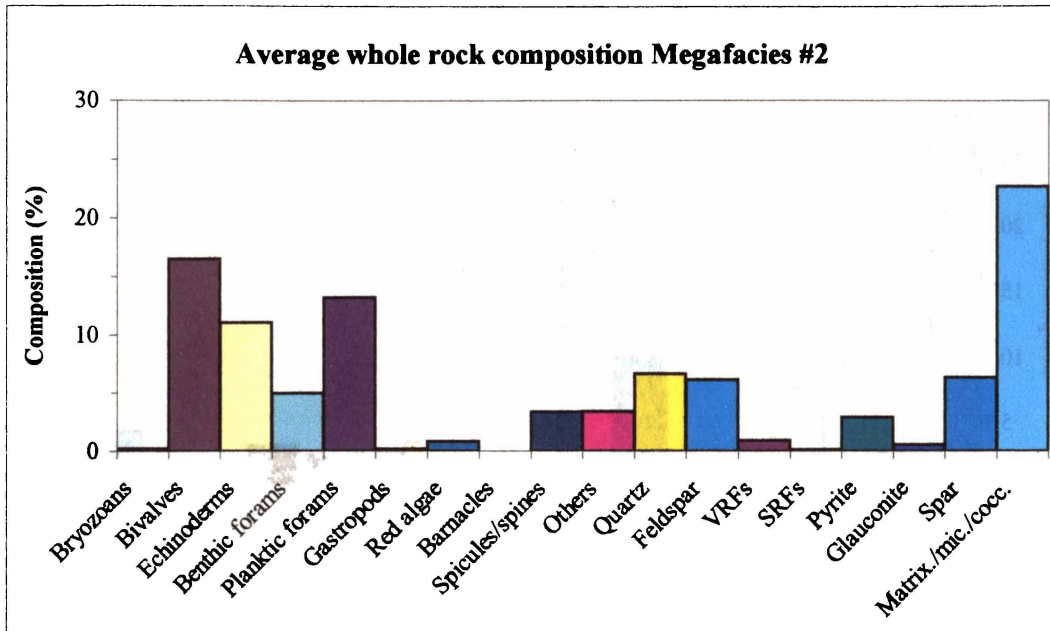


B

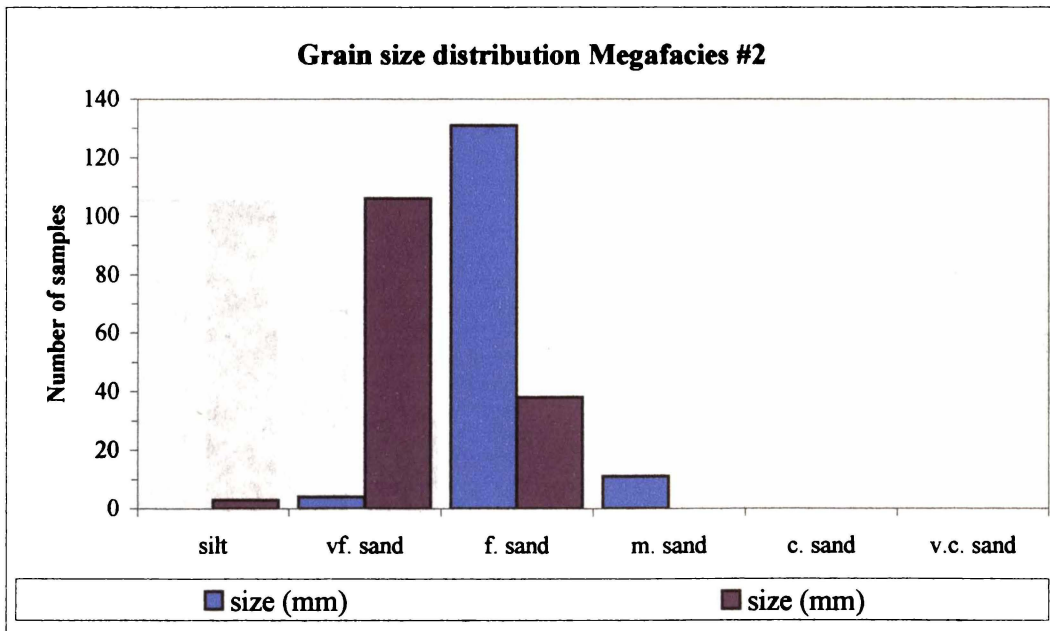
Fig. 4.18 Summary compositional (A) and textural (B) petrographic data for the shallow-shelfal (bryozoan/barnacle/calcareous red algae/benthic foraminifera) Megafacies 1 (reference well Hu Rd. 1A). See Appendix 4.7 for grainsize scale.

Megafacies #2

Bivalve/echinoderm/planktic foraminifera/coccolith



A

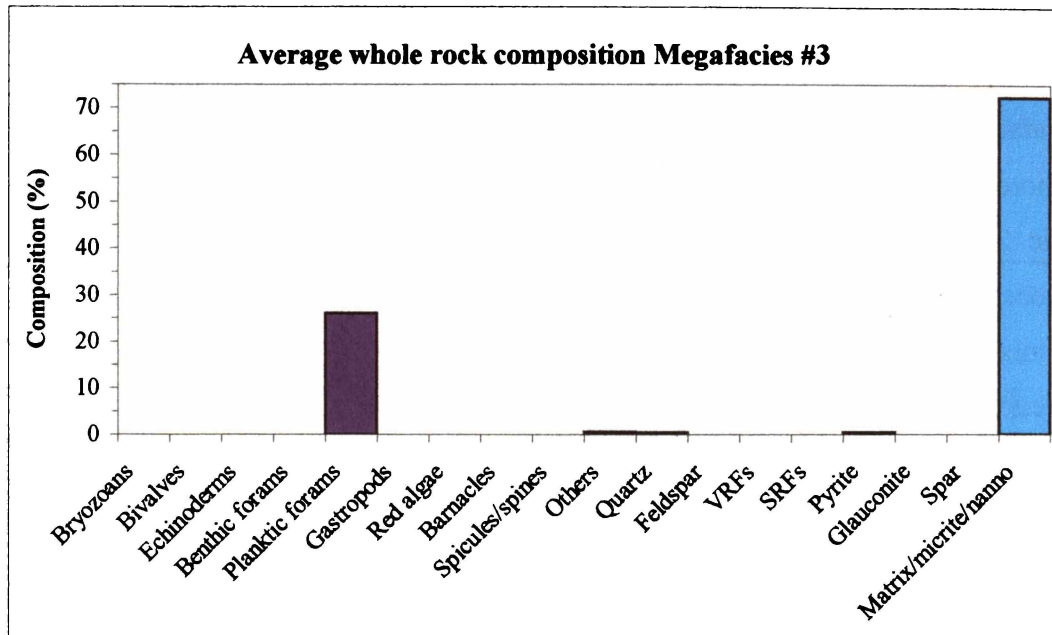


B

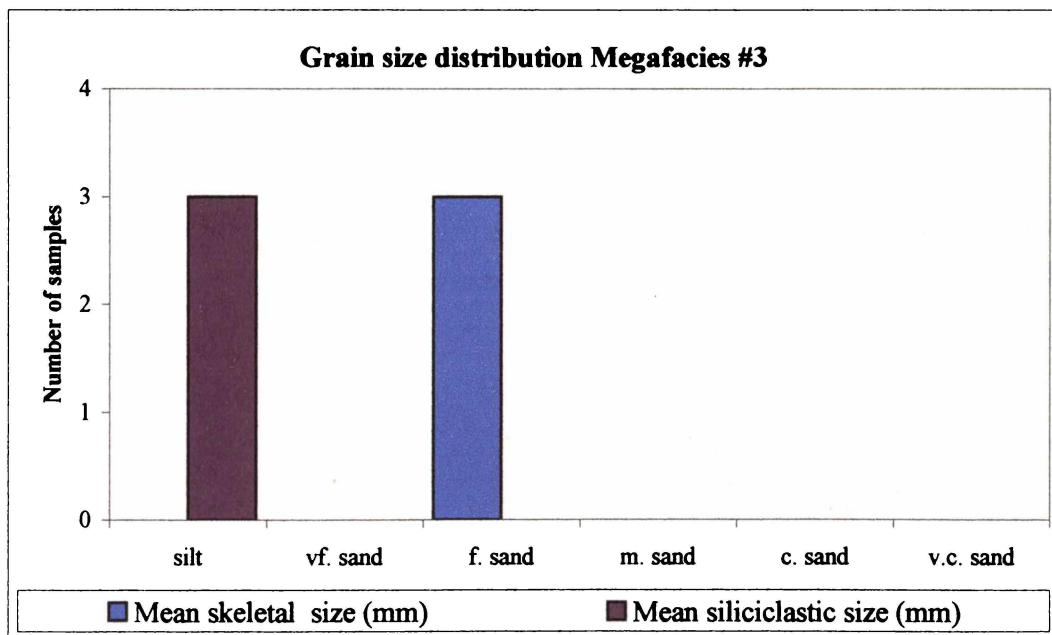
Fig. 4.19 Summary compositional (A) and textural (B) petrographic data for the foredeep redeposited (bivalve/echinoderm/planktic foraminifera) Megafacies 2 (reference well Waihapa-5). See Appendix 4.7 for grainsize scale. mic = micrite; cocco = coccoliths (nannofossils).

Megafacies #3

Planktic foraminifera/nannofossil (coccolith)



A



B

Fig. 4.20 Summary compositional (A) and textural (B) petrographic data for the basinal pelagic (planktic foraminifera/nannofossil (coccolith) Megafacies 3 (reference well Maui-1). See Appendix 4.7 for grainsize scale. Nanno = nannofossils (coccoliths).

the initiation of subduction and early development of the “modern” plate boundary and associated foreland basin (carbonate foredeep) into which the majority of the earliest Miocene Tikorangi Formation was deposited.

The inferred across-basin relationships of the three megafacies forming the Tikorangi Formation at this time are summarised in Fig. 4.23. A progressive decrease in formation thickness occurs from the proximal shallow-shelf megafacies (260 m thickness) to the carbonate foredeep megafacies (210 m) to the offshore basinal megafacies at Maui-1 (145 m). These thicknesses are reported in Topic 2. The basinal megafacies is the longer lived, forming throughout the Oligocene and Early Miocene (Whaingaroan to Otaian), while the shallow-shelfal and mixed shelfal/basinal foredeep megafacies in the study wells are restricted to earliest Miocene (Waitakian) age.

4.14.1 Megafacies 1

Megafacies 1 rocks are interpreted to represent shallow-shelfal deposits formed in a moderately high energy environment. The presence of barnacles, calcareous red algae and large *Amphistegina*, coupled with the very coarse sand-sized textures, are supportive of a shallow-shelfal, nearshore rocky coastal type environment (Hayton et al. 1995). Hu Rd-1A taxa are consistent with oxygenated waters and bottom water circulation expected in agitated inner-shelf environments (NZ Oil & Gas 1992). Seagrasses may have supported large *Amphistegina* benthic foraminifera (Rao 1996), while barnacles encrusted rocky shores or shell material, and bivalves and echinoderms inhabited the coarse sandy substrates.

Siliciclastic-rich layers in this shallow-water megafacies are dominated by Mesozoic basement greywacke rock fragments and associated derived siliciclastics which are generally well sorted and subrounded to rounded, further suggesting a high-energy depositional environment and a proximal basement source. The rare occurrence of brecciated basement lithoclasts in Hu Rd-1A core (see Appendix 4.5) indicates close proximity to subaerially exposed basement, either as an isolated Mesozoic basement paleo-high, or perhaps a fault-controlled block of the Patea-Tongaporutu-Herangi High upon which the Tikorangi Formation may have onlapped (Fig. 4.23), a suggestion portrayed by King &

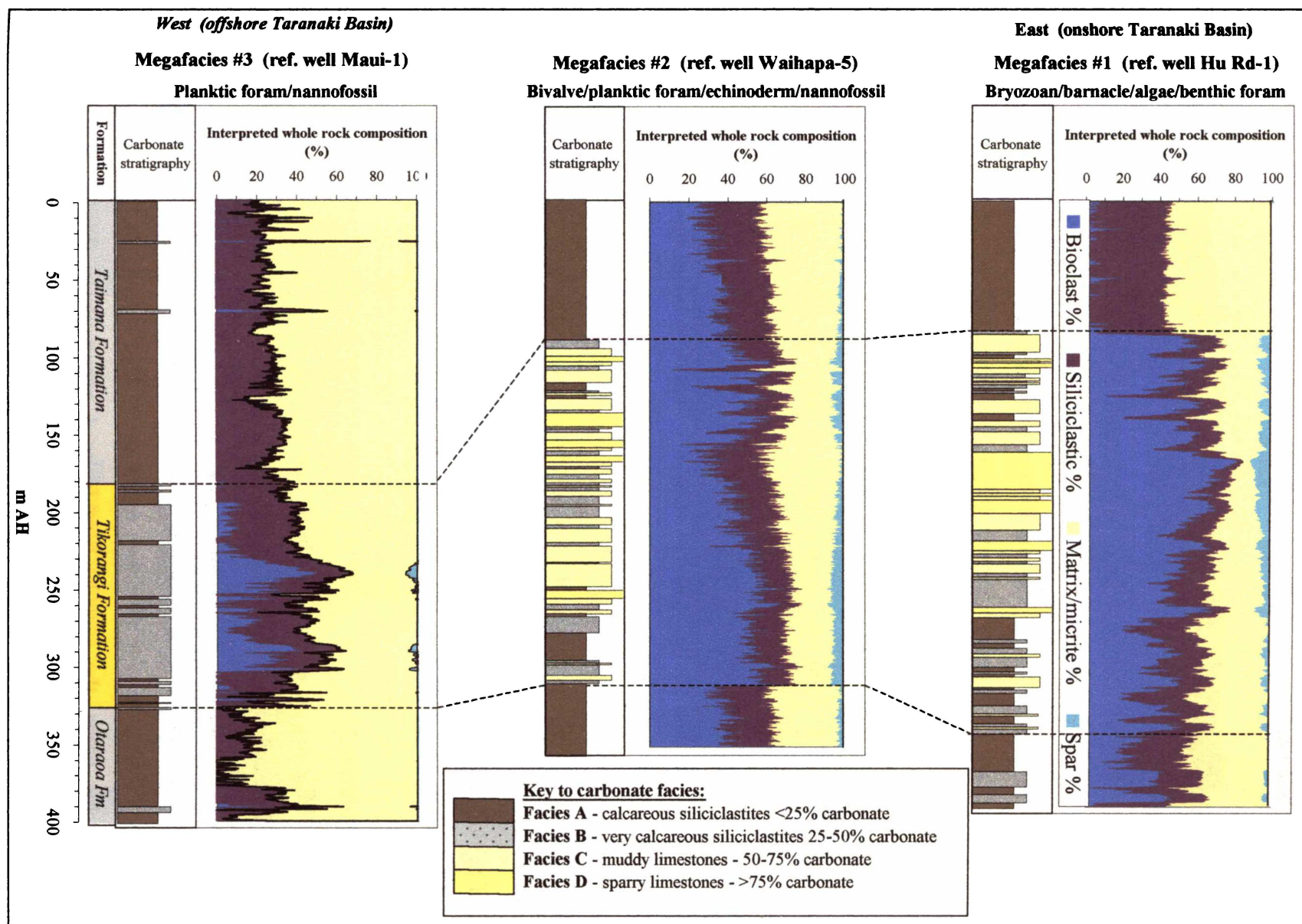


Fig. 4.21 Summary lithostratigraphy and interpreted whole rock compositions for the three Tikorangi Formation megafacies.

Thrasher (1996, p. 104). Uplift of the basement Patea-Tongaporutu-Herangi High progressed from mid-Oligocene and culminated in the earliest Miocene (late Waitakian) (King & Thrasher 1996).

A supply of proximal basement rock fragments, unseen in the other megafacies, decreases upcore as the bioclast content increases. This suggests that while the carbonate production sites kept pace with a relative sea-level rise, the major supply of siliciclastics progressively declined as the basement source(s) became increasingly submerged by the ensuing marine transgression, which reached its peak at the time of Tikorangi Formation deposition. The HST can be identified from well logs as occurring within the top of the Tikorangi Formation (see Topic 3) with maximum onlap and clastic starvation at the end of Tikorangi deposition. Timing is constrained by the age of the Tikorangi Formation seismic reflector dated at ~25.5-22 Ma (King & Thrasher 1996).

Shelfal megafacies rocks are typically coarse sparry and poorly washed grainstones dominated by barnacle and bryozoan fragments (Plate 4.2A). These limestones are very similar to many age equivalent deposits in the Te Kuiti Group in the neighbouring North Wanganui Basin (Nelson 1978; Nelson et al. 1994) and also more generally elsewhere in New Zealand at this time (Hood 1993, Hood & Nelson 1996). King & Thrasher (1996) placed the Hu Rd-1/1A well in an outer shelf or slope environment, different from the rather shallower carbonate platform setting invoked here.

4.14.2 Megafacies 2

By earliest Miocene the eastern margin of Taranaki Basin had developed into a carbonate slope and foredeep which later plunged to bathyal water depths (King & thrasher 1996). Despite these bathyal depths this study has shown the predominance of fine fragmental shallow-water skeletal debris intermixed with pelagic biota as evidence for basinward redeposition from shallow shelfal areas, or topographic highs, the sites of Megafacies 1 accumulation (Plate 4.2B). Detailed microfaunal studies in Waihapa-1, proximal to Waihapa-2, show skeletons characteristic of inner to mid shelf conditions, further evidence of shelfal material redeposition into the foredeep (Young & Carter 1989).

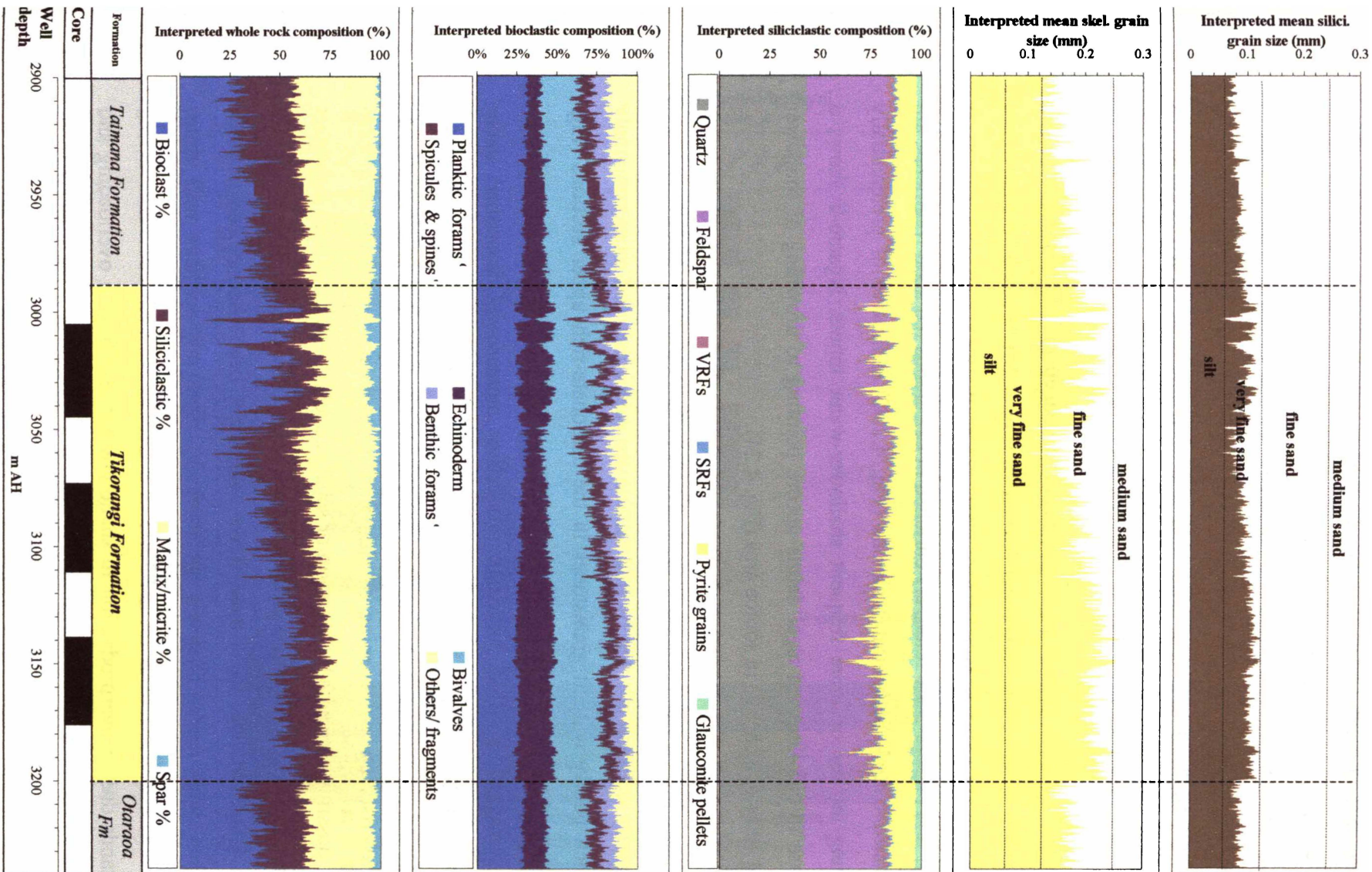


Fig. 4.22 Interpreted Tikorangi Formation compositions and textures for the foredeep Megafacies #2 reference well, Waihapa-5, derived from integration of geophysical log and petrographic data from limited core to derive a complete petrographic stratigraphy. Silici. = siliciclastic; skel. = skeletal.

Increased water depths during this basin-wide transgressive phase and foredeep development are reflected in increased numbers of planktic foraminifera (Fig. 4.22, 4.23) upcore. This may be interpreted as a shift toward the more open oceanic microfauna and flora characteristic of the offshore pelagic bathyal megafacies seen at Maui-1 well, and one consistent with a rapidly subsiding foredeep trough. In addition, decreasing grainsize upcore is further reflective of increasing water depths and retrogradation of facies belts.

Individual wells in the mixed shelfal/basinal foredeep megafacies delineate the site specific nature of the Tikorangi Formation (Fig. 4.24). Waihapa-6 well shows a dominance of planktic foraminifera, while especially the more northern wells of Toko-1 and Ngaere-2 are relatively enriched in calcareous red algal fragments, are dominated overall by shelfal skeletons (Fig. 4.25C) indicative of preferentially receiving thicker or more frequent shallower-water inputs. Ngaere-2 shows a decrease in coralline red algal debris upcore pointing to drowning of shallower shelfal areas or a change in source area (Fig. 4.24).

Rock textures in the foredeep megafacies reference well (Waihapa-5) are dominantly wackestones, but by mid-section are packstones and more commonly approach poorly washed grainstones in the carbonate-rich upper sections (Fig. 4.16, 4.21, 4.22). This is suggestive of dwindling siliciclastic source areas as sea-level transgressed while carbonate production increasingly flourished under reduced siliciclastic input. Shelfal areas such as at Hu Rd-1A are inferred to have developed carbonate build-ups, possibly as shoals or banks, during this period of sea-level rise. Over-steepening or slumping of carbonate sediment from these banks, possibly associated with storm or seismic events, may have been important trigger mechanisms for mass sediment movement downslope (Foreman et al. 1991). Once initiated, these mass flows could have been channelled in some instances, with feeder channels preferentially supplying northern well areas. Carbonate resedimentation is generally thought to be more common during highstands due to overproduction in shallow-water resulting in overloading and steepening of the slope and instability leading to failure and the generation of sediment gravity flows (Tucker & Wright 1990). Mass redepositional events are likely to have occurred with increased frequency as sea-level neared its

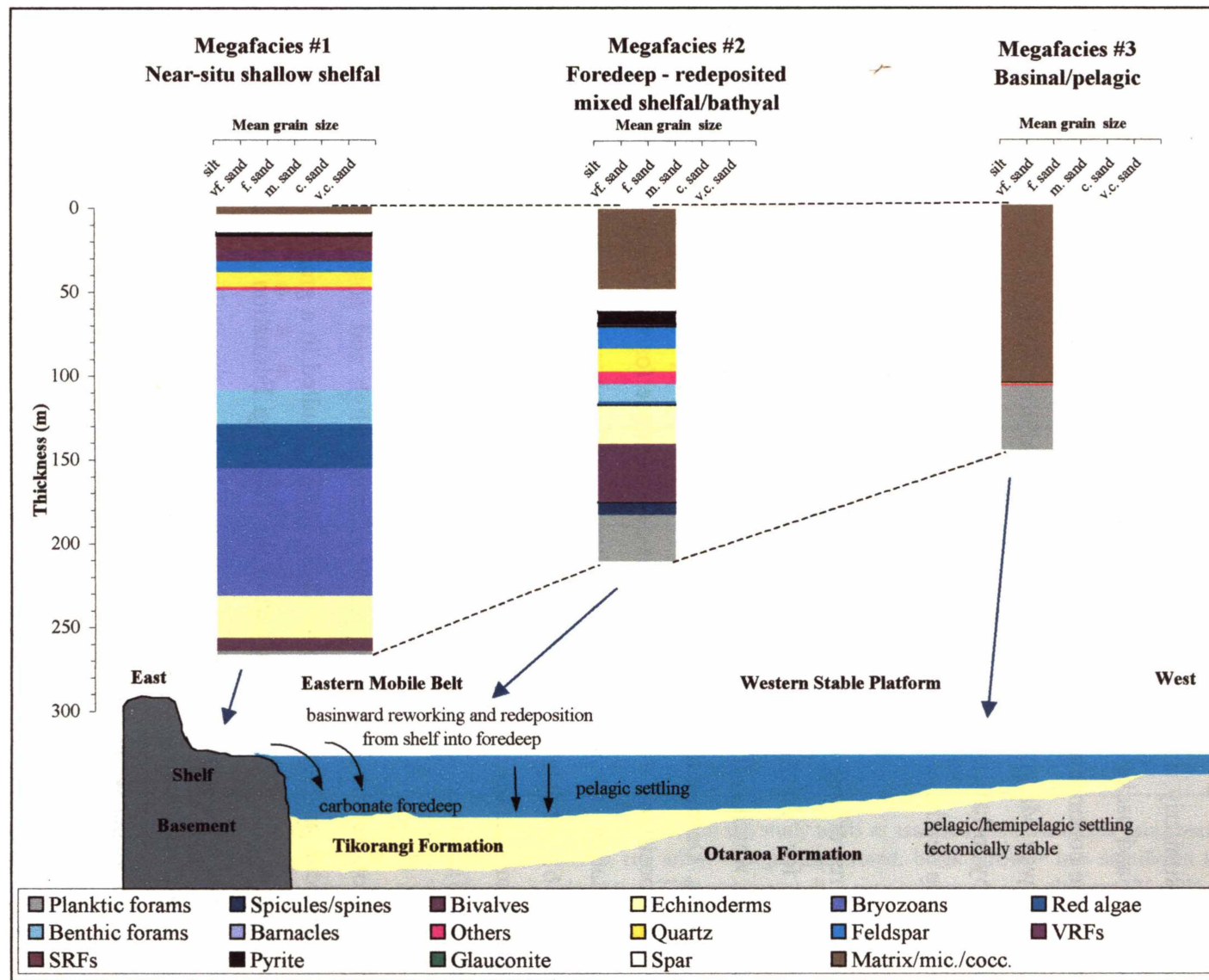


Fig. 4.23 Tikorangi Formation megafacies summary compositional and textural differences, and setting. mic= micrite, cocc. = coccoliths (nannofossils).

transgressive peak, resulting in more regular highstand influxes or pulses of coarser carbonate material when the shelfal carbonate factories reached peak production.

Holdgate and Gallagher (1997) have documented in the Australian Gippsland basin that similarly fine-grained carbonate-rich rocks comprising bioclastic wackestones and packstones have been redeposited from adjacent shallower shelf areas onto the continental slope. A similar situation is reported by Passlow (1997) from the Otway Margin, southeastern Australia, where transgressive sequences are marked by influxes of coarser material from shallower shelfal areas to upper and mid slope depths.

Subsequent reworking of sediment by often intense bioturbation is probably responsible for destruction of any clear sedimentological evidence for redeposition, which is in agreement with the findings of Naish (1991) on Toko-1 core samples. Despite this, trace fossil evidence can provide useful information about the depositional environment. In this case the trace fossils mainly appear to be representative of the *Planolites-Chondrites-Zoophycos* assemblage (see Appendix 4.6) (Ekdale et al. 1984), typical bathyal depth indicators widely reported from calcareous oozes and chalk facies in the southwestern Pacific (Nelson 1985).

With uplift of eastern Patea-Tongaporutu-Herangi High and potentially South Island basement, an increase in siliciclastic supply resulted in a gradual decrease in bioclastic material in the upper part of the Tikorangi Formation at Waihapa 5, and a much more dramatic cut-off of bioclastic input in the shelfal Hu Rd-1/1A locality. This could imply there remained reworking of drowned carbonate factories into deeper water while no new production was occurring on the shelf at Hu Rd-1/1A. Eventually siliciclastic input overwhelmed carbonate production ending deposition of the carbonate-rich Tikorangi Formation, and heralding deposition of the Taimana Formation.

Increased tectonic activity culminated in formation of the Tarata Thrust Zone and the Taranaki Fault in the Early-Middle Miocene (King & Thrasher 1996), the

Well	Carbonate %	Carbonate facies	Petrofacies	Total bioclast %	Bivalves %	Echinoderms %	Calcareous red algae %	Benthic forams %	Planktic forams %	Spicules & spines %	Others/ fragments
Ngaere-2	→	—	—	—	←	←	←	→	→	—	←
Waihapa-4	→	→	→	→	→	→	—	←	→	→	←
Waihapa-6	—	→	→	→	→	←	—	—	→	→	→
Waihapa-2	→	→	→	→	→	—	—	→	→	←	←
Waihapa-5	←	→	→	→	→	→	←	←	→	→	→

Well	Max. skel. size (mm)	Mean skel. size (mm)	Siliciclast %	Quartz %	Feldspars %	Glauconite %	Max. silici. size (mm)	Mean silici. size (mm)	Matrix/ micrite	Spar cement %
Ngaere-2	←	—	→	→	→	→	—	—	←	→
Waihapa-4	←	←	←	←	←	→	←	←	←	→
Waihapa-6	—	—	←	←	—	—	—	—	—	—
Waihapa-2	—	—	←	←	←	—	—	—	←	→
Waihapa-5	←	←	←	←	←	—	←	←	←	←

Fig. 4.24 Summary upcore trends in Megafacies 2 (bivalve/echinoderm/planktic foram) for five of the study wells as assessed from trendlines using textural and compositional petrographic data. Arrow to right=increase upcore, arrow to left = decrease upcore, red arrow = significant trend, black arrow = less significant trend. Carbonate facies increase=rise to higher carbonate content i.e. A to D where A = calcareous siliciclastites (<25% carbonate), B = very calcareous siliciclastites (25-50% carbonate), C = muddy limestones (50-75% carbonate), D = sparry limestones (>75% carbonate). Petrofacies increase = rise to higher number where Petrofacies I = mudstones, II = wackestones, III = packstones, IV = poorly washed grainstones, V = grainstones, skel. = skeletal, silici. = siliciclast.

earliest substantial movement within the basin in the Neogene. This period of intense east-west compression associated with development of the Pacific/Australian plate boundary was responsible for the fracturing of the Tikorangi Formation and its ability to host oil within its complex fracture networks.

4.14.3 Megafacies 3

The more basinal pelagic setting of Maui-1 saw accumulation of foraminiferal nannofossil wackestones (Plate 4.2C), far removed from the influence of redepositional events. However, the siliciclastic (dominantly quartz and feldspar) and matrix-rich nature of these calcareous siliciclastic-dominated units indicates a significant siliciclastic input to this offshore area, contrary to the 'starved basin' nature implied by King & Thrasher (1996). Fine siliciclastic sediments are likely to have been sourced from eastern Taranaki, and South Island provinces, the latter via an ancient equivalent of the modern Westland Current (Hudson 1996) suggested to have had a greater importance from earliest Miocene times following drowning of eastern sources.

4.14.4 Depositional models

Mullins & Neumann (1979) & Mullins (1983) have developed several carbonate depositional models from the modern Bahama Platform, of which the escarpment model (eastern side of the Little Bahama Bank) has some applicability to the ancient Tikorangi Formation depositional setting. Here a steep high relief escarpment supplies a base-of-escarpment talus prism from the shallow-water shelf/platform by a range of slides, debris and grains flows, and turbidites mechanisms. Tucker & Wright (1990) consider this to be an appropriate model for ancient platform margins bounded by a steep, perhaps fault-controlled slope, which in the Tikorangi case would be the Taranaki Fault.

Likewise the base-of-slope apron facies model developed by Mullins & Neumann (1979) & Mullins (1983) from the northern margin of Little Bahama Bank is also useful for study of the Tikorangi Formation. Here shallow-water debris is shed basinwards from a line source as opposed to a point source as in the submarine fan model. However, in this base-of-slope model much of the material bypasses the

Well Petrographic Summary

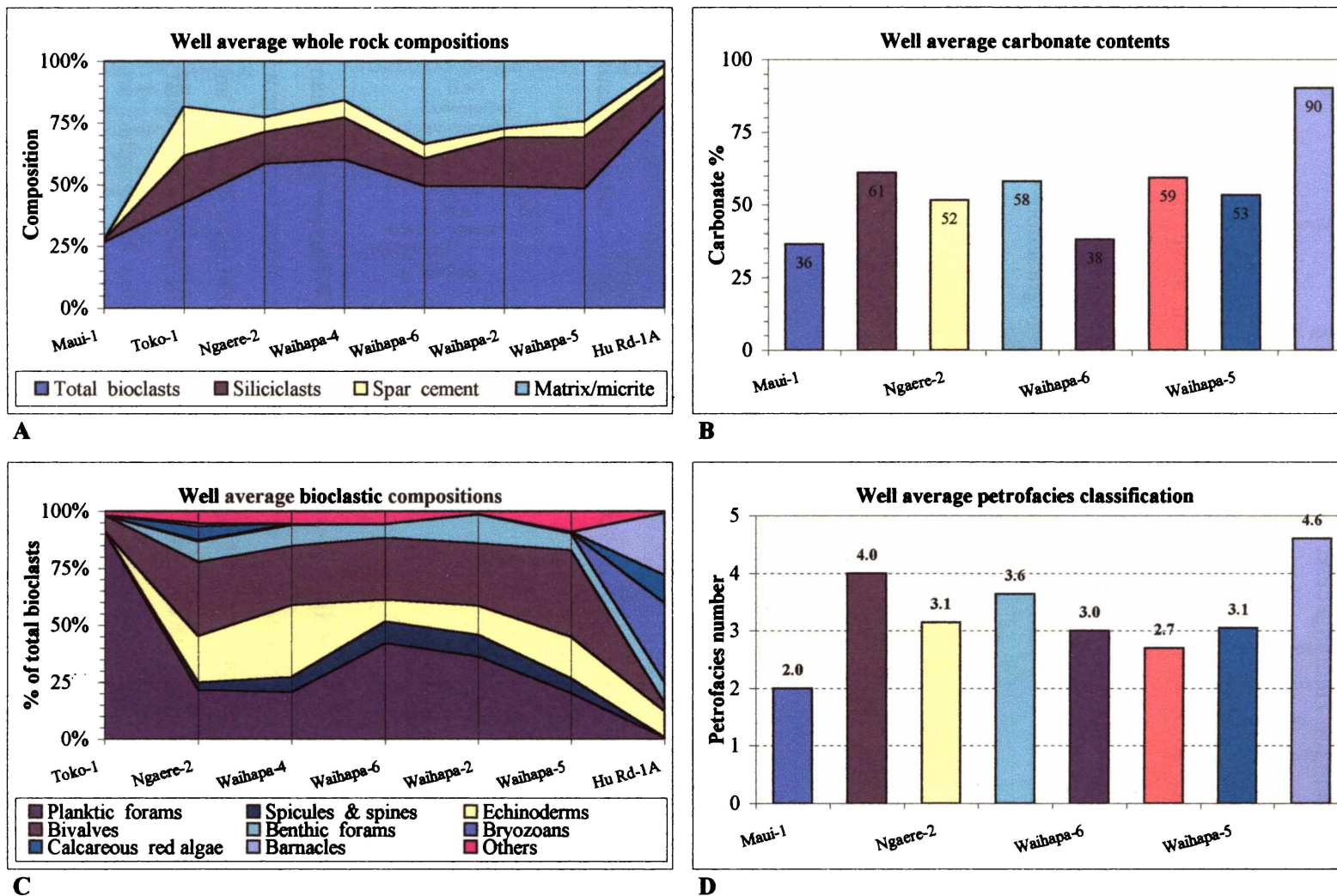


Fig. 4.25 Petrographic summary for the eight study wells showing average (A) whole rock compositions, (B) carbonate contents, (C) bioclastic compositions, and (D) petrofacies classification. In latter 1 = mudstone, 2 = wackestone, 3 = packstone, 4 = poorly washed grainstone, 5 = grainstone.

upper slope before redeposition onto the lower slope. Variations where the absence of an upper bypass zone resulted in sediment being supplied from the whole length of the platform, with only local channelling occurring, is suggested more applicable to the Tikorangi case.

The talus carbonate foredeep would have prograded by rapid deposition of debris into the foredeep from carbonate build-ups. Redeposition however would have been discontinuous, being triggered storm and seismic events, and interbedded and intermixed with the background pelagic facies more typical of the basinal setting to be deposited in laterally extensive aprons. Progradation would have been controlled by the rate of basinal sedimentation, rate of foredeep subsidence, platform width and foredeep depth. Initial deepening upward sequences show foredeep subsidence outpaced sedimentation (Topic 3). Shallowing upward sequences developed in the upper part of the Tikorangi Formation (Topic 3) when sedimentation exceeded subsidence/sealevel rise so that the foredeep was gradually filled with Tikorangi Formation carbonates and siliciclastics associated with uplift and subaerial exposure of eastern Taranaki and South Island basement rocks. Renewed clastic input to the basin began in the Early Miocene as a result of tectonic uplift and erosion, and by the end of the Early Miocene rates of clastic supply surpassed rates of subsidence.

4.15 CONCLUSIONS

Previous studies of the Oligocene-Early Miocene (Whaingaroan-Otaian) Tikorangi Formation, often referred to as Tikorangi Limestone in petroleum circles, have been narrowly focused and limited to obtaining a seismic and structural understanding of this fractured oil reservoir to fulfil petroleum industry objectives. A need for a more comprehensive and detailed stratigraphic and sedimentological evaluation of this important reservoir rock has been the impetus for this study which has shown the Tikorangi Formation to be stratigraphically rather complex (Topics 2 and 3). From a petrographic viewpoint, this translates into a spectrum of compositionally and texturally variable interbedded rock types

Tikorangi Formation - Escarpment Depositional Model

Earliest Miocene, prior marine transgression maxima, Taranaki Basin

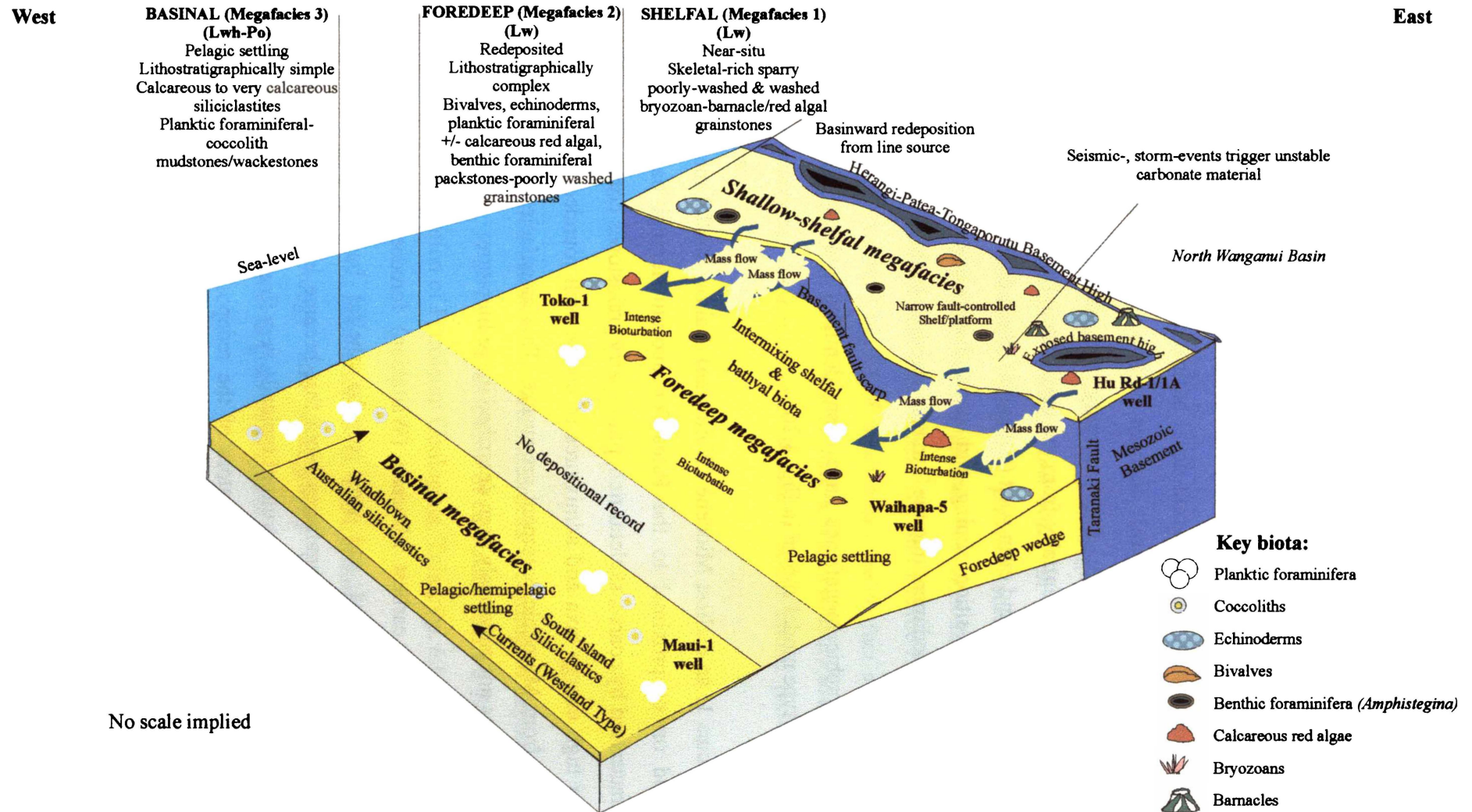


Fig. 4.26 Tikorangi Formation depositional model showing the location and major characteristics of the three identified megafacies. Lwh = Whaingaroan; Lw = Waitakian; Po = Otaian.

ranging from calcareous mudstones to wackestones to packstones to clean grainstones.

Petrographic variability over short vertical intervals results from the complex interplay of a number of controlling factors: (1) the rapidly evolving tectonic setting which provided a range of co-existing shelfal, tectonically active foreland basinal, and tectonically quiescent distal basinal settings; (2) deposition during a number of relative sealevel changes within an overall transgressive or submergence regime; (3) the proximity to, and availability of, different siliciclastic sources potentially from the east (Patea-Tongaporutu-Herangi High), south (South Island) and even west (Australia) (Stein & Robert 1986); and (4) the variability of composition, timing, and spatial distribution of mass redepositional events supplying sediment into the Taranaki foredeep basin.

Three petrographic megafacies have been identified and are summarised in an escarpment type model shown in Fig. 4.26.

Megafacies 1: an earliest Miocene (Waitakian) shallow-shelfal megafacies which formed on or proximal to the Patea-Tongaporutu-Herangi basement high is characterised by coarse, skeletal-rich, pure sparry grainstones comprising shallow-water high energy taxa and admixtures of coarse well rounded siliciclastic sand derived from Mesozoic basement greywacke. This megafacies, referenced to Hu Rd-1/1A, has not previously been described in the literature.

Megafacies 2: an earliest Miocene (Waitakian) foredeep megafacies formed immediately basinward and west of the shelfal basement platform from redeposition of shelfal megafacies biota that became intermixed with near situ bathyal taxa to produce a spectrum of typically very fine to fine mudstones though to sparry grainstones. Key indicators of the redepositional history include the fragmental and highly abraded nature of the shelfal skeletons, including former photic dwellers such as calcareous red algae and large benthic foraminifera. The resulting skeletal mix is unlike that in any of the age equivalent limestones in the neighbouring onland North Wanganui Basin. Planktic foraminifera generally increase in abundance upcore, while siliciclastic material decreases in content as

facies belts migrated landward with ongoing basinwide marine transgression. High levels of bioturbation of the sediment enhanced skeletal mixing and destroyed any original depositional bedding structures; occurrence of a *Planolites-Chondrites-Zoophycus* assemblage is indicative of bathyal depths. Uplift of eastern basement siliciclastic source areas in the Early Miocene brought an abrupt halt to carbonate production by drowning shallower carbonate factory sites and diluting pelagic test fallout.

Megafacies 3: an Oligocene-Early Miocene (Whaingaroan-Otaian) offshore basinal megafacies approaching a “*Globigerina* ooze” in composition formed away from redepositional influences. Although previous studies (e.g., King & Thrasher 1996) have emphasised the siliciclastic sediment-starved setting of Maui-1, the reference well for this megafacies, the siliciclastic-rich nature and mainly low carbonate content (<41%) of these rocks are in fact suggestive of continued siliciclastic input in this distant basinal setting, probably sourced from oceanic currents carrying suspended sediment from South Island provenances exposed at this time.

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BURIAL DOLOMITISATION OF THE MID-TERTIARY MIXED SILICICLASTIC-CARBONATE TIKORANGI FORMATION IN TARANAKI BASIN, NEW ZEALAND

5.1 ABSTRACT

The Oligocene to Early Miocene carbonate-rich Tikorangi Formation is a subsurface fracture-producing oil reservoir in Taranaki Basin, New Zealand and is distinct from well studied, uplifted and exposed age-equivalent New Zealand limestones which contain virtually no dolomite. The formation comprises a stratigraphically and sedimentologically complex sequence of mixed redeposited and pelagically settled deposits comprising a spectrum of mudstones to sparry grainstones. The Tikorangi Formation has been partially dolomitised by ubiquitous but generally small quantities (typically <20%, rarely up to 50%) of unimodal, very fine (20-90 μm), scattered free-floating euhedral dolomite rhombs, occasionally forming planar-e (idiotopic) fabrics. Rhombs have dull luminescent Fe-rich cores, and often oscillatory bright and dull concentric outer zones. The dolomites are invariably poorly-ordered non-stoichiometric calcian-rich (av. 58 mol% CaCO_3) and highly ferroan (av. 13 mol% FeCO_3) varieties.

Major controls on the dolomitisation of the Tikorangi Formation have been: the rapid transition into, and continued residency at, significant burial depths (2-3 km); the matrix/micritic-rich nature of the original sediments; the formation of diagenetically closed microenvironments through substantial porosity/permeability reduction by physical/chemical compaction and burial cementation. Kinetic constraints to dolomitisation were overcome by elevated temperatures, pressures, and salinities associated with burial producing warm saline-enriched marine-modified formation waters with elevated Mg/Ca ratios but with relatively low levels of dolomite supersaturation and high levels of calcite saturation. Elevated Mg/Ca ratios were likely attained by redistribution and sequential addition of Mg to pore fluids by several mechanisms including:

stabilisation of HMC/IMC skeletons to LMC; compaction of associated “shale-like” facies; transformation of smectite to illite and release of Mg from clay mineral surfaces; pressure-dissolution of LMC skeletons; and the removal of some excess Ca by precipitation of LMC cements.

Dolomitisation occurred as a single episode, with simultaneous localised micro-scale dissolution of calcite and replacement by inclusion-rich dolomite rhombs resulting in non-pervasive and fabric-selective replacement of interparticle, and rarely intraparticle, micritic/clay-rich matrix. Micritic components provided an ideal substrate for dolomite nucleation and crystal growth because of its high surface area and finely crystalline nature. Partial dolomitisation occurred at a relatively slow rate; in a closed chemical system in which pore fluid trace element concentrations were modified over time due to the precipitation of concentrically zoned dolomite; without development of secondary porosity; and without affecting more coarsely crystalline skeletal grains. Fe was largely supplied from the siliciclastic-rich units and that released during smectite to illite transformation.

The timing of dolomitisation is constrained to the period following earliest Miocene (~22.5-23 Ma) deposition up until when compressional tectonics initiated fracturing of the Tikorangi Formation associated with formation of the Tarata Thrust Zone during the Early Miocene (~21.8-16.3 Ma) to mid Miocene (~14 Ma). Depths of dolomitisation range from an earliest and minimum of 1000 m to a latest and maximum of 2250 m, corresponding to burial paleotemperatures in the range 36-72°C. This agrees with planar fabrics forming below the theoretical critical roughening temperature of 50-100°C.

Dolomite-rich units would have been more susceptible to brittle fracture which may have implications for the location of fracture network systems and for hydrocarbon prospectivity and production in the Tikorangi Formation.

Keywords dolomitisation; carbonate diagenesis; mid-Tertiary; Tikorangi Formation; hydrocarbons; fractured reservoir; Taranaki Basin; New Zealand

5.2 INTRODUCTION

The mid-Tertiary (Whaingaroan-Waitakian) mixed siliciclastic-carbonate Tikorangi Formation is an important fracture-producing reservoir within the onshore Waihapa-Ngaere Field, the fourth largest and only fracture and carbonate reservoir within Taranaki Basin, New Zealand (Fig. 5.1) (King & Thrasher 1996). The Tikorangi Formation, presently lies at subsurface depths of about 3 km beneath Taranaki Peninsula (Fig. 5.1B, C) and provides an opportunity of unravelling a record of burial diagenesis of temperate limestones that is largely unaffected by subsequent uplift and direct meteoric exposure. The stratigraphic context of the Tikorangi Formation (of the Ngatoro Group) within the thick (up to 8 km) sedimentary fill of Taranaki Basin is schematically summarised in Fig. 5.2

This paper presents the first comprehensive diagenetic study of the temperate-latitude Tikorangi Formation, and specifically focuses on the nature and origin of dolomite in the rocks. The presence of dolomite strongly contrasts the Tikorangi Formation with all other well studied age-equivalent uplifted limestones in the adjacent North Wanganui Basin (Te Kuiti Group) (Fig. 1B, C), as well as comparable facies elsewhere in New Zealand, despite them having similar passage through the burial diagenetic realm (e.g., Nelson 1973; Nelson et al. 1988, 1994; Hood 1993; Hood & Nelson 1996; Dodd & Nelson 1998). With rare exception (Table 5.1), dolomite is absent from these limestones.

The burial diagenetic environment is probably the least understood of all diagenetic realms (Tucker & Wright 1990) and the ubiquitous occurrence of significant quantities of dolomite within the Tikorangi Formation suggests some significant divergence in burial diagenetic history compared to the other mid-Tertiary New Zealand carbonates. The occurrence of dolomites can also be of economic significance as they fracture more easily than limestones (Jordon & Wilson 1994) and make superior fracture reservoirs (e.g., dolomite hosts many commercial oil and gas reservoirs in the Western Canada Sedimentary Basin). Consequently the delineation of dolomite-rich facies may have implications for predicting the occurrence of key fracture systems within a formation (Videtic 1994).

Despite dolomitisation being a process estimated to have effected some 30-40% of limestones (Tucker & Wright 1990), dolomite itself is a complex mineral whose origin remains a major unsolved problem due to its highly ordered nature and the kinetic constraints which hinder its precipitation (Land 1980, 1983; Greg 1988; Morse & Mackenzie 1990; Tucker & Wright 1990). Studies have shown that dolomite forms under varied chemical and physical conditions from various salinities in a wide range of environmental conditions.

There remains considerable disagreement among workers as to the origins of dolomite and which controls exert the most influence in particular situations, while contradictions between laboratory synthesised and naturally occurring dolomites is a major area of concern (Purser et al. 1994). Dolomite has not yet been synthesised in the laboratory under conditions typical of sedimentary deposition, either by replacement or by direct nucleation (Land 1980). The current view is that primary dolomite is very rare, and that the majority of dolomite occurring in the geological record has a replacement origin after a CaCO_3 precursor (Land 1980, 1983).

The kinetic factors hindering dolomite formation are a consequence of the high degree of order of the dolomite crystal lattice and of the differences in hydration behaviour of the Ca^{2+} , Mg^{2+} and CO_3^{2-} ions. The extent to which these factors inhibit dolomite are thought to be governed largely by the interplay of: (1) the rate of crystallisation; (2) the Mg/Ca ratio; and (3) a CO_3/Ca ratio greater than one where anaerobic bacterial reduction of sulfate in solution may limit dolomite (Morrow 1990a). Sea water may be supersaturated with respect to dolomite but because of kinetic factors it does not precipitate widely in the normal marine environment. The kinetic hindrances to dolomite formation in normal marine waters are overcome in dolomitisation models by invoking chemical modification of sea water by evaporation or freshwater dilution.

Three prerequisites for dolomitisation were suggested by Land (1980) to be the import or addition of Mg, the export of Ca, and a mechanism for supplying the Mg-rich fluids. There is difficulty in obtaining a significant source of Mg, especially for the more pervasively dolomitised rocks, while maintaining the

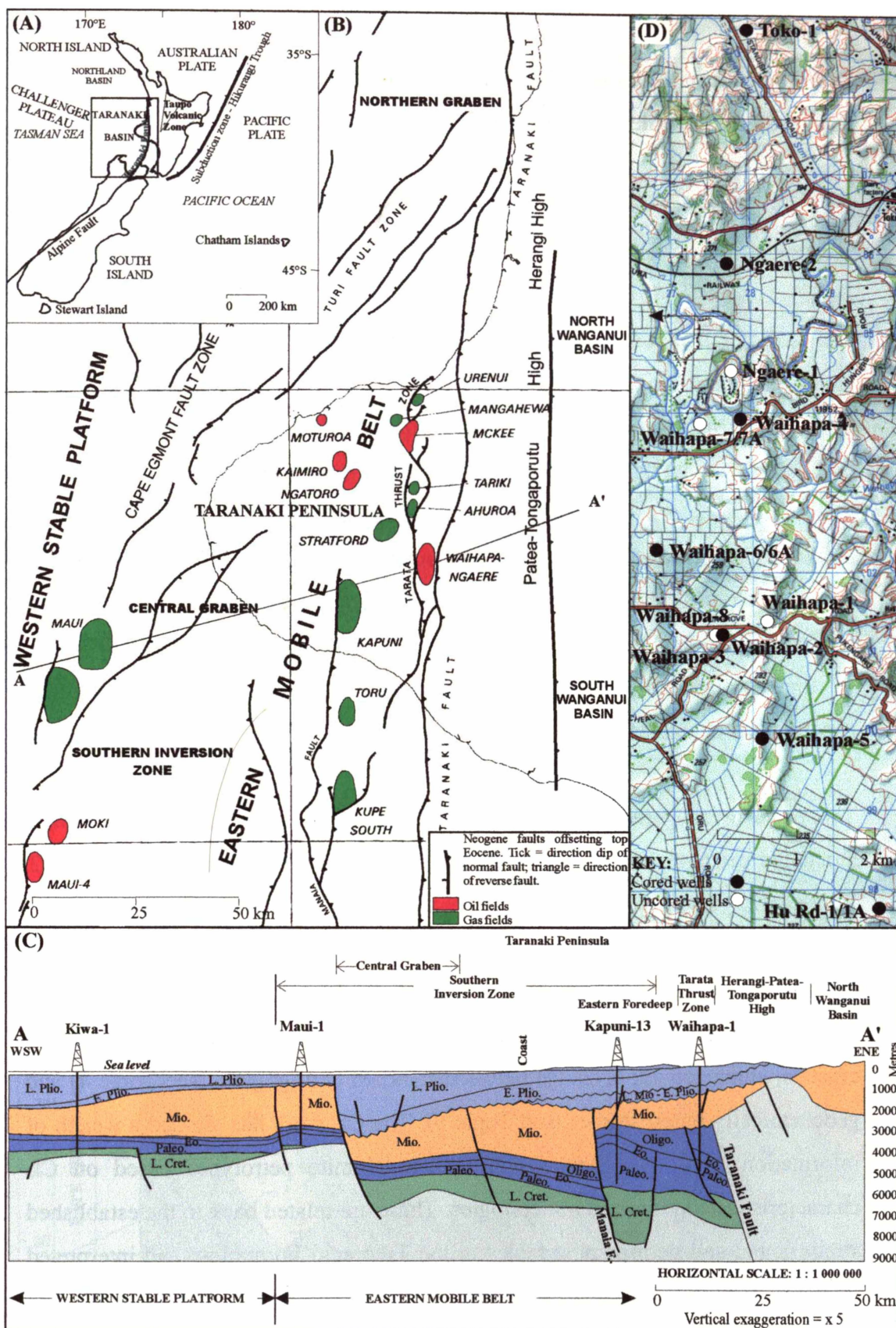


Fig. 5.1 (A) Location of Taranaki Basin in New Zealand. (B) Major structural and tectonic elements and main oil/condensate accumulations within Taranaki Basin. The Tikonangi Formation is dated as earliest Miocene in the east (Waihapā-1) and Oligocene-Early Miocene in the west (Maui-1). Adapted from King & Thrasher (1996). (C) Structural cross-section of a transect running WSW - NE through offshore Maui-1 and onshore through the Waihapā-Ngaere Field, Tarata Thrust Zone (see location in B). Adapted from King & Thrasher (1996). Shading: = late Neogene, = early Neogene, = Paleogene, = Late Cretaceous, = basement. E. Plio. = Early Pliocene; L. Plio. = Late Pliocene; Mio. = Miocene; Oligo. = Oligocene; Paleo. = Paleocene; L. Cret. = Late Cretaceous. E. Plio. = Early Pliocene; L. Plio. = Late Pliocene; Mio. = Miocene; Oligo. = Oligocene; Paleo. = Paleocene; L. Cret. = Late Cretaceous. (D) Location of the seven onshore wells (solid circles) providing core from the Tikonangi Formation within the Waihapā-Ngaere Field that form the basis for this study.

hydrological conditions necessary to supply a sufficient flux of Mg-rich fluids that will result in dolomite formation (Morse & Mackenzie 1990).

Because of the wide variety of dolomite fabrics and mineralogies that occur in the geological record there can be no single process of dolomitisation and no unique model to explain all dolomite formation (Zenger & Dunham 1980; Land 1983), and so a range of dolomitisation models exists, often with overlapping characteristics. Using uniformitarian principles, many of these models are based on modern small-scale marine intertidal, supratidal and evaporitic environments, while modern analogues at depth are restricted to the freshwater-marine phreatic mixing zone. Tucker & Wright (1990) suggest that the common occurrence of dolomite in certain modern intertidal-supratidal-evaporitic environments has probably clouded the interpretation of many ancient dolomites. Inevitably the interpretation of ancient dolomites should be based first on a sound understanding of the stratigraphic, facies, paleogeographic, petrographic, diagenetic and geochemical characteristics of the deposits (Morrow 1990b).

This paper investigates the origin of dolomite in the Tikorangi Formation through a detailed petrographic study of core material from seven (Hu Rd-1A, Ngaere-2, Waihapa-2, -4, -5, -6, Toko-1) onshore wells (Fig. 5.2D) and a single offshore well (Maui-1) (Fig. 5.2C; see Appendix 2.2 for sample catalogue, Appendix 4.1,4.2 for general petrographic data, Appendix 5.1 for diagenetic petrographic data). The study focuses on the cathodoluminescence (CL) patterns in dolomite crystals which provide a bridge between standard petrographic (see Topic 4) and geochemically-based studies (see Topic 6). The CL work has yielded a wealth of information used to define a number of dolomite petrotypes based on CL characteristics and inferred mineralogies. These are related back to the established stratigraphic and petrographic facies in the Tikorangi Formation, and interpreted in terms of pore fluid chemistries and associated diagenetic environments. The petrography and geochemistry of the dolomite, combined with inferred tectonic and burial histories of the rocks, enables an assessment of the physical and geochemical conditions of dolomitisation, including depth, timing, temperature, and fluid nature. This paper does not deal directly with the geochemistry of dolomites, for which the reader is referred to Topic 6.

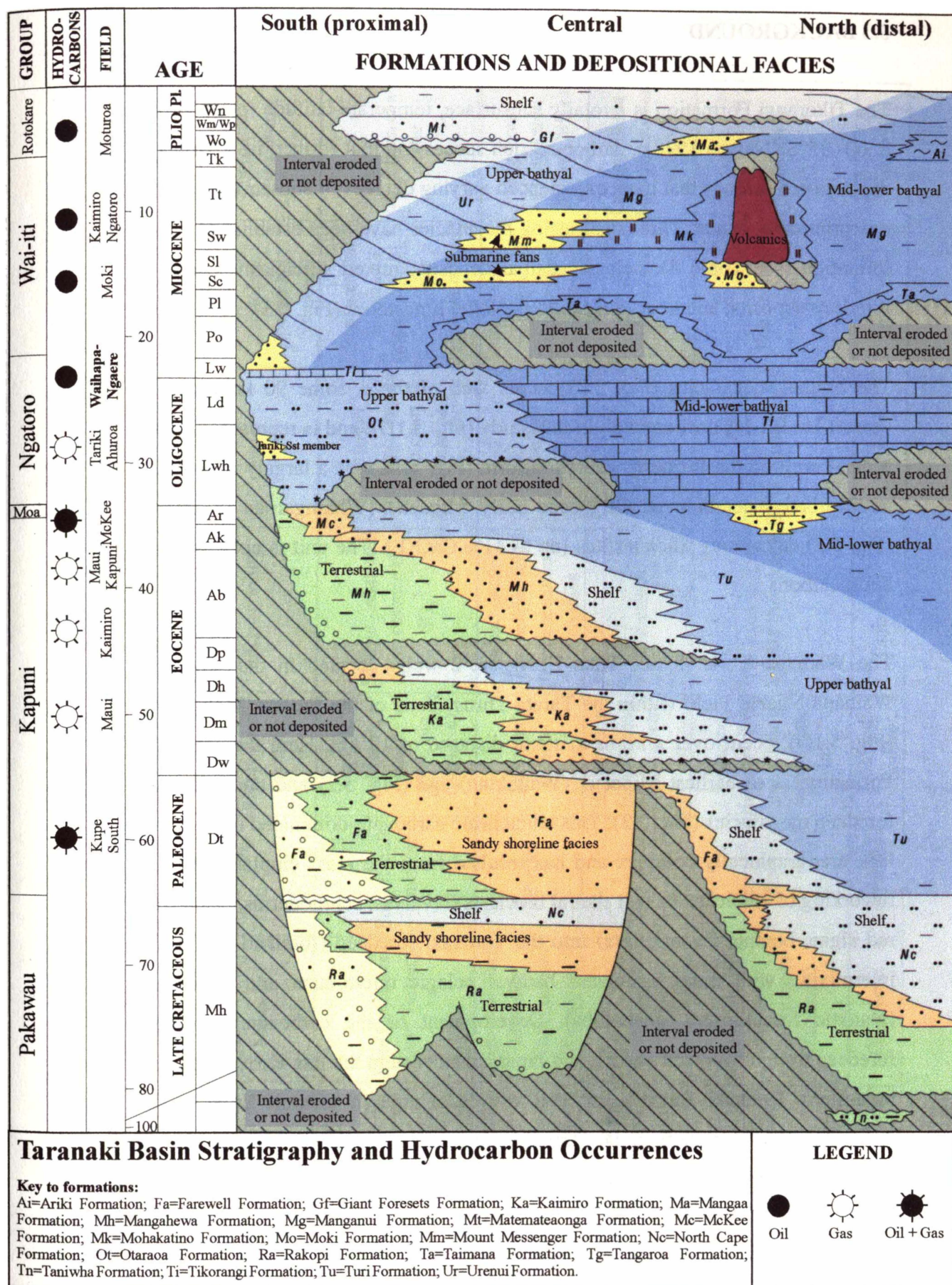


Fig. 5.2 Taranaki Basin stratigraphy, depositional facies, and hydrocarbon fields and occurrences. The Tikorangi Formation carbonates form part of the Ngatoro Group. Modified from King & Thrasher (1996).

5.3 BACKGROUND

The Tikorangi Formation is a totally subsurface, temperate-latitude (paleolatitude c. 60- 35°S (Nelson 1978)), carbonate-rich succession that formed in a variety of depositional settings that have experienced varying degrees of subsequent tectonic overprint/disturbance. Three contrasting megafacies have been established for the formation (see Topic 4): pelagic basinal deposits; mixed siliciclastic-carbonate foredeep deposits; and *near-situ* shallow-shelfal limestones (Fig. 5.3).

The basinal megafacies (Fig. 5.3) occurs well offshore, some 90 km from the nearest Hu Rd-1A onshore well in this study (Fig. 5.1D), and is represented in the Maui-1 well on the Western Stable Platform (Fig. 5.1C), by a largely tectonically undisturbed succession of Oligocene-Early Miocene (Whaingaroan to Otaian) (Fig. 5.2) calcareous siliciclastites (up to 41% CaCO₃). The unit is not producing hydrocarbons.

The Waihapa-2, -4, -5, -6, Toko-1, Ngaere-2 wells, located in the producing Waihapa-Ngaere Field within the Tarata Thrust Zone of the Eastern Mobile Belt (Fig. 5.1D), occur over a north to south distance of 12 km. Here the Tikorangi Formation is of earliest Miocene (Waitakian) age (Fig. 5.2) and comprises the foredeep megafacies (Fig. 5.3). This siliciclastic carbonate-dominated unit is often lithostratigraphically complex and has resulted from the mass emplacement and reworking of siliciclastics and shelfal bioclasts (bivalves, echinoderms, calcareous red algae, benthic foraminifera) into the Taranaki foredeep (foreland basin) and intermixing with more basinward bathyal pelagic microfauna and microflora (planktic foraminifera, coccoliths). Development of the carbonate-dominated foredeep trough followed sudden and rapid subsidence in the late Early Oligocene in eastern Taranaki Basin associated with a change in tectonic style of the Australian-Pacific plate boundary through New Zealand (King & Thrasher 1996). The unit is mainly an oil producer.

The Tikorangi Formation in the Hu Rd-1A well, located at the southern- and easternmost end of the Tarata Thrust Zone, and only 2.8 km from the nearest Waihapa-5 well of the foredeep megafacies, also has an earliest Miocene

Table 5.1 Documented occurrences of dolomite within other New Zealand temperate Cenozoic carbonates.

Author	Formation	Age	Relative abundance	Description	Host	Timing	Mode	Source Mg/Si
Leask (1980)	Takaka Limestone	Waitakian - Otaian (Early Miocene)	Minor	40 - 80 μm rhombs. Rarely Fe-rich centres	Bryozoan zooecia, microstylolites	Late stage -deep burial	Pressure dissolution; zooecia and stylolites permeable conduits	Clays and/or bryozoan dissolution
Lawrence (1989)	Amuri Limestone Group	Late Cretaceous- Early Tertiary	Some/locally common	Ca-rich, rhombs, lenses - idiopic (planar-e)	Micrite - restricted by presence of SO_4^{2-}	Early <60°C; contemporaneous with chert formation	Replacement; associated sulfate reduction in upper sediment column	Mg from sea water
Anderson (1984)	Punakaiki and Tiropahi Limestones	Oligocene-Early Miocene (Whaingaroan-Waitakian)	Minor	Scattered rhombs	In carbonates interbedded with terrigenous/mud-rich units	Late stage	Replaces bioclasts and cements in grainstones	Mg from compaction derived brines
Haywick (1990)	Darky's Spur Formation	Late Pliocene	Very minor	Concretion (non-ferroan stoichiometric)	Limestone	Unknown	Unknown	Organic fluids - bacterial sulfate reduction
German (1976)	Nile Group	Oligocene-Early Miocene (Whaingaroan-Waitakian)	Minor	Scattered rhombs 10-60 μm . Cloudy cores, clear rims	Muddy limestones	Early to late burial	Replacement matrix	Unknown
Hayton (1995)	Bobs Cove	Oligocene	Very minor	Scattered rhombs	Limestone	Unknown	Unknown	Unknown

(Waitakian) age and consists of *near-situ* shallow shelfal limestone (Fig. 5.3). Skeletons are dominated by relatively shallow-water high energy taxa indicative of a photic, shallow-marine nearshore depositional environment. Interbedded siliciclastic-rich layers comprise subrounded to rounded greywacke lithic fragments which, together with rare angular brecciated blocks of greywacke, suggest accumulation on or very near variably exposed Murihiku Mesozoic basement rocks associated with the Herangi High forming the eastern boundary of Taranaki Basin. This carbonate shelf probably sourced the shelfal skeletons evident in the associated foredeep megafacies, mentioned above. This unit is not producing hydrocarbons.

Tectonic compression and uplift of siliciclastic source areas to the east in the Early Miocene ended deposition of the Tikorangi Formation with a change from carbonate to siliciclastic-dominated sedimentation, and later fracturing and allochthonous emplacement of low-angle overthrusts involving Tikorangi Formation along the eastern margin (Tarata Thrust Zone) of the basin (Fig. 5.2C).

5.4 METHODOLOGY

Uncovered polished thin sections (sample catalogue Appendix 2.2) of Tikorangi Formation were prepared using standard procedures. Representative thin sections were stained following the technique of Dickson (1965) using potassium ferricyanide and Alizarin Red-S to help distinguish nonferroan/ferroan calcite and dolomite mineralogies. CL observations were made using a Technosyn cold cathode luminescence 8200 MkII instrument, optimum luminescence typically occurring at 15 kv and a gun current of 450 μ m. The generally low levels of luminescence negated simple visual descriptions of the CL images which were recorded instead on sensitive 400 ASA colour film using exposure times of up to 12 minutes.

Bulk powders of selected samples of Tikorangi Formation were prepared using a ring mill with a tungsten-carbide head to prevent any iron contamination. Unoriented powder mounts were analysed using a Philips analytical x-ray

Tikorangi Formation - Escarpment Depositional Model

Earliest Miocene, prior marine transgression maxima, Taranaki Basin

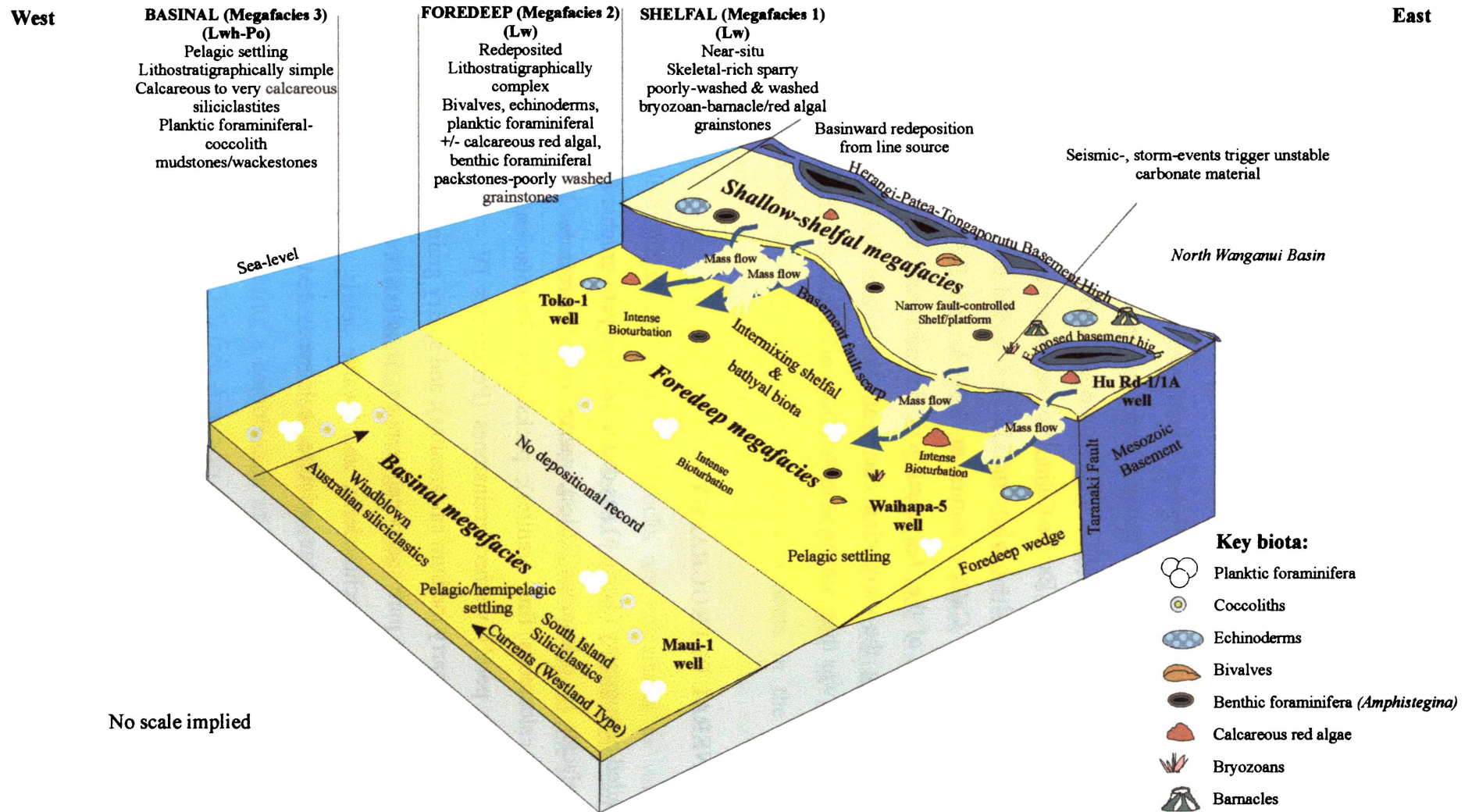


Fig. 5.3 Tikorangi Formation depositional model showing the location and major characteristics of the three identified megafacies. Lwh = Whaingaroan; Lw = Waitakian; Po = Otaian.

diffractor with a PW1729 x-ray generator and a PW1840 diffractometer control. X-ray diffraction (XRD) analysis was conducted on un-oriented powder mounts, to determine the amount of Mg substitution in the calcite and dolomite lattices (Tucker 1988), and the quantity of Fe in the dolomite lattice. Mounts were slow scanned at $0.25^{\circ}2\theta/\text{minute}$, with the addition of an analytical grade NaCl (halite) spike for accurate peak position determination. Calibration curves for determination of dolomite % in calcite were taken from Al-Hashimi & Hemingway (1974). Determination of the displacement of the d_{104} peak of calcite with increasing mol% MgCO_3 to dolomite is based on the calibration curve of Goldsmith et al. (1961). Excess Ca in dolomite was calculated after Tucker (1988) as: $\text{mol\% CaCO}_3 = md + b$ where $m=333.33$; $b = -911.99$; and d = lattice spacing in Å where 50% CaCO_3 occurs at 2.886Å and 55% CaCO_3 at 2.901Å . Displacement the of the d_{104} spacing of dolomite relative to FeCO_3 wt% was calculated using the calibration curve of Al-Hashimi & Hemingway (1974). FeCO_3 (wt%) was then converted to FeCO_3 (mol%) following Smith (1992).

5.5 GENERAL PETROGRAPHY

Detailed petrography (Topic 4) has delineated five petrographic facies: mudstones (Petrofacies I - calcareous lutites); wackestones (Petrofacies II - moderately to strongly calcareous fine arenites); packstones (Petrofacies III - fine muddy calcarenites); poorly washed grainstones (Petrofacies IV - impure fine muddy calcarenites to sparry medium calcarenites); and sparry grainstones (Petrofacies V - fine to very coarse pure sparry calcarenites). Bioclasts are overall dominated by planktic foraminifera, echinoderm, and bivalve debris with lesser amounts of benthic foraminifera, sponge spicules, calcareous red algae, bryozoans, and barnacle fragments.

The three Tikorangi Formation megafacies noted earlier (Section 5.3) have been defined (Topic 4) on petrographic textural and compositional differences. Megafacies 1 (shallow-shelfal) (Fig. 5.3) is characterised by very coarse sand-sized, poorly washed and very pure grainstones (80-99% carbonate) dominated by benthic foraminifera, calcareous red algae, barnacles, and bryozoan debris.

Interbedded siliciclastic-rich layers comprise subrounded to rounded greywacke lithic fragments. Rocks are highly pressure-dissolved and exhibit limited (<10%) interparticle volume filled dominantly by equant microsparite cements, but also by lesser micrite/matrix with no visible porosity.

Megafacies 2 (foredeep megafacies) (Fig. 5.3) comprises a spectrum of variably siliciclastic, generally skeletal-dominated rocks ranging from rare mudstones to grainstones, but dominated by wackestones, packstones, and poorly washed grainstones. Skeletons comprise a range of highly fragmented fine sand-sized bioclastic debris including planktic foraminifera, coccoliths, bivalves, echinoderms, calcareous red algae, and benthic foraminifera. Burial-induced pressure-dissolution has resulted in tight, often fitted fabrics and dissolution seams visibly enriched in insoluble residues, while tectonic compression has produced stylolites at high angles to bedding and more localised pressure-dissolution. Interparticle space is occluded by micrite/matrix in the dirtier packstones/wackestones and by equant microsparite cements in the cleaner grainstones. No porosity is visible.

Megafacies 3 (basinal megafacies) (Fig. 5.3) rocks are calcareous to very calcareous wackestones comprising pelagically settled planktic foraminifera and nannofossil (coccoliths) skeletons, but are mainly dominated by clay- to fine silt-sized siliciclastic material.

5.6 DOLOMITE IN THE TIKORANGI FORMATION

This study has positively identified dolomite within the carbonate-rich Tikorangi Formation for the first time using a combination of XRD (dolomite d_{104} peak averages 2.90Å (58 mol% CaCO₃)) (see Appendix 5.3), SEM (Appendix 5.4) and standard microscope petrography, and geochemistry. Dolomite appears in plane polarised light (PPL) as tiny rhombohedra, typically ranging in size from 20-90 μm. Dolomites have been grouped for this reason into three main petrotypes based on distinctive and reoccurring cathodoluminescent (CL) patterns. Differences in CL zoning, CL intensity and/or CL colour have been used to subdivide the main

petrotypes into a total of seven subtypes (Table 5.2A, B). The characteristics of these seven petrotypes are discussed in the following section, diagrammatically summarised in Fig. 5.4, and illustrated under both PPL and CL in Plate 5.1, 5.2. The ability to provide higher-power images than those shown was not possible due to the lack of a microscope objective greater than x10 on the CL microscope used in this study. Appendix 5.2 contains a list of representative samples containing the various CL petrotypes together with general host rock petrographic properties. CL zones are referred to as “Z” (i.e., zone 1 = Z1) and zones are numbered from the core outwards.

5.6.1 Petrotype I

Petrotype I dolomite CL signatures are distinguished by rhombs having brightly luminescent cores, absent in other Tikorangi Formation petrotypes, about which two further simple concentric zones appear. Two petro-subtypes have been identified, Ia and Ib (Fig. 5.4).

5.6.1a Petro-subtype Ia

Dolomite rhombohedra of petrotype (petro-subtype) Ia have simple CL patterns involving moderately bright orange/yellow CL throughout the entire dolomite crystal (Plate 5.1B; Table 5.2B). Very subtle changes in CL intensity and colour may define a simple concentric zonation pattern where a slightly brighter more yellow/orange Z1 core up to 35 μm across fades into a marginally less bright red/orange zone (Z2) up to 30 μm thick. An abrupt return to a brighter orange/yellow CL envelope delineates a thin (up to 15 μm) outer Z3. Some Ia rhombs appear to lack zoning except for a very thin non-luminescent outer zone (Z4) which does not encompass the whole crystal. Rare examples show a very dull intrasectoral zoning limited to one apex of the rhomb. CL signatures of more sparry (“cleaner”) and more micritic (“dirtier”) sections of the dolomite rhombs are indistinguishable.

The majority of petrotype Ia dolomite crystals appear as isolated euhedral rhombs from about 20 - 80 μm size (Plate 5.1B; Table 5.2A). Less commonly there are intergrown clusters comprising two or three rhombs. Petrotype Ia dolomite is restricted to the shallow-shelfal megafacies of Hu Rd-1A, where it forms up to 10-

Table 5.2A Occurrence and dolomite crystal properties of the seven cathodoluminescence (CL) defined petrotypes in the Tikorangi Formation.

CL Petrotype	Dolomite occurrence						Dolomite crystal properties					
	General abundance	Well(s) occurrence	Tikorangi Fm megafacies	Pore volume	Pore fill	Common rock type	Size (μm)	Habit	Fabric	Clarity	Origin	% Rock volume
Ia	some	Hu Rd	shelfal	inter/intra	micrite/ matrix/ microspar	poorly washed grainstone	60-90	euhedral	rhombs/ rare clusters	very dirty >sparry	replace- ment	10-15
Ib	some	W-2,-4, -5, Ng- 2	foredeep	inter	micrite/ matrix/ microspar	wackestone/ packstone	30-40	euhedral	rhombs	brown/ dirty	replace- ment	to 5
IIa	some	W-2, -4, -5, - 6, Ng-2	foredeep	inter	micrite/ matrix/ microspar	wackestone - poorly washed grainstone	40-70	euhedral	rhombs- idiotopic	very dirty/ inclusions	replace- ment	to 15
IIb	rare	W-5, Ng-2	foredeep	inter	micrite/ matrix/ microspar	wackestone- packstone	40-60	euhedral	rhombs- idiotopic	sparry & dirty	replace- ment	to >50
IIc	rare	W-6, Ng-2	foredeep	inter	micrite/ matrix/ microspar	wackestone- grainstone	70-90	euhedral/ curved faces	rhombs	dirty/ inclusions	replace- ment	to 7
IIIa	very common	W-5, Ng-2	foredeep	inter	micrite/ matrix/ microspar	poorly washed grainstone	40-60	euhedral	rhombs/ clusters	very dirty> sparry	replace- ment	5-20
IIIb	some	W-2, -5	foredeep	inter	micrite/ matrix/ microspar	packstone	40-70	euhedral	rhombs	sparry & dirty	replace- ment	5-10

Notes: Hu = Hu Rd-1A; Ng = Ngaere; W-2 = Waihapa-2; inter = interparticle; intra = intraparticle.

15% of samples (see Plate 5.1A, B) and is restricted in occurrence to both intra- and interparticle micrite/matrix-rich (geopetally) filled areas, often now altered to neomorphic microspar (Plate 5.1A). The host rocks are generally tightly pressure-dissolved, siliciclastic-rich packstones (some 50% carbonate) or skeletal-rich (bryozoans, barnacles) packstones/grainstones (80%+ carbonate). Commonly rhombs mimic the original matrix/micritic fabric and are at best only vaguely evident under plane polarised light PPL (Plate 5.1A) while a few of the rhombs exhibit clearer, more sparry, but irregular centres. Limited asymmetric and truncated zones within a small number of rhombs occur, while a single dolomite crystal sits adjacent to a spar cement-filled microfracture in a skeletal grain which itself shows no evidence of fracture.

5.6.1b Petro-subtype Ib

Petrotype Ib dolomites are characterised by moderately bright yellow Z1 cores up to 40 μm across, succeeded by a dull maroon luminescent Z2 usually less than 3 μm thick (rarely up to 15 μm) and a slightly thicker (< 5 μm) dull to moderately dull orange/red Z3 (Plate 5.1D; Table 5.2B). Zones Z2 and Z3 are not always equally concentric and can show limited but variable thickness, while some Z1 cores exhibit very dull intrasectoral zoning in one apex only of a rhomb. Very rarely rhombs appear to have a non-luminescent and irregularly shaped Z4. A single rhomb has partially replaced an already neomorphosed former aragonitic bivalve which has recrystallised to calcite. Overall the petrotype Ib dolomites are the smallest of the seven petrotypes.

The Ib rhombs are restricted in occurrence to former interparticle matrix/micrite or its neomorphic microspar equivalent (Plate 5.1C; Table 5.2A). There is no evidence of dissolution and porosity development within dolomite-bearing areas. Only rarely do dolomites occur within intraskeletal pores, which are typically spar cemented. Rhombs are scattered and about 5% of sample volume, and are difficult to discern in PPL although some are dirty with a honey brown appearance (Plate 5.1C).

Petrotype Ib is restricted to relatively small numbers of wackestones and packstones rock types with up to 60% carbonate (planktic foraminifera,

Table 5.2B Dolomite crystal cathodoluminescence (CL) characteristics of the seven CL petrotypes in the Tikorangi Formation.

CL	CL zones and characteristics																	
	Z1(core)			Z2			Z3			Z4			Z5			Z6		
Petro-type	Intensity	Colour	Width (µm)	Intensity	Colour	Width (µm)	Intensity	Colour	Width (µm)	Intensity	Colour	Width (µm)	Intensity	Colour	Width (µm)	Intensity	Colour	Width (um)
Ia	bright	orange/ yellow	to 35	mod. bright	red/ orange	to 30	bright	orange/ yellow	to 15	non	black	10						
Ib	mod. bright	yellow	to 40	dull	maroon	3-15	mod. bright	orange/ red	<5									
IIa	dull- v. dull	maroon	20-30	bright	yellow	<10												
IIb	v. dull	maroon	30-50	mod. - dull	orange/ red	<10												
IIc	dull-non	maroon	to 80	dull-mod. bright	yellow/ orange	<10												
IIIa	dull	maroon	20-35	mod. bright	yellow/ orange	<10	dull- v. dull	maroon	<10	bright	yellow/ orange	<10						
IIIb	v. dull	maroon	to 20	dull-mod. bright	orange/ yellow	<5	dull	orange/ maroon	<10	mod. bright	orange/ yellow	<10	dull	maroon	<10	mod. bright	yellow/ orange	<5

Notes: mod. = moderately; v = very.

echinoderms, bivalves) and variable siliciclastic contents from within the Waihapa-2, -4, -5, and Ngaere-2 wells. The dolomite distribution within the individual wells appears to be confined to particular depth ranges, but too few examples are available to confirm this relationship.

Limited evidence of pressure–dissolution occurs in some rhombs with lightly dissolved margins and distortion of CL zones. Plate 5.1C, D however shows a micro-fractured dolomite rhomb within a Tikorangi Formation host fragment incorporated into a calcite healed fracture. This points to dolomitisation occurring prior to fracturing and subsequent vein mineralisation.

5.6.2 Petrotype II

Petrotype II CL signatures are distinguished from petrotype I by their generally dull, very dull to rarely non-luminescent cores with a single, variably luminescent concentric outer zone. Three petro-subtypes have been identified, IIa, IIb, and IIc (Fig. 5.4).

5.6.2a Petro-subtype IIa

Petrotype IIa dolomites are dominated by maroon dull to very dull luminescent cores (Z1) which are typically overgrown by a moderately bright yellow Z2 (Plate 5.1F; Table 5.2B). Rhomb sizes are unimodal and range from 20 - 50 μm , rarely up to 90 μm . Z1 is thickest, typically 20 - 30 μm , while Z2 is thin, < 10 μm . The dolomite crystals are typically single euhedral rhombs within matrix/micrite or dirty microspar, although rarely the rhombs exhibit intergrown fabrics (Plate 5.1 E, F). The dolomite rhombs are mainly undetectable under PPL. They may form up to 15% of the rock volume and have not been seen to replace skeletal material.

Petrotype IIa dolomites are randomly distributed throughout Ngaere-2 and Waihapa -2, -4, -5, and -6 core. They occur dominantly within the matrix/micrite/microspar-rich interparticle areas within skeletal-rich (bivalve, echinoderm, planktic foraminifera) packstones, and occasionally in wackestones and poorly washed grainstones including moderate amounts of siliciclastic material (Plate 5.1E). Rock fabrics are tight and generally pressure-dissolved with no evidence of porosity enhancement often associated with the dolomitisation

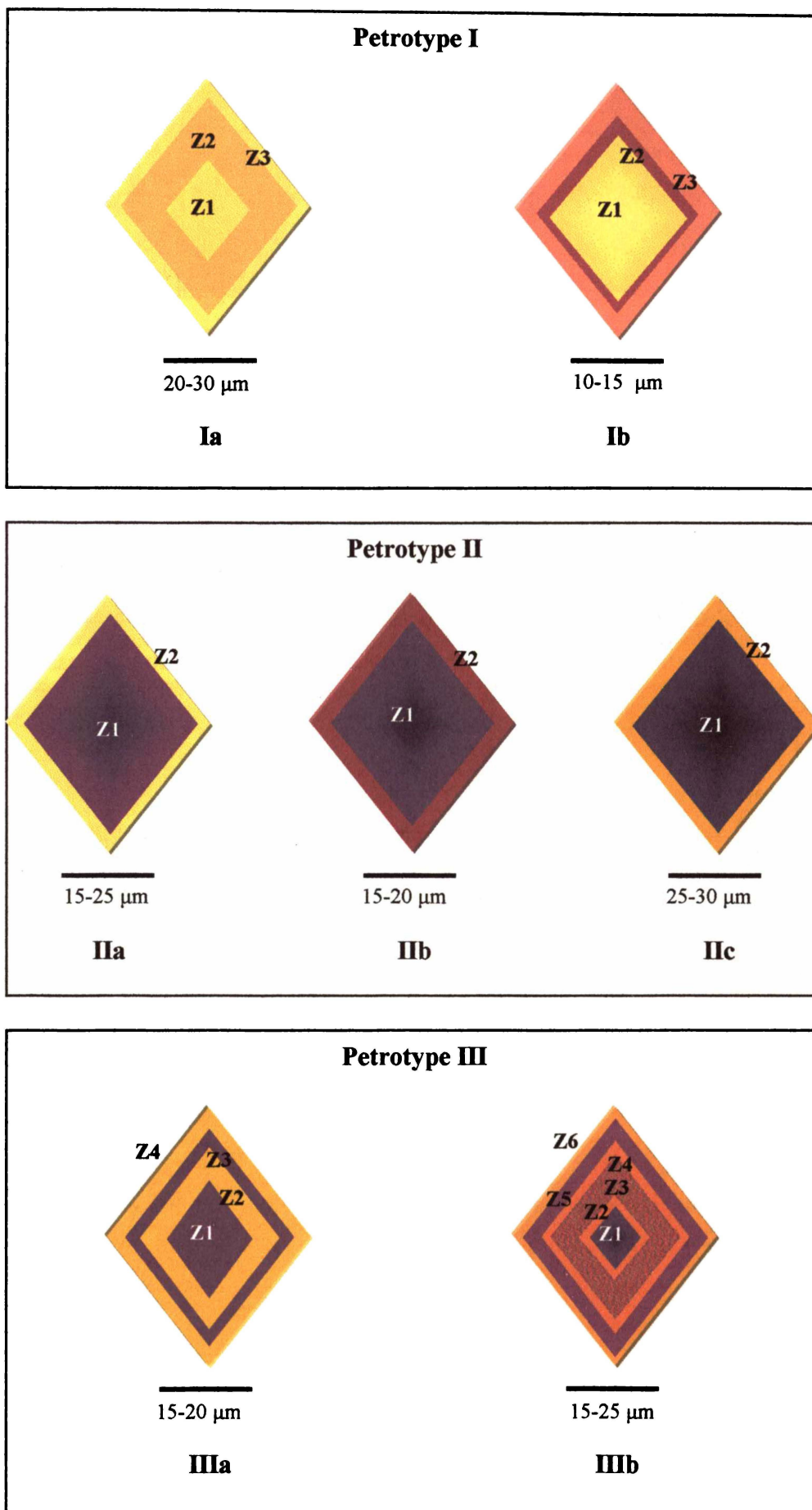


Fig. 5.4 The seven CL petrotypes defined in the Tikorangi Formation showing typical sizes and CL colour and zoning characteristics.

process (Scoffin 1987; Jordan & Wilson 1994).

5.6.2b Petro-subtype IIb

Petrotype IIb dolomites have similar CL signatures to those of petrotype IIa, but the thin ($< 10\ \mu\text{m}$) outer Z2 has a much duller orange-red luminescence (Plate 5.1H; Table 5.2B). The Z1 core is typically a very dull deep maroon/purple and ranges from 30-50 μm across. Together the IIa and IIb dolomites form pervasive planar-e or idiotopic fabrics (i.e., most dolomite crystals are euhedral rhombs - Tucker & Wright 1990) which locally may form greater than 50% of the rock forming dolostones (Plate 5.1H). Crystals in these more pervasive fabrics occur in clusters rather than as scattered single rhombs as in all other petrotypes. Individual rhombs are in point or facial contact, not intergrown, and they have a unimodal size distribution within the 40 - 65 μm range. Crystals have selectively replaced micrite/matrix leaving skeletal grains unaffected by the dolomitisation process.

Compared to the other petrotypes, in PPL these planar rhombs are often visible sparry crystals, although are rather dirtier within the darkest micrite/clay-rich areas (Plate 5.1G). Host rocks are both wackestones and packstones with variable skeletal contents comprising primarily bivalve and/or planktic foraminiferal material. Examples are rare and confined to the Waihapa-5 and Ngaere-2 wells (Table 5.2A).

5.6.2c Petro-subtype IIc

Petrotype IIc dolomite rhombs are dominated by large very dull to non-luminescent cores up to 80 μm across (Plate 5.2B; Table 5.2B), the coarsest of any of the Tikorangi Formation dolomites. The surrounding dull to moderately bright yellow/orange Z2 outer envelope is less than 10 μm thick. Crystals are characteristically euhedral, but given their large size it is possible to see that some rare crystal faces are curved, characteristic of saddle or baroque dolomite (Plate 5.2B; Appendix 5.4).

In PPL the petrotype IIc dolomites are typically inclusion-rich and merge into a dirty microspar background (Plate 5.2A). Their host rocks range from packed

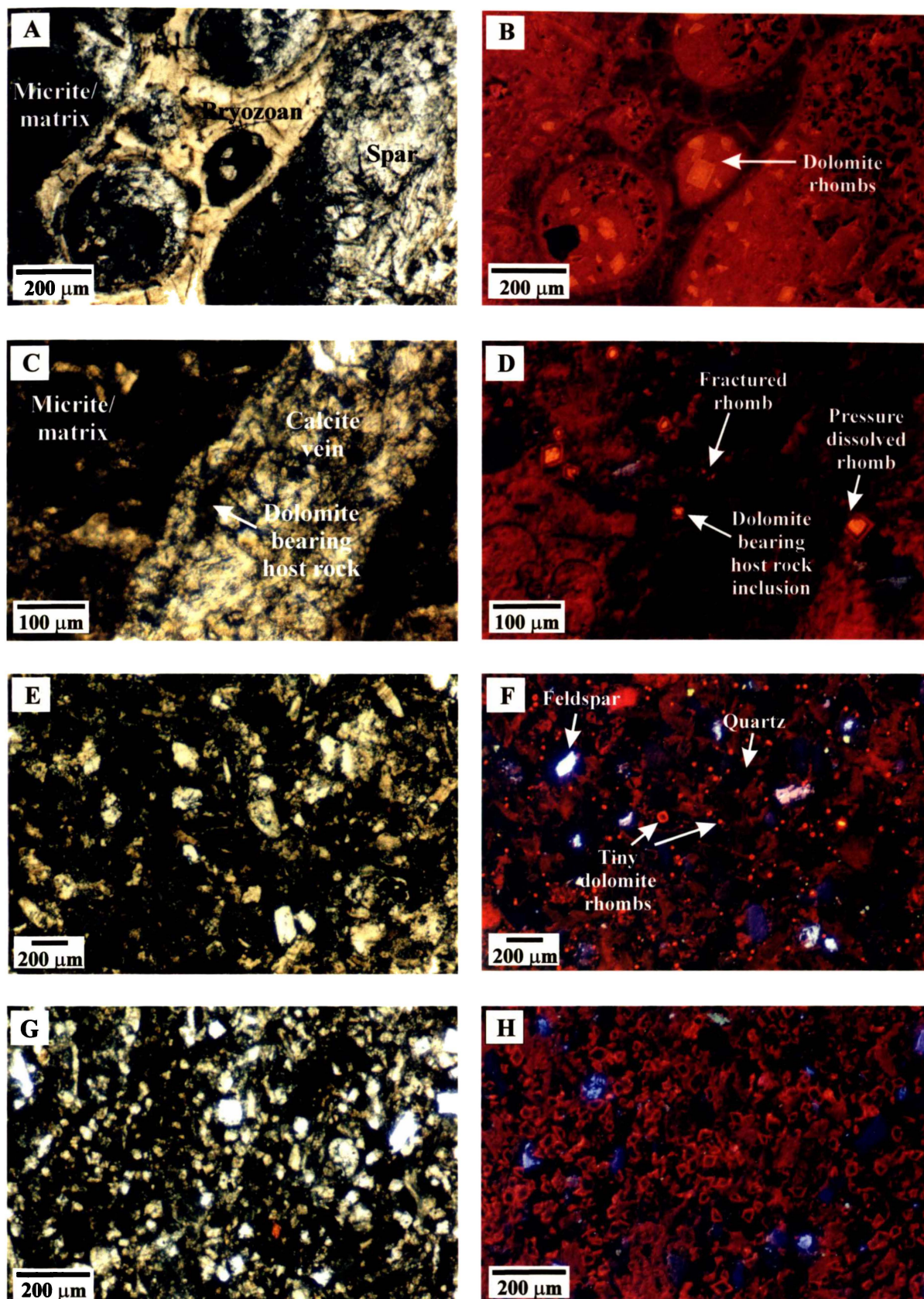


Plate 5.1 Photomicrograph pairs under plane polarised light (left) and cathodoluminescence light (right) of CL petrotypes in the Tikorangi Formation. (A) Petrotype Ia restricted to and mimicking original micrite/microsparite exhibiting in (B) bright yellow/orange cores and outer zones (sample Hu2.4, shelfal megafacies). (C, D) Petrotype Ib occurring within dark micrite/matrix (C) is characterised in (D) by bright yellow luminescent cores, a dull maroon Z2, and moderately dull orange/red Z3. Dolomitisation predates non-luminescent calcite vein (sample W2.1.6A, foredeep megafacies). (E, F) Petrotype IIa occurring as typically tiny scattered euhedral rhombs (E) within siliciclastic/matrix/micrite-rich areas exhibiting (F) dull to very dull luminescent cores (Z1) enveloped by moderately bright yellow Z2 (sample NG2.6.8, foredeep megafacies). (G, H) Petrotype IIb with dull- non-luminescent cores and orange-red luminescent Z2 forming an uncommon pervasive planar-e or idiotopic fabric (sample W5.6.2, foredeep megafacies). See Appendix 2.2 for sample details.

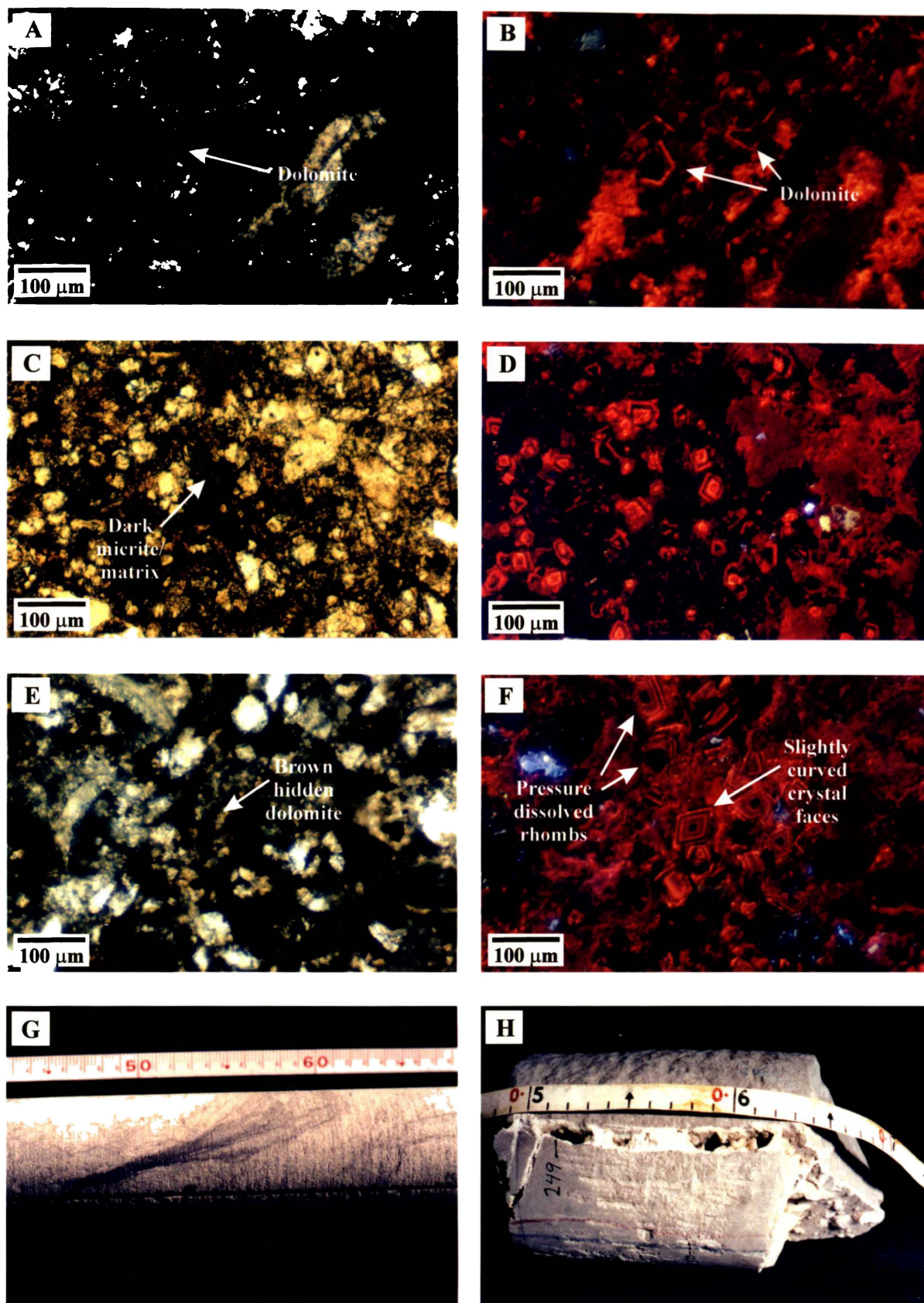


Plate 5.2 Photomicrograph pairs under plane polarised light (left) and cathodoluminescence light (right) of CL petrotypes in the Tikorangi Formation. (A) Petrotype IIc occurring in dark micrite/matrix (B) comprising large very dull- to non-luminescent cores with a dull- to moderately-bright yellow/orange Z2 (sample NG2.4.1). (C, D) Petrotype IIIa, the most common CL petrotype, with rhombs displaying oscillatory zoning (sample W5.4.6). (E, F) Petrotype IIIb dolomites commonly exhibit six oscillatory concentric zones and show evidence of tectonic pressure dissolution (sample W2.2.7). (G) Core showing horse-tail stylolite resulting from tectonic compression occurring largely post-dolomitisation as evidenced by pressure dissolved rhombs in (F) (sample NG2.4.10). (H) Tectonically-induced hydrocarbon-bearing fracture-porosity partially healed by carbonate minerals, both post-dating dolomite formation (sample W4.7.2B). See Appendix 2.2 for sample details.

biosparites with 90% carbonate dominated by bivalves and echinoderms with minimal matrix/micrite (5%) to wackestones with less than 40% carbonate dominated by matrix/micrite (50%) and planktic foraminifera. The dolomite is most prevalent in the wackestones where it forms up to 7% of the rock volume. Samples have no visible porosity and are restricted in occurrence to the Waihapa-6 and Ngaere-2 wells.

5.6.3 Petrotype III

Petrotype III dolomites, like type II, have dull- to non-luminescent cores but are characterised by a series of outer concentric zones, as many as 4-6. Two petro-subtypes have been identified, IIIa and IIIb (Fig. 5.4), based on the number and characteristics of these encasing zones.

5.6.3a Petro-subtype IIIa

Petrotype IIIa dolomites range in size from 35-50 μm and are the most common CL type within the Tikorangi Formation (Plate 5.2C, D; Table 5.2B). The planar rhombs have a variably dull red/orange to maroon luminescent Z1 core, from 20 - 35 μm across, which may brighten outwards. Z2 is commonly a moderately bright orange/yellow, rarely bright yellow, zone of less than 10 μm thickness (Plate 5.2D). Most commonly the boundary from Z1 to Z2 is sharp, but it is sometimes gradational and may result from intrasectoral zoning of the core. Z3 is again a dull to very dull, very occasionally non-luminescent zone having a variable thickness of up to 10 μm , and is usually sharply defined. Z4 is a repetition of Z2, forming oscillatory zoning, and again is less than 10 μm thick.

In PPL these dolomites are characteristically very dirty and inclusion-rich, are most prevalent in the darkest micritic/clay-rich areas of samples, and are extremely difficult to identify (Plate 5.2C). Occasionally they are sparry. Where rhombs are more densely packed they are usually in point or planar contact and rarely exhibit inter-growth textures. No obvious replacement of skeletal grains is evident.

In the majority of samples containing petrotype IIIa dolomite the crystals

commonly form about 5% of the rock volume, but occasionally as much as 20%. These concentrically zoned dolomites occur in dominantly skeletal limestones (bivalves, echinoderms, planktic foraminifera) in the Ngaere-2 and Waihapa-2 and -5 wells. Samples are mainly poorly washed grainstones, rarely wackestones and packstones.

Often the outer zones (Z2-Z4) show disruption of the concentric oscillatory zonation and/or are absent. Clear evidence of pressure-dissolution has occurred against microstylolites or dissolution seams (Plate 5.2D). The distribution of IIIa petrotypes within individual wells shows some well depth correlation along hole; the majority of Ngaere samples occur within a 2 m core interval, while most samples from Waihapa-5 occur over a 6 m interval with only occasional samples occurring at other depths.

5.6.3b Petro-subtype IIIb

Petrotype IIIb dolomites have the most complex CL zonation of any petrotype in the Tikorangi Formation, the rhombohedra commonly exhibiting six concentric zones (Plate 5.2F). Like the majority of petrotype II and III dolomites, the Z1 core, up to 20 μm across, is characteristically a very dull maroon colour. Some intrasectoral zoning is evident within the core, which in some instances shows an outward gradation to a brighter CL signature. The boundary with Z2 is sharp and Z2 itself is typically very thin ($< 5 \mu\text{m}$) and characterised by moderately dull to moderately bright yellow/orange luminescence. Z3 is a thicker ($< 10 \mu\text{m}$) dull maroon zone with less defined boundaries. Z4 is similar in thickness and CL characteristics to Z2, although often slightly brighter. Z5 is $< 10 \mu\text{m}$ thick and has a very dull maroon luminescence like Z1. The outermost Z6 is a moderately bright but very thin ($< 5 \mu\text{m}$) zone which may exhibit irregular bright outer margins. The broad CL similarity of zones 1, 3, and 5, alternating with 2, 4, and 6 is an example of oscillatory concentric zoning (Plate 5.2F).

Dolomite rhombs again frequent the “dirtiest” most matrix/micrite/clay-rich areas of samples and most commonly occur as clusters or scattered isolated planar rhombs (Plate 5.2E). Commonly dolomite constitutes about 5% of the rock volume, reaching up to 10% or more in some samples. In PPL there is no

evidence of skeletal replacement, while rhombs vary from being quite clean and sparry to the more typical dirty and inclusion-rich crystals “hidden” within areas of interparticle fines. The tight pressure-dissolved nature of the host rock fabric is more evident than in other petrotypes with the majority of grains having clay/insoluble residue-rich coatings (Plate 5.2E). In rare instances dolomite appears to be prevalent adjacent to, but not within, clay-rich dissolution seams. Away from pressure-dissolution zones there can be interpenetration of dolomite rhombs by siliciclastic grains, as well as distortion of the concentric oscillatory zoning pattern in rhombs (Plate 5.2F). In some Waihapa-2 samples up to 50% of some dolomite rhombs has been lost to dissolution. Dolomite does not occur within the microstylolite seams themselves.

Petrotype IIIb dolomites occur mainly in packstones having a mix of skeletons (planktic foraminifera, bivalves, echinoderms) and moderately low siliciclastic contents in rare samples within Waihapa-2 and -5 wells. They are mainly very restricted in core occurrence with samples occurring in close association (1 m spacing) with each other along the well holes and also with those samples classified as IIIa.

5.7 DISCUSSION

A generalised schematic model of dolomitisation for the Tikorangi Formation is provided in Fig. 5.5, and discussion of the various model components follows below.

5.7.1 Dolomite crystal size

Irrespective of differences in well location, well depth, rock fabric, and CL properties, the maximum crystal size of the dolomite rhombs invariably falls between 20 and 90 μm (av. 30 - 40 μm) (Table 5.2A), and the crystal populations in a sample exhibit a typically unimodal size distribution within this size range. This suggests that dolomite formation in the Tikorangi Formation was linked to a single nucleation event in time which combined with uniform growth rates to precipitate fine-grained (dominantly silt but includes very fine sand sized)

equidimensional rhombohedra (e.g., Sibley & Gregg 1987). The fine nature of rhombs in the Tikorangi Formation is compatible with a burial origin (Scoffin 1987). Decreasing dolomite crystal size has been related to increasing salinity where hypersaline dolomites ($<15\mu\text{m}$) are finer than normal marine dolomites which are finer than mixing zone dolomites ($<500\mu\text{m}$) (Tucker 1988; Morrow 1990a). Tikorangi dolomite size from 20 - 90 μm may reflect some degree of increased salinity. Presumably formation temperatures were sufficiently elevated to overcome the kinetic constraints associated with dolomitisation but were not sufficiently elevated to produce a relatively coarser crystalline aggregate typical of higher temperature and greater burial depths.

5.7.2 Dolomite fabric

The Tikorangi Formation dolomites characteristically occur as scattered single free-floating planar rhombs (Plate 5.1A-F, 5.2A-F; Table 5.2A). Rarely do these cluster to form more pervasively dolomitised planar-e (euhedral) idiomatic fabrics, except in examples from petrotype IIa and IIb where crystals then tend to be in either point or planar facial contact. Intergrowth textures are uncommon (Plate 5.1G, H). Planar rhombs, and where concentrated to form planar-e fabrics, are generally favoured to form at lower temperatures than for anhedral forms, unseen in the Tikorangi Formation, and thought to relate to the critical roughening temperature (CRT) suggested to be 50-100°C (Sibley & Gregg 1987). Some idiomatic textures may form however at higher temperatures where crystals grow into cavities or are affected by clay and organic matter (Burns et al. 1988). Certainly the latter may have been an influence in the more micritic-rich facies. Planar faces have formed by the nucleation and lateral migration of atomic layers within the crystal and are characteristic of relatively lower supersaturation levels and/or temperatures. Rare development of slight curvature of crystal faces in petrotype IIc samples may be taken to suggest these dolomites are approaching subhedral forms (Plate 5.2C-F). These uncommon crystals may have formed at higher supersaturations and/or temperatures above the CRT, crystal growth occurring by random addition of atoms.

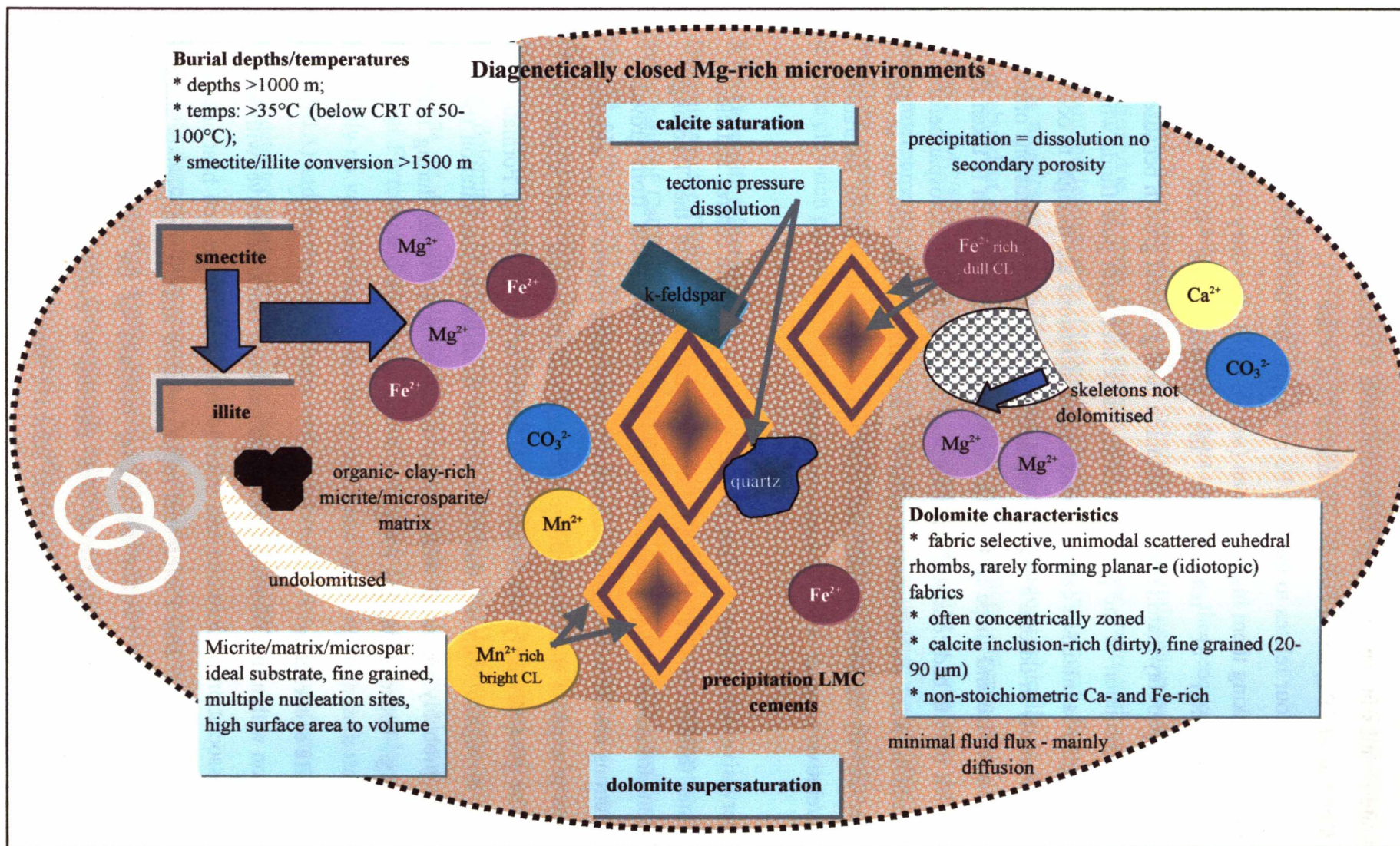


Fig. 5.5 Schematic petrographic model showing the common CL (cathodoluminescence) characteristics of Tikorangi Formation dolomite, together with some of the major chemical conditions and associated processes suggested as necessary for dolomite formation.

5.7.3 Dolomite colour

Dolomite rhombs in the Tikorangi Formation have a typically dirty, often honey brown colour in PPL, and a cloudy appearance (e.g., Plate 5.1, 5.2; Table 5.2A). The brownish colour relates to the high Fe content of the dolomites, typically 13 mol% FeCO_3 , making them highly ferroan (see Topic 6). The dirty crystals result from incorporation of residues of the original fine host material (micrite/microspar/clay/matrix) into the dolomite during crystal growth because of incomplete dissolution of the precursor fabric associated with pore fluids which remained highly saturated in calcite. Relict calcite inclusions are thought to occur almost universally in dolomite that has replaced calcite. Calcitic inclusions often have the same size and shape as the host microsparite fabrics, which is taken to indicate that micrite had commonly neomorphically aggraded to microspar before dolomitisation. Rare occurrences of clearer sparry rhombs, particularly in the more pervasively dolomitised samples, may indicate a lower calcite saturation level or relatively higher dolomite supersaturation.

Truly pervasive dolomitisation often produces cloudy dolomite centres and clear outer rims (Sibley & Greg 1987), a situation not evident in the Tikorangi Formation dolomites. Cloudy cores are inclusion-rich and result from growth from solutions unable to completely dissolve the precursor calcite phase, whereas clear rims precipitate from more dilute solutions undersaturated with respect to calcite. The generally dirty and inclusion-rich nature of the Tikorangi Formation dolomites throughout suggests that the solutions from which precipitation took place were probably saturated with respect to calcite at all times during their formation (e.g., Tucker & Wright 1990).

5.7.4 Dolomite occurrence

Dolomitisation within the Tikorangi Formation has been fabric selective, with an ubiquitous association of dolomite and micritic/matrix/microspar-rich host areas (Plate 5.2, 5.2; Table 5.2A). Preferential replacement of mainly interparticle and occasionally intraparticle (within the coarser bioclasts of the shallow-shelfal megafacies) micrite (or microsparite after micrite) is evident in almost all observed dolomite occurrences. The fabric selective nature is well demonstrated in Plate 5.1, 5.2 where the fine equant spar cement has only very rarely been

dolomitised while the micritic-rich matrix has been. Skeletal material has resisted dolomitisation, due to its coarser and often complex crystalline structure affording unfavourable sites for crystal nucleation and/or the relatively low supersaturation levels of dolomite within the pore fluids.

Lime and clay-bearing muds, ubiquitous throughout the redeep megafacies, have provided an ideal substrate for dolomitisation in the Tikorangi Formation due to their high surface area to volume ratio and consequently abundant nucleation sites (Sibley & Gregg 1987). In general, fine precursor CaCO_3 mosaics are more likely to be replaced pseudomorphically as there are more abundant nucleation sites (Tucker & Wright 1990). Micrite with an often initial IMC/HMC mineralogical component can provide Mg-rich microenvironments and a supply of Mg for dolomitisation (e.g., Leask 1980), and would be consistent with the characteristic association of dolomite with the most micritic clay-rich portions of samples.

5.7.5 Dolomite mineralogy

Dolomites in the Tikorangi Formation are non-stoichiometric (not having the ideal molar ratio of $\text{CaCO}_3/\text{MgCO}_3$ of 50:50) Ca- (av. 58 mol% CaCO_3) and Fe-rich (av. 13 mol% FeCO_3). These dolomites are highly ferroan [ferroan > 2 mol% FeCO_3 (Tucker 1988; Tucker & Wright 1990)] approaching ankerite in composition (arbitrarily set at 20 mol% FeCO_3) and may be termed calcian-rich ferroan dolomites. Fe incorporation into dolomite has lowered the ordering reflections in dolomite (intensity 015 peak/intensity 110 peak) and hence Tikorangi Formation dolomites are poorly ordered. Dolomite mineralogy shows essentially no variation across the study wells and is the same in both the shelfal (Hu Rd-1A) and foredeep (Waihapa wells, Ngaere-2, Toko-1) megafacies wells (it was not detected in samples from the basinal Maui-1 well).

Burial late stage dolomites commonly have high Fe and Mn levels associated with precipitation from often highly reduced pore fluids in the presence of iron-rich siliciclastic material and can approach ankeritic compositions especially where associated with siliciclastic rocks (Scoffin 1987; Land 1983). The mixed siliciclastic-carbonate nature of the Tikorangi Formation ensured a local

siliciclastic source of iron.

Saddle or baroque dolomite with curved/warped as opposed to straight crystal boundaries, mentioned earlier as occurring in some particularly petrofacies IIc dolomites in the Tikorangi Formation, is both Ca- and Fe-rich. Trace element enrichment is a reported characteristic of such late stage dolomites and may be explained by associated pore fluid decreases in pH and alkalinity commonly occurring with increased salinity (e.g., Tucker & Wright 1990; Zenger & Dunham 1988). Further details relating to mineralogy are discussed under CL petrography.

5.7.6 Cathodoluminescence petrography

A number of dolomite petrotypes have been defined for the Tikorangi Formation on the basis of their CL colours and zonation patterns (Fig. 5.4; Table 5.2B). At least 26 factors govern the CL of diagenetic carbonates (Machel & Burton 1991). Visual CL colours and intensities are commonly correlated with Mn^{2+} and Fe^{2+} contents, the Mn^{2+} being the most important activator of luminescence in calcite and dolomite, and Fe^{2+} the most important quencher of Mn^{2+} activated luminescence (Marshall 1988; Machel et al. 1991; Budd et al. 2000). Changes in CL colour and intensity within the Tikorangi Formation dolomites are inferred to correspond to distinct compositional changes controlled by the Fe/Mn ratio. Regardless of high iron, zones may still luminesce if sufficient Mn is present. Three groups of processes are likely to have been involved in determining the element concentrations in the diagenetic pore fluids within the Tikorangi Formation, and hence in the precipitating dolomites: changes in redox potential, closed system element partitioning, and organic matter and clay mineral diagenesis (Machel & Burton 1991).

Petrotype Ia dolomites (Fig. 5.4; Plate 5.1A, B; Table 5.2B) are unique in the Tikorangi Formation due to their moderately bright yellow/orange luminescence throughout, inferred to result from a relatively lowered Fe/Mn ratio. Studies have shown that 10-20 ppm Mn is required for visible activation in the absence of quenchers (less than 150 ppm Fe) with emission intensity increasing with increasing Mn^{2+} content (Machel et al. 1991; Machel & Burton 1991). Bulk carbonate trace element analysis has shown the petrotype Ia host rocks contain

relatively high Mn concentrations of 200-500 ppm and are relatively Fe poor, from 1100 to commonly < 2300 ppm (see Topic 6).

Petrotype Ib (Fig. 5.4; Plate 5.1 C, D; Table 5.2B) has a large and similarly bright Z1 core to Ia, with a dull red Z2 and brighter orange Z3. With increasing Fe content there is commonly a shift from brighter yellow-orange to deep orange (Z3), even to maroon and deep red (Z3) and finally to dark brown (Machel et al. 1991). Petrotype Ib is therefore suggested to have Fe-poor cores (Z1), a relatively Fe-enriched Z2 zone, and a slightly lesser Fe content in Z3. A change from bright to dull luminescence implies a decrease in Mn independent of Fe up to 2000 ppm (Machel et al. 1991). Petrotype Ib are the only dolomites in the Tikorangi Formation to suggest an overall increase in Fe content with crystal growth. A decrease in Eh can increase the concentrations of first Mn^{2+} and then Fe^{2+} , which could result in bright (Z1) then dull (Z2) or non CL (Machel & Burton 1991). Bulk trace element analysis shows substantial Fe enrichment (>12,000 ppm Fe) in comparison to petrotype Ia and comparatively lower Mn concentrations of about 150 ppm (see Topic 6).

All petrotype II dolomites (Fig. 5.4; Plate 5.1 E-H, 5.2 A, B) are genetically linked with typically Fe-rich dull maroon luminescent cores (Table 5.2B) which increase in Fe content from petrotypes IIa to IIc. Host rocks are typically siliciclastic-rich wackestones to packstones, so a local Fe supply was probably plentiful. Fe often appears to be enriched in relatively deeper burial later diagenetic dolomites, especially those formed from saline formation waters (Zenger & Dunham 1988), and where the transformation of smectite to illite is accompanied by the release of Fe^{2+} so that Fe-rich dolomites are precipitated (Morrow 1990b).

These petrotype II dolomites have relatively thin Z2 outer zones exhibiting varying degrees of dull to bright luminescence (Table 5.2B), with IIb having the highest Z2 Fe content. Variations in non- to dull luminescence, as seen from Z1 to Z2 in petrotype IIb (Plate 5.1 G, H), have been shown in other studies to be independent of Fe up to 200 - 1000 ppm (Machel et al. 1991), while a change from dull to bright luminescence (Z1 to Z2 in petrotypes IIa and c) implies an

increase in Mn with the dull to bright boundary placed at about 400 ppm Mn independent of Fe up to 2000 ppm (Machel et al. 1991). Brighter outer zones result from the presence of elements with higher atomic numbers compared to the dull core and Mg^{2+} depletion of the outer rim relative to the low Mn^{2+} core (Tucker & Wright 1990). The virtually non-luminescent IIc cores may have as little as 30-35 ppm for Fe^{2+} to quench the Mn activated CL (Machel & Burton 1991), while true non-luminescent core centres imply lack of activation or complete extinguishing of any CL (Machel et al. 1991). The often blue/maroon colour of petrotype II cores may result from traces of Eu^{2+} , which can produce a blue CL (Machel & Burton 1991).

Petrotype III dolomites (Fig. 5.4; Plate 5.2 C-F; Table 5.2B) are distinct from petrotype II dolomites, despite having similar outermost zones, because the uniform dull to non-luminescent Z1 core of petrotype II is replaced by an oscillatory concentric zonation pattern. A decrease in Eh can explain the change from bright (Z2) to dull (Z3) in IIIa (Plate 5.2 C, D), and again between Z4 and Z5 in IIIb (Plate 5.2 E, F) (Machel & Burton 1991). Petrotype III dolomites with more abundant brighter zones than in petrotype II dolomites therefore imply relatively Fe-poor pore fluids, with host rocks being more carbonate-rich and comparatively siliciclastic-poor in relation to petrotype II rocks. Many factors may have been involved in the formation of the concentrically zoned petrotype III dolomites, including changes in bulk solution composition, changes in growth rate, and changes in temperature. Simple concentric and cyclic zoning is commonly associated with concentration changes of trace elements in solution (Machel & Burton 1991). Sharp boundary changes are common in all petrofacies and imply rapid concentration changes, while uncommon colour fading suggests slower chemical changes (Machel & Burton 1991).

Oscillatory zoning involving alternation of very narrow zones with equally thick zones having different CL colours/intensities has been attributed to formation only in systems far from equilibrium (Fig. 5.4; Plate 5.2 C-F) (Machel & Burton 1991). Fluctuating growth rates cause a corresponding variation in Mn incorporation which is very growth rate dependent (Reeder 1991). Some examples of oscillatory zoning are thought to reflect a periodic instability of the growth mechanism rather

than a change in pore fluid chemistry. Zoning may also reflect a microbial influence on Fe and Mn concentrations (Machel & Burton 1991). Concentric zonation in some of the Tikorangi Formation dolomites therefore suggests that crystals formed out of equilibrium with the pore fluid composition, probably due to fluctuating growth rates. Zonation suggests pore fluids became Fe-depleted or more Mn-rich as a consequence of changes in the oxidation potential of the fluids (Videtic 1994). In semi-closed or closed systems that contain low contents of clay minerals and organic matter carbonate cementation will lead to increases in fluid concentrations of elements such as Sr and decreases of Mn and Fe (Machel & Burton 1991). Organic matter and clay mineral diagenesis are possible sources and sinks of many trace elements and can influence CL zonation (Machel & Burton 1991).

Rare (intra)sectoral zoning in the Tikorangi Formation dolomites arises from differences in composition that vary for time-equivalent, but crystallographically non-equivalent, growth sectors giving rise to different CL intensities in adjacent centres (Machel & Burton 1991).

5.7.7 Cement versus replacement origin

Replacement of calcite by dolomite can range from fabric destructive to retentive and from fabric selective to pervasive, the important controlling factors being original mineralogy, crystal size, timing and nature of dolomitising fluids (Tucker & Wright 1990). Dolomitisation within the Tikorangi Formation appears to have been dominantly by replacement as evidenced by the dirty and inclusion-rich nature of rhombs, making them extremely difficult to differentiate from micrite or neomorphic microspar (e.g., Plate. 5.1A; Table 5.2A).

If the dissolution of the precursor calcite phase had occurred rapidly then voids would have been created into which clear crystals would have grown as a cement. However, without any substantial porosity development it is likely that calcite dissolution was more or less balanced by dolomite growth and simultaneous incorporation of contaminant inclusions (e.g., Purser et al. 1994). Replacement dolomitisation would have involved the dissolution of the precursor carbonate and precipitation of dolomite via a solution film (Purser et al. 1994). Relict calcite

inclusions are thought to occur almost universally in dolomite that has replaced calcite (Evamy 1967), and these are possibly responsible for the dirty inclusion-rich appearance of many of the Tikorangi Formation rhombs (e.g., Plate 5.1A).

5.7.8 Dolomite stabilisation and dedolomitisation

Dolomite tends to change or mature with time. Initially metastable disordered and non-stoichiometric Ca-rich dolomites, such as typify many Holocene dolomites (Land 1983), later recrystallise to more stoichiometric forms resulting in re-equilibrium of trace elements and isotopic ratios. The Tikorangi Formation dolomites show no obvious evidence of recrystallisation, being presently Ca-rich and non-stoichiometric, possibly a result of their relatively young age compared to many ancient dolomites (Tucker & Wright 1990). There is no evidence of dedolomitisation or corrosion of the Tikorangi Formation dolomites.

5.7.9 Sources of Mg^{2+} and Fe^{2+}

While the elevated temperatures of the subsurface tend to favour dolomitisation, a major constraint on burial dolomitisation is the source and delivery of Mg^{2+} to the site of dolomitisation (Greg 1988; Tucker & Wright 1990; Morrow 1990a, b). Mg may have been supplied to pore fluids in the Tikorangi Formation by several mechanisms, but because of the generally modest quantities of dolomite formed, large quantities of Mg and major fluid circulation and delivery mechanisms were not likely required. What was required was a means of achieving a sufficiently high Mg/Ca within pore fluids supplied internally from redistribution of several sources as part of a closed system internal Mg budget.

An early diagenetic Mg source was likely supplied to pore fluids via the stabilisation of IMC/HMC skeletons to LMC, invoked by Wanless (1979) as a mechanism for providing local Mg sources for dolomitisation. While stabilisation commonly occurs during early shallow-burial diagenesis in the temperate carbonate setting (Hood & Nelson 1996) and Mg may have been removed from solution by absorption onto clay mineral surfaces, it however remained within the closed internal Mg budget for later release during clay mineral transformation.

A later-derived diagenetic Mg source is from the compaction of shale-like

lithologies, a commonly invoked mechanism of sourcing Mg in fine-grained shaly sediments such as carbonate Facies A and B in the Tikorangi Formation (see Topic 2). Gradual expulsion of Mg-bearing fluids is considered capable of producing modest volumes of dolomite (Morrow 1990b) and in the Tikorangi Formation could have passed upwards into the more carbonate-rich Facies C and D in the Tikorangi Formation (see Topic 2). Theoretically however, Mg enrichment of marine porewater (sea water typically 1290 ppm) by this mechanism would have occurred also as a relatively early diagenetic process prior to lithification, and potentially some Mg may have been removed from the porewater by absorption/incorporation onto/in clay minerals before the dolomitisation event (Gregg 1988), but nevertheless again remained within the internal Mg budget.

With greater depths of burial Mg is likely to have been released internally in the Tikorangi Formation by diffusion from clay mineral structures and surfaces from within micritic/matrix/clay-rich material associated with the clay mineral transformation of smectite to illite. The common loss of smectite in sediments below about 1500 m is reportedly due to its conversion to illite (North 1985), releasing cation-rich waters commencing at around 2000 m burial depth (Morrow 1990b) and 60°C in the US Gulf Coast (Choquette & James 1990). It is generally accepted that this transformation occurring during relatively deep-burial releases Mg in small quantities sufficient to partially dolomitise limestones (Scoffin 1987; Morse & Mackenzie 1990; Morrow 1990b; Tucker & Wright 1990), as has occurred in the dolomitic Tikorangi Formation limestones. XRD analysis confirms the presence of generally small quantities of illite as well as the parent smectite clays and mixed smectite-illite intermediaries (see Topic 7) and therefore smectite to illite transformation was a potential mechanism for producing the modest (generally <20% volume) quantities of dolomite in the Tikorangi Formation.

Pressure-dissolution (Plate 5.2 D, F) and stylolitisation (Plate 5.2G), common diagenetic features within the Tikorangi Formation, have been suggested as a local mechanism for providing Mg for late stage dolomite formation (Moore 1989; Morse & Mackenzie 1990) as Mg must be derived from the precursor LMC

calcite. On the other hand, dissolution of LMC skeletons is more likely to lower the Mg/Ca ratio, which however could be overcome by subsequent precipitation of LMC spar cements prior to dolomitisation, again increasing the Mg/Ca ratio in favour of dolomite precipitation.

The Fe-rich nature of the Tikorangi Formation dolomites is thought to have resulted from high Fe concentrations released to pore waters by diffusion (closed system) from siliciclastic/matrix-rich facies (also possibly organic-rich) which contained Fe in the form of oxide coatings on clays, and that bound within/with clay mineral structures and organic matter. Smectite to illite transformation is also accompanied by release of Fe^{2+} so that ferroan dolomite is a common product (Morrow 1990b).

5.7.10 Dolomitisation in an open or closed system

Ca-rich non-stoichiometric Tikorangi Formation dolomites are characteristic of formation in a diagenetically closed system that experienced minimal fluid flux and an internal supply of Mg (Morse & Mackenzie 1990; Tucker & Wright 1990). The lack of pervasive and fabric destructive fabrics is likewise indicative of low rates of partial dolomitisation in a closed system (Scoffin, 1987). Such closed system dolomitisation is commonly associated with matrix/micritic/clay-rich sediments that contain internally substantial amounts of Mg (Morse & Mackenzie 1990) and can create Mg-rich environments (Leask 1980) promoting the formation of Ca-rich dolomitic limestones, the situation for the Tikorangi Formation.

Fabric destructive dolomitisation, unseen within the Tikorangi Formation, is conversely associated with open systems and the production of more stoichiometric dolostones (>90% dolomite) (Tucker & Wright 1990; Morse & Mackenzie 1990). Had Tikorangi Formation dolomites formed in a comparatively open system then both a more uniform concentration of trace elements (see Topic 6) and rather more homogeneous CL signatures might have been anticipated.

A closed system favours changes in pore fluid trace element concentrations with time (Scoffin 1987), commonly leading to high Sr and Ca values, and often

producing complex concentric zoning as occurs in some of the Tikorangi Formation dolomites (Plate 5.2 D, F). Closed system dolomitisation is often a slow fabric preserving process (Scoffin 1987) duplicating the precursor fabric while experiencing high Mg, Sr and Ca concentrations, commonly associated with matrix/micrite/clay-rich sediments (Morse & Mackenzie 1990).

The fact that dolomite is suggested to have formed within a closed, low porosity and permeability environment precludes an externally derived Mg source which may have been derived from high pore water fluxes associated with an open system (Bjorlykke 1994). Closed system dolomitisation within the Tikorangi Formation would have necessitated a substantial reduction in original pore volumes by physical and chemical compaction and cementation prior to dolomitisation taking place. Dolomite formation therefore occurred relatively late in the formation's diagenetic history.

5.7.11 Porosity enhancement

Partial dolomitisation of the Tikorangi Formation has not resulted in the development of any associated secondary porosity. The common association of dolomitisation and porosity enhancement results from a 12.5% volume reduction in the calcite to dolomite transformation (Scoffin 1987; Jordan & Wilson 1994). The relationship is well developed only where dolomitisation rates have been high, as in open fabric destructive systems, resulting in a sucrosic texture with often high intercrystalline porosity (Purser et al. 1994). The Tikorangi Formation's closed diagenetic system, high calcite saturation, inability to remove precursor carbonate, and low pore fluid flux have negated the opportunity for porosity development. Instead calcite inclusions are common within the dolomite crystals due to incomplete dissolution and the inability to completely remove calcite from the site of dolomite nucleation and growth. This has direct implications for the lack of porosity and permeability (<0.01 md) within the Tikorangi Formation host rocks (Halliburton Services 1988) and their inability to host hydrocarbons outside of the fracture systems (Plate 5.2H).

An absence of feldspar dissolution in the Tikorangi Formation is further evidence of a lack of throughflow of porewater and a chemically closed system as (e.g.,

Bjorlykke 1994). This contrasts with many of the sandstone reservoirs in Taranaki Basin (e.g., Kapuni Formation) that have experienced intense feldspar dissolution resulting in high degrees of hydrocarbon-bearing secondary porosity.

5.7.12 Sulfate inhibition

Many studies have shown that transformation of calcium carbonate to dolomite is retarded or inhibited by sulfate contents in fluids as low as 5%, the value in sea water (Scoffin 1988, Morse & Mackenzie 1990; Tucker & Wright 1990; Wright 1999; Mazzullo 2000). However the reaction products of sulfate reduction causing increased alkalinity may also be more important in increasing the rate of dolomite formation than is sulfate at inhibiting it (Morse & Mackenzie 1990). Microbial reduction of SO_4^{2-} is an early diagenetic process typically occurring within the upper sediment column and is an effective mechanism of reducing sulfate; the process is particularly well documented in fine-grained deep-sea organic-rich sediments (Tucker & Wright 1990; Carozzi 1993). Ammonia produced during sulfate reduction may have also released Mg^{2+} enhancing the Mg/Ca ratio (Scoffin 1987). The existence of small quantities of pyrite (few %) with dolomite is confirmation of bacterial sulfate reduction having taken place, potentially removing the sulfate inhibition effect to dolomite formation within the Tikorangi Formation.

5.7.13 Environmental and geochemical conditions

Elevated temperatures associated with tectonically-induced burial, prolonged residency times at depth, and locally Mg-enriched and SO_4^{2-} -depleted pore fluids have combined to overcome many of the kinetic hindrances to dolomite formation to produce modest amounts of burial-derived dolomite within the Tikorangi Formation (e.g., Tucker & Wright 1990). The resultant fine rhombic dolomite often associated with near-surface freshwater or salinity-enriched evaporitic (tropical) settings may imply a degree of increased salinity of pore fluids within the Tikorangi Formation and point to connate burial-derived pore fluids being present during dolomitisation.

In the burial environment the relative stability of dolomite with respect to calcite would have been more pronounced than in surface environments because the

dolomite-calcite equilibrium would have shifted towards higher Mg to Ca ratios, increasing saturation levels of dolomite with respect to those of calcite (Morrow 1990a; Morse & Mackenzie 1990). Diluting sea water with meteoric water overcomes high ionic strength and the problem of rapid rates of precipitation, but due to the burial history of Tikorangi Formation meteoric mixing is not considered a possibility. A burial-type dolomitisation best explains the Tikorangi Formation dolomites which contrasts with meteoric mixing models used to explain dolomite in similar aged southern Australian limestones (Rao 1990; James et al. 1993; Nicolaides 1995, 1997).

As dolomite forms from the carbonate anion (CO_3^{2-}) rather than bicarbonate ion (HCO_3^-), dolomitisation is favoured from solutions with high alkalinity and pH (Tucker & Wright 1990). A lowering of pH within Tikorangi Formation pore fluids would have occurred if salinities had increased significantly with burial depth; the effect however on pH is one of decreasing pH from 7-9 at moderate salinities to 3-4 at high salinities (Hanor 1994). Alkalinity in general also decreases with increasing salinity and is contributed predominantly by the carbonate anion and should decrease with an increase in dissolved calcium (Hanor 1994). It is therefore unlikely that despite the reported trend of increasing salinity in some basins the Tikorangi Formation experienced no major salinity enrichment with depth. However, with some increase in salinity the relative proportion of Na would have decreased while Mg and Ca increased, thus promoting dolomitisation (Hanor 1994).

Evidence of the saturation state of the dolomitising fluids may be provided by the lack of pervasive dolomitisation in the Tikorangi Formation. Relatively lower saturation states are likely to result in only the selective replacement of finely crystalline components, such as micrite and microspar, and not coarser skeletal grains and equant cements (Tucker & Wright 1990). Pore fluid movements would have been slow in the burial realm and consequently rates of dolomite precipitation were likely to have been low (Tucker & Wright 1990).

The fluids associated with fabric preserving dolomitisation and dirty inclusion-rich dolomites were probably modified marine formation waters saturated with

respect to calcite. The absence of limpid (clean, glassy appearance) dolomite in the Tikorangi Formation suggests that at no time were pore fluids undersaturated with respect to calcite. Inclusion-rich dolomites formed from the incomplete dissolution of precursor components due to high calcite saturation. This is further evidenced by a complete lack of (chemical) dissolution features which would be evident had pore fluids been undersaturated, as can occur where there is much organic degradation and high CO₂ (Tucker & Wright 1990). The dolomitising solution was somewhat less supersaturated with respect to dolomite so the micritic matrix was dolomitised preferentially while skeletal grains remained undolomitised. Bioclasts remained undolomitised because of the lower dolomite saturation and the limited number of nucleation sites provided by coarser crystal structures (Purser et al. 1994).

5.7.14 Timing of dolomitisation

An interpreted diagenetic sequence within which dolomitisation is placed is shown in Fig. 5.6. Evidence of dolomitisation in a closed diagenetic system suggests significant burial-related diagenesis occurred within the Tikorangi Formation prior to dolomitisation. Physical compaction would have dominated to burial depths of 200-250 m where porosities would have been reduced by some 25%, transforming the fine sediment to a consistency similar to chalk (e.g., Choquette & James 1990). From 200-250 to 1000+ m chemical compaction and associated cementation would have become dominant and continued until diminishing permeabilities limited pore water circulation producing a closed environment within which dolomitisation could take place.

Dolomitisation post-dated the neomorphism of rare former aragonitic bivalves, with occasional dolomite rhombs sitting within bivalve neomorphic sparry calcite. The apparent incorporation of microsparite (Plate 5.1A) within many dolomite rhombs suggests that neomorphic aggradation of micrite to microspar had occurred prior to dolomitisation and is further evidence of a later diagenetic origin for the dolomite.

Dolomitisation in the Tikorangi Formation predates the majority of tectonically-induced stylolitisation and fracturing features and post-dates the bulk of burial

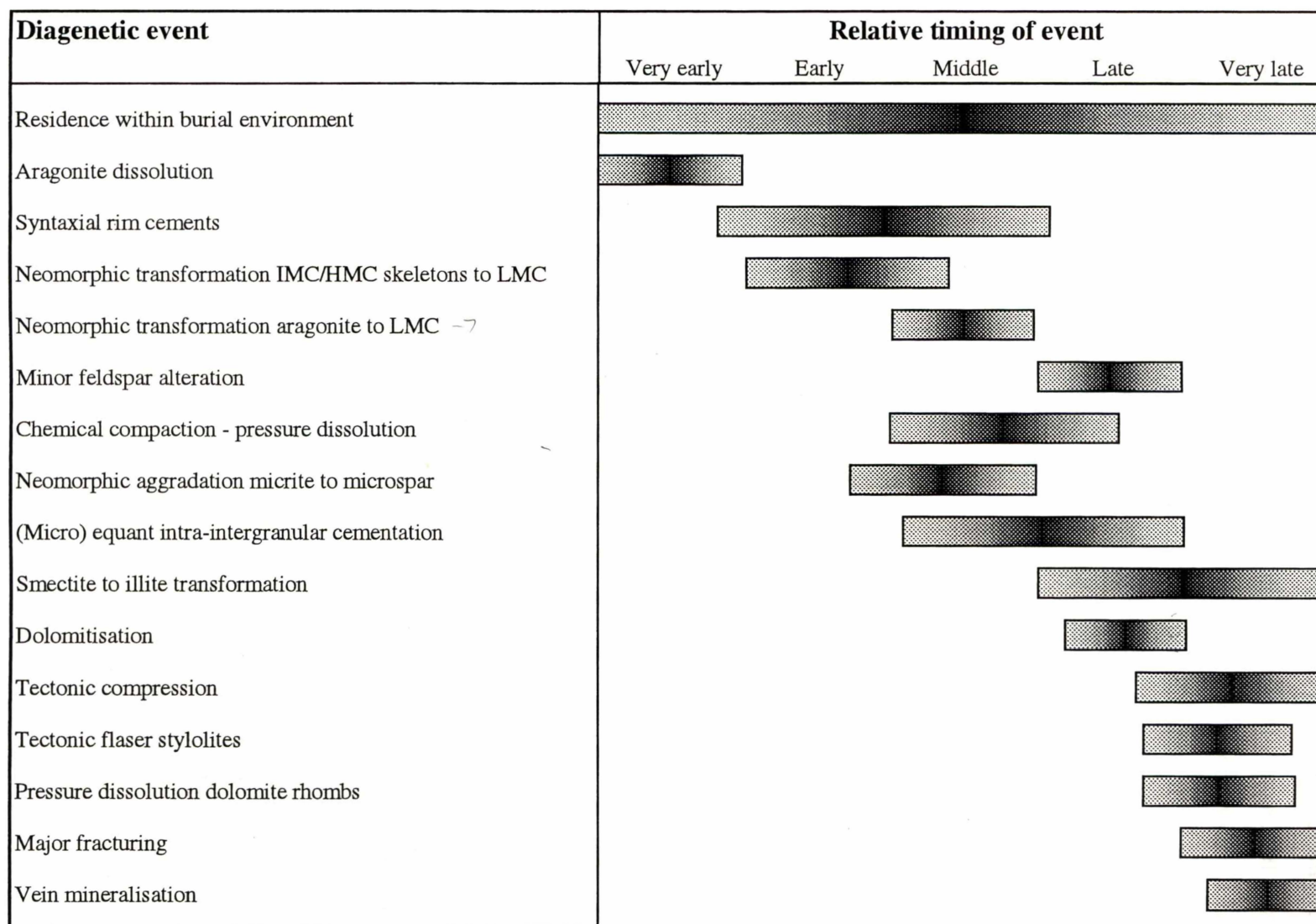


Fig. 5.6 Diagenetic sequence of events in the Tikorangi Formation placing dolomitisation as a late deep-burial diagenetic process.

pressure-dissolution (Plate 5.2G, H). Evidence is provided by the occasional distortion of CL rhomb zonation patterns and by partial dissolution of dolomite rhombs in proximity to wispy discontinuous flaser (horse-tail) stylolites orientated at high angles to bedding in cores, related to tectonic compression. In other areas away from tectonically-induced stylolites no evidence of pressure-dissolution is seen and therefore dolomitisation post-dates burial-related pressure-dissolution. The creation of tectonically-induced fracture porosity and associated vein minerals (Plate 5.2H) (Kamp & Hood 1994) containing brecciated dolomitised host rock fragments (Plate 5.1E, F) is further testimony to a pre-fracturing dolomitisation event. Rare occurrences of dolomite rhombs truncated by veining were noted previously (Plate 5.1E, F).

The timing of dolomitisation can therefore be constrained to the period post-Tikorangi Formation deposition but prior to major tectonically-induced fracturing and stylolitisation. Knowing the earliest Miocene age of the Tikorangi Formation whose seismic reflector is dated at ~22.5-23 Ma, and that major compression associated with the Tarata Thrust Zone development was initiated sometime in the Early Miocene (~21.8-16.3 Ma), but that development of the Tarata Thrust Zone continued episodically from the Early Miocene to mid Miocene (~14 Ma) (King & Thrasher 1996), dolomitisation must have occurred at some point during this interval. Extrapolation of the timing of dolomitisation to a geohistory plot for Waihapa-1 (Fig. 5.7), produces depths of dolomitisation ranging from an earliest and minimum depth of burial of 1000 m (using 21.8 Ma as timing of fracturing) to a latest and maximum burial depth of 2250 m (using 14 Ma as timing of fracturing). Assuming an average geothermal gradient for Taranaki Basin of 29°C/km (Armstrong et al. 1996) and a mid-Tertiary sea-floor temperature of about 7°C (based on Antarctic Intermediate Water paleotemperature in Late Miocene at 1000 m of 6.5°C (Head & Nelson 1994) and a modern temperature of 7-11°C at 400 m (Tomezah & Godfrey 1994)), this yields dolomitisation paleotemperatures in the range 36-72°C. This is in good agreement with planar-e fabrics forming below the theoretical CRT of 50-100°C (Sibley & Gregg 1987). Also if iron mobilisation was linked to clay mineral transformation then optimum temperatures nearing 80-100°C would have been required for the release of Fe (Dix 1993).

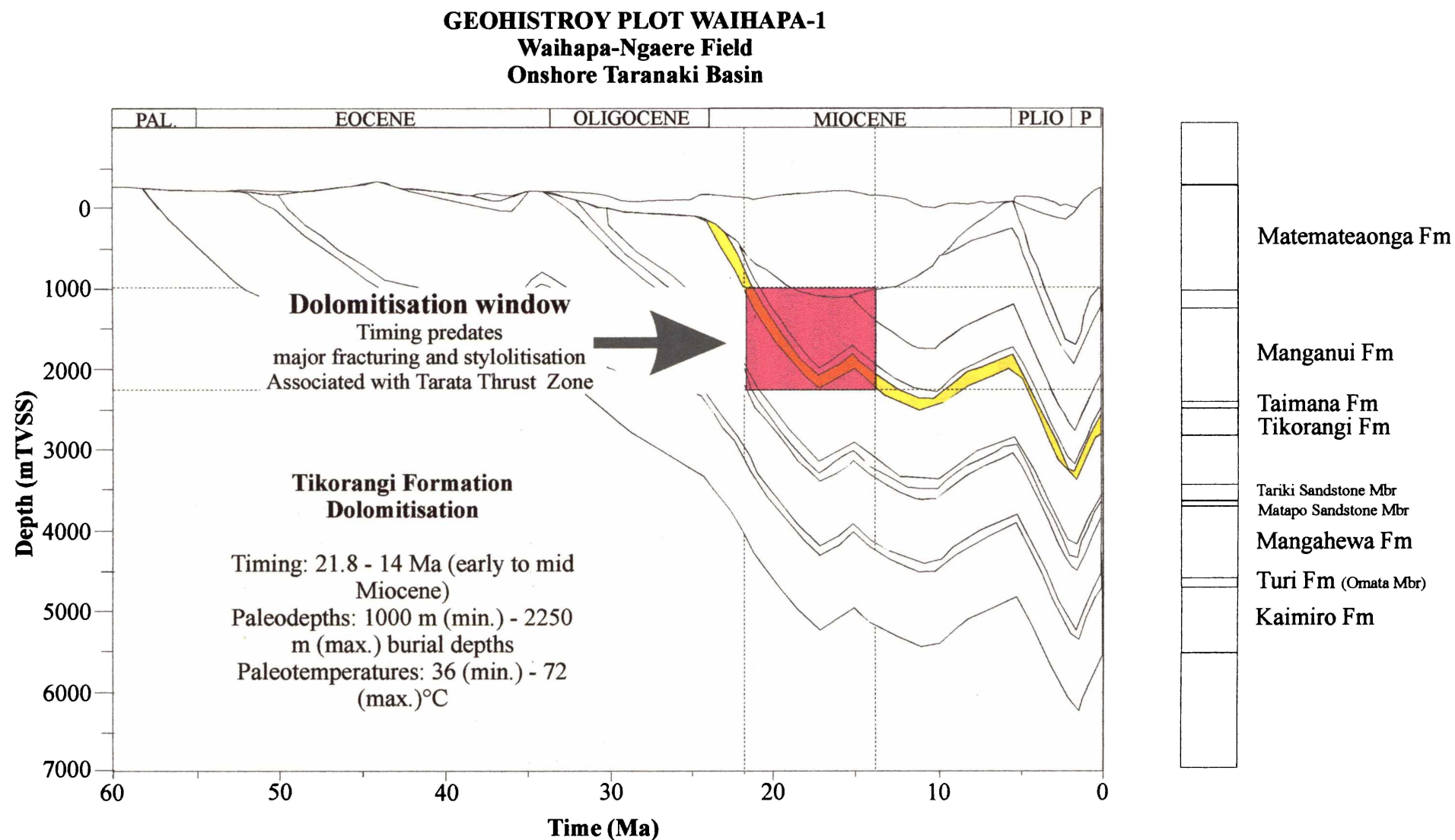


Fig. 5.7 Geohistory plot for Waihapa-1 within the Waihapa-Ngaere Field in close proximity to the onshore study wells used to constrain depths, temperatures, and timing of dolomitisation within the Tikorangi Formation.

5.8 CONCLUSIONS

A summary table outlining the key properties and petrogenesis of Tikorangi Formation dolomite is provided in Table 5.3 and is discussed below. The Tikorangi Formation provides a unique, currently subsurface example of burial dolomitisation within a New Zealand temperate carbonate. The Tikorangi Formation has been partially dolomitised during a single episode during which uniform crystal growth rates resulted in an unimodal planar-e (euhedral) fabric of randomly scattered and rarely clustered idiomorphic mosaics of fine (20-90 μm) dolomite rhombs (Table 5.3). The crystals have preferentially but incompletely dolomitised interparticle and rarely intraparticle micritic/clay-rich matrix resulting in a range of dolomitic mixed siliciclastic-carbonate (calcitic) rocks.

The fine often siliciclastic and matrix/micritic/clay -rich nature of the majority of Tikorangi Formation facies has provided an ideal substrate with high surface area and multiple nucleation sites for fabric selective dolomitisation and has provided localised Mg-enriched microenvironments to form non-stoichiometric (poorly ordered) calcian ferroan dolomites (Table 5.3). They formed from reduced pore waters with Fe^{2+} supplied predominantly from interbedded siliciclastic-rich units. There is no evidence of dolomite recrystallisation to more ordered stoichiometric forms, perhaps reflecting their relatively young age in comparison to global stoichiometric pre-Tertiary dolomites. Dolomite mineralogies and fabrics are consistent and are best explained by a general burial dolomitisation model involving some degree of marine-modified pore fluids.

Dolomitising fluids had a relatively low supersaturation with respect to dolomite, resulting in non-pervasive (typically <20% by volume, rarely up to 50% by volume), selective and often mimic replacement of predominantly finely crystalline components, but leaving skeletal grains undolomitised (Table 5.3). Mg for dolomitisation was probably derived from a variety of sources including: the upward driven expulsion of Mg-rich fluids from compacting and pressure-dissolving interbedded clay/siltstones; pressure-dissolution of skeletons; the transformation of smectite to illite associated with burial depths beyond about >1.5 km; combining to produce modified formation and/or connate pore fluids.

Table 5.3 Summary of the petrographic properties and the diagenetic conditions associated with formation of dolomite in the Tikorangi Formation.

Tikorangi Formation Dolomite Petrogenetic Summary	
<i>Properties</i>	
Crystal habit	Euhedral with rare curved surfaces (?saddle dolomite)
Crystal size	Commonly 30-40 μm , range 20-90 μm
Crystal colour	Dirty to clean sparry, often brown, inclusion-rich
Quantity	Commonly less than 20% but rarely up to >50% rock volume
Occurrence	Interparticle, rarely intraparticle, micrite/microspar/matrix (shelfal and foredeep facies - not seen in basinal facies)
CL	Commonly zoned (often concentric oscillatory zoning) dull-non cores and bright outers
Fabrics	Free floating scattered to clustered rhombs, occasionally planar-e (idiotopic) fabrics
Origin	Micro-scale dissolution of finely crystalline micrite/matrix/microspar (calcite); mimic non-pervasive, fabric-selective replacement; skeletons not dolomitised
FeCO ₃ content	Highly ferroan (av. 13 mol% FeCO ₃)
CaCO ₃ content	Ca-rich (av. 58% CaCO ₃)
Resulting rock types	Dolomitic siliciclastites to dolomitic limestones, rarely dolostones
<i>Pore fluid conditions</i>	
Salinity	Modified sea water with enriched salinity (>35 ppt)
Redox potential (E_h)	Strongly reducing ($-E_h$)
Fe contents	Highly enriched
Fe sources	Siliciclastics, smectite to illite transformation, organic matter
Dolomite saturation	Relatively low supersaturation
Mg sources	Shale compaction, smectite to illite transformation, pressure dissolution of LMC skeletons
Calcite saturation	Saturated
Ca sources	Pressure dissolution
Circulation	Diagenetically closed system - diffusion only
<i>Tectonic setting</i>	
Tectonic setting	Burial environment, Taranaki Basin
Burial temperatures	36 - 72 °C assuming av. geothermal gradient of 29°C/km
Timing	21.8 - 14 Ma
Burial depths	1000 - 2250 m
Tectonic factors	Deep burial environment - elevated temperatures and pressures, burial (pressure dissolution) diagenesis, LMC cements

Dolomitising fluids were saturated with respect to calcite to produce incomplete host dissolution and consequently formation of inclusion-rich dolomite rhombs. Dissolution more or less balanced precipitation, preventing development of secondary porosity and permeability enhancement and so limiting the Tikorangi Formation's ability to act directly as a hydrocarbon reservoir outside of fracture porosity.

Dolomitisation occurred at a relatively slow rate in a closed chemical environment as a result of prior lithification and considerable porosity/permeability destruction during burial diagenesis which allowed only slow and diffuse pore water movement. CL zoning in the dolomites indicates that trace element concentrations in pore fluids changed with time. A lack of feldspar dissolution is testament to a low porosity/permeability and hydrodynamically closed system with no flushing by corrosive fluids as has occurred in certain other Taranaki Basin sandstone reservoirs, such as the Kapuni Formation, and which resulted in sometimes extensive secondary porosity development.

The rapid transition of the Tikorangi Formation sediments into the deep burial environment (> 1 km) in the earliest Miocene and continued residency at depths over 2 km since the Early Miocene, with current burial depths close to 3 km (Fig. 5.7), have provided conditions of elevated temperatures, pressures, and salinity conducive to dolomite formation by increasing the saturation of dolomite with respect to calcite by shifting to higher Mg/Ca ratios. The timing of dolomitisation is constrained to the period following earliest Miocene (Waitakian) deposition and into the Early Miocene (~ 21.8 - 16.3 Ma) when compressional tectonics initiated formation of the Tarata Thrust Zone, which continued episodically until the mid Miocene (~ 14 Ma), the formation of which post-dates dolomite formation. Extrapolation of the timing of dolomitisation to a geohistory plot for Waihapa-1 provides burial depths of dolomitisation which range from 1000 m in the earliest instance to 2250 m in the latest instance, and dolomitisation paleotemperatures of 36 - 72°C assuming an average geothermal gradient for Taranaki Basin of about $29^{\circ}\text{C}/\text{km}$. This is in agreement with planar-e fabrics forming below the theoretical CRT of 50 - 100°C .

Dolomite formation post-dates aragonite neomorphism, the transformation of micrite to microspar, and substantial lithification and cementation resulting from pressure-dissolution. Dolomite formation predates tectonically-induced pressure-dissolution and major fracturing and vein mineralisation associated with hydrocarbon-bearing fracture porosity. Dolomite-rich units are likely to have been more susceptible to brittle fracture during Miocene compressional tectonics, which could have implications for the location of fracture networks and therefore hydrocarbon prospectivity and production.

A paucity of dolomite in age-equivalent limestone exposed onland may be explained by comparison with various Tikorangi Formation characteristics, for example: a paucity of suitable micritic- and clay-rich substrates for nucleation and for provision of a Mg-rich microenvironment (the limestones are typically clean grainstones); a lack of associated shale-like lithologies for providing a Mg source; lower burial depths and therefore insufficiently elevated temperatures, pressures, and salinity to overcome the kinetic constraints on dolomitisation; insufficient burial temperatures to transform smectite to illite, thereby negating a further likely Mg source; and lower residency times at depths sufficient for dolomitisation to occur.

Dolomitisation is relatively rare within New Zealand carbonates of all ages, especially so when compared with Australian and other global carbonate occurrences. Some aspects of similarity exist between the Tikorangi Formation and the dolomite-bearing Takaka Limestone (Table 5.1). The few other New Zealand dolomite-bearing limestones are also muddy and micritic-rich, much like the Tikorangi Formation, although suggested mechanisms and timing of dolomitisation vary considerably and are formation specific (Table 5.1).

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GEOCHEMISTRY OF THE MID-TERTIARY DOLOMITIC MIXED SILICICLASTIC-CARBONATE TIKORANGI FORMATION RESERVOIR, TARANAKI BASIN, NEW ZEALAND: A COMPARATIVE STUDY BASED ON TRACE ELEMENT ANALYSIS

6.1 ABSTRACT

A paucity of geochemical data exists for cool-water carbonates compared to well-studied warm-water carbonates. This paper contributes to the deficient cool-water carbonate database, and to the New Zealand Cenozoic carbonate database in particular, by determining major and minor elemental compositions (Ca, Mg, Sr, Na, Fe, and Mn) of the carbonate fraction of bulk samples from the Tikorangi Formation reservoir, a partially dolomitised subsurface (~3 km) mixed siliciclastic-carbonate-dominated sequence in Taranaki Basin, New Zealand's only commercially-producing petroleum province. The occurrence of dolomite is rare within New Zealand Cenozoic carbonates, and in cool-water carbonates more generally, and is shown to have had a dramatic effect on the bulk geochemistry in comparison with other published cool-water carbonate data.

The average elemental composition of 65 samples of Tikorangi Formation carbonate is about: Mg – 15,500 ppm; Ca – 318,500 ppm; Na - 4,600 ppm; Fe - 13,400 ppm; Sr - 3,400 ppm; and Mn - 300 ppm. Element-element plots show more similarities with modern Tasmanian cool-water low- and intermediate-Mg calcite carbonates, with elevated Mg, Na, and Sr values compared to most other low-Mg calcite New Zealand Cenozoic limestones. The increased trace element contents are directly attributable to the trace element-enriched nature of the ubiquitous burial-derived dolomites. Fe levels in the Tikorangi Formation carbonates far exceed both modern and ancient cool- and warm-water analogues, while Sr values are also higher than those in modern Tasmanian cool-water

carbonates, and approach modern Bahaman warm-water carbonate values.

Rare undolomitised, wholly calcitic carbonate samples have the following average composition: Mg – 3,200 ppm (2,300-3,700); Ca – 287,000 ppm (225,000-390,000); Na – 900 ppm (600-1450); Fe – 7,400 ppm (2000-11,400); Sr – 2,900 ppm (1,900-4,700); and Mn 140 ppm (80-220). These data are consistent with skeletal growth in a temperate cool-water paleoenvironment followed by later burial cementation from pressure-dissolution of low-Mg calcite skeletons under reducing conditions. The cement is ferroan low-Mg calcite, characteristic of cool-water burial cements.

Tikorangi Formation dolomite-rich samples have average values of: Mg – 47,300 ppm (23,000-86,000); Ca – 258,000 ppm (131,000-375,000); Na – 4,900 ppm (800-9,000); Fe – 27,000 ppm (7,800-46,000); Sr – 3,100 ppm (900-4,400); and Mn – 490 ppm (130-1,400). Dolomites are trace element-enriched, metastable, Ca-rich (58 mol% CaCO_3), non-stoichiometric, ferroan dolomite indicative of: dissolution and incomplete Mg replacement of a calcite precursor resulting from low Mg pore-fluid concentrations; reducing conditions in association with an Fe-rich diagenetically closed and rock-buffered system; relatively warm saline-enriched pore fluids; and a relatively “recent” late burial diagenetic origin. Mg sources were probably from often bioturbated clay-rich micrite involving the transformation of smectite to illite and release of Mg from clay mineral surfaces. Pressure-dissolution of low-Mg calcite skeletons may have been an important addition source. Fe was supplied from siliciclastics and from within clay mineral structures.

Summary elemental matrices for idealised meteoric, shallow burial, and burial diagenetic trends have been constructed and show an absence of any meteoric influence in dolomite-rich samples. A persistent low-level meteoric signature, particularly in wholly calcitic rocks, may be explained by the introduction of meteoric fluids through extensive fracture systems resulting in the dissolution and reprecipitation of small amounts of calcite. Moreover, the combination of low

carbonate contents and relatively enriched fine siliciclastic material may afford the wrong facies for direct application of the summary elemental matrix approach to elucidating diagenetic environments.

Keywords carbonate geochemistry; trace elements; dolomite; mixed siliciclastic-carbonate; Tikorangi Formation; Oligocene-Miocene; Taranaki Basin; hydrocarbons; fractured reservoir; limestone

6.2 INTRODUCTION

Outside of studies of Tasmanian (Rao 1981, 1986, 1990a, b, c, 1991, 1996) and New Zealand carbonates (Winefield et al. 1996), few geochemical data exist for both modern and ancient cool-water carbonate deposits, as well as for mixed dolomitic-calcitic carbonates in general (e.g., Török 2000). For the Australian and New Zealand-based studies the content of major (Ca, Mg) and minor (Sr, Na, Mn, Fe) elements in bulk samples has provided valuable environmental and diagenetic information about the carbonate deposits not otherwise always evident from other techniques (Veizer 1983; Morrison & Brand 1986; Brand & Morrison 1987; Rao 1996; Winefield et al. 1996).

Carbonates contain co-precipitates in quantities which reflect the fluid compositions and environmental conditions at the time of skeletal and inorganic crystal growth. Trace element (TE) concentrations in fluids at the time of lattice incorporation are controlled by a host of physical, chemical (pH, Eh, temperature, pressure, solubility, type and concentration of ions present), organic (biomineralisation), and inorganic parameters (dissolution, leaching, replacement, recrystallisation) (Veizer 1983; Morrison & Brand 1986; Brand & Morrison 1987; Morse & Mackenzie 1990; Winefield et al. 1996).

An understanding of the geochemistry of sedimentary carbonates, and more particularly their carbonate cements, has not only been of considerable

paleoenvironmental significance, but is also of considerable economic importance (Morse & Mackenzie 1990). Some 60% of the world's known petroleum reserves occur in carbonate rocks in which cements can exert a major influence on the porosity and permeability of the petroleum reservoirs (North 1985).

The mid-Tertiary Tikorangi Formation is presently the sole carbonate-producing reservoir within Taranaki Basin, currently New Zealand's only economically-producing sedimentary basin (Fig. 6.1A) (King & Thrasher 1996). Despite its association with hydrocarbons, the Tikorangi Formation provides not only an example of a reservoir host (Fig. 6.2), but also of a wholly subsurface temperate-latitude carbonate containing ubiquitous but modest quantities of dolomite throughout. Rocks comprise a range of variably siliciclastic-carbonate-dominated mixtures and a diversity of shelfal, foredeep, and basinal megafacies (Fig. 6.3). The Tikorangi Formation therefore presents a sequence consisting largely of carbonate rocks which are distinctive and considerably well removed, not only in a spatial sense, from other comparatively well-studied, uplifted and exposed, age-equivalent New Zealand temperate limestones such as the Te Kuiti Group, in North Wanganui Basin (Fig. 6.1B) (Nelson 1978).

As part of a wider stratigraphic, sedimentological, petrographic, and diagenetic study of the Tikorangi Formation, this geochemical aspect of the study focuses on the bulk trace element geochemistry as firstly a tool for comparing and distinguishing this temperate subsurface sequence with suggested fields for both modern and ancient warm- and cool-water carbonates based largely on the work of Rao (1991) and Winefield et al. (1996). The effect of dolomite on the positioning of the Tikorangi Formation within the typically reported temperate carbonate element-element fields will be assessed.

Secondly, TE geochemistry will be used to further aid diagenetic understanding of the Tikorangi Formation gained from more traditional petrographic study. While no distinct petrographic features have so far emerged to characterise particular dolomitisation models (Morrow 1990b; Tucker & Wright 1990; Török 2000), the

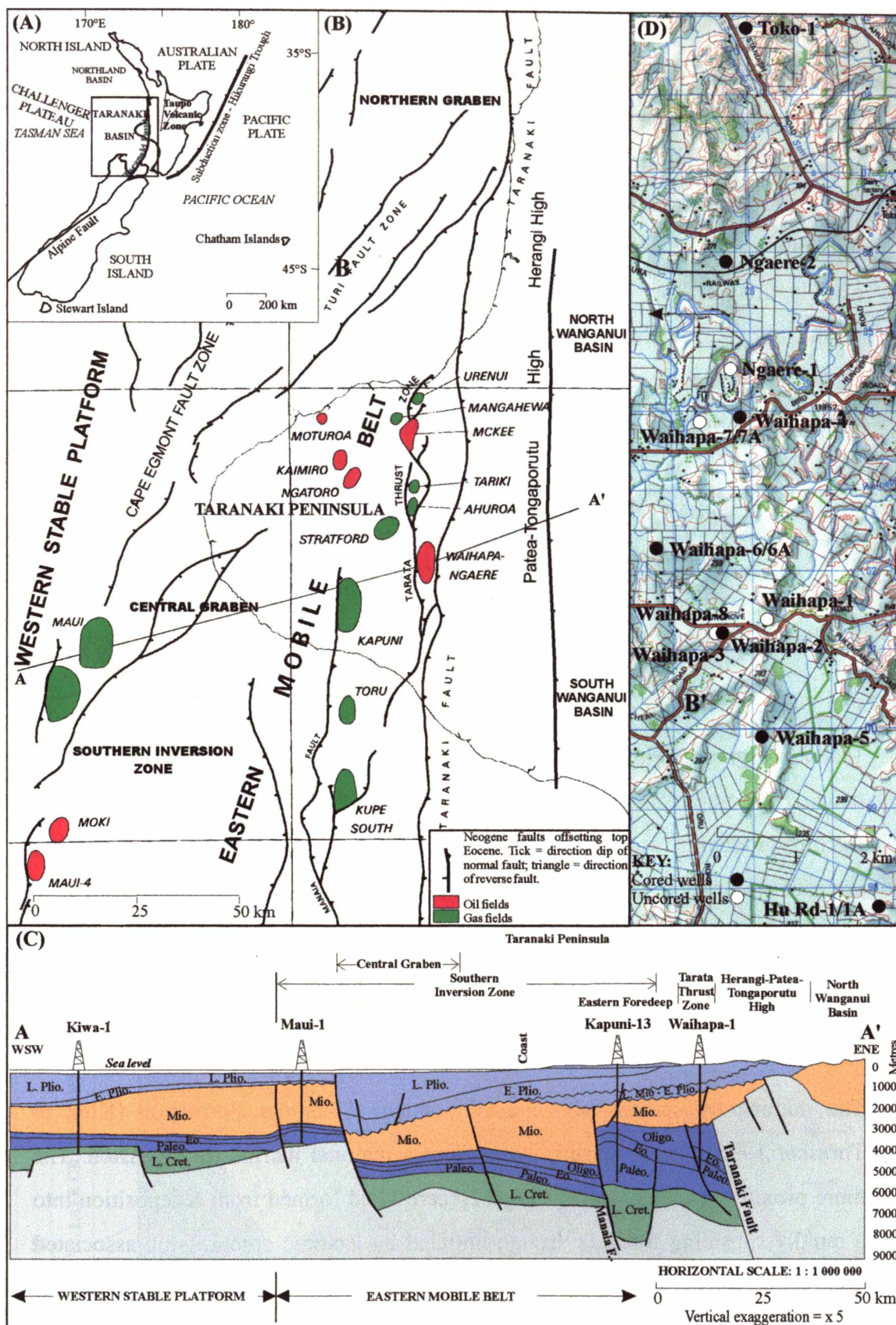


Fig. 6.1 (A) Location of Taranaki Basin in New Zealand. (B) Major structural and tectonic elements and main oil/condensate accumulations within Taranaki Basin. The Tiorangi Formation is dated as earliest Miocene in the east (Waihapā-1) and Oligocene-Early Miocene in the west (Maui-1). Adapted from King & Thrasher (1996). (C) Structural cross-section of a transect running WSW - NE through offshore Maui-1 and onshore through the Waihapā-Ngaere Field, Tarata Thrust Zone (see location in B). Adapted from King & Thrasher (1996). Shading: = late Neogene, = early Neogene, = Paleogene, = Late Cretaceous, = basement. E. Plio. = Early Pliocene; L. Plio. = Late Pliocene; Mio. = Miocene; Oligo. = Oligocene; Paleoc. = Paleocene; L. Cret. = Late Cretaceous. E. Plio. = Early Pliocene; L. Plio. = Late Pliocene; Mio. = Miocene; Oligo. = Oligocene; Paleoc. = Paleocene; L. Cret. = Late Cretaceous. (D) Location of the seven onshore wells (solid circles) providing core from the Tiorangi Formation within the Waihapā-Ngaere Field that form the basis for this study.

use of elemental data in conjunction with X-ray diffraction data (XRD) will: (a) provide a better assessment of the skeletal, calcite and dolomite mineralogies than was possible petrographically; (b) establish TE trends within the various Tikorangi Formation petrofacies; (c) enable assessment of the contribution of the dolomite and calcite components to the bulk TE geochemistry; and (d) enable an examination of the use and applicability of summary elemental matrices (Winefield et al. 1996) for providing an overall assessment of the influence of each of the meteoric, shallow burial and deep burial diagenetic signatures in the Tikorangi Formation. Some consideration of the clay mineral species and their geochemistry is also made, which may have implications for providing TE sources, particularly Mg, the key element in the dolomitisation equation.

6.3 GEOLOGICAL BACKGROUND

Limestone of the Tikorangi Formation is an important oil producer within the Waihapa-Ngaere Field, Taranaki Basin (Fig. 6.1B). The Tikorangi Formation is unique in being Taranaki Basin's only non-sandstone reservoir, and the only fracture-producing reservoir (Fig. 6.2). The mixed siliciclastic-carbonate sequence represents a temperate-latitude, totally subsurface, lithostratigraphically complex, often redeposited carbonate-rich sequence within the mudstone-dominated Ngatoro Group (Fig. 6.2). The reader is referred to Topics 1-3 for discussions of the wider geologic setting and detailed stratigraphy of the deposits.

The dominantly earliest Miocene (Waitakian) Tikorangi Formation (King & Thrasher 1996) formed during the peak of a regional marine transgression. The more proximal facies of the Waihapa-Ngaere Field formed from redeposition into a rapidly subsiding foredeep trough initiated by tectonic compression associated with early formation of the Australian-Pacific plate boundary through New Zealand. Later fracturing and overthrusting of the Tikorangi Formation occurred with the associated formation of domed and overthrust structures along the eastern margin of the basin (Tarata Thrust Zone) (Fig. 6.1B, C), including the Waihapa asymmetric north-south-trending anticline. Hydrocarbon generation (sourced from

Late Cretaceous-Eocene terrestrial coals) and migration took place in the Pliocene (King & Thrasher 1996). In contrast to the more proximal deposits in the east, condensed Oligocene-Early Miocene (Whaingaroan-Otaian) basinal equivalents formed offshore in a region of relative tectonic stability, exemplified by the Maui-1 drill site (Fig. 6.1C).

This work builds on that already presented (Topics 2 - 5) based on 7 onshore wells (Waihapa-2, -4, -5, -6, Ngaere-2, Toko-1, Hu Rd-1A) (Fig. 6.1D) and a single offshore well (Maui-1) for which core material for the Tikorangi Formation interval is available. Integration of sample characteristics and well log profiles has provided a complete and detailed carbonate lithostratigraphy for the Tikorangi Formation within these wells (Topic 2).

Petrographic study of core samples (Topic 4) delineated five petrographic facies: rare mudstones (Petrofacies I - calcareous lutites); common wackestones (Petrofacies II - moderately to strongly calcareous fine arenites); abundant packstones (Petrofacies III - fine muddy calcarenites) (Plate 6.1A, B); common poorly washed grainstones (Petrofacies IV - impure fine muddy calcarenites to sparry medium calcarenites); and occasional sparry grainstones (Petrofacies V - fine to very coarse pure sparry calcarenites).

Skeletal varieties within these petrofacies have aided identification of three texturally and compositionally distinctive megafacies for the Tikorangi Formation (Fig. 6.3): Megafacies 1, an earliest Miocene (Waitakian) near-situ, shallow-shelfal limestone defined by, and limited to, Hu Rd-1A well (Plate 6.1C, D); Megafacies 2, prominent in the study wells in the Waihapa-Ngaere oil field, is an earliest Miocene (Waitakian) foredeep megafacies comprising a spectrum of variably siliciclastic, generally carbonate-dominated rocks formed from the mass redeposition of siliciclastics and shelfal bioclasts (bivalves, echinoderms, calcareous red algae, benthic foraminifera) into the Taranaki foredeep (foreland basin) and mixing with pelagically settled sediments (Plate 6.1A, B, E-H); and Megafacies 3, which occurs well offshore and more basinward, and is an

Tikorangi Formation - Escarpment Depositional Model **Earliest Miocene, prior marine transgression maxima, Taranaki Basin**

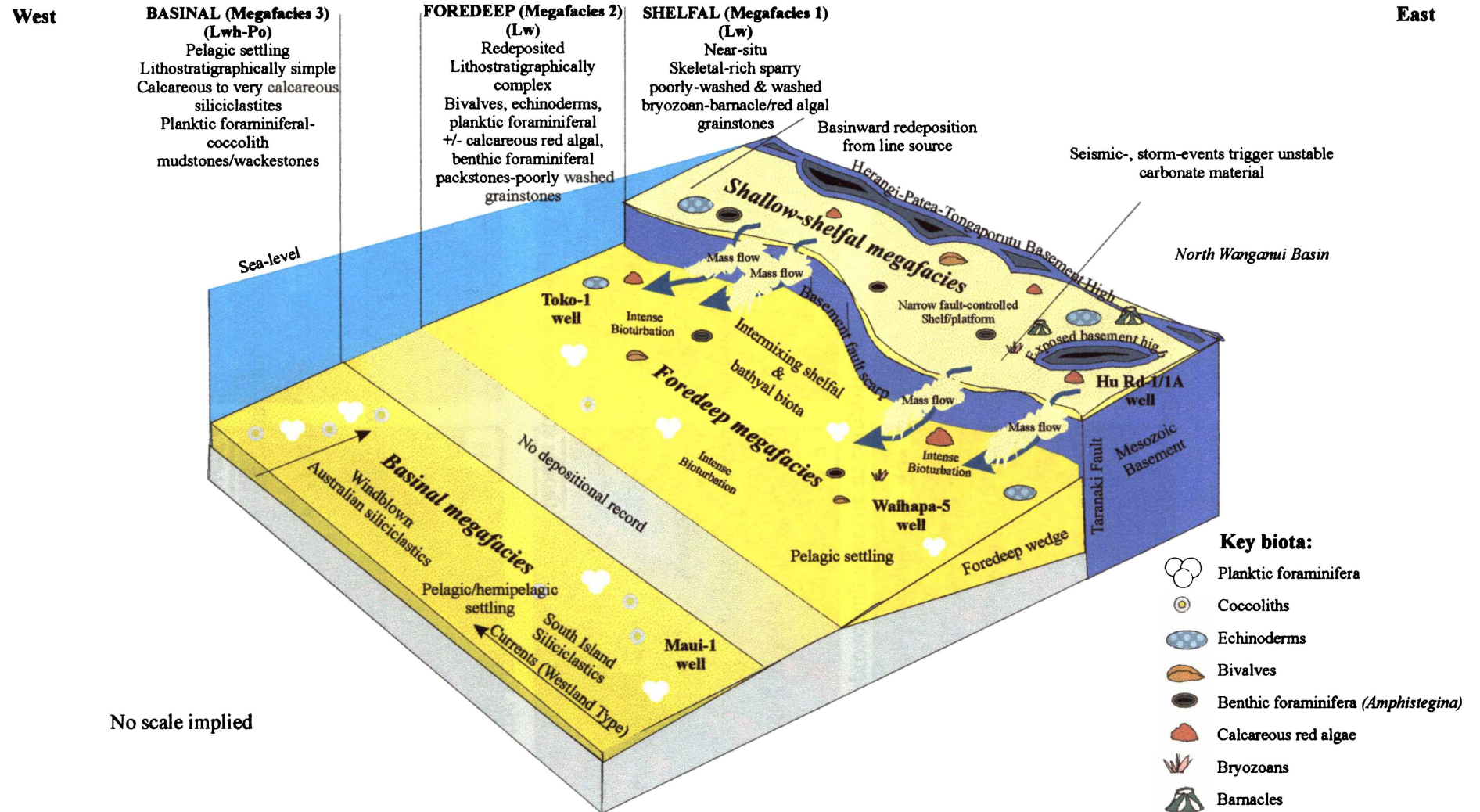


Fig. 6.3 Tikorangi Formation depositional model showing the location and major characteristics of the three identified megafacies. Lwh = Whaingaroan; Lw = Waitakian; Po = Otaiian.

Oligocene-Early Miocene (Whaingaroan to Otaian) deeper water equivalent comprising pelagically settled skeletal types, as at offshore Maui-1 on the Western Stable Platform. Rocks here are very calcareous wackestones (up to 41% carbonate) containing planktic foraminifera and coccoliths, but are mainly dominated by clay- to fine silt-sized siliciclastic material.

The Tikorangi Formation has been partially dolomitised (Topic 5) by ubiquitous but generally small quantities (typically <15%, rarely up to 50%) of unimodal, very fine (20-90 μm), scattered free-floating euhedral rhombs (Plate 6.1 C-H) of highly ferroan dolomite, less commonly forming planar-e (idiotopic) fabrics. Rhombs display characteristically dull luminescent Fe-rich cores, and often oscillatory concentrically zoned bright/dull outers (Plate 6.1E-H). Dolomites are invariably non-stoichiometric Ca- (av. 58 mol% CaCO_3) and Fe (av. 13 mol% FeCO_3) rich, approaching ankerite in composition.

Partial dolomitisation has resulted in non-pervasive, fabric-selective dolomitisation of typically interparticle, and rarely intraparticle, bioturbated micritic/clay-rich matrix, leaving skeletal grains undolomitised. Dolomitisation is not associated with any secondary porosity development. Dolomite fabrics and mineralogies are largely consistent with a burial dolomitisation origin (Topic 5), a relatively young age, and without stabilisation of the dolomite to more stoichiometric forms.

6.4 CARBONATE GEOCHEMISTRY BACKGROUND

The landmark paper of Chave (1967) first recognised there were skeletal differences between carbonates forming in cool-water polewards of 30°N and S and those forming in the warm waters of the tropics. More recently, studies by Lees & Buller (1972), Lees (1975), James et al. (1992), Hood (1993), and Hayton et al. (1995), for example, have categorised the nature of these skeletal assemblage differences and emphasised that a major control on the primary carbonate mineralogy of deposits is sea water temperature. High-Mg calcite

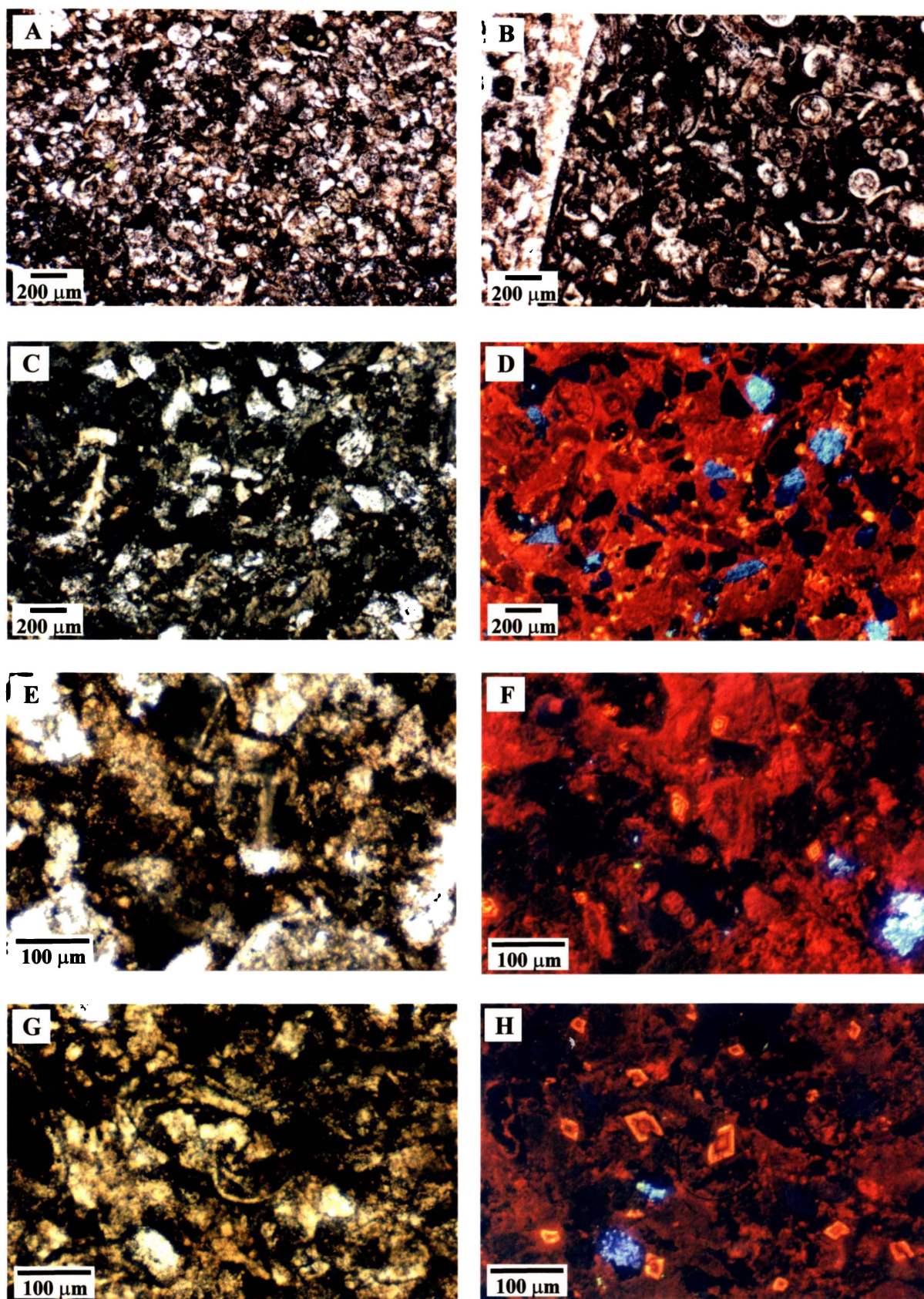


Plate 6.1 Photomicrographs in plane-polarised and photomicrograph pairs in plane-polarised (left) and cathodoluminescence light (right) of a representative selection of samples of the Tikorangi Formation. (A) Planktic foraminiferal packstone, foredeep megafacies (sample NG2.3.1). (B) Planktic foraminifera, bivalve, and echinoderm fragments forming a sparry grainstone separated from a micritic-rich packstone by a stabilised former aragonitic bivalve, foredeep megafacies (sample W2.2.3). (C, D) Siliciclastic-rich shelfal limestone containing scattered bright yellow luminescent dolomite rhombs, shelfal megafacies (sample Hu2.6A). (E, F) Poorly-washed grainstone containing scattered pressure-dissolved euhedral dolomite rhombs displaying oscillatory concentric zoning, foredeep megafacies (sample W2.1.1). (G, H) Planktic foraminiferal and bivalve-rich packstone with concentrically zoned dolomite rhombs, foredeep megafacies (sample W5.1.2).

(HMC; >12 mol% MgCO_3) and aragonite are the primary mineralogies in the warm-water (or tropical) skeletal and inorganically precipitated carbonates inside the bounds of 30° N and S, and intermediate-Mg calcite (IMC; 4-12 mol% MgCO_3) and low-Mg calcite (LMC; <4 mol% MgCO_3) mineralogies more typically dominate cooler-water temperate (or nontropical) carbonates.

Studies of cool-water carbonates are far outnumbered by studies of their warm-water counterparts, and consequently our present level of understanding of cool-water carbonates is in its infancy. While cool-water carbonates are now beginning to receive greater recognition world-wide (Nelson 1988; James 1997), there is a long way to go to establish their spectrum of origins, including the vexed question of superimposed dolomitisation at temperate latitudes. Due largely to the work of Rao (1981, 1986, 1990a, b, 1991, 1996) and others (Veizer 1983; Morrison & Brand 1986; Brand & Morrison 1987; Morse & Mackenzie 1990; Winefield et al. 1996), a geochemical approach is developing for helping differentiate calcitic cool-water carbonates from their warm-water counterparts, based on their TE makeup, while parallel advances remain to be made for dolomite-bearing carbonates.

Chemical discrimination between cool-water and warm-water carbonates has been suggested on the basis of characteristic fields within bivariate elemental plots (Rao 1981, 1986, 1990a, b, 1991; Winefield et al. 1996). Rao (1991) noted that the concentrations of Na, Sr, and Mn differed between subtropical, cool-temperate and subpolar Tasmanian limestones and that element-element plots could be used to discriminate different fields. Winefield et al. (1996) found that in New Zealand cool-water limestones, the Mg and Sr contents are mainly lower than occur in many warm-water carbonates, while Na, Fe, and Mn are relatively higher. Element-element plots of Na and Sr were used to good effect by Winefield et al. (1996), with New Zealand limestones plotting well outside the field for warm-water carbonates and within a cool-water field having Sr values of 100-1000 ppm and Na values of 500-5000 ppm.

Differences in cool-water and warm-water geochemistry not only reflect the paleo-latitudinal setting, but also the diagenetic environment of the carbonates. Diagenetic alteration and cement formation generally lowers the concentration of Sr, Mg, and Na values, and increases the Fe and Mn values (Al-Aasam & Veizer 1986; Winefield et al. 1996; Al-Aasam & Packard 2000). A number of studies have used bivariate plots to aid in the discrimination of diagenetic environments for limestones. While this type of study is still in its infancy, several workers (Brand & Veizer 1980; Al Aasam & Veizer 1986; Brand & Morrison 1987; Lawrence 1989, 1991; Rao 1990a) have shown that element-element plots and summary elemental matrices can be invaluable tools to infer diagenetic environments. Recent studies by Winefield et al. (1996) and Nelson et al. (in prep.) have shown the usefulness of this approach for cool-water limestones, particularly when integrated with other sedimentological and petrographic data. Similar investigations of Quaternary carbonate-secreting organisms and sediments have shown that their trace element compositions and isotopic signatures are particularly useful for interpreting limestone genesis (Rahimpour-Bonab et al. 1997).

Brand and Veizer (1980) have specifically used a negative correlation between Sr and Mn to describe a meteoric influence. With increasing meteoric diagenesis Fe and Mn increase (Brand & Morrison 1987) while Sr, Na, and Mg decrease. Oxidising conditions prevent incorporation of Mn, whereas large concentrations of Mn favour reducing conditions. Thus if Mn concentrations decrease in relation to increasing Fe concentrations, this suggests the influence of meteoric water under oxidising conditions. Rao (1990a) and Al Aasam & Veizer (1986) found a decrease in Sr and Na, while Mn increased, reflected meteoric diagenesis. Rao (1990a, b) found that increasing Na in relation to Mn infers a marine Mn origin, while a positive correlation of Mg and Mn indicates predominantly marine conditions. An increase in Fe/Mn ratio is thought to result from reducing conditions caused by burial (Lawrence 1991).

6.5 METHODOLOGY

Representative bulk samples for geochemical analysis were selected from the various petrofacies previously identified for the Tikorangi Formation (Topic 4). The predominantly fine-grained nature of the rocks negated the ability to extract microspar cements or individual dolomite rhombohedra from samples, a problem noted for other partially dolomitised fine limestones (Török 2000). Powders of a total of 84 bulk samples including: 65 Tikorangi Formation (Appendix 6.1); 15 Tikorangi Formation vein material (Appendix 7.1); and 4 other New Zealand samples (Appendix 6.2) were prepared using a ringmill with a tungsten-carbide head to prevent any iron contamination. Samples were then subject to acid digestion following the procedures of Robinson (1980) and Winefield (1995), which involved digestion of 1 g of powdered sample in 1M HCl. Following appropriate dilution, the sample solutions were analysed for Ca, Mg, Na, Fe, Sr, and Mn using a GBC909AA double beam atomic absorption spectrophotometer. The reader is referred to Winefield (1995) for more specific details. Errors are $\pm 1\%$ for Ca and Mg, and ± 5 ppm for Sr, Na, Mn, and Fe.

Clay mineral investigations initially involved the XRD of insoluble residues of HCl-digested samples. Analysis was performed using a Philips PW1729 X-ray generator and a PW1840 diffractometer with a slow scan rate of $0.25^\circ 2\theta/\text{minute}$ over the range of $3\text{--}15^\circ 2\theta$. The poor quality of clay mineral peaks necessitated digestion of new powder samples in 1:4 acetic acid for two hours, a procedure regarded as non-destructive of clays (Hume & Nelson 1982). Dropper-on-glass-slide oriented mounts were X-rayed in each of air-dry state, following glycolation for 12 hours, and after heating to 500°C for 1 hour (Hume & Nelson 1982).

XRD of un-oriented powder mounts was used to determine the amount of Mg substitution in calcite and dolomite lattices (Tucker 1988), and of Fe in the dolomite lattice. Mounts were slow scanned at $0.25^\circ 2\theta/\text{minute}$, with the addition of an analytical grade NaCl (halite) spike for accurate peak position determination. Calibration curves for determination of dolomite % in calcite were taken from Al-Hashimi & Hemingway (1974) and Al-Lumsden (1979).

Displacement of the d_{104} peak of calcite with increasing mol% MgCO_3 to dolomite is based on the calibration curve of Goldsmith et al. (1961). Displacement of the d_{104} spacing of dolomite relative to FeCO_3 wt% uses the calibration curve of Al-Hashimi & Hemingway (1974).

6.6 TIKORANGI FORMATION GEOCHEMISTRY

6.6.1 Trace element values

Elemental concentrations for the Tikorangi Formation, pooled as a whole data set (Appendix 6.1), show a wide range of values. Average concentrations (Table 6.1) are: Mg 15,500 ppm (range 1,485-91,100 ppm); Ca 325,000 ppm (range 131,100 – 758,00 ppm); Na 4,600 ppm (range 164 – 22,187 ppm); Fe 12,600 ppm (range 1,100 – 92,300); Sr 3,500 ppm (range 360 – 21,700 ppm); and Mn 270 ppm (range 24 – 1,500 ppm). Summary histograms of all results are shown in Fig. 6.4.

6.6.2 Trace element trends

The wide range of values demands closer investigation as to the possible contributing factors. This has been done initially by segregating the data into the main megafacies and more specific petrofacies previously identified for the Tikorangi Formation (Table 1). At the larger scale, comparison of elemental concentrations across the three megafacies in the formation is of limited value due to the relatively small number of samples available for megafacies 1 and 3 (Appendix 6.1). However, some general trends are evident (Fig. 6.5).

Comparison of average elemental data for the five petrofacies (Table 1) shows clear emerging patterns with generally declining Mg, Na, Fe, Sr and Mn, but increasing Ca values, with increasing petrofacies order from matrix/micrite-rich mudstones to sparry grainstones (Fig. 6.6). Linear correlations performed on the average trace element values versus petrofacies support these general observations, with a lowest R^2 value of 0.56 for Mg and highest of 0.90 for Na (Fig. 6.7).

Table 6.1 Summary trace element data for Tikorangi Formation host and vein samples, including data for other New Zealand limestones. Data for the Tikorangi Formation are summarised for petrofacies and megafacies and are based on Appendix 6.1. Vein mineral data is contained in Appendix 6.2. A New Zealand limestone average has been calculated from data compiled by Winefield et al. (1996) and contained in Appendix 6.3. Samples of reportedly dolomite-bearing Bobs Cove Limestone (151 of Hayton 1995), South Island, and potentially dolomite-bearing Orahiri Limestone (16252-OrB2, 16143-OrB5 of Nelson 1973) and Otorohanga Limestone (16711-OtC2 of Nelson 1973) from the South Auckland region have been analysed here for comparative purposes. See Hayton (1995) and Nelson (1973) respectively for stratigraphic and petrographic details of these samples.

PETROFACIES	No. of samples	Mg (ppm)	Ca (ppm)	Na (ppm)	Fe (ppm)	Sr (ppm)	Mn (ppm)
Mudstone	2	51,108	196,011	10,987	35,425	3,512	655
Wackestone	23	15,802	320,454	6,676	16,901	4,318	374
Packstone	15	12,157	292,216	4,037	14,434	3,491	209
Poorly washed grainstone	14	18,856	305,963	2,969	8,169	2,560	207
Grainstone	11	9,446	380,267	1,967	5,751	2,218	164
Tikorangi Fm av.	65	15,515	325,040	4,589	12,647	3,483	273
MEGAFACIES							
1 - Shallow-shelfal	4	10,287	458,451	956	2,607	874	273
2 - Foredeep	59	13,859	275,280	4,476	12,742	2,994	215
3 - Basinal	2	1,085	267,420	1,437	3,595	1,339	1,002
ASSESSED VALUES							
Calcite	5	3,167	287,334	878	7,381	2,876	141
Dolomite (>15 % in sample)	8	47,260	257,971	4,880	27,049	3,078	486
VEIN MINERALS							
Calcite vein material	11	6,908	294,959	795	6,716	20,526	203
Dolomite vein material	4	48,240	219,300	582	46,743	7,078	520
OTHER NZ LIMESTONES							
NZ limestones av.	548	5,508	419,574	1,392	2,428	555	577
OrB5	1	3,970	251,735	331	1,112	429	63
OrB2	1	4,382	388,628	615	896	431	62
OtC2	1	6,522	387,790	422	2,438	294	143
Bobs Cove	1	14,346	373,194	354	1,055	3,360	47

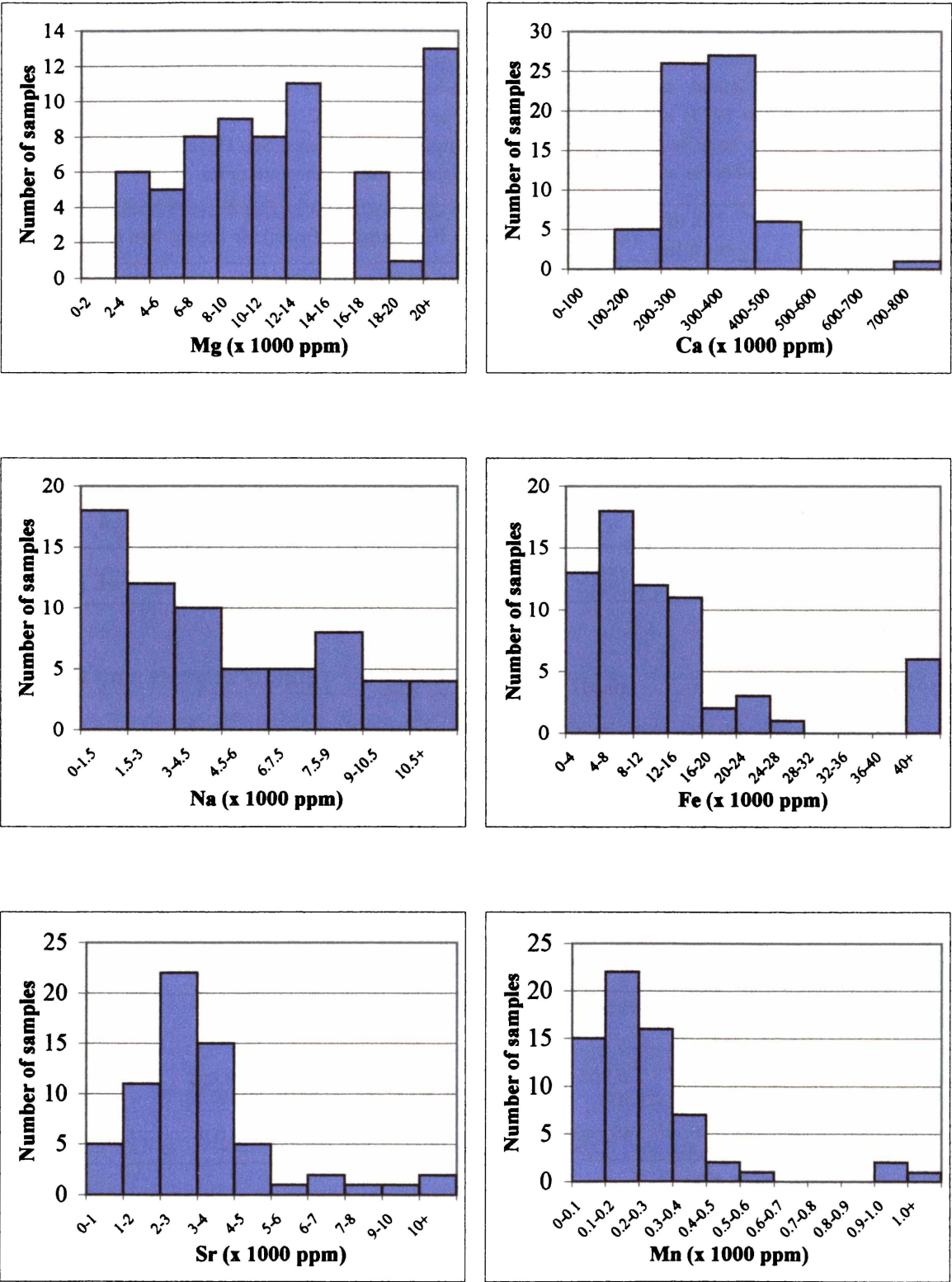


Fig. 6.4 Histograms displaying the range of elemental concentrations in the carbonate fraction of representative Tikorangi Formation samples.

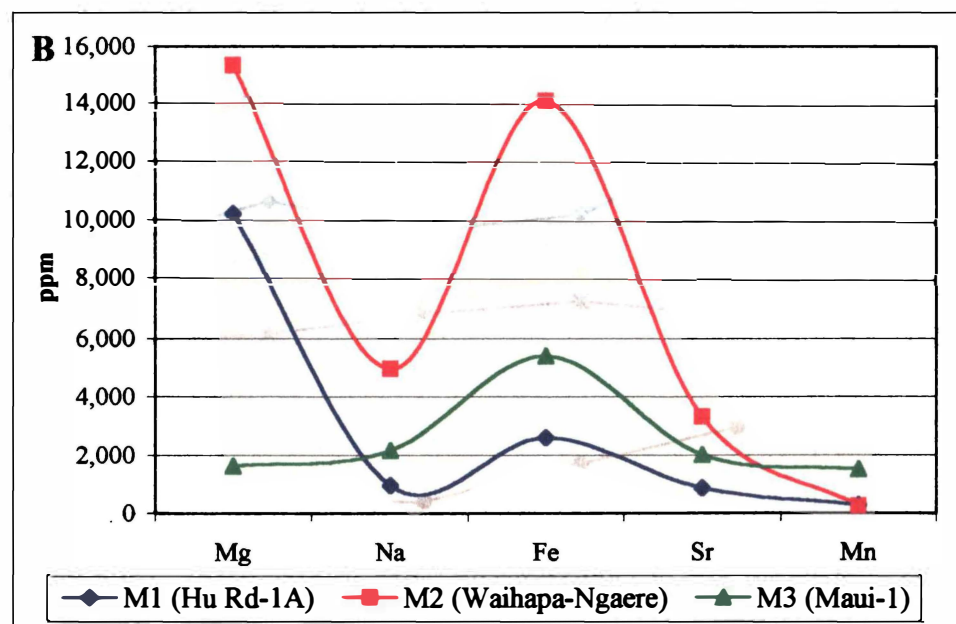
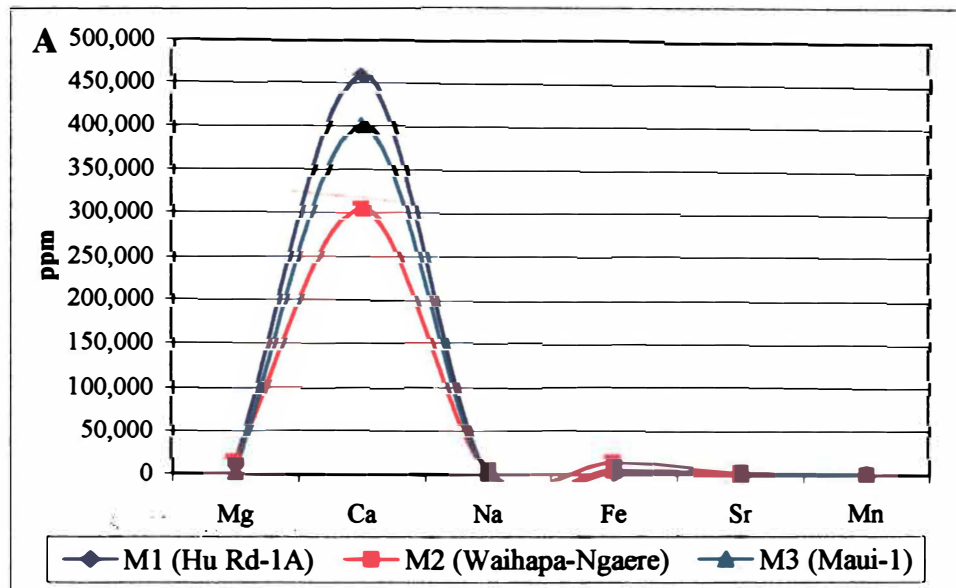


Fig. 6.5 (A) Plot showing the difference in trace element values in ppm across the three Tikorangi Formation megafacies. Note that Ca concentrations decrease from megafacies M1 to M3. (B) M2 shows generally the highest TE values; the lowest Na, Fe and Sr values are in M1; M3 is noticeably depleted in Mg compared to the other megafacies. M1 = shallow shelfal limestone megafacies; M2 = foredeep mixed siliciclastite-carbonate megafacies; M3 = basinal megafacies.

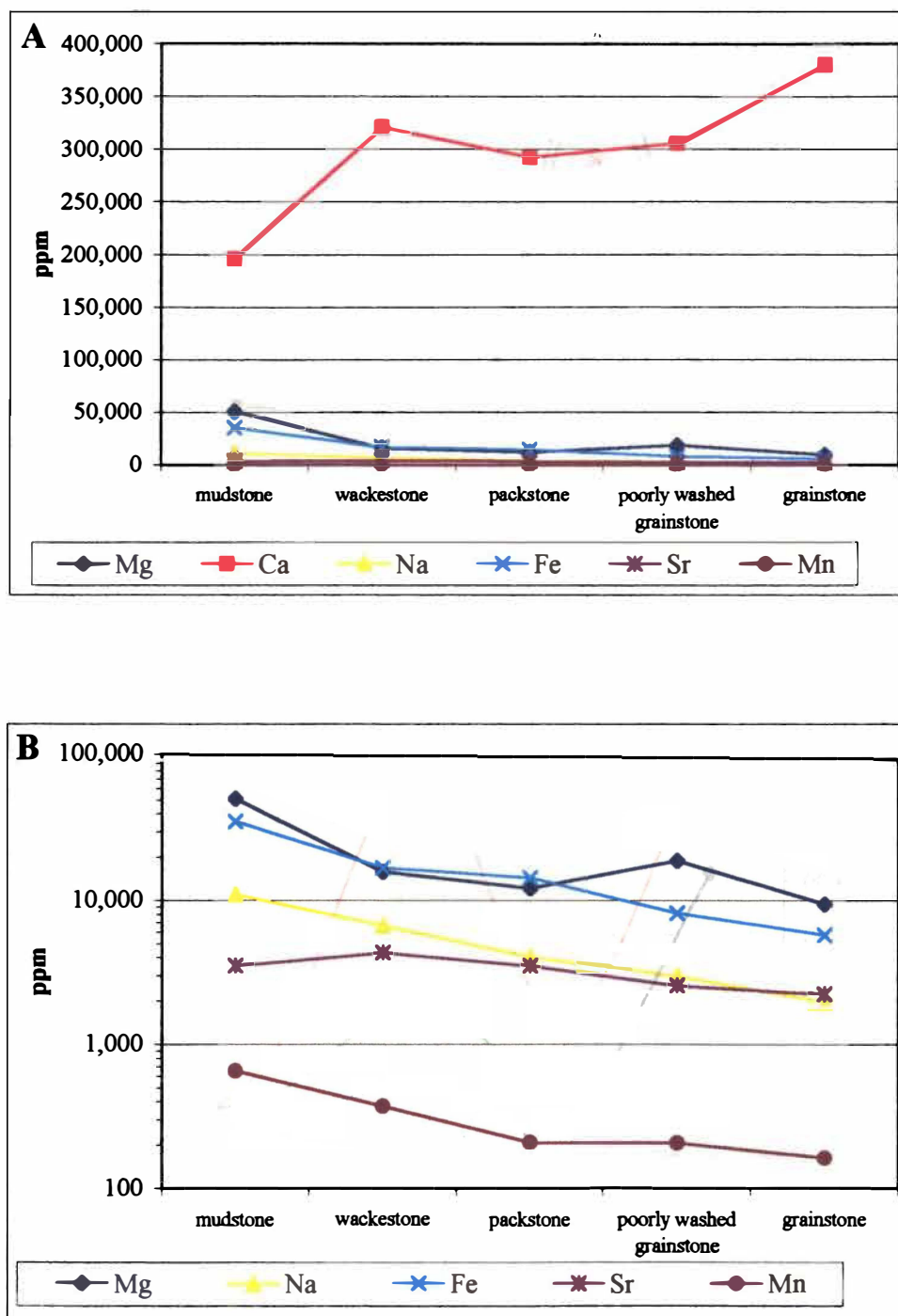


Fig. 6.6 (A) Plot showing general increase in Ca content from mudstone through grainstone petrofacies in the Tikorangi Formation. (B) A reverse trend to that occurring for Ca is one of decreasing Mg, Na, Fe, Sr and Mn from mudstones to grainstones.

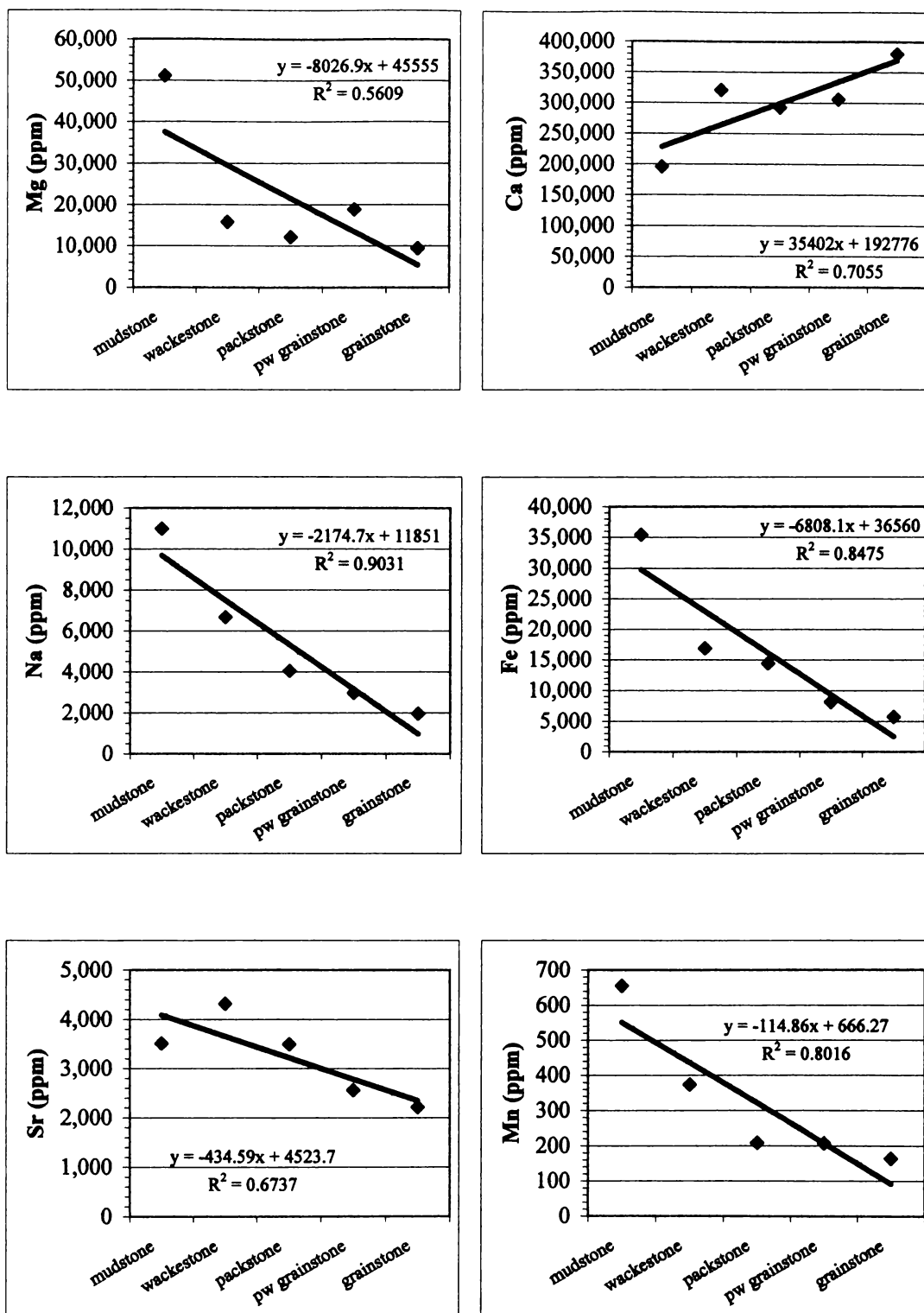


Fig. 6.7 Linear correlations for each of the mudstone through grainstone petrofacies in the Tikorangi Formation based on the average TE value for each rock type shows. With the exception of Ca, there is a significant decreasing trend in concentrations from mudstones through to grainstones. Pw grainstone = poorly washed grainstone.

6.7 COMPARATIVE GEOCHEMISTRY

6.7.1 Elemental plots

Initial comparisons of average elemental concentration data for the Tikorangi Formation as a whole (no segregation based on petrofacies or megafacies) with the average New Zealand Cenozoic temperate limestone database of Winefield et al. (1996) (Appendix 6.3) show that the Tikorangi Formation exhibits elevated Mg and Na values with substantially elevated Fe and Sr values (Fig. 6.8; Table 1). Conversely, Ca and Mn values are reduced in the Tikorangi Formation in relation to the New Zealand average.

A few of New Zealand limestones are reported to be dolomitic and generally show Ca values between the lower Tikorangi Formation average and the higher New Zealand limestone average, although OrB5 from the Orahiri Limestone displays the lowest Ca value of all (Fig. 6.9, Table 1). Bobs Cove Limestone has similar Mg values to the Tikorangi Formation average, while all other samples are similarly low and cluster close to the New Zealand limestone average, which is not surprising considering their minor dolomite content. With the exception of the high Tikorangi Formation Na and Fe values, all other samples cluster at substantially lower values, while Sr values from Bobs Cove and the Tikorangi Formation average are very similar. Comparatively little difference is seen in Mn values across all samples.

The dolomite-bearing OtC2 of the Otorohanga Limestone and Bobs Cove Limestones exhibit similar trace element trends to that of the Tikorangi Formation dolomite-bearing carbonates, namely relatively elevated Mg and Fe but relatively depleted Na and Mn, although Sr in OtC2 is significantly lower.

6.7.2 Bivariate elemental plots

Bivariate elemental plots have been constructed (Fig. 6.10A-J) to graphically compare the entire Tikorangi Formation trace element database with the entire available New Zealand limestone database, as well as suggested fields for both

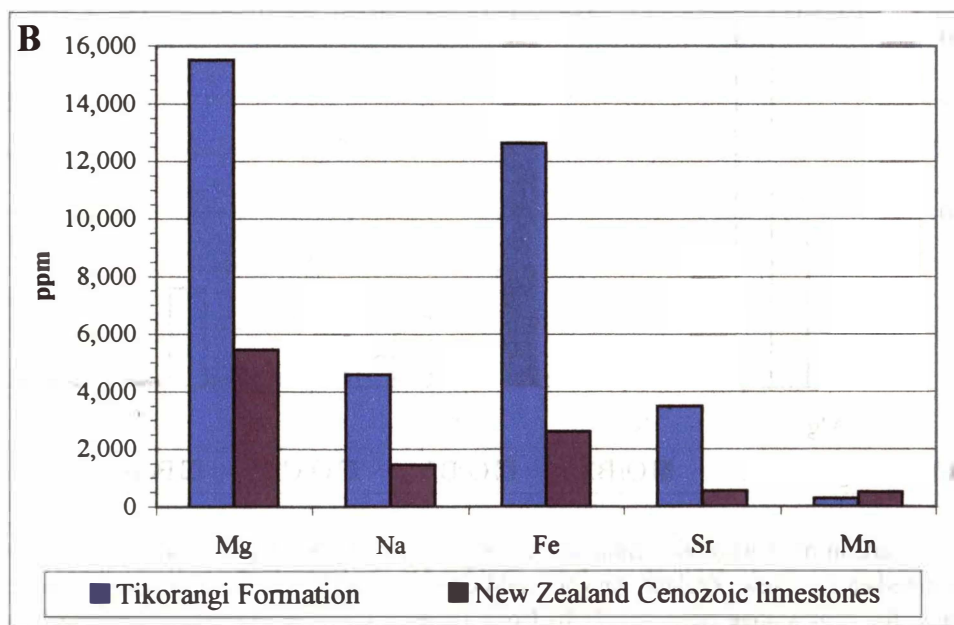
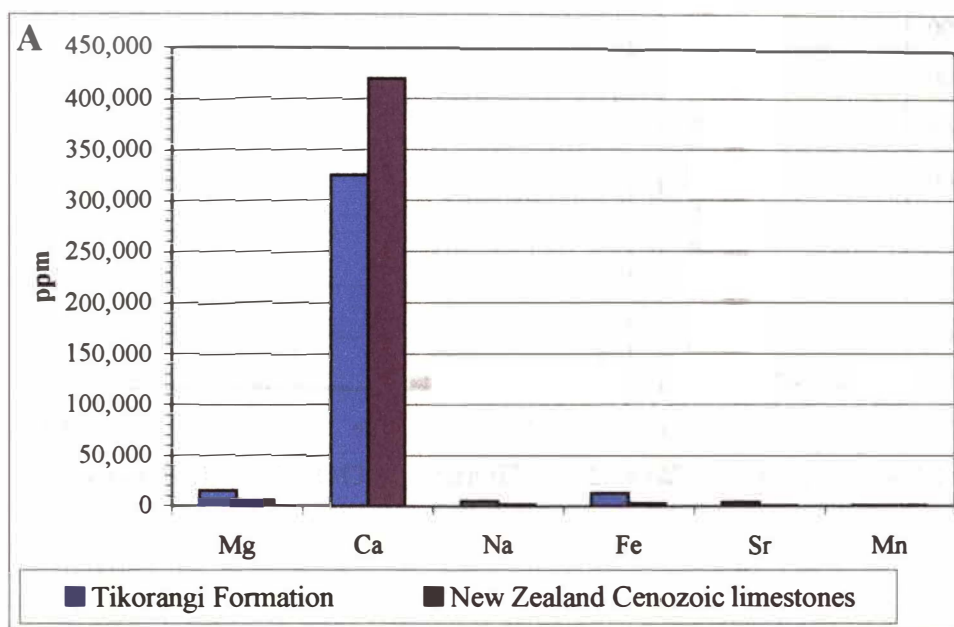


Fig. 6.8 Comparison of average TE concentrations in the Tikorangi Formation with those for New Zealand Cenozoic limestones showing (A) the Tikorangi Formation is relatively depleted in Ca and (B) considerably enriched in Mg and Fe, with lesser enrichment in Na and Sr.

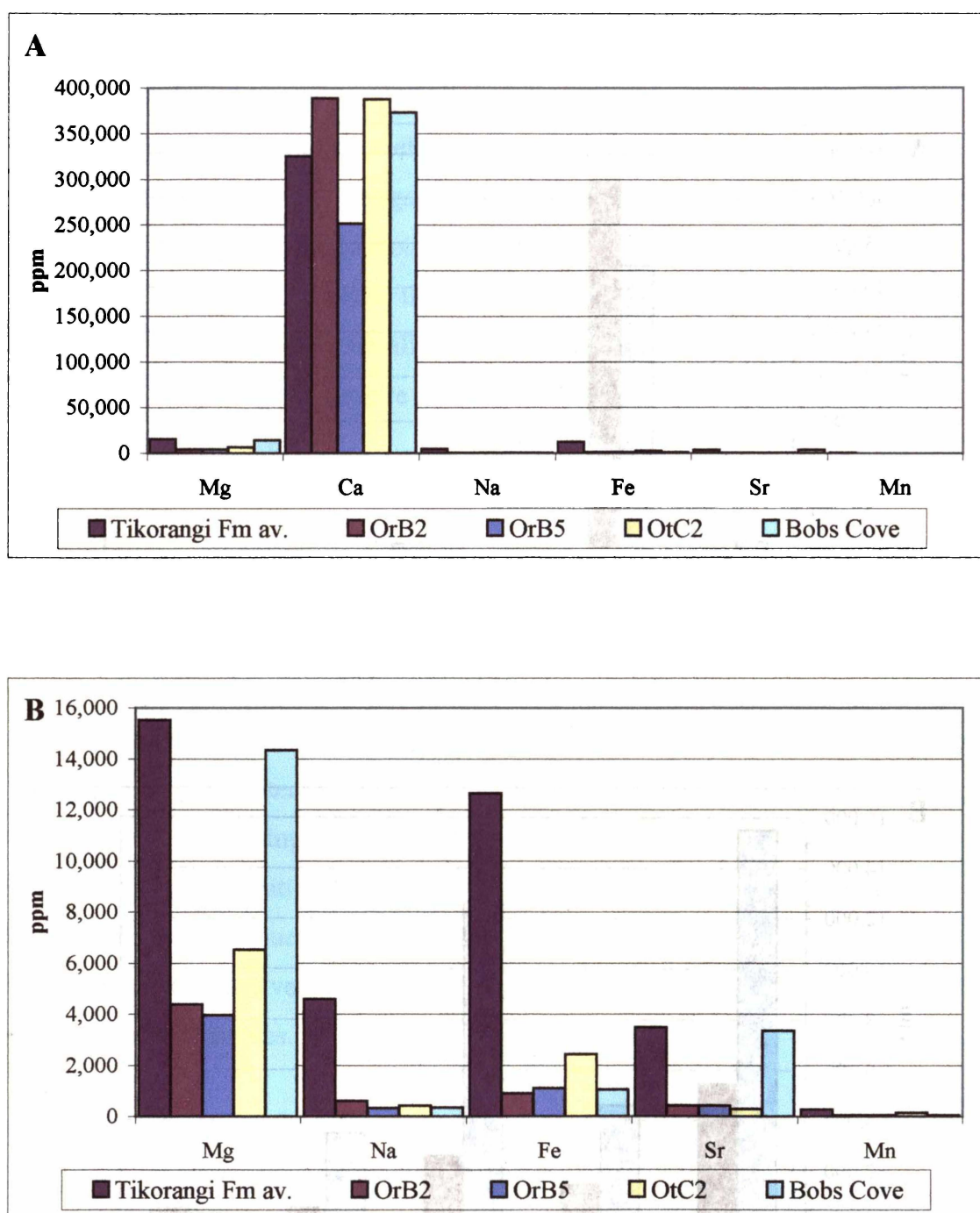


Fig. 6.9 Comparison of average elemental concentrations for the Tikorangi Formation with reportedly other dolomite-bearing New Zealand Oligocene-Miocene limestones. These limestones have been analysed here for comparative purposes. Bobs Cove Limestone is significantly dolomitic with similar values to the Tikorangi Formation, while the others appear not to be. Bobs Cove Limestone = sample 151 of Hayton (1995), South Island; OrB2 and OrB5 = Orahiri Limestone samples 16252, 16143 of Nelson (1973); and Otorohanga Limestone sample 16711 of Nelson (1973) from the South Auckland region. See Hayton (1995) and Nelson (1973) respectively for stratigraphic and petrographic details. Data are summarised in Table 6.1 and contained in Appendices 6.1, 6.2 and 6.3 for the Tikorangi Formation, other dolomite-bearing New Zealand Oligocene-Miocene limestones, and other New Zealand limestones respectively.

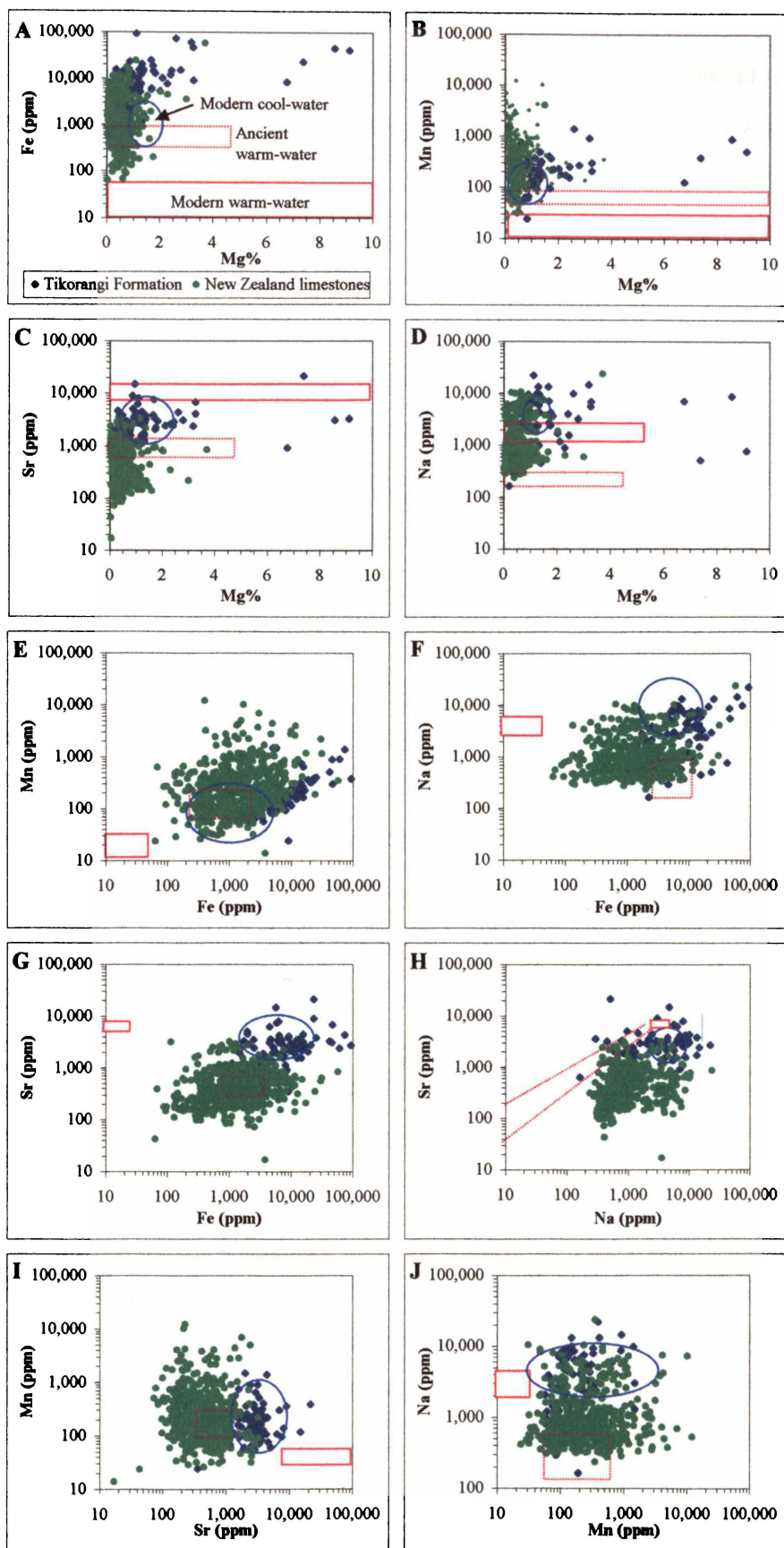


Fig. 6.10 A selection of element-element plots comparing typical fields for modern warm-water, modern Tasmanian temperate, and Ordovician Tasmanian subtropical shelf carbonates with data points for bulk samples of the Tikorangi Formation (blue points) and New Zealand Cenozoic temperate limestones (green points). Solid red box = modern warm-water Bahaman-type (aragonite + HMC) shelf carbonates; red dashed box = ancient (Ordovician) Tasmanian warm-water shelf carbonates; blue ellipse = modern Tasmanian (IMC + LMC) cool-water shelf carbonates.

modern and ancient warm- and cool-water carbonates. Display of the entire data as opposed to calculated averages provides a better feel for overall differences in the element distributions.

The Mg vs Fe plot (Fig. 6.10A) shows some overlap of the Tikorangi Formation and New Zealand limestone samples, but many of the former have much elevated Mg levels due to the presence of dolomite. In many respects the elevated Mg concentrations have more affinities with modern Bahaman aragonite and HMC-dominated carbonates, the highest Mg values being comparable to those in the subtropical Ordovician Tasmanian carbonates. Fe concentrations overlap with higher Fe values in modern cool-water shelf carbonates and ancient New Zealand limestones, but extend also to much higher concentrations.

The Mg vs Mn plot (Fig. 6.10B) shows the Mn values for the Tikorangi Formation samples are mainly within the lower range of values shown by New Zealand limestones. Mn values are similar to, but generally higher than, modern cool-water Tasmanian carbonates, and are substantially elevated in relation to both modern and ancient warm-water carbonates. Mg values are elevated, as discussed above.

The Mg vs Sr diagram (Fig. 6.10C) shows that Sr levels are at the high end of the New Zealand carbonate database and similar to modern Tasmanian cool-water shelf carbonates.

The Mg vs Na plot (Fig. 6.10D) shows that Na values for the Tikorangi Formation overlap the high end of the New Zealand limestones and modern cool-water shelf carbonates from Australia, with some lower values also falling in the Bahaman field. Mg values again extend to a range of values.

Fe vs Mn values (Fig. 6.10E) for the Tikorangi Formation plot on the lower side of Mn values, but higher side of Fe values, for New Zealand limestones.

Fe vs Na values (Fig. 6.10F) for the Tikorangi Formation plot closest to modern Tasmanian carbonates, but extend to appreciably higher Fe contents, and they are far removed in their Fe content from the very low values characterising modern Bahaman carbonates. Na values are generally at the higher end of the New Zealand limestone field.

Fe vs Sr values (Fig. 6.10G) are considerably higher for both elements compared to most fields, but most closely match the modern cool-water Tasmanian carbonates. Values are considerably higher than modern warm-water examples, with similar Sr levels to ancient Tasmanian carbonates.

Na vs Sr values (Fig. 10H) show a similar range of values to New Zealand Cenozoic limestones, although they mainly compare best with the more Na-rich samples. Sr values overlap the high end of the New Zealand examples and extend into higher concentrations, comparing well with the modern cool-water Tasmanian carbonate field and reaching levels associated with modern warm-water carbonates.

In the Sr vs Mn plot (Fig. 10I), Sr values again overlap and extend beyond the highest New Zealand limestone concentrations, while Tikorangi Formation Mn concentrations compare with the lower end of the New Zealand values. Again the greatest similarity is seen with the modern Tasmanian cool-water shelf carbonates.

Tikorangi Formation samples in the Mn vs Na plot (Fig. 10J) best fit the modern cool-water Tasmanian field and overlap with the highest New Zealand limestone Na values.

In summary, the Tikorangi Formation samples have commonly elevated Mg, Na, Fe, and Sr TE values in comparison to age equivalent New Zealand Cenozoic carbonates, and are most similar to modern Tasmanian (IMC +LMC) cool-water shelf and modern warm-water Bahaman (aragonite + HMC) shelf carbonates.

6.7.3 Trace elements versus age

Table 6.2 shows a breakdown of TE average values for the New Zealand limestone database, excluding the Tikorangi Formation samples, from the Pleistocene back to the Eocene-Oligocene. Two elements show significant trends. Mn values are lowest at about 200 ppm in the Pleistocene, generally increasing with age to over 500 ppm in the Oligocene-Miocene (Fig. 6.11). The converse applies for Sr, with highest values of 840 ppm in the Pleistocene and lowest of 375 ppm in Eocene-Oligocene samples. For both elements the trends “level off” after the Miocene. Studies by Haywick (1990) and Hood & Nelson (1996) have shown that the younger limestones comprise a significant quantity of meteoric-derived cements, and their TE data probably reflects that fresh-water influence; in the Miocene and older limestones most of the cements have a burial origin (Nelson et al. 1988; Hood & Nelson 96; Dodd & Nelson 1998).

A comparison can then be made between the above values and those of the Tikorangi Formation to assess any possible meteoric influence on its TE concentrations. Mn values are about 200 ppm in three of the five Tikorangi Formation petrofacies, and generally higher in wackestones and mudstones which contain higher dolomite contents. Therefore any potential meteoric influence in the cleaner facies is not evident in the dolomite-rich facies. The retention of high Mn values in the more micritic and clay-rich facies may have been due to a more diagenetically closed system, with preservation of TE values. A similar trend is evident for Sr. Clearly average Sr values in the Tikorangi Formation of 3,500 ppm (Table 6.1) are well in excess of those in the youngest New Zealand limestones (Table 6.2), which otherwise have relatively high values and include conspicuous meteoric cement (Hood & Nelson 1996).

6.7.4 Trace elements versus rock composition

To aid in the explanation of TE values within the Tikorangi Formation, correlations have been performed between individual TE values and petrographic data from the same samples (Topic 4) in order to gauge the influence of rock composition, and therefore original sediment makeup, upon the TE geochemistry.

Table 6.2 TE average values for the New Zealand limestone database, excluding the Tikorangi Formation samples, from the Pleistocene back to the Eocene. Data compiled from Winefield et al. (1996).

Age	No. of samples	Mg (ppm)	Na (ppm)	Fe (ppm)	Sr (ppm)	Mn (ppm)	Ca (ppm)
Pleistocene	38	3,481	15,566	1,379	839	205	408,102
Pliocene	40	4,595	1,463	2,542	739	245	406,604
Miocene	108	7,484	1,522	3,442	626	475	410,634
Oligo-Miocene	200	6,644	1,455	1,825	450	508	439,665
Oligocene	109	3,864	1,160	3,170	497	553	397,050
Eo-Oligocene	21	3,437	558	1,142	375	451	439,023

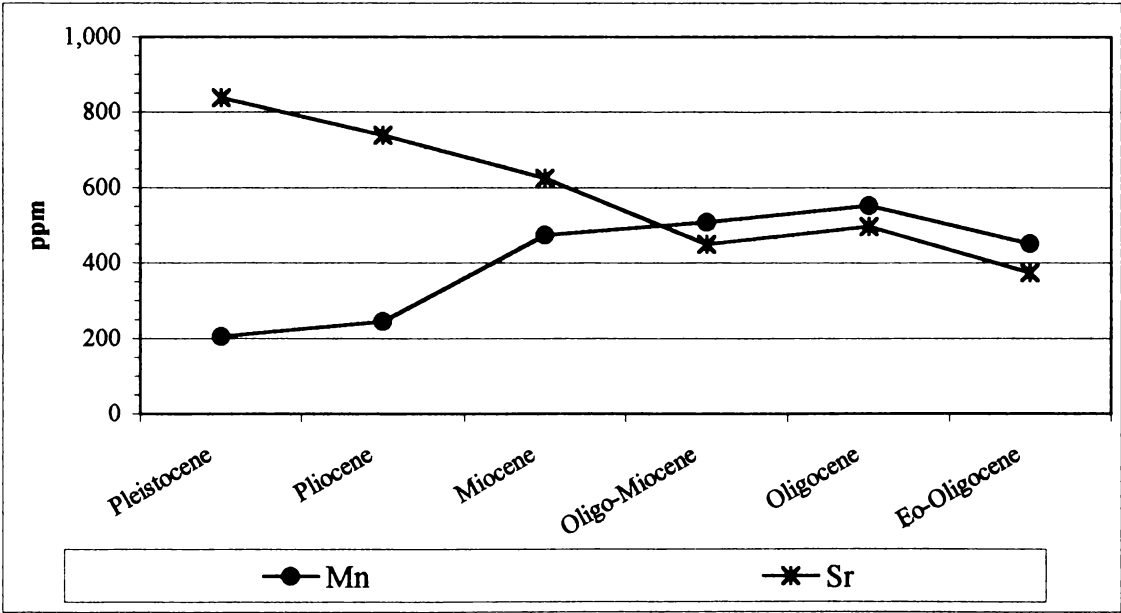


Fig. 6.11 Plot of Sr and Mn average TE data for New Zealand Cenozoic limestone age groups. Mn values are the lowest at about 200 ppm in the Pleistocene, generally increasing with age to over 500 ppm in the Oligocene. The converse applies for Sr, with highest values of 840 ppm in the Pleistocene and lowest of 375 ppm in Oligocene-Eocene samples. Studies have shown that these young limestones comprise a significant quantity of meteoric-derived cements, and their TE data probably reflect this meteoric influence, while in the Miocene and older limestones most of the cements have a burial origin.

Fig. 6.12 presents a summary of these results, and they are discussed briefly below.

Correlations between carbonate % and each of Mg, Na, Fe, Sr, and Mn are all negative (Fig. 6.12, 6.13). The Mg trend is likely to be a result of dolomite being more prevalent in relatively micrite/clay-rich and carbonate-poor facies (see following section; Topic 5). Similarly, decreasing Fe concentrations with decreasing carbonate content imply a major influence from increased quantities of siliciclastics providing a potential Fe source. Carbonate % versus Ca shows a positive correlation, the cleaner units (grainstones) being generally more calcitic with a paucity of Mg substitution in the carbonate lattice in relation to the reduced carbonate, but more dolomite-rich, facies.

Correlations were similarly performed for average TE values from the main petrofacies versus carbonate % (Fig. 6.14). The results better portray and reinforce the initial trends evident in Table 6.1 and Fig. 6.7. Here again Mg, Na, Sr, Fe, and Mn show decreasing concentrations with increasing carbonate content, the R^2 values ranging from about 0.57 to 0.86. Only Ca again shows a positive correlation, with an R^2 of 0.81. The TE trends reinforce the probable strong influence of non-carbonate sediment (clay minerals, fine siliciclastics) in supplying trace elements for co-precipitation into the carbonate cements in the Tikorangi Formation.

Other correlations performed on different skeletal types vs TE concentrations, but not included here, provided two noteworthy positive correlations. Sr increased with increasing percentage of planktic foraminifera, while a similar trend between Mn and echinoderms was also evident.

6.7.5 Dolomite content and trace element relationships

This section investigates the influence of dolomite content (wt%) on the bulk TE values. The wt% dolomite in selected Tikorangi Formation samples was determined previously (Topic 5) using XRD. Dolomite contents of 5-10%

	Mg (ppm)	Ca (ppm)	Na (ppm)	Fe (ppm)	Sr (ppm)	Mn (ppm)
Total carbonate %	—	+	—	—	—	—
Dolomite %	+	—	+	+		+
Spar cement %	—	+	—	—	—	—
Micrite/matrix/clay %	+	—	+	+	+	+
Skeletal %	—	+	—	—	—	—
Siliciclastic %	+	—	+	+	—	

Fig. 6.12 Schematic summary of correlation trends in sample composition versus individual trace elements. Positive and negative values denote the sign of the slope of linear regression lines drawn through the composition versus trace element plots. For example as total carbonate % increases Mg contents decrease. Blank denotes no discernable trend.

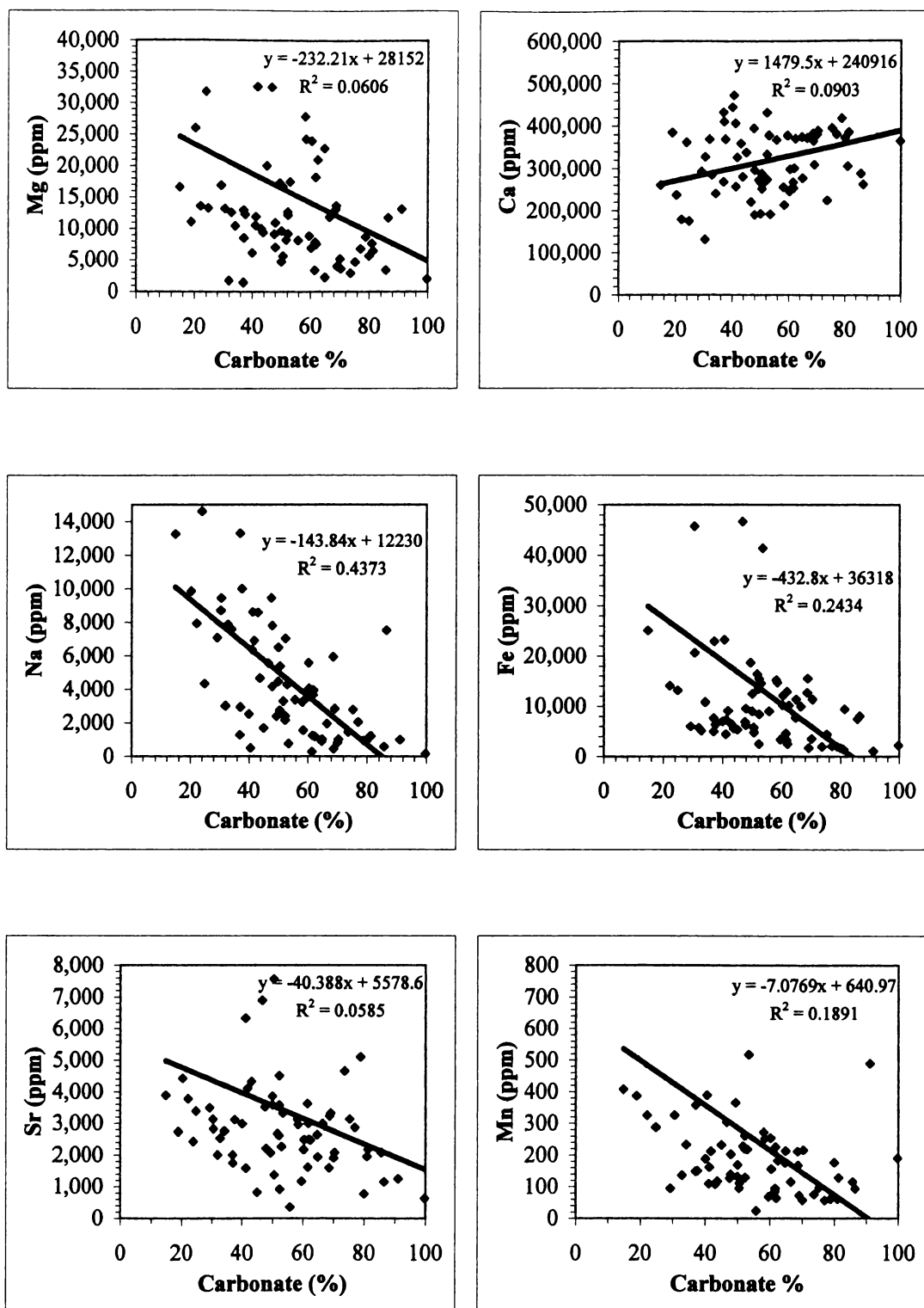


Fig. 6.13 Correlation plots of carbonate % versus individual trace element concentrations in bulk samples of the Tikorangi Formation. The y-axis scale has been used to accommodate the majority of samples but some may plot off scale. With the exception of Ca, other TE values show a decrease with increasing carbonate content.

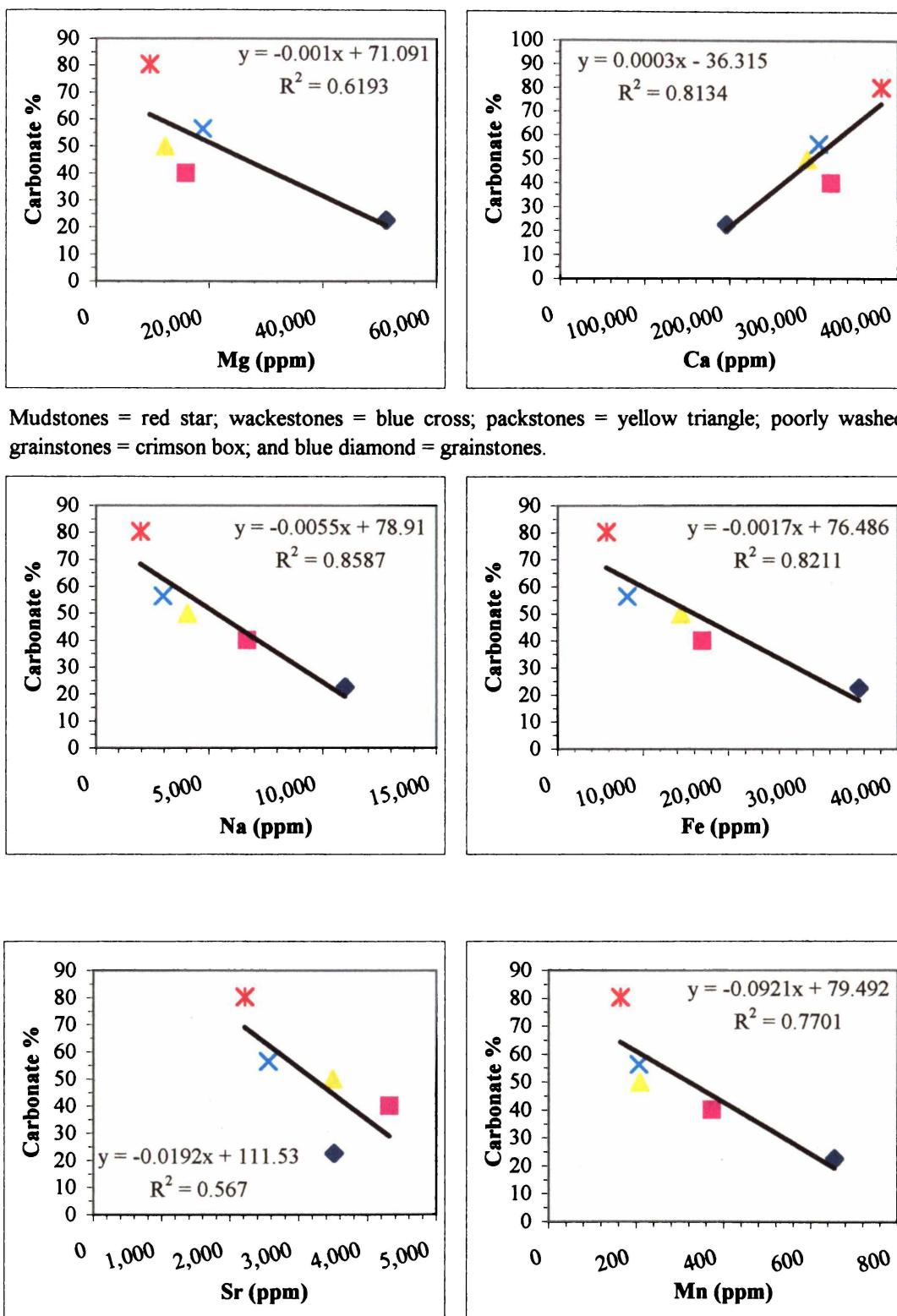


Fig. 6.14 Average TE concentrations for the five Tikorangi Formation petrofacies correlated with their corresponding carbonate % values. With the exception of Ca, there are increasing TE values from mudstones through to grainstones as carbonate content decreases.

dominate, with rare values as high as 20-50%. As an additional aid to determining dolomite percentage values a correlation between Mg (ppm) and XRD determined wt% dolomite was performed yielding a very good correlation ($R^2 = 0.93$) (Fig. 6.15A). Using this correlation ($0.0008 \times \text{Mg}(\text{ppm}) - 2.5669$), dolomite contents were calculated from the Mg (ppm) values for the 65 bulk samples of Tikorangi Formation on which TE geochemistry was performed (Fig. 6.15B). Samples contain ubiquitous, but generally small, amounts (~5%) of dolomite, with similar numbers of samples having 5-10%. Values above 15% are rare, and range up to 55%, and are in good agreement with the percentage values determined petrographically (Topic 5).

Correlations were also performed between dolomite % and the other TE concentrations (Fig. 6.16). A negative correlation exists with Ca, the Ca ions having been replaced by Mg in the carbonate lattice. Na, Fe, and Mn, together with Mg, show clear positive relationships of increasing concentrations with increasing dolomite content. The Fe trend reflects the fact that the dolomite is iron-rich, previously determined from petrographic and XRD analysis (Topic 5). Mn, a major control in activating CL within the Tikorangi Formation dolomite rhombs, is naturally present in higher quantities in the dolomite-rich rocks compared to the non-dolomite-bearing non-luminescent calcite cements (Topic 5).

Samples were segregated into three groups based on dolomite contents of 0%, 1-15%, and >15%. The "dolomite effect" on TE geochemistry within the Tikorangi Formation is clearly seen for the three groups (Fig. 6.17) with variably elevated Mg, Na, Fe, Sr, and Mn contents occurring with increasing dolomite percentage, while the converse occurs for Ca.

Further correlations were attempted with petrographically measured rock components, not shown here, in an attempt to explain TE sources in dolomite. Dolomite % vs carbonate % showed negative correlation, as did dolomite vs spar cement. A positive correlation however was produced between dolomite % and micrite/matrix and siliciclastic percentages, emphasising a key relationship

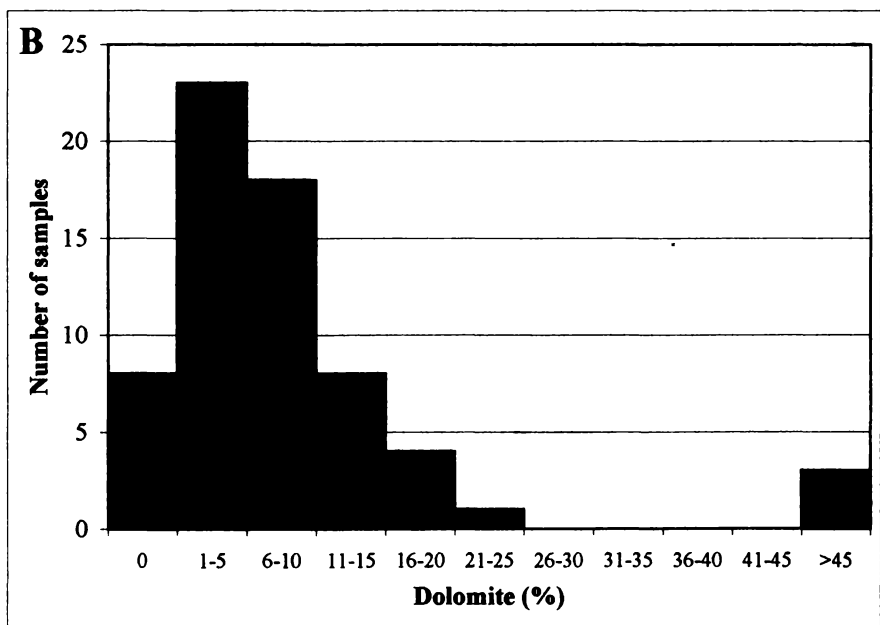
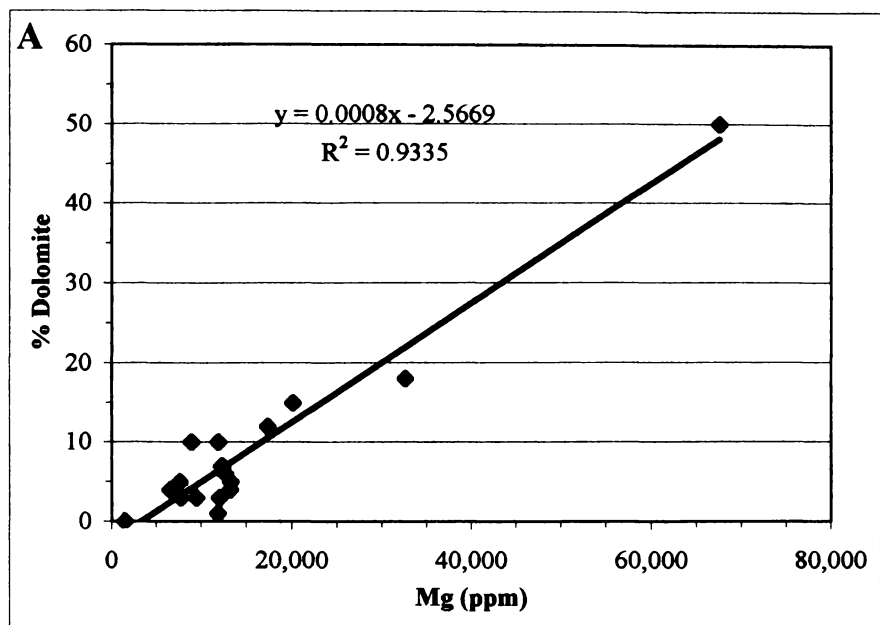


Fig. 6.15 (A) Correlation of dolomite % as determined by XRD on selected samples and Mg (ppm) determined from bulk trace element analysis has been used in (B) to produce a histogram plot of dolomite % in those samples on which TE analysis was conducted. This enables the effect of dolomite content on the TE values to be determined.

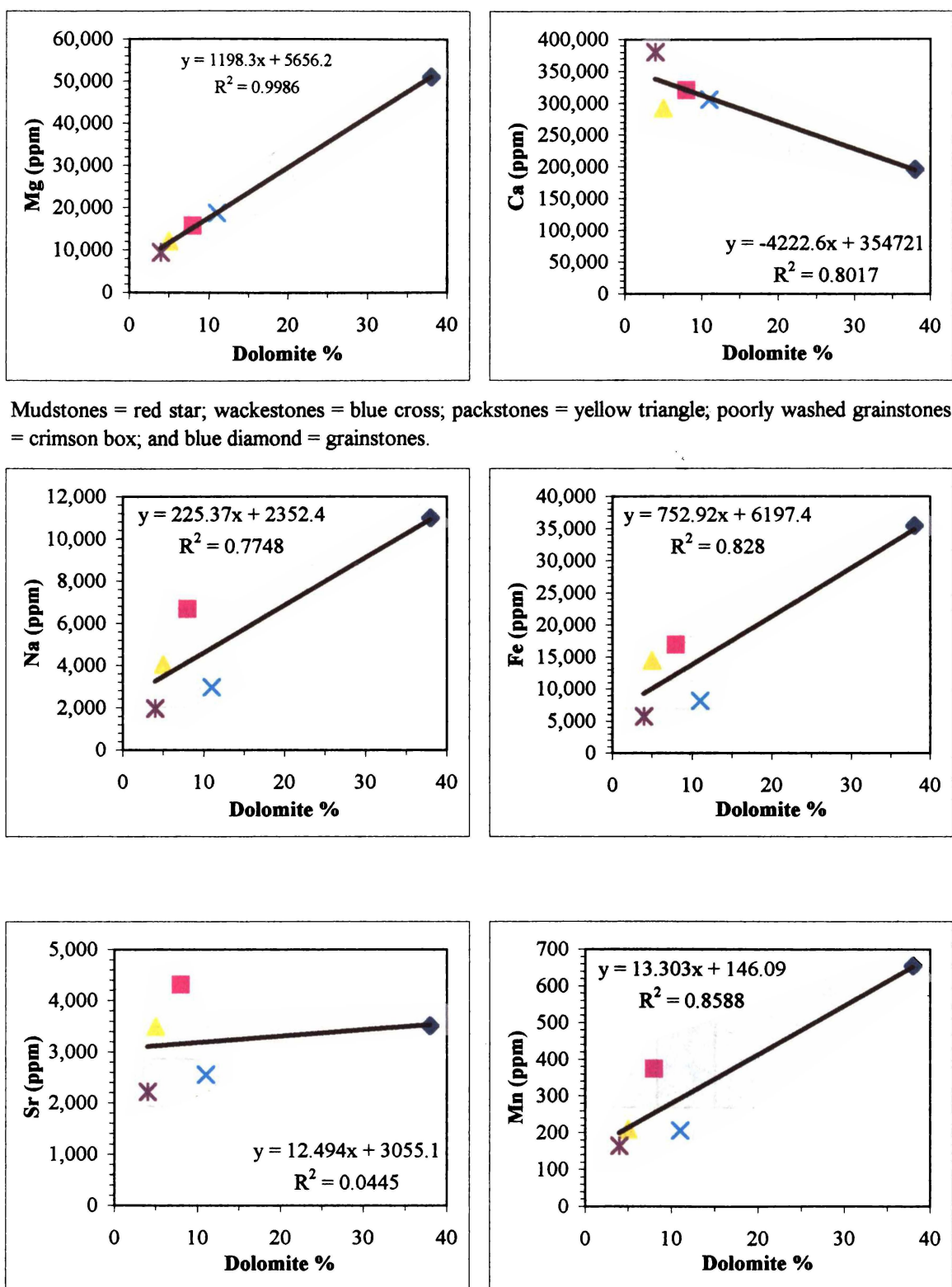


Fig. 6.16 Correlations of dolomite % and average TE values for the five petrofacies in the Tikorangi Formation showing a general trend of increasing TE concentration with increasing dolomite % with the exception of Ca and Sr.

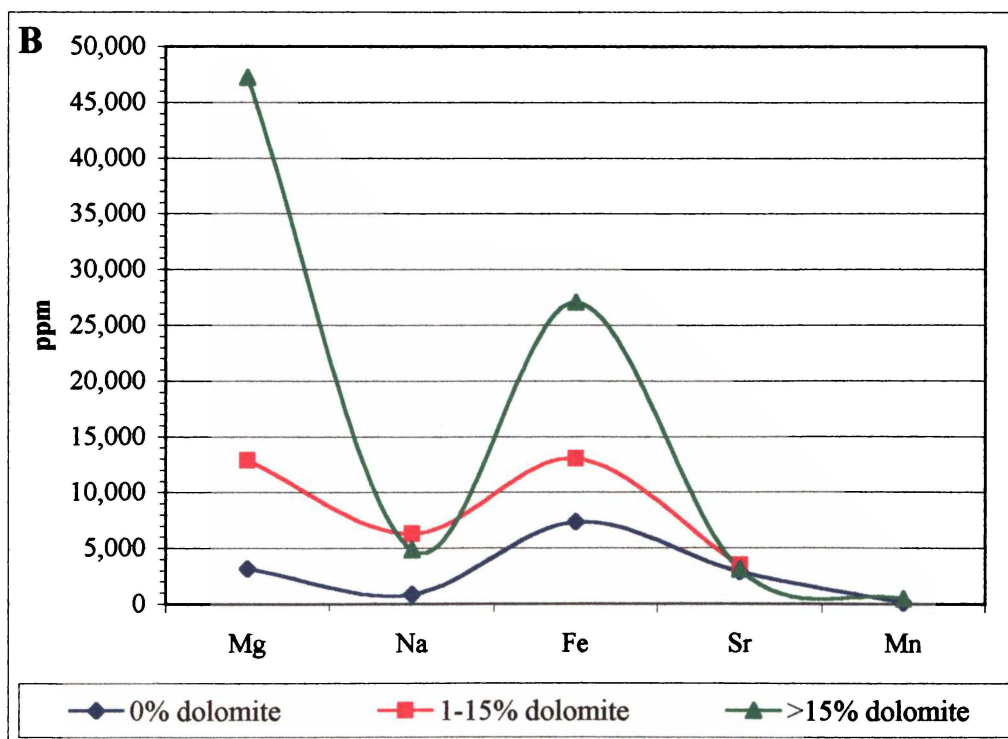
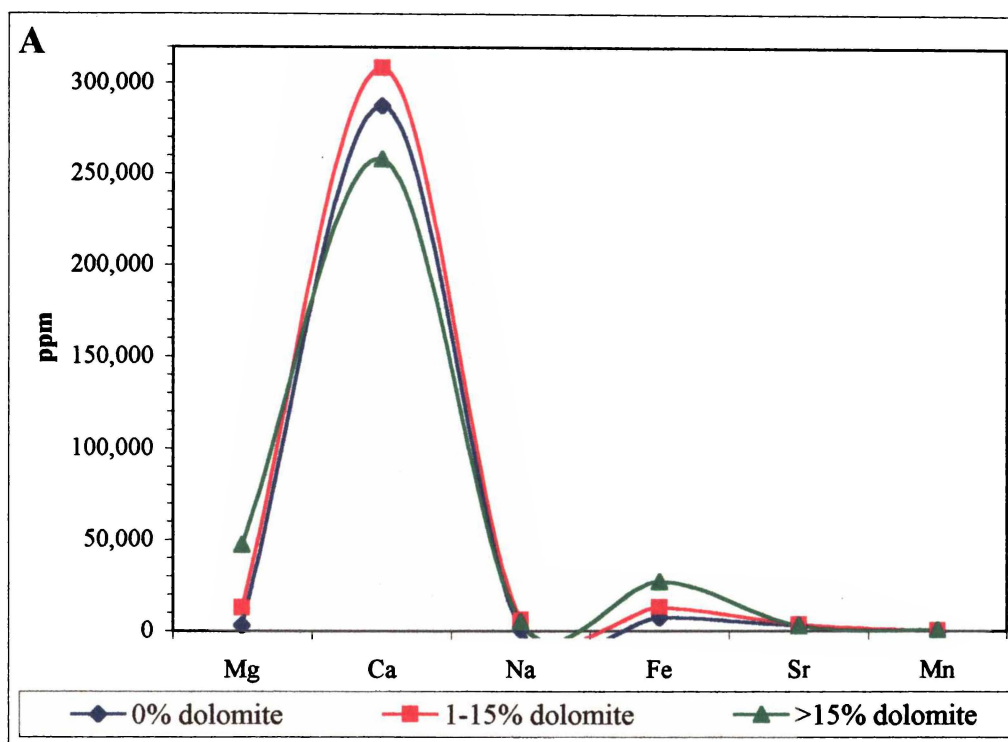


Fig. 6.17 Changes in TE values with dolomite % in representative samples of the Tikorangi Formation showing depletion of Ca (A) and TE enrichment of particularly high Mg and Fe (B) in comparison to non-dolomite-bearing samples. Na, Mn and Sr are also enriched in dolomitic samples, but to a much lesser extent.

between micrite/matrix-rich and siliciclastic contents with high dolomite percentages averaging greater than 35% (Fig. 18A). These results further reinforce the petrographic observations that dolomite preferentially occurs in the finer siliciclastic- and micrite/matrix-rich carbonates. Poorly washed grainstones and wackestones are the next most dolomitic rocks (typically 5-10%). Packstones and grainstones mainly have < 5% dolomite contents.

6.7.6 Comparison with other New Zealand dolomitic limestones

Samples of Hayton's (1995) Oligocene-Miocene South Island Bobs Cove Limestone were analysed and contain similarly small amounts (~10 wt%) of calcian-rich (58 mol% CaCO_3) non-stoichiometric ferroan dolomite (7 mol% FeCO_3). The composition is similar to the dolomite in the Tikorangi Formation, but is less iron-rich. The calcite is analogous to that in the Tikorangi Formation, being LMC with 2 mol% MgCO_3 . High Mg values averaging 14,300 ppm (Table 6.1; Fig. 6.9) are very similar to the Tikorangi Formation average of 15,500 ppm. Average Sr values at 3,400 ppm are the same as those in the Tikorangi Formation, while Fe, Na, and Mn are considerably less (Table 6.1).

Samples of Nelson's (1973) Oligocene-earliest Miocene South Auckland Orahiri and Otorohanga Limestones from the neighbouring North Wanganui Basin were also analysed (Table 6.1; Fig. 6.9) because they were reported to contain rare rhombic crystal cements, possibly dolomite. However, geochemically the samples plot within the average New Zealand limestone field of Winefield et al. (1996), particularly the Orahiri Limestone samples. The petrographic evidence for former dolomite in these samples could be explained by subsequent dedolomitisation. Dolomite does constitute <5 wt% in a single sample of the Otorohanga Limestone (sample 16711 from Nelson (1973) column C117, in the OtC2 unit within the upper flaggy Otorohanga Limestone which contains minor shale units). This dolomite is calcian-rich (45 mol% MgCO_3) and ferroan (7 mol% FeCO_3), and is again not unlike Tikorangi Formation dolomites.

6.8 TRACE ELEMENT GEOCHEMISTRY OF CALCITE AND DOLOMITE

6.8.1 Skeletal mineralogy

An absence of aragonite and IMC/HMC, as assessed using XRD, attests to the current LMC mineralogy of all carbonate skeletons within the Tikorangi Formation.

6.8.2 Calcite geochemistry

XRD analysis shows calcite in the Tikorangi Formation is LMC with 1-3 mol % MgCO_3 . Thin-section staining shows the majority of the calcite is ferroan.

Due to the ubiquitously dolomitic nature of the majority of the Tikorangi Formation it is difficult to assess the TE Mg contents of the calcite from bulk rock analysis, but assuming the lowest Mg (ppm) values with calculated 0% dolomite contents, Mg values are nearing half of the New Zealand limestone average at 3,400 ppm (Table 6.1). Relatively higher New Zealand Mg values may be a function of some IMC (and HMC) retention in the younger Plio-Pleistocene limestones from East Coast, and consequently the average value does not represent wholly LMC limestones.

The ferroan nature of the Tikorangi Formation calcite, averaging 7,400 ppm Fe, is significantly higher than the New Zealand limestone average and for burial-cemented Otorohanga and Orahiri Limestone age equivalents (Table 6.1). This again emphasises the Fe-rich nature of the mixed siliciclastic-carbonate Tikorangi Formation sediments. Ca levels at about 287,000 ppm are lower in the Tikorangi Formation than in the New Zealand average at 420,000 ppm (Table 6.1). Na levels in the Tikorangi Formation at 900 ppm are comparable but lower than the New Zealand average of 1,450 ppm, but are substantially elevated in relation to specific age equivalents discussed earlier (Orahiri, Otorohanga, Bobs Cove Limestones) (<600 ppm). Sr at 2,900 ppm is elevated with respect to all the other comparable data, being more than 5 times higher than the New Zealand limestone average.

The Mn average of 141 ppm is considerably lower than the New Zealand limestone average at 500 ppm.

Modern cool-water shelf bulk skeletal data from the eastern Tasmanian shelf, Australia (Rao 1996), which include a range of LMC to HMC and aragonite, have the following average TE content: Ca - 368,000 ppm; Mg - 14,000 ppm (5.6% MgCO_3); Sr - 3200 ppm; Na - 4,200 ppm; Fe - 1,700 ppm; Mn - 53 ppm. Ca values in the Tikorangi Formation compare well with the Tasmanian data, while Sr and Mg are comparatively lower and Na, Fe, and Mn higher than in the Tikorangi Formation.

Calcite samples from veins within the Tikorangi Formation show generally comparable values to the host rock, with averages of: Mg - 6,900 ppm, Ca - 295,000 ppm, Na - 800 ppm, Fe - 6,700 ppm, and Mn - 200 ppm. However, Sr is markedly enriched in the vein material at almost 20,500 ppm Sr (Table 6.1). The higher Mg values within calcitic vein material may result from some dolomite replacement within the calcite veins (see Topic 7).

6.8.3 Dolomite geochemistry

XRD shows dolomite within the Tikorangi Formation to contain most typically 58 mol% CaCO_3 , so that it is a non-stoichiometric calcian-rich dolomite. The dolomite is commonly also Fe-rich, having typically about 13 mol% FeCO_3 (ferroan dolomite).

TE data for dolomite alone are difficult to access from the bulk analyses, but using the most dolomite-rich (>15%) samples TE Mg values of up to 91,000 ppm occur, with substantially reduced Ca values, as low as 131,000 ppm. Na values reach 9,900 ppm or more, with Fe up to 74,000 ppm, Sr averaging 3,100 ppm, and Mn up to 1,400 ppm. To compare with calcite mineralogies, average dolomite TE values have been calculated for those dolomitic-rich samples having >15% dolomite (Fig. 6.18B, C). These show for dolomite significant enrichment in Mg and Fe contents by up to 20 and 7 times respectively, with 5 times more Mn and

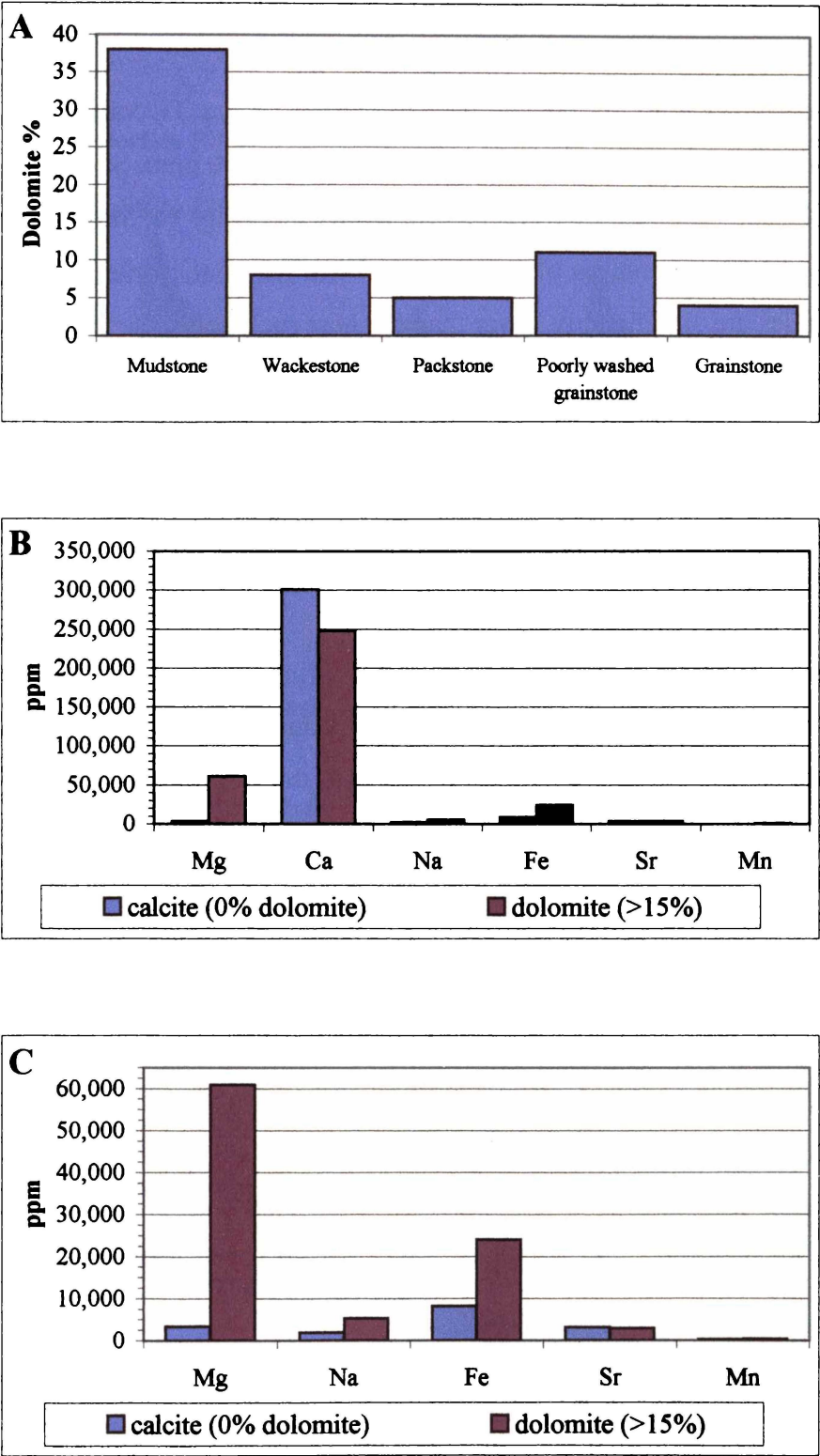


Fig. 6.18 (A) Dolomite occurrence in the five Tikorangi Formation petrofacies/rock types is ubiquitous, reaching significant quantities in mudstone facies. (B) Comparison of TE concentrations in wholly calcitic and dolomitic samples within the Tikorangi Formation showing reduced Ca values in dolomitic samples in relation to calcitic ones. (C) TE enrichment of Mg, Na, and Fe occurs in dolomitic samples in relation to calcitic ones, while Sr and Mn show similar levels in both rock groups.

Na, only slightly elevated Sr, and a reduced Ca concentration.

For comparison, dolomitic vein material provides average TE values of: Mg - 48,200 ppm, Ca - 219,000 ppm, Na - 580 ppm, Fe - 46,700 ppm, Sr - 7,100 ppm, and Mn - 490 ppm (Table 6.1). The comparatively high Mg, Fe, Sr, and Mn may be explained by the pureness of the dolomite vein material, while the dolomite vein Na values are significantly lower than the host rock dolomite and may relate to a different paragenesis and formation from meteoric-influenced pore fluids (see Topic 7).

6.9 CLAY MINERALOGY

Clay mineral peaks in insoluble residues following acetic acid digestion of samples were unexpectedly subdued. This may be due to low clay contents and a predominance of silt-sized siliciclastic material in the fine fractions, to possibly poor crystallinity of clay species, and to the presence of mixed-layer clay mineral species. These matters require future study.

XRD analysis positively identifies smectite, mixed-layer illite-smectite (I-S), and illite (Fig. 6.19). Smectites are variably crystalline and have a range of broad to rarely sharply defined peaks. From the position of the smectite (001) peak at 14 to 15 Å in the air-dry (untreated) state the smectites are dioctahedral and contain Ca and/or Mg as the exchangeable cation associated with two layers of water (Hume & Nelson 1982). Smectite swelled to 16.7 to 17 Å upon glycolation.

Illite, identified by a strong basal (001) reflection at 9.8 Å in air-dry samples, remained unaffected by other treatments (Fig. 6.19). Illite is fine-grained and poorly crystalline as evidenced by broad low intensity peaks. No evidence of chlorite was noted, although trace quantities of kaolinite may be present. Trace quantities of kaolinite (< 2%) were similarly reported in limited analyses of 4 samples of Waihapa-2 and Toko-1 core by Halliburton Chemical Labs (1988). Again from very limited analysis Naish (1991) suggested chlorite was a possible

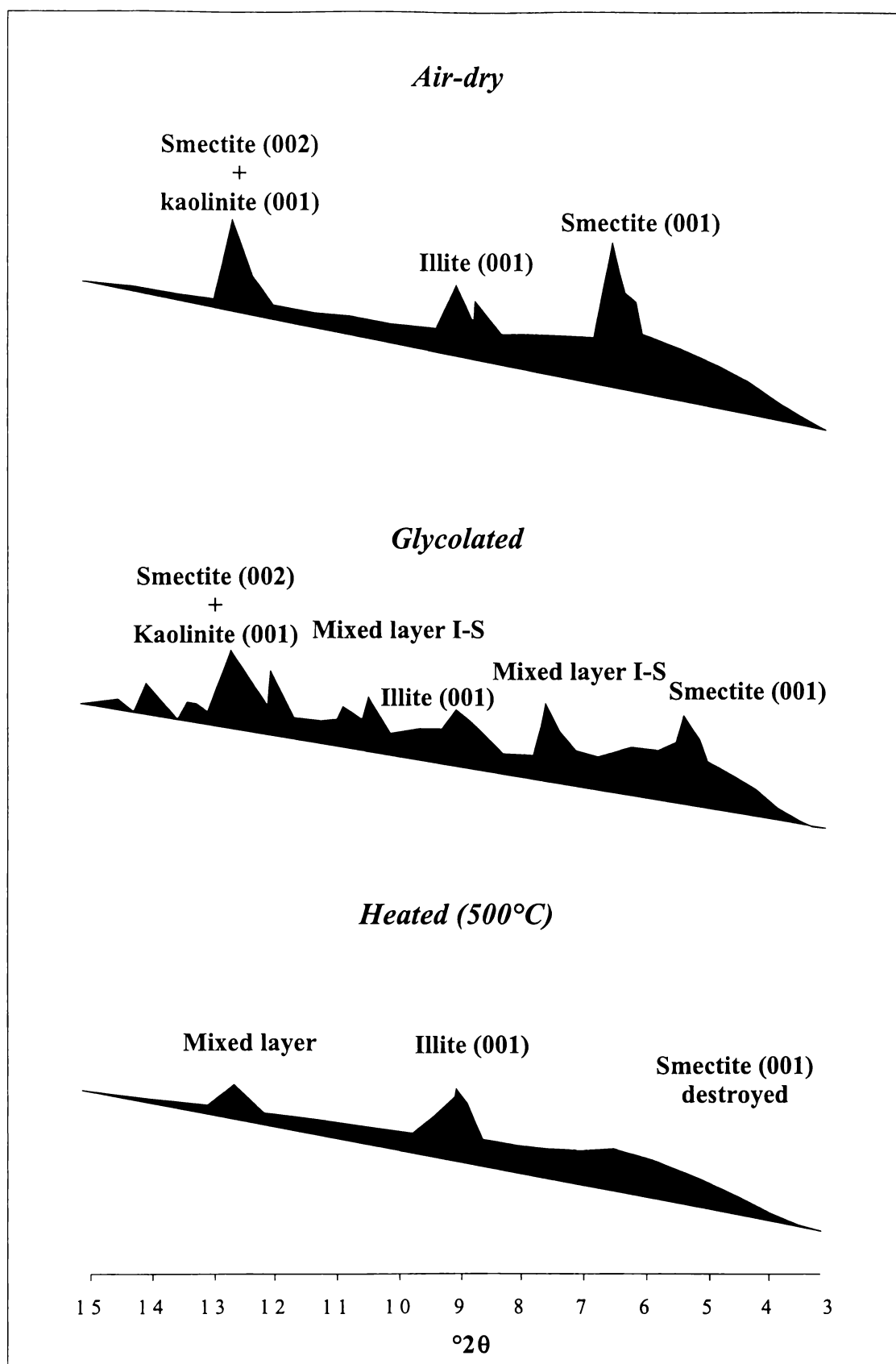


Fig. 6.19 Schematic compiled from several diffractograms of the characteristic x-ray diffraction trace for the insoluble fraction in the Tikorangi Formation showing the presence of smectite, illite, and possible kaolinite and their behaviour in air-dry, glycolated and heated states. Smectite and mixed-layer clays swell, shifting peak position to the right because of increased d -spacing, while in the heated state these are destroyed.

clay species in Toko-1 core samples. Traces of smectite were also reported in these samples. Smale et al. (1999) report traces (1-5%) of illite, minor to common smectite, and trace to common mixed-illite/smectite in samples from Waihapa-2.

The appearance of previously unseen peaks in the air-dry state upon glycolation at 11.8Å which collapsed to 9.8Å on heating (Fig. 6.19) is inferred to be indicative of randomly interstratified illite-smectite (I-S) mixed-layer clays which upon glycolation may have re-orientated to provide more definitive and better ordered reflective planes.

Semi-quantification of clay abundances using peak areas in untreated slide mounts suggests roughly equal proportions of smectite to illite in the majority of samples analysed with smectite dominating in some samples. Halliburton Chemical labs (1988) reported a predominance of smectite with lesser illite in limited analyses of 4 samples from Waihapa-2 and Toko-1 core.

In reported analyses of neighbouring North Wanganui Basin Orahiri and Otorohanga Limestone correlatives, smectite and I-S clays dominate with rare or no chlorite (Nelson 1973; Hume & Nelson 1982).

6.10 GEOCHEMICAL DISCRIMINATION OF DIAGENETIC ENVIRONMENTS

6.10.1 Diagenetic environments defined

The point at which sediments leave the “traditionally defined” marine (seafloor) diagenetic realm and enter the shallow burial diagenetic realm is difficult to define. It could be argued to occur very close below the sediment-water interface as conditions change from oxidising to reducing. Shallow burial diagenesis is considered here to involve pore fluids having near “normal” marine salinity (~35 ppt) and may involve sub-seafloor depths down to several of 10s of metres or more. This study uses the term deep burial diagenetic realm when burial depths

were sufficient for the onset of chemical compaction as a result of increasing overburden pressure. For carbonate deposits this typically ranges from a few to several 100 m of burial (e.g., Hood & Nelson 1996; Borre & Fabricius 1998). By this stage pore fluid chemistry would typically reflect increased temperatures and pressures, and possibly salinities, in a strongly reducing environment, involving marine-modified or connate fluids.

Meteoric diagenesis is defined here as including meteorically-derived fluids introduced into pore spaces in the subsurface, and does not have to have involved subaerial exposure. The postulated introduction of meteoric fluids into the deeply buried Tikorangi Formation, (see Fig. 6.24) would have necessitated a direct link from the upper levels experiencing meteoric circulation (Allis et al. 1997) into the subsurface environment via the extensive fracture networks within the formation (Kamp & Hood 1994) (see Topic 7).

6.10.2 Element-element plots

Element-element plots may be used to help infer the diagenetic environments that have influenced carbonate deposits. Summary elemental matrices were developed by Winefield et al. (1996) for idealised meteoric, marine, and burial diagenetic trends. The use of the term marine diagenesis by Winefield et al. (1996) was probably inappropriate because in the strictest sense it involves only alterations and cements formed in sea water at or very close to the sediment-water interface (Nelson & James 2000), not those formed at greater burial depths. The suggestion of commonly occurring marine diagenesis in New Zealand Cenozoic carbonates by Winefield et al. (1996) is misleading because these limestones only rarely contain marine cements (Hood & Nelson 1996; Nelson & James 2000), and these are absent in the Tikorangi Formation. It is suggested here that the bulk of the marine-influenced diagenesis in the Winefield et al. (1996) scheme formed in fact in the shallow burial realm (Hood 1993; Hood & Nelson 1996). Consequently the hence the concept of marine diagenetic trends inferred from the element-element plots is taken to actually reflect shallow-burial diagenetic trends.

Summary elemental matrices are shown for meteoric (meteoric diagenesis within the burial realm), shallow burial, and deep burial diagenesis in Fig. 6.20. The degree of agreement of these “standard” matrices with individual matrices for the Tikorangi Formation petrofacies has been used to infer their diagenetic histories, following the approach of Winefield et al. (1996).

Summary elemental matrices for individual Tikorangi Formation petrofacies are shown in Fig. 6.21. For example, the summary elemental matrix for mudstones has six out of eight regressions in agreement with those for meteoric diagenesis (regressions have same sign), two for which no data are available, and two which are in disagreement, giving an overall meteoric agreement at face value of 6/8 or 75%. Similarly, calculating for shallow burial diagenesis 3/8 are in agreement, and for deep burial 2/6 are in agreement giving an overall ratio of meteoric>>shallow burial>deep burial (75:38:33) which is shown in the partner schematic pie diagram for mudstones.

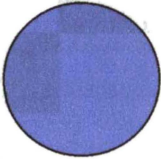
Fig. 6.22A shows the apparent complex mix of diagenetic environmental signatures determined from the face value acceptance (e.g., have not discounted influence if more negative than positive correlations) of the summary elemental matrix approach of Winefield et al. (1996). A trend of decreasing meteoric influence from mudstones through wackestones to packstones is apparent, with a concomitant increase in a shallow burial/deep burial influence. Simplifying diagenetic signatures for all petrofacies combined gives a co-dominant deep burial and shallow burial, and lesser meteoric influence (Fig. 6.21F).

6.10.3 Dolomite effect on summary elemental matrices

Summary elemental matrices for samples containing 0%, 1-14% and >15% dolomite have been derived (Fig. 6.23) to assess the effect that the presence of dolomite may have on each diagenetic regime. Results are summarised in Fig. 6.22B and show a tendency towards a reduced meteoric influence with increasing dolomite content (Fig. 22C), approaching zero in those rocks with 15% or more of dolomite in the Tikorangi Formation. The converse applies for the deep burial

A. Meteoric diagenesis

Mg	Na	Fe	Sr	Mn	
		—		—	Mg
		—	+	—	Na
			—	+/-	Fe
				—	Sr
					Mn



B. Shallow burial diagenesis

Mg	Na	Fe	Sr	Mn	
		+		+	Mg
		+	+	+	Na
			+	—	Fe
				+	Sr
					Mn



C. Deep burial diagenesis

Mg	Na	Fe	Sr	Mn	
					Mg
		+	+	+	Na
			+	+	Fe
				+	Sr
					Mn



+

—

Fig. 6.20 Summary elemental matrices for idealised meteoric, shallow burial, and deep burial diagenetic trends. Positive and negative symbols delineate the sign of the slope of linear regression lines drawn through element-element plots. Schematic pie diagrams show the relative influence of each diagenetic regime for an unknown matrix (in this case 100%). Adapted from Winefield et al. (1996).

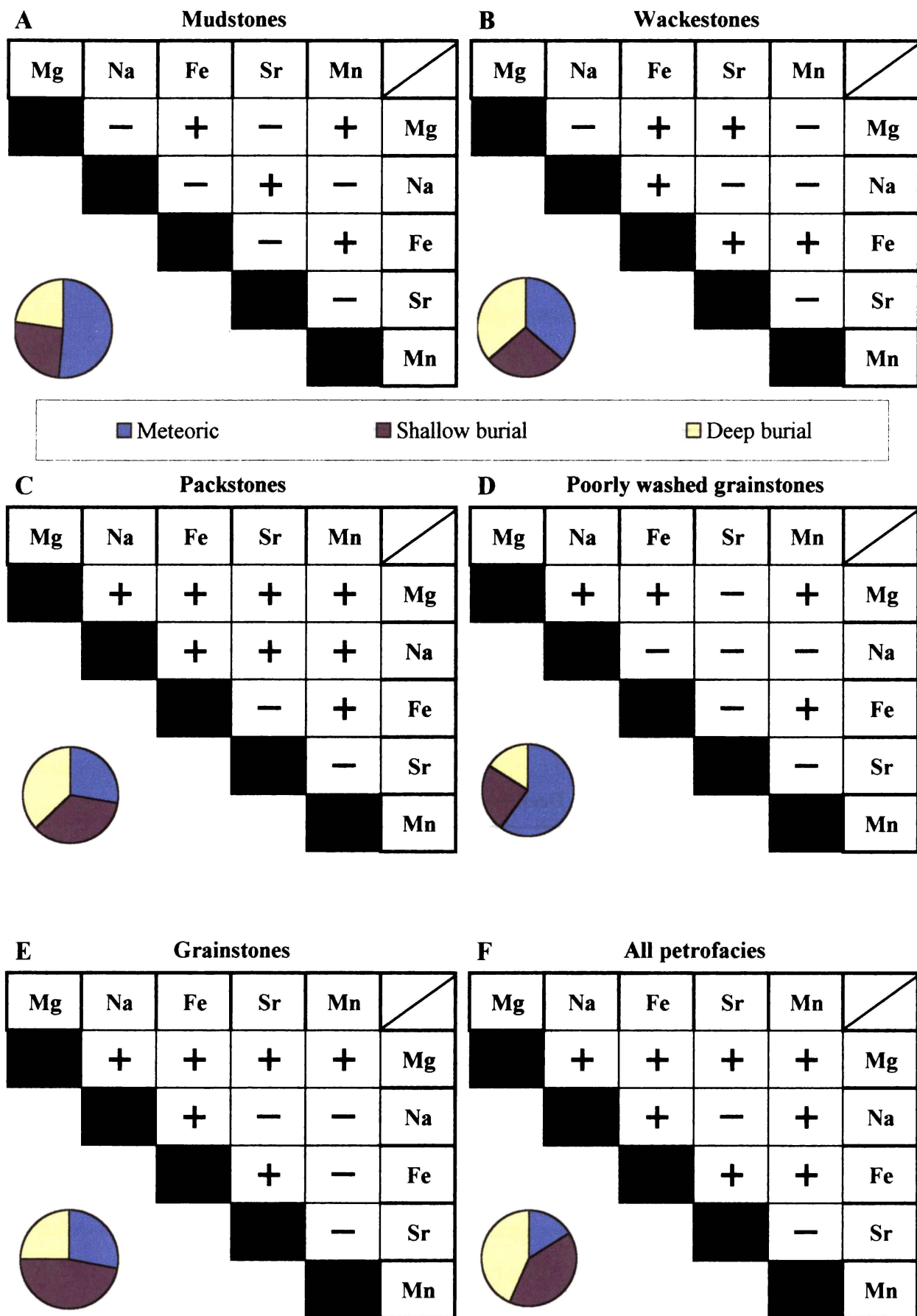


Fig. 6.21 Summary elemental matrices and pie diagrams for individual petrofacies in the Tikorangi Formation.

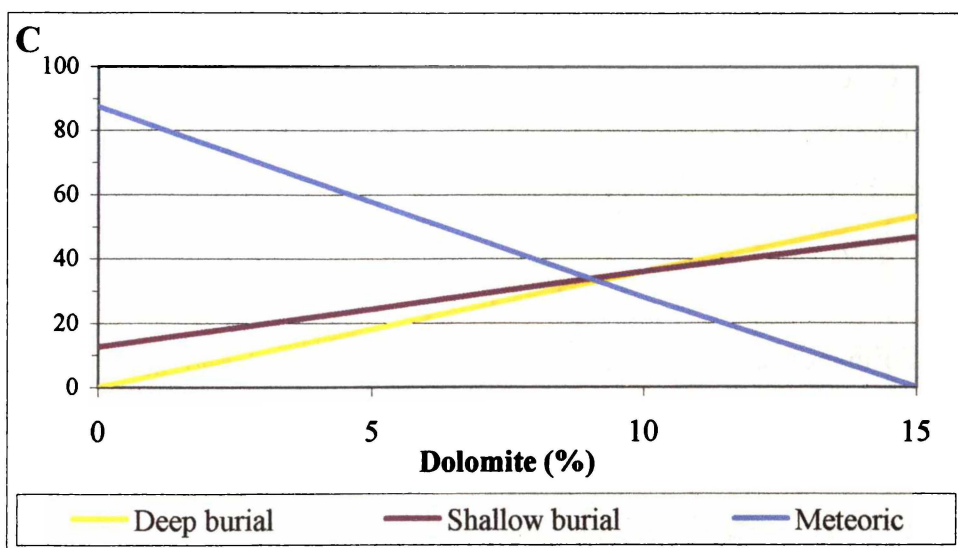
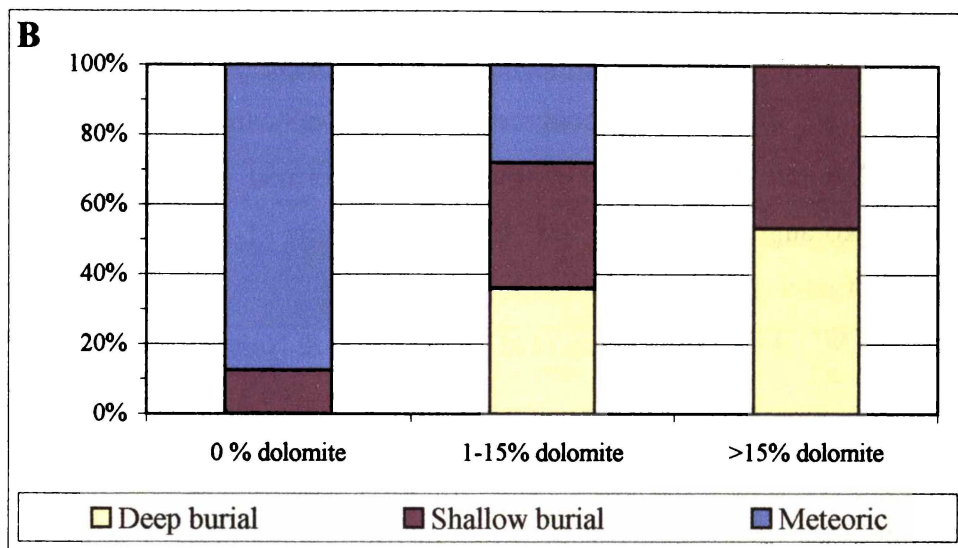
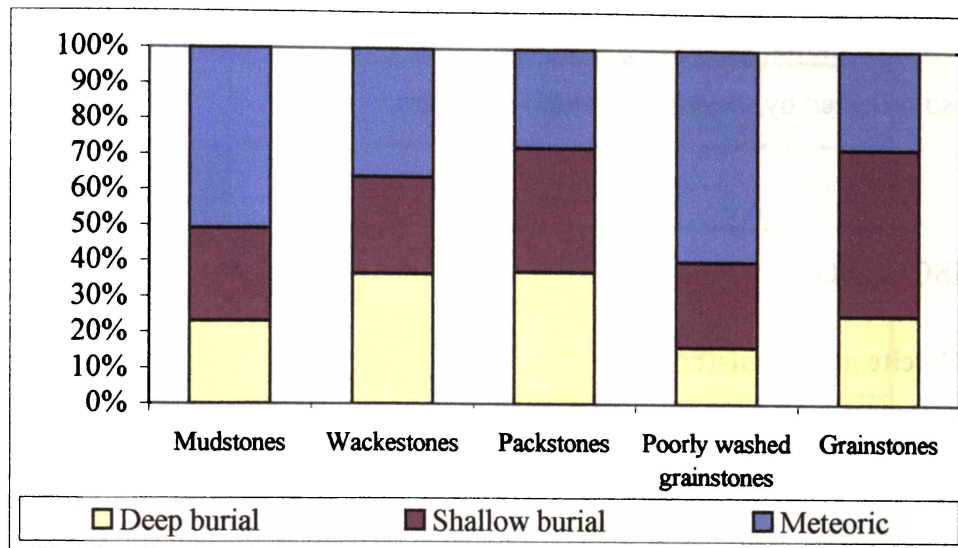


Fig. 6.22 Diagenetic signatures in (A) individual Tikorangi Formation petrofacies and in (B) non-dolomite-bearing calcitic and dolomite-rich samples of the Tikorangi Formation. A meteoric influence persists in the calcitic rocks and disappears in the dolomitic-rich samples (>15% dolomite). Both shallow burial and deep burial diagenetic signatures increase with increasing dolomite %. (C) Effect of dolomite % on diagenetic environmental signatures in the Tikorangi Formation.

regime which shows increasing influence with increasing dolomite percent, a trend also reflected by the shallow burial signature.

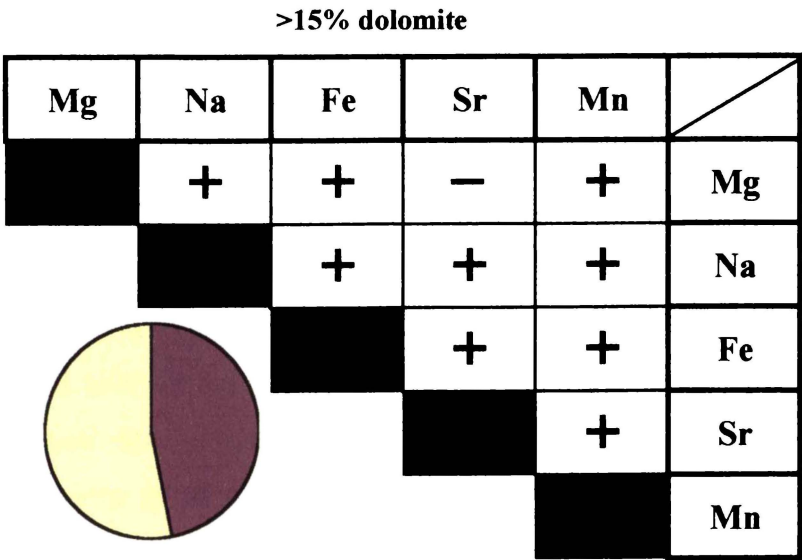
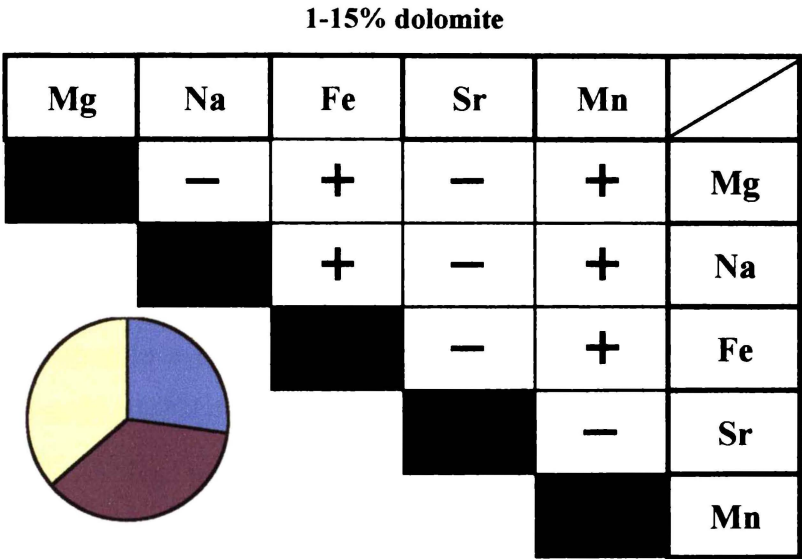
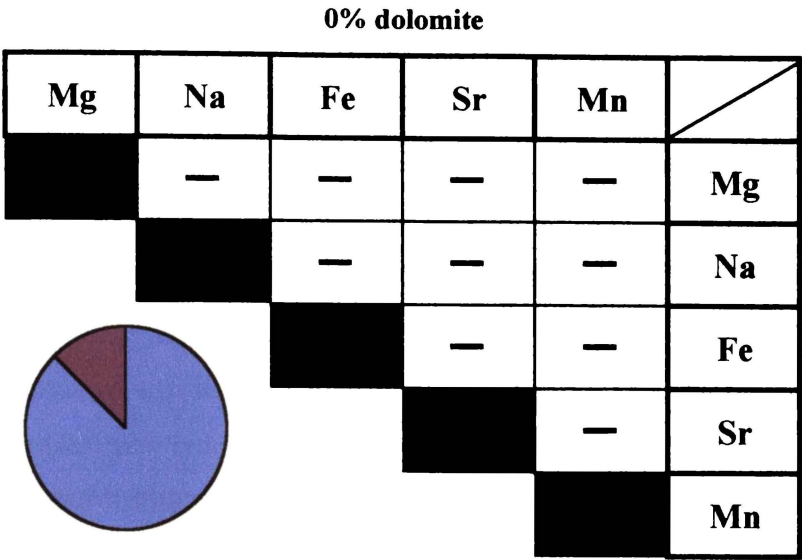
6.11 DISCUSSION

6.11.1 Calcite geochemistry

Elemental compositions of the Tikorangi Formation carbonates have provided data consistent with their formation in a temperate cool-water paleoenvironment. Skeletal mineralogies were dominated by LMC species controlled by relatively cool water temperatures ($< 20^{\circ}\text{C}$). Original IMC/HMC skeletons (echinoderms, benthic foraminifera, calcareous red algae, bryozoans) have been transformed to more stable LMC forms via incongruent dissolution, while rare originally aragonitic skeletons have been neomorphically transformed to LMC. Cements within the Tikorangi Formation are LMC containing 1-3 mol% MgCO_3 , characteristic of cool-water carbonate mineralogies and derivation from pressure dissolution of LMC skeletons (Nelson et al. 1988; Hood & Nelson 1996).

The interpretation of a ferroan calcite cement mineralogy from petrography is supported by Fe values from >2000 ppm to many thousand ppm, which are consistent with advanced diagenetic alteration of the carbonates (Winefield et al. 1996). Fe-rich or ferroan calcites are a common feature of those cements formed in reducing conditions associated with the burial environment (Tucker & Wright 1990) where Fe has been mobilised from the Fe-rich mixed siliciclastic-carbonate sediments to co-precipitate within the carbonate cements (Morse & Mackenzie 1990; Rao 1996).

Tikorangi Formation calcite cements are typically also enriched in Mn (>100 ppm), a characteristic of burial-related cements (Choquette & James 1990). Sr and Na values are low in comparison with bulk skeletal values for modern Tasmanian cool-water carbonates (Rao 1996), in agreement with Rao's suggestion that Sr and Na become relatively more depleted with cement formation.



■ Meteoric
 ■ Shallow burial
 ■ Deep burial

Fig. 6.23 Summary elemental matrices and pie diagrams for samples of Tikorangi Formation containing 0%, 1-15%, and 15+% dolomite showing increased burial influence in the more dolomitc-rich rocks.

6.11.2 Dolomite geochemistry

Tikorangi Formation dolomites typically form about 10% of samples, rarely up to 50%, and have been shown (Topic 6) to be scattered tiny euhedral rhombohedra selectively replacing matrix/micrite (Topic 5). Replacement dolomitisation would have involved the dissolution of a precursor carbonate and the precipitation of dolomite via a solution film associated with an intervening void (Purser et al. 1994).

Dolomite is both Ca- and Fe-rich non-stoichiometric dolomite. Morrow (1990a) states that saline solutions should produce dolomites markedly enriched in trace elements, as is found in the Tikorangi Formation. Geochemistry of these fluids may be comparable to those found in hypersaline settings forming Holocene dolomites producing metastable and Ca-rich dolomites which grew in solutions of high ionic strength.

The poor stoichiometric and fabric selective nature of the incomplete dolomitisation in the Tikorangi Formation is indicative of a closed system with high Sr and Na contents (Scoffin 1987; Tucker & Wright 1990), often associated with clay-rich micrites and shales (Morrow 1990b; Cioppa et al. 2000; Török 2000). Poor stoichiometry is also a function of their late diagenetic origin as older dolomites in the rock record world-wide tend to recrystallise to more stoichiometric ordered forms (Tucker & Wright 1990; Al-Aasam & Packard 2000). Dolostones of nearly stoichiometric dolomite are conversely thought to be a result of large-scale circulation of fluids providing Mg in an open system (Morse & Mackenzie 1990).

The Ca-rich nature of the Tikorangi Formation dolomites is suggestive of low Mg concentrations in the pore fluids, whereas Mg-rich solutions would have formed more stoichiometric forms (Rao 1996). Their Ca-rich nature is a result of incomplete Mg replacement of the calcite precursor, Ca being consumed in the newly formed dolomite rather than being released to produce Ca-rich dolomite from the equation: $\text{CaCO}_3 + \text{Mg}^{2+} + \text{CO}_3^{2-} \rightarrow \text{CaMg}(\text{CO}_3)_2$ (Rao 1996). Non-

stoichiometric dolomite is favoured at relatively lower temperatures of formation where lower Mg/Ca ratios favour non-stoichiometric and Mg-poor dolomite (Tucker & Wright 1990). Tikorangi Formation dolomites, having about 58 mol% CaCO_3 , are consistent in composition to most deep marine (burial) dolomites which typically contain 55-60 mol % CaCO_3 (Lumsden & Lloyd 1988).

Mg values average up to 51,000 ppm in dolomite-rich mudstones and in individual samples may reach 91,000 ppm (9.1 mol% MgCO_3). Mg sources were internally sourced from within clay-rich micrite, from the transformation of smectite to illite and from that bound to clay mineral surfaces. An additional source is likely to have been from chemical compaction of dominantly LMC and locally IMC/HMC where its preservation to burial depths occurred (e.g., Wanless 1979). Generally the pressure-dissolution of LMC for dolomite precipitation requires vast quantities to be dissolved (Morse and Mackenzie 1990), although it locally can provide an important source sufficient for the generally modest quantities of dolomite formed within the Tikorangi Formation. Such a LMC source would further account for a low Mg/Ca ratio (Nicolaidis 1997) encouraging non-stoichiometric dolomite formation.

Significant quantities of Fe^{2+} substituted for Mg^{2+} in the Tikorangi Formation dolomites. Higher Fe concentrations in the dolomites compared to the Tikorangi Formation calcites are a result of the Fe preferentially replacing Mg, which has higher values in dolomites compared to calcites. Average Fe values reach up to 35,400 ppm in dolomitic-rich mudstones (individually 92,000 ppm) attesting to the highly ferroan and poorly ordered nature of the Tikorangi Formation dolomites.

Ferroan dolomite is a common late diagenetic precipitate in the form of burial cements, which are commonly Fe- and Mn- rich, often containing over 5 wt% Fe (Moore 1989; Tucker & Wright 1990). Tikorangi Formation ferroan dolomites formed in reducing porewaters in conjunction with siliciclastic sediments (Lewis & McConchie 1994), reflecting the large amount of iron commonly present in the

siliciclastic system (Land 1983). In contrast to the Tikorangi Formation dolomites, those early formed shallow-burial dolomites and those involving meteoric fluids (mixing models) are both Fe- and Mn- poor due to oxidising conditions and the inability to incorporate Fe^{3+} into the crystal lattice (Tucker & Wright 1990; Dix 1993). Fe was supplied from oxide coatings on clays, and from within clay mineral structures, particularly that released with the transformation of smectite to illite (Tucker & Wright 1990). If iron mobilisation from basinal sediments or shaley carbonates was linked to clay mineral transformation then the optimum temperatures of 80-100°C would have been required for the release of Fe (Dix 1993). Using a geothermal gradient of 29°C/km in Taranaki Basin this would equate to burial depths of 2,800 to 3,500 m. These correspond to current burial depths, averaging about 3,000 m, having been uplifted from greater depths (Fig. 6.24). Such depths are also well below those associated with bacterial sulfate reduction (early shallow burial) where H_2S would not be available to react with Fe^{2+} enabling incorporation into the dolomite structure (Gregg 1988).

The Ca-rich nature of the Tikorangi Formation dolomites has also enabled abundant trace element substitutions, especially by Sr and Na, indicative of rapid crystal growth in solutions of high ionic strength in a structure with many faults and dislocations (Scoffin 1987). Na values are markedly higher in dolomite in comparison to calcitic phases, reaching up to 22,000 ppm, and are reportedly characteristic of those precipitated from more saline solutions (Rao 1996). Rao (1996) reports Na in dolomites ranging from low 100-2,500 ppm values in marine (Baffin Bay, Persian Gulf) to mixing zone dolomites and higher values in hypersaline dolomites (Rao 1996). Na enrichment also has been used by Burns et al. (1988) to be indicative of a calcite precursor, with the source of Ca and Mg unlikely to have been sea water but rather dissolution of pre-existing calcite. Dolomite precipitated from marine-derived fluids can have a high Na content and may well explain the values in the Tikorangi Formation dolomites. Ancient stabilised dolomites exhibit lower values again of only a few hundred ppm Na (Tucker & Wright 1990). Mn values in dolomite-bearing Tikorangi Formation carbonates are elevated (up to 1,420 ppm) in comparison with all of the non-

GEOHISTORY PLOT WAIHAPA-1 **Waihapa-Ngaere Field** **Onshore Taranaki Basin**

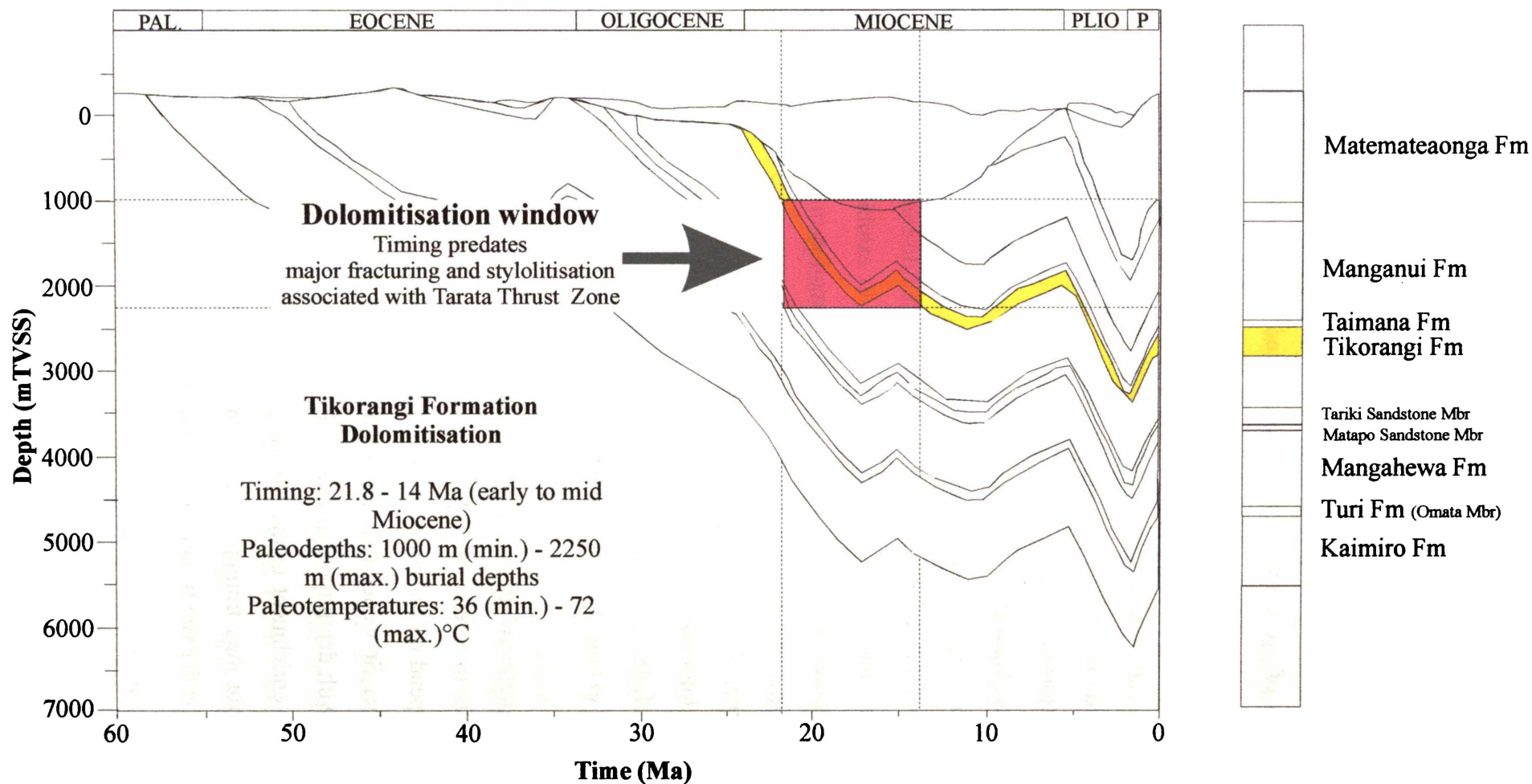


Fig. 6.24 Geohistory plot for Waihapa-1 within the Waihapa-Ngaere Field in close proximity to the onshore study wells used to constrain depths, temperatures, and timing of dolomitisation within the Tikorangi Formation.

dolomite bearing facies (220 ppm max.), the calcitic limestone age equivalents (up to 430 ppm), and the modern cool-water Tasmanian shelf carbonates (53 ppm). This results from the ability of Mn to substitute for Mg in dolomite, and the Tikorangi dolomite values reflect this.

Sr values of up to 15,000 ppm are elevated in dolomite-bearing facies and are higher than average values for bulk Tasmanian cool-water modern carbonates. High Sr concentrations are a result of the non-stoichiometric character of the dolomite and abundant lattice imperfections that can incorporate Sr, which can also substitute for Ca in the dolomite lattice (Zenger & Dunham 1988; Morrow 1990a). Stoichiometric dolomite has only about 50 ppm Sr, but Sr averages 3,500 ppm in the Tikorangi Formation. Modern marine and hypersaline dolomites have Sr concentrations of 600 ppm, while ancient dolomites contain as little as 200 ppm Sr pointing to expulsion during dolomite stabilisation (Scoffin 1987). Many subsurface enriched saline brines are reported to exhibit high Sr/Ca ratios, the high Sr values being indicative of dolomite formation in a closed marine system with no meteoric flushing (Tucker & Wright 1990). Tucker & Wright (1990) suggest that Sr values >500 ppm should be precipitates of hypersaline fluids. Modern dolomites in pelagic sediments from the Gulf of California have Sr contents of 300-700 ppm, while Sr values of 3,000 ppm in Jamaican dolomites are attributed to closed system dolomitisation (Tucker & Wright 1990).

Sr being preferentially excluded from the crystal lattice (Nicolaidis 1995) enables pore fluids in a relatively closed system to become Sr-enriched with time. As values depend on the composition of the pore fluids, hypersaline dolomites will have higher Sr values than marine dolomites. Sr/Ca ratios commonly show an increase with depth through release of Sr^{2+} from the sediment (Tucker & Wright 1990). Sr-enrichment in the Tikorangi Formation dolomites may alone provide evidence for their timing of formation as post-dating the dominant LMC cement precipitation derived from pressure dissolution (see Topic 5).

Modern marine and hypersaline dolomites have Sr contents of 600 ppm, yet few

ancient dolomites have more than 200 ppm with Sr having been expelled during stabilisation to a more ordered form (Scoffin 1987). In any recrystallisation of dolomite Sr will be lost (Tucker & Wright 1990). The high levels in the Tikorangi Formation dolomite-rich rocks are therefore suggestive of young age and the unstabilised nature of the dolomites. Generally poorly ordered calcian dolomites are metastable and should recrystallise with loss of Sr given a sufficient period of time (Lewis & McConchie 1994). Once expelled, Sr is then available to form celestite (Land 1983). High Sr values have been documented in deep-sea oozes and may form SrSO_4 (celestite) (Baker 1986). Aragonitic bivalves are relatively rich in Sr which is thought to be released following neomorphic transformation of aragonite to calcite. Petrographic observations place the timing of dolomite formation in the Tikorangi Formation as post-dating the neomorphic transformation of aragonite, which may have provided a Sr source.

6.11.3 Clay mineralogy

Scattered dolomite rhombs in argillaceous limestones suggest that Fe, Mg, and Ca may have been released during conversion of smectite to illite at elevated temperatures during burial (Tucker & Wright 1990). XRD analysis has shown smectites in the Tikorangi Formation to be dioctahedral with Ca and/or Mg as the exchangeable cation associated with two layers of water, so a local source of Mg was likely. Fe^{2+} , Ca^{2+} , Si^{4+} , and Na^+ are also likely to have been released in the conversion of smectite to illite ($\text{smectite} + \text{Al}^{3+} + \text{K}^+ = \text{illite} + \text{Si}^{4+}$) (Gregg 1988; Berger et al. 1999), which may aid in the explanation of high Na values in dolomite-bearing facies.

The remaining presence of detectable but small amounts of smectite, mixed-illite intermediates, and illite in the Tikorangi Formation, as also occurs in the age equivalent limestones cropping out in nearby North Wanganui Basin (Nelson & Hume 1987), is suggestive of insufficiently deep burial and high temperatures to fully complete the clay mineral transformation. Present burial depths are about 3 km. A lack of evidence for obvious feldspar dissolution suggests the Tikorangi Formation smectites currently reside in the shallow 1.85-3.0 km deep ion-

exchange zone of Gier (1998). He has distinguished three depth-related reaction zones for illite formation beneath the Gulf of Mexico: K-ion exchange stage resulting in smectite transformation to illite in a shallow 1.85-3 km zone; illite neoformation from dissolution of coarser K-bearing phases and smectite by organic acids in a middle zone (3 - 4 km); and illite recrystallisation at > 4 km depth. Clearly the smectite to illite transformation mechanism involves mixed-layer intermediates, as identified in the Tikorangi Formation, while the overall controlling factors on the reaction are temperature and burial time (Gier 1998).

6.11.4 Diagenetic environments

The use of summary elemental matrices as devised by Winefield et al. (1996) can be useful for supporting diagenetic environmental interpretations based on more conventional petrographic studies. However, too strict an application of this technique to the Tikorangi Formation may be inappropriate because of its ubiquitous dolomitic nature and the significant TE enrichment of the dolomite phases. Geochemical diagenetic signatures obtained across the range of non-dolomitic to dolomite-rich samples in the Tikorangi Formation using this method have produced interesting results, namely that no meteoric influence is evident in the dolomite-rich samples yet this influence persists in the wholly calcitic rocks. This persistent but small meteoric influence, based on face values of the elemental summary matrices, is evident within all calcitic rock types and is most noticeable in the more carbonate-poor micritic/matrix/siliciclastic-rich rocks. Possibly the combination of low carbonate contents and relatively enriched fine siliciclastic material affords the wrong facies for direct application of the summary elemental matrix approach to elucidating diagenetic environments.

Given the continuing residence of the Tikorangi Formation within the burial environment following deposition it is initially difficult to envisage any major meteoric influence in the subsurface (Fig. 6.24). However, given the post-lithification fracturing of these rocks, the introduction of pore fluids including a meteoric component is possible. According to Brand (pers. comm. 1999), this is the situation today beneath Taranaki peninsula. This may imply dissolution and

reprecipitation of small amounts of calcite which have taken on a meteoric diagenetic signature reflected in TE summary plots. This may have occurred by slow diffusion of meteoric-tainted fluids, with dissolution and recrystallisation occurring on a micro-scale with no intervening void, after dolomitisation and tectonic fracturing events. In diagenetic studies of sandstones within Taranaki Basin late (burial environment) calcite is thought to have formed in Eocene Kapuni Group from meteoric-derived fluids (Smale et al. 1999). The occurrence of the most significant meteoric signatures in the more micritic/matrix-rich facies may have resulted from some uncemented porosity and preferential alteration of the tiniest calcite crystals with the highest surface to volume ratios.

6.12 CONCLUSIONS

Trace element geochemical and X-ray diffraction analysis of the Tikorangi Formation carbonates have provided data consistent with skeletal formation and deposition in a temperate cool-water paleoenvironment, followed by later burial diagenesis under reducing conditions with pressure-dissolution of dominantly LMC skeletons to produce ferroan (> 2000 ppm Fe) LMC cements characteristic of cool-water carbonate mineralogies. Fe was mobilised from the Fe-rich mixed siliciclastic-carbonate sediments to co-precipitate within the carbonate cements. Tikorangi Formation calcite cements are typically enriched in Mn (>100 ppm) and depleted in Sr and Na in comparison with bulk skeletal values for modern Tasmanian cool-water carbonates, characteristics of burial- related cements.

Later burial dolomitisation by selective and partial replacement of often highly bioturbated clay-rich micrite/matrix involved the dissolution and incomplete Mg replacement of the calcite precursor because of low Mg pore-fluid concentrations. Slow precipitation of dolomite from relatively saline-enriched pore fluids occurred under reducing conditions in a diagenetically closed system, producing trace element-rich, metastable, Ca-rich, non-stoichiometric ferroan dolomite. Mg sources may have been supplied by chemical compaction of dominantly LMC and

locally IMC skeletal grains, and by Mg released from smectite to illite transformation. The metastable, poorly ordered, non-stoichiometric nature of the dolomites is testament to their relatively “young age” and late burial diagenetic origin.

Higher Fe concentrations in the Tikorangi Formation dolomites compared to the calcites is a result of Fe replacing Mg. Fe was supplied from siliciclastics and from Fe (and also Mg) within clay mineral structures, particularly associated with the transformation of smectite to illite.

The Ca-rich dolomites had many lattice imperfections which enabled abundant trace element substitutions, especially by Sr and Na, from evolved solutions of high ionic strength and Sr content. Mn values are elevated because of the ready ability of Mn to substitute for Mg (Tucker & Wright 1990). Given time, the Tikorangi Formation dolomites are likely to recrystallise to more stable stoichiometric forms.

The TE geochemistry of the Tikorangi Formation has been shown using element-element plots to have many affinities with modern Tasmanian cool-water LMC and IMC carbonates (Fig. 6.25), involving elevated Mg, Na, and Sr values in relation to ancient LMC New Zealand limestones. Enriched trace element values are directly attributable to the presence of burial-derived dolomites in the Tikorangi Formation, which is in contrast with the anticipated lowering of these element concentrations with progressive carbonate diagenesis in calcitic limestones. In many respects the elevated Mg concentrations have “falsely” more affinities with modern Bahaman aragonitic and HMC-dominated carbonates than with modern cool-water examples, while the highest Mg values are comparable to those of ancient warm-water Ordovician Tasmanian carbonates; the apparent anomalies are explained by the presence of dolomite in the Tikorangi Formation. Fe levels in the Tikorangi carbonates far exceed both modern and ancient cool- and warm-water analogues (Fig. 6.25) and point to very Fe-rich pore fluids probably sourced from compaction in interbedded siliciclastic shale-like

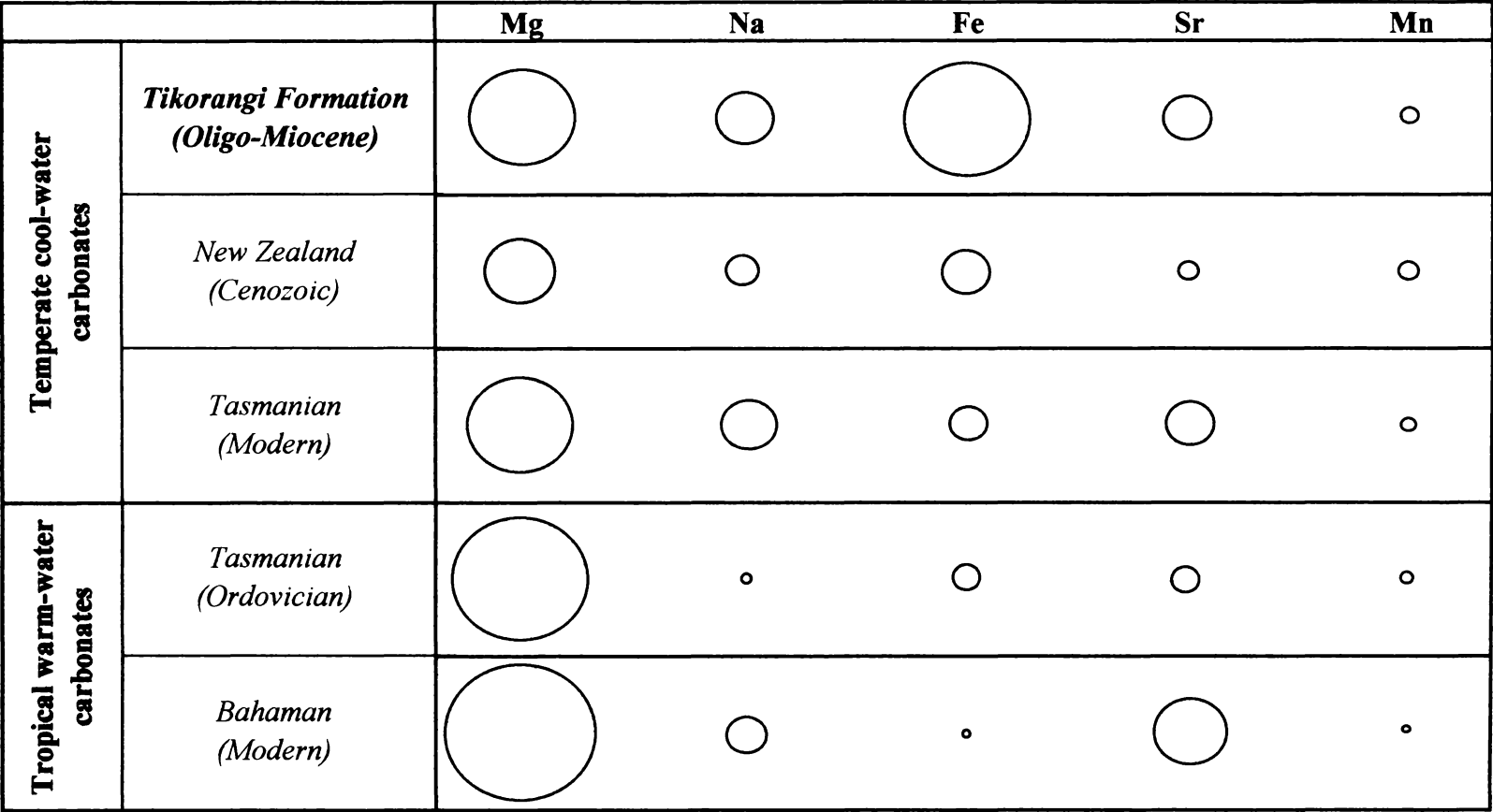


Fig. 6.25 Schematic summary of relative abundances of trace elements in the Tikorangi Formation and comparison with other temperate cool-water and tropical warm-water carbonates. The radius of the circles is roughly proportional to the average concentration of each element in the respective samples. Modified from Winefield et al. (1996).

sequences. Elevated Mn levels are similarly attributable to dolomite formation at considerable depths and elevated temperatures. Sr values are enriched in dolomite-bearing facies and are higher than average values for bulk Tasmanian cool-water modern carbonates and approach values found in modern Bahaman carbonates (Fig. 6.25).

Trace element data used in conjunction with more traditional petrographic data have aided in the diagenetic interpretation of the carbonate-dominated Tikorangi sequence. Results have been particularly useful for providing more definitive evidence for burial dolomitisation of the deposits and the general nature of associated pore fluids. An absence of any meteoric influence derived from elemental summary matrices in dolomite-rich samples further reinforces their marine burial origin. Given the modest proportion of very small dolomite crystals with commonly intricate CL zoning, the bulk geochemical approach can be defended as an evolving technique with the ability to provide perhaps more meaningful data than that which may have been derived from microprobing specific crystal zones.

This study has contributed to the paucity of geochemical data for carbonates generally and to cool-water carbonates more specifically, at the same time providing bulk trace element data for a mixed dolomite-calcite temperate sequence. The occurrence of dolomite is rarely reported in New Zealand Cenozoic carbonates, and from cool-water carbonates more generally, and is shown here to have had a dramatic effect on the bulk rock elemental geochemistry in comparison with most other cool-water calcitic carbonate occurrences. The elemental geochemistry supports a marine burial origin for the temperate dolomites in the Tikorangi Formation carbonates. Current models of cool-water carbonates, both diagenetically and geochemically, remain under development, with aspects such as dolomitisation requiring incorporation into these evolving models. Variables in the dolomitisation equation, such as association with siliciclastics and clay mineral transformations as key trace element providers, the openness of the diagenetic system, subsurface temperatures, pressures, and residency time, are all key factors worthy of future study. Some of these factors may explain the paucity

of dolomite in age-equivalent New Zealand limestones, which typically experienced shallower burial depths and shorter burial residency times than is the case for the Tikorangi Formation (Nelson 1978; Nelson et al. 1988; Hood & Nelson 1996).

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FRACTURE-INDUCED POROSITY AND VEIN MINERALISATION IN THE HYDROCARBON-PRODUCING EARLY MIOCENE TIKORANGI FORMATION, WAIHAPA-NGAERE FIELD, TARANAKI BASIN, NEW ZEALAND: EVIDENCE FOR METEORIC AND BASINAL BRINE MIXING

7.1 ABSTRACT

The fractured carbonate-dominated Tikorangi Formation is a unique play and prolific oil producer within Taranaki Basin, New Zealand. Hydrocarbons are hosted and produced from open, tectonically-induced fracture systems formed by Neogene overthrusting. Productivity has been ultimately determined by tectonism, original depositional facies, and diagenetic processes. Repeated fracturing, dilatation and episodic fluid flow in response to tectonic loading precipitated a calcite-baroque dolomite-celestite-quartzine vein mineral assemblage which substantially healed and reduced fracture porosities and permeabilities prior to major hydrocarbon emplacement. Petrographic, trace element, stable isotope ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$), and fluid inclusion data are consistent with complex and varied pore fluid geochemistries and have enabled a paragenetic sequence of eight major diagenetic and mineralisation events to be determined. Vein mineralisation records a history of changing pore fluid chemistry and heating during burial, punctuated by changes in the relative input and mixing of downward circulating meteoric and upwelling basinal fluids.

The earliest Miocene Tikorangi Formation host rock was cemented by calcite microspar (event 1) during burial diagenesis, which began at temperatures of about 20°C, corresponding to 0.5 km burial, and continued until about 1 km burial depth some 2 m.y. after deposition. By this stage the limestones had strongly pressure-dissolved fabrics and were tight with essentially zero porosity and permeability. They were partially dolomitised (event 2) at burial depths and temperatures of 1.0–1.5 km and 36–50°C over a duration of some 2 m.y.

Subsequent brittle fracturing (event 3) is constrained to a period following lithification and dolomitisation, but before precipitation of first generation vein calcite (event 4). This calcite has dull luminescence, is isotopically depleted and fluid inclusion-rich, and was rapidly precipitated as ferroan low-Mg calcite from Fe-rich, meteorically-modified marine fluids at temperatures of about 50-60°C at burial depths of 1.4-1.8 km, from about 20-18 Ma. Mixing occurred by deep downward percolation of groundwaters, particularly in cascade zones during seismic pumping/draw-down events. Dull to non-luminescent, isotopically depleted, fluid-inclusion poor, trace element enriched, non-stoichiometric baroque dolomite formed slowly (event 5) following a period of Mg-enriched basinal fluid input. The dolomite formed mainly as a primary cement but also as a calcite replacement at temperatures of 65-80°C, corresponding to burial depths of 2-2.5 km, and was also associated with volumetrically minor precipitates of quartzine and celestite (event 6). These three minerals could have formed over a period spanning some 12 m.y. from 17.5–6 Ma, and cannot be considered to be mutually exclusive. Ferroan second generation low-Mg calcite formed (event 7) at cooler temperatures (53-65°C) and shallower depths of burial (1.6–2.0 km) over a period of some 3 m.y. following a period of inversion. The presence of petroleum fluid inclusions in second generation calcite suggests in some cases precursory hydrocarbon-bearing fluids have migrated along with aqueous fluids since about 8 Ma, but the major period of hydrocarbon emplacement (event 8) has occurred over the last 5 m.y.

Keywords fracture porosity; vein minerals; hydrocarbons; Tikorangi Formation; fractured reservoir; limestone; carbonate geochemistry; trace elements; stable isotopes; Miocene; Waihapa-Ngaere Field; Taranaki Basin

7.2 INTRODUCTION

The discovery in 1988 of the Waihapa oil field in southern onshore Taranaki within the fractured carbonate-dominated Tikorangi Formation (Simpson 1992) opened up a new play in Taranaki Basin, New Zealand's only commercially producing hydrocarbon basin (Fig. 7.1 A, B) (King & Thrasher 1996). The earliest

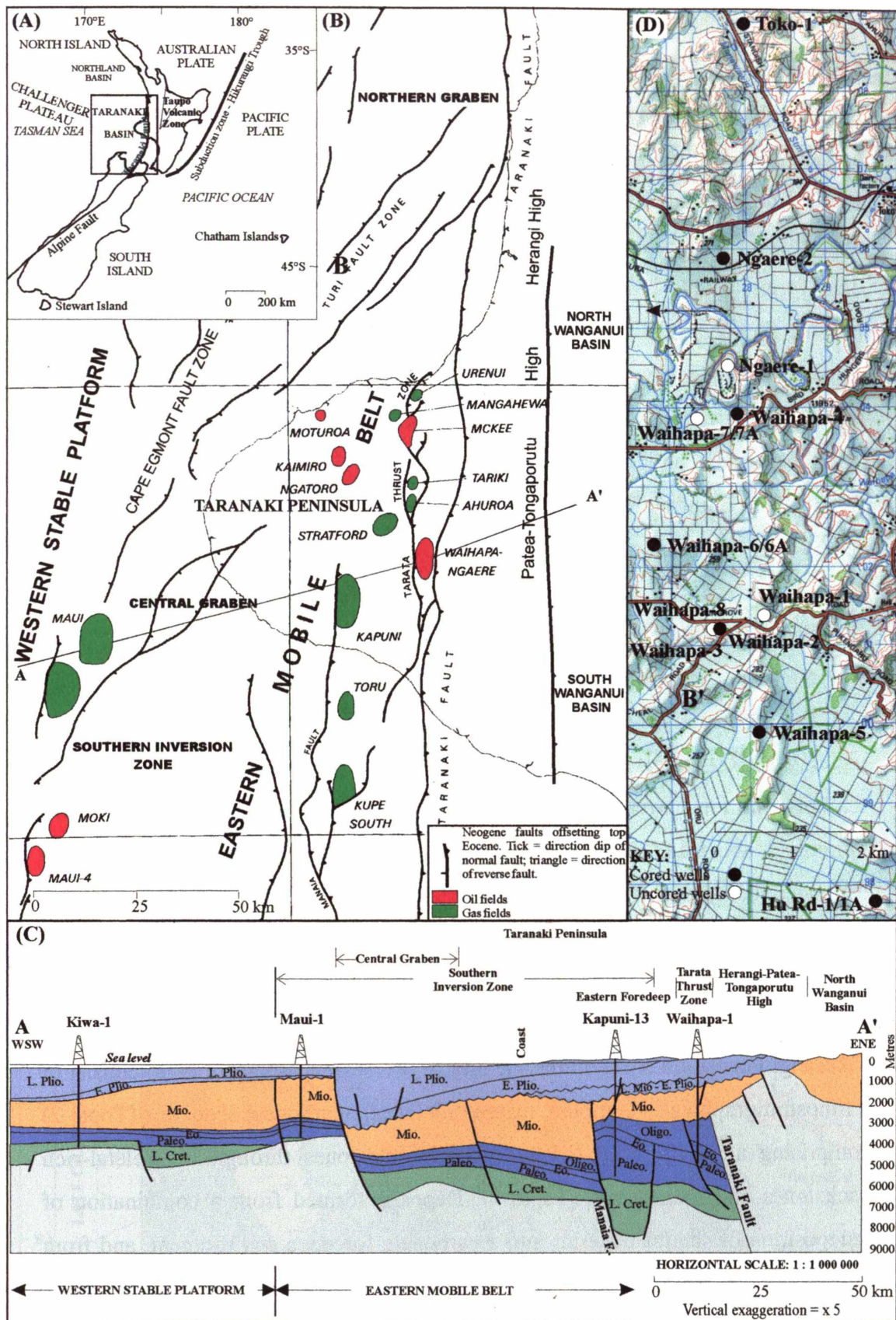


Fig. 7.1 (A) Location of Taranaki Basin in New Zealand. (B) Major structural and tectonic elements and main oil/condensate accumulations within Taranaki Basin. The Tikorangi Formation is dated as earliest Miocene in the east (Waihapā-1) and Oligocene-Early Miocene in the west (Maui-1). Adapted from King & Thrasher (1996). (C) Structural cross-section of a transect running WSW - NE through offshore Maui-1 and onshore through the Waihapā-Ngaere Field, Tarata Thrust Zone (see location in B). Adapted from King & Thrasher (1996). Shading: = late Neogene, = early Neogene, = Paleogene, = Late Cretaceous, = basement. E. Plio. = Early Pliocene; L. Plio. = Late Pliocene; Mio. = Miocene; Oligo. = Oligocene; Paleoc. = Paleocene; L. Cret. = Late Cretaceous. E. Plio. = Early Pliocene; L. Plio. = Late Pliocene; Mio. = Miocene; Oligo. = Oligocene; Paleoc. = Paleocene; L. Cret. = Late Cretaceous. (D) Location of the seven onshore wells (solid circles) providing core from the Tikorangi Formation within the Waihapā-Ngaere Field that form the basis for this study.

Miocene limestone-rich reservoir (Fig. 7.2) hosts hydrocarbons in open, but often extensively mineralised fracture systems formed by Neogene overthrusting (see section 7.3). Until 1988, all Taranaki Basin production had come from internally hosted, porous, siliciclastic sandstones (King & Thrasher 1996; Smale et al. 1999). The fractured limestone play is dominantly an oil-producer with economic discoveries to date limited to the Waihapa Field and its northern extension the Ngaere Field. The Waihapa-Ngaere Field is located within the Tarata Thrust Zone, a zone of intense deformation in eastern Taranaki Peninsula (Fig. 7.1B, C) (King & Thrasher 1996). Hydrocarbons migrating within proximity to the closed Waihapa-Ngaere anticlinal structure have been trapped, whereas in areas away from intense deformation the Tikorangi Formation forms a seal (King & Thrasher 1996).

Where the Tikorangi Formation is fractured and positioned within the appropriate structural environment, it has continued to be a prime reservoir target. Six years ago, the Waihapa-Ngaere Field was the biggest onshore producer in Australasia, yielding 18,000 barrels of oil a day (BOPD) with initial reserves estimated at 22.9 mmbbls (million barrels) (MOC 2000). Oil production for 1998 was about one mmbbls at about 1,000 bbl/day (barrels per day). Current known oil reserves are estimated at only 1.4 mmbbls (MOC 2000). The Tikorangi Formation has continued to attract both recent and on-going exploration activity in new prospecting areas outside the currently producing fields.

Tikorangi Formation rocks in the vicinity of the Waihapa-Ngaere Field consist of a lithostratigraphically complex, mixed siliciclastic-carbonate sequence (Topic 2) comprising a spectrum of siliciclastic-rich mudstones through to skeletal-rich packstones and grainstones (Topic 4). Deposits formed from a combination of redeposition of shelfal material into a carbonate foredeep environment, and from intermixing or interbedding with deeper water sediments (Topic 3). This intermediary outer shelf to slope setting was part of a wider shallow shelf to basin depositional system present during and at the climax of a basinwide marine transgression in Taranaki Basin in the earliest Miocene (King & Thrasher 1996).

Carbonate-dominated rocks such as the partially dolomitised limestones of the

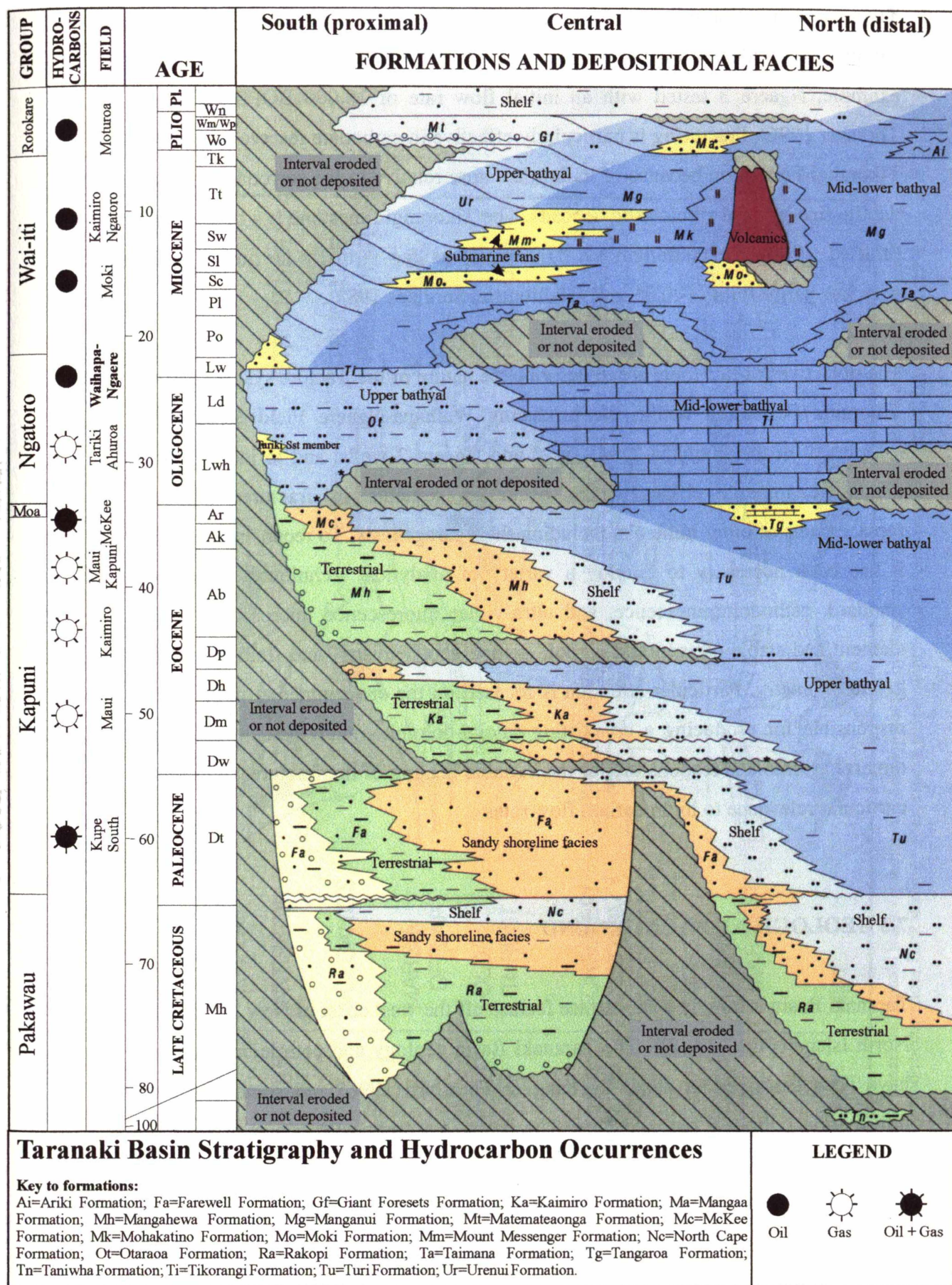


Fig. 7.2 Taranaki Basin stratigraphy, depositional facies, and hydrocarbon fields and occurrences. The Tikorangi Formation carbonates form part of the Ngatoro Group. Modified from King & Thrasher (1996). New Zealand stage symbols are defined in Appendix 1.2.

Tikorangi Formation that have been subjected to deep burial diagenesis (Topic 5) can provide an ideal lithology for high fracture-production rates (North 1985). For example, Ngaere 3 tested with an initial flow rate of 10,000 BOPD (King & Thrasher 1996). Fracturing is particularly effective in carbonate reservoirs like the Tikorangi Formation because of its brittle nature relative to the surrounding more ductile fine-grained siliciclastic deposits. The Tikorangi limestone is a dense, well lithified, strong rock (strength av. 37,000 psi) having virtually no porosity and very low permeability (<0.01 md) (Halliburton Services 1988).

The objectives of this topic are to describe the nature of the fracture systems in the Tikorangi Formation within the producing Waihapa-Ngaere Field using core samples from the Waihapa-2, -4, -5, -6 and Ngaere-2 wells, and to identify late diagenetic mineral phases which occur as cements in fractures and as replacements of other minerals, including their paragenesis. To reconstruct events it has been necessary to employ a variety of analytical techniques, including standard, cathodoluminescence, and ultra-violet fluorescence microscopy, trace element and stable oxygen and carbon isotope geochemistry, and fluid inclusion geothermometry. Particular attention is focused on the environmental parameters responsible for producing a co-existing calcite-dolomite-quartzine-celestite vein mineral assemblage responsible for the variable healing of the fractures, and is of particular relevance to hydrocarbon flow rates.

7.3 GEOLOGICAL BACKGROUND

Taranaki Basin is largely a subsurface feature off the west coast of New Zealand's North Island (Fig. 7.1A, B). The Taranaki Basin geology and petroleum systems have been described in detail by King & Thrasher (1996) and some relevant information is briefly outlined here. The basin is a composite one with several distinct phases of evolution that have provided a proven geological setting for the generation and entrapment of hydrocarbons (Fig. 7.3). The sedimentary fill records a Cretaceous through Cenozoic depositional megacycle involving an overall transgressive phase from the Late Cretaceous to Early Miocene followed by a regressive phase which remains ongoing (King & Thrasher 1996).

AGE		TARANAKI BASIN HISTORY		HYDROCARBON ELEMENTS
~Ma				
NEOGENE	5-0	RIFT		STRUCTURE/ BURIAL + MATURITY
	5-0	MARGIN OFFLAP		
	10-5	INVERSION		STRUCTURE
	13-8	VOLCANICS		STRUCTURE +RESERVOIR
	18-5	MARGIN OFFLAP		RESERVOIR /SEAL
	22-10	FOLD/ THRUST		STRUCTURE
PALEOGENE	32-23	FOREDEEP/ PLATFORM SUBSIDENCE	 	RESERVOIR /SEAL
		PASSIVE MARGIN		RESERVOIR /SEAL SOURCE
	60+	RIFT		SOURCE

Fig. 7.3 Major phases of Taranaki Basin evolution and development of hydrocarbon system elements. Black dots represent position of known hydrocarbon occurrences. Dark shading = source rocks, pale shading = clastic reservoir rocks. (After King & Thrasher 1996).

A passive margin setting changed in the Oligocene with the development of the Australia-Pacific convergent plate boundary through New Zealand. Subsidence started at about 35 Ma in northern areas of basin and moved southwards and eastwards reflecting progressive foundering of the shelf (King & Thrasher 1996). The Ngatoro Group, a carbonate-dominated sequence of Oligocene to Early Miocene age, was deposited into a rapidly subsiding foredeep (Fig. 7.2, 7.3). A major convergent phase began with renewed tectonism about 21-22 Ma when basement was thrust westwards along the major east-dipping reverse Taranaki Fault to override the Tikorangi Formation reflector dated at 22.5-23 Ma (King & Thrasher 1996). During this compressive phase, the basin was partitioned into two distinctive tectonic settings: an active margin (Eastern Mobile Belt) and a passive margin (Western Stable Platform) (Fig. 7.1B, C).

The Eastern Mobile Belt is a broad region of Neogene tectonic deformation comprising two sectors: the Southern Inversion Zone; and the Tarata Thrust Zone which has experienced up to 7 km of contraction (Fig. 7.1B, C) (King & Thrasher 1996). Palmer & Andrews (1993) suggested the timing of major thrusting occurred in the Late Miocene, while King & Thrasher (1996) suggested that movement on both the Tarata Thrust Zone and the Taranaki Fault in the Early-Middle Miocene represents the earliest substantial movement within the basin in the Neogene. The Tarata Thrust Zone delineates a major zone of intense deformation in which a number of stratigraphic traps, including the Waihapa-Ngaere Field structure, are located. The zone comprises a series of imbricate en echelon thrust faults (thin-skinned overthrusting) and associated anticlines which contain most of the petroleum occurrences discovered to date (Fig. 7.4) (King & Thrasher 1996).

The Waihapa-Ngaere structure at the producing level is an asymmetric north-south trending anticline with a steeply dipping western flank (30-40°) and a gently dipping eastern flank (15°). Thinning of the Taimana and Manganui Formations (above the Tikorangi Formation; Fig. 7.2) onto the anticline indicates that structuring occurred during the Early Miocene (PEL 1995), in agreement with King & Thrasher (1996).

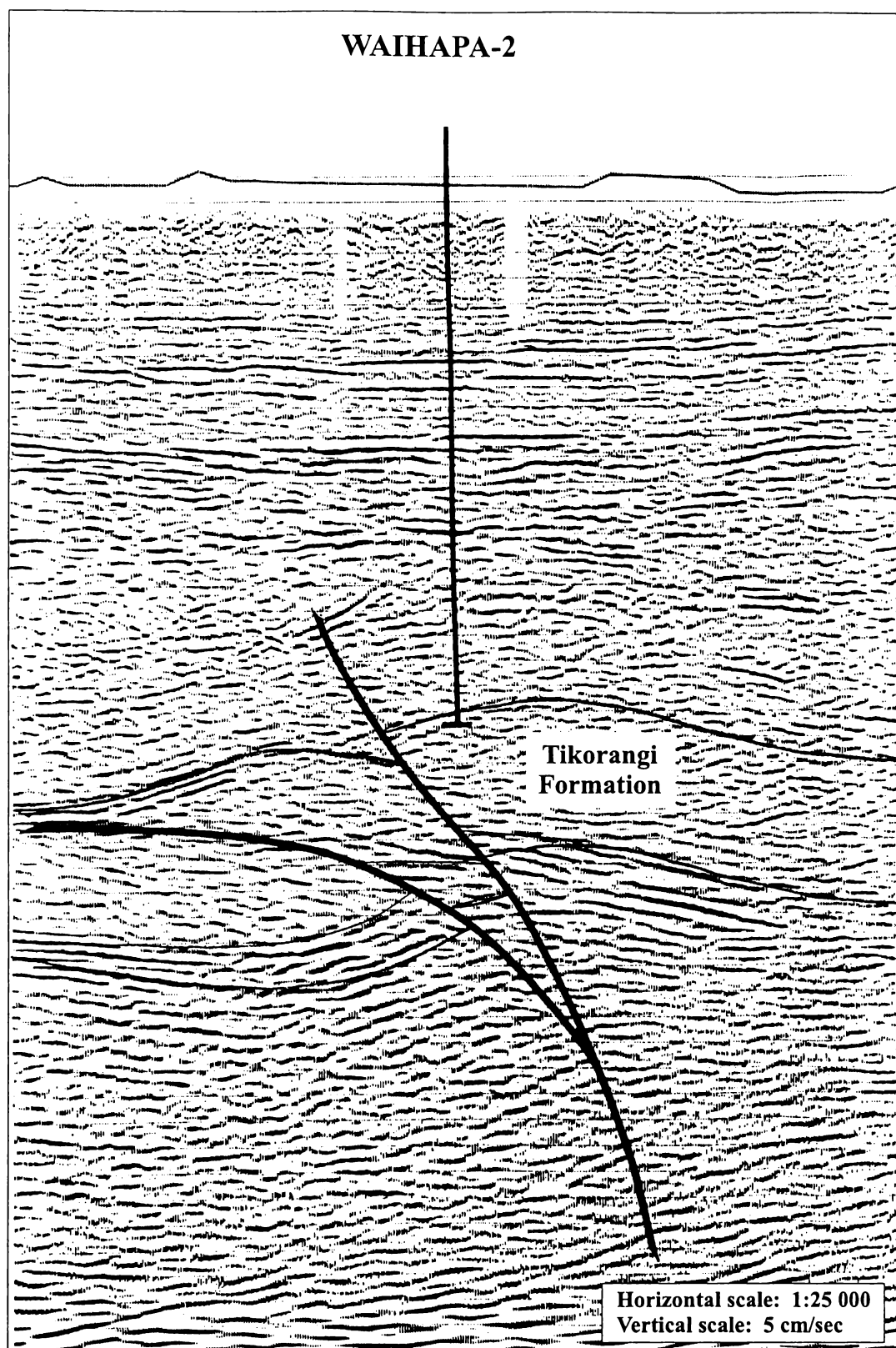


Fig. 7.4 Seismic reflection profile showing Tikorangi Formation overthrusts in the Waihapa-2 well, Waihapa-Ngaere Field, Tarata Thrust Zone, formed as a result of Miocene tectonic compression. For location see Fig. 7.1.

7.4 PREVIOUS WORK

Kamp & Hood (1994) conducted a reconnaissance study of vein mineralisation in samples from the Waihapa-Ngaere Field. The work was undertaken without reference to any stratigraphic or structural data for the sample wells, and so genetic interpretations were limited. Relevant data from that unpublished report are incorporated in this wider study and placed within the stratigraphic/structural framework now established.

Other contracted studies for Petrocorp Exploration (now Fletcher Challenge Energy) are typically rather specific in aim, and often generalised in content, but provide some data relevant to this study, especially porosity and permeability measurements. These limited studies include van der Lingen's (1993) study of fractures and stylolites within the Tikorangi Formation in the Waihapa Field; Halliburton Services (1988) reporting of basic geotechnical data for the Tikorangi Formation; Johnston's (1990) report evaluating the prospectivity of the Tikorangi Formation; and the structural studies by MacFarlan (1993) and Barr (1993) on core samples from the Waihapa-2 and Ngaere-2 wells, respectively.

7.5 METHODOLOGY

A variety of data were obtained from thin-sections of vein and host rock samples. Selected thin-sections were etched and stained to distinguish ferroan and non-ferroan varieties of calcite and dolomite (Dickson 1965). Ferroan calcite develops a mauve-royal blue stain, whereas non-ferroan calcite appears very pale pink-red. Ferroan dolomite stains a green/blue colour, while non-ferroan dolomite remains un-coloured. Calcite cements were further differentiated from dolomitic cements by visibly lowered topographic relief due to acid etching. Thin-section photographs were taken using plane polarised light (PPL) and cross-polarised light (CPL) on 100 and 200 ASA Kodak colour print film.

Other thin-sections were ground for cathodoluminescence (CL) study using 800 grit then 1200 grit metallographic grinding paper for about two min., followed by

polishing with 3 µm diamond compound for two min. CL observations were made on a Technosyn Cold Cathodoluminescence 8200 MkII stage using a gun voltage of 14 kV and a gun current of generally 350-400 µA. Photographs were captured using 400 ASA colour print film and typical exposure times of 8-10 min. Selected thin-sections, slabs, and doubly polished wafers were examined under incident light UV fluorescence provided by a blue UV light source to help identify hydrocarbon-bearing fluid inclusions, which fluoresce intense white (Dravis & Yurewicz 1985; Goldstein & Reynolds 1994).

Doubly-sided polished wafers for fluid inclusion analysis were made using standard techniques (Shepherd 1985). Wafers were polished on both sides using 3 µm diamond polish. Homogenisation temperatures (T_h = minimum temperature of mineral formation) and freezing temperatures (T_m ice = temperature of final melting of ice) of liquid-gas inclusions were measured using a USGS gas-flow heating/freezing system (Fluid Inc.) in accordance with the manufacturers specifications. The salinity of precipitation waters was estimated using derived T_m values where $\text{NaCl (ppt)} = 0.17 - (19.22 \times T_m) - (0.93 \times T_m^2) - (0.34 \times T_m^3)$ after Goldstein & Reynolds (1994).

X-ray diffraction (XRD) analysis of individual crystals, of drillings of vein minerals, and of samples of host limestone were undertaken on un-orientated powder mounts using a Philips Analytical X-ray Diffractometer with a PW1729 X-ray generator and a PW 1840 diffractometer control. A scan range of 20-40°2θ was typically used at a scan speed of 0.5°2θ/min. and a chart speed of 20 mm/min. Samples were spiked with analytical grade NaCl to enable determination of exact peak positions.

Trace element geochemistry was determined for representative vein mineral samples of calcite and dolomite. Powders were prepared using a ringmill with a tungsten-carbide head to prevent any iron contamination. Samples were acidified following the procedures of Robinson (1980) and Winefield (1995), which involved digestion of 1 g of powdered sample in 1M HCl. Following appropriate dilution, the sample solutions were analysed for Ca, Mg, Na, Fe, Sr, and Mn using

a GBC909AA double beam atomic absorption spectrophotometer. Winefield (1995) provides more specific details of analytical technique. Errors are $\pm 1\%$ for Ca and Mg, and ± 5 ppm for Sr, Na, Mn, and Fe.

Stable oxygen ($\delta^{18}\text{O}$) and carbon ($\delta^{13}\text{C}$) isotope analysis of selected samples was undertaken using a VG Micromass 602E Mass Spectrometer. Samples were powdered and completely reacted with 100% orthophosphoric acid at 90°C , typically for about 2 hours for calcite samples and 24 hours for dolomite. The evolved CO_2 was separated, purified and isotopically analysed in relation to a locally produced CO_2 reference gas (Waikato Limestone Standard) previously calibrated by daily comparison with sub-samples of the international standard NBS-19. The isotope data are expressed in conventional per mil (‰) deviations from the Pee Dee Belemnite Standard and have an analytical precision of better than ± 0.05 ‰ for $\delta^{13}\text{C}$ and ± 0.10 ‰ for $\delta^{18}\text{O}$.

Paleotemperatures have been derived from the $\delta^{18}\text{O}$ data. Values have been calculated using a range of water (SMOW) values (-1‰ , 0‰ , $+1\text{‰}$ PDB) for slightly meteorically influenced through to slightly enriched marine. For calcitic samples the paleotemperature equation of Shackleton (1967) was used: $T(^{\circ}\text{C}) = 16.9 - 4.38(\delta^{18}\text{O}_{\text{c-w}}) + 0.1(\delta^{18}\text{O}_{\text{c-w}})^2$ where $\delta^{18}\text{O}_{\text{c-w}}$ is the isotope composition of calcite minus that of water. Paleotemperatures for dolomite were calculated from the equation of Fritz & Smith (1970) where: $T(^{\circ}\text{C}) = 31.9 - 5.55(\delta^{18}\text{O}_{\text{d-w}}) + 0.17(\delta^{18}\text{O}_{\text{d-w}})^2$ where $\delta^{18}\text{O}_{\text{d-w}}$ is the isotope composition of dolomite minus that of water. Burial depths of vein mineral formation have been estimated assuming a starting depositional bottom-water temperature of 8°C and an inferred geothermal gradient of $29^\circ\text{C}/\text{km}$, both comparable to the modern situation (Head & Nelson 1994; Armstrong et al. 1996).

7.6 FRACTURE SYSTEMS

7.6.1 Controls

The key role of fracturing in the Tikorangi Formation has been the creation of

fracture porosity and permeability enhancement in otherwise essentially non-porous and impermeable host limestones. Most fractures in folded rocks are not formed as a result of the regional stress that caused the folding, but are generally related to the folding process (Barr 1993). The degree of fracturing in the Tikorangi Formation in the Waihapa-Ngaere Field was very evident at the time of drilling because of heavy to severe mud losses, the presence of gas ratio plots with sharp total gas peaks, and the common occurrence of drilling breaks (Johnston 1990; Simpson 1992). Drill core samples from these intervals show substantial and often highly mineralised fracture systems (Plate 7.1A). In contrast, wells encountering the Tikorangi Formation away from areas of structural deformation show no evidence of mud loss, fracturing, or wet gas peaks during drilling (Simpson 1992). In these situations Johnston (1990) considered the Tikorangi Formation strata to be autochthonous. In contrast the Tikorangi Formation encountered in the Waihapa-Ngaere Field wells is regarded as allochthonous (Johnston 1990), comprising a series of westward-dipping thrust sheets (Palmer & Andrews 1993; King & Thrasher 1996).

The distribution and productivity of fractured Tikorangi Formation, while ultimately determined by tectonic configuration, is equally dependent upon the original depositional facies and the subsequent diagenetic processes affecting the rocks (Topics 2-6) (e.g., Martindale & Boreen 1997). Due to the lithological complexity of the Tikorangi Formation carbonates (Topics 2-4) the resultant fracturing is clearly variable in location and magnitude. In general fine-grained carbonates (foredeep megafacies) (Topic 4) will tend to have a greater fracture density than coarser-grained varieties (shelfal megafacies), and there is decreasing brittleness from dolomite to limestone. In general, reservoirs formed in facies with fine-grained dolomite tend to have excellent fracture permeability (Martindale & Boreen 1997), the situation in the dolomite-rich facies within the Tikorangi Formation.

So far, no specific well logs in the Tikorangi Formation have been consistently able to identify open productive fractures (Simpson 1992). However, it is possible to predict from the lithological and sedimentological data gained in this study (Topic 2) that Facies C (50-75% carbonate; mainly packstones) and Facies D

(>75% carbonate; mainly grainstones) rocks would likely provide the “best” fracture porosity opportunities. The rocks in these facies are typically dense, low porosity, well cemented limestones, often dolomitic (Topic 5), having the lowest GR and highest Dt values of all Tikorangi Formation samples (Topic 3). Qualitatively, the highest frequency of fractures in the Tikorangi Formation cores appears to be associated more with the lighter coloured, often light grey to white, more carbonate-rich and well cemented sections of Facies C and D than with the more micritic and siliciclastic-rich, darker brown/green core sections of Facies A and B.

7.6.2 Fracture geometries

Most fractures appear to be extensional and many exhibit shear characteristics and have been partially or totally healed by vein mineralisation (Kamp & Hood 1994) (Plate 7.1A, B). Many fractures have been a general N to S trend (Barr 1993), compatible with the general orientation of E-W compression in the region associated with plate boundary development (see Section 7.3). Fractures display a range of orientations but commonly are closer to the vertical than the horizontal (Kamp & Hood 1994). Most fractures are partially to wholly mineralised (or healed) with consequent substantial reduction of the initial fracture porosity.

A spectrum of effective fracture widths or apertures occur, ranging from micro- (<1 mm) to macro-size (several cm). Broken fractures, recognised as fracture planes but which have the accompanying rock plane missing, have unidentifiable apertures. The history of fracturing, mineralisation, and movement is highly complex. Not only are there multiple phases and directions of movement, but also multiple phases, degrees, and types of mineralisation which may incorporate host rock fragments and be stained with hydrocarbons. Brittle fractures provide a history of successive periods of mineralisation and intervening movement that has produced slickensiding upon many mineral surfaces, especially within early phase calcite precipitates. No evidence of dissolution enhancement of original fractures occurs.

7.6.3 Vein mineralisation

Calcite and dolomite are the main vein minerals present (Plate 7.1). Surface

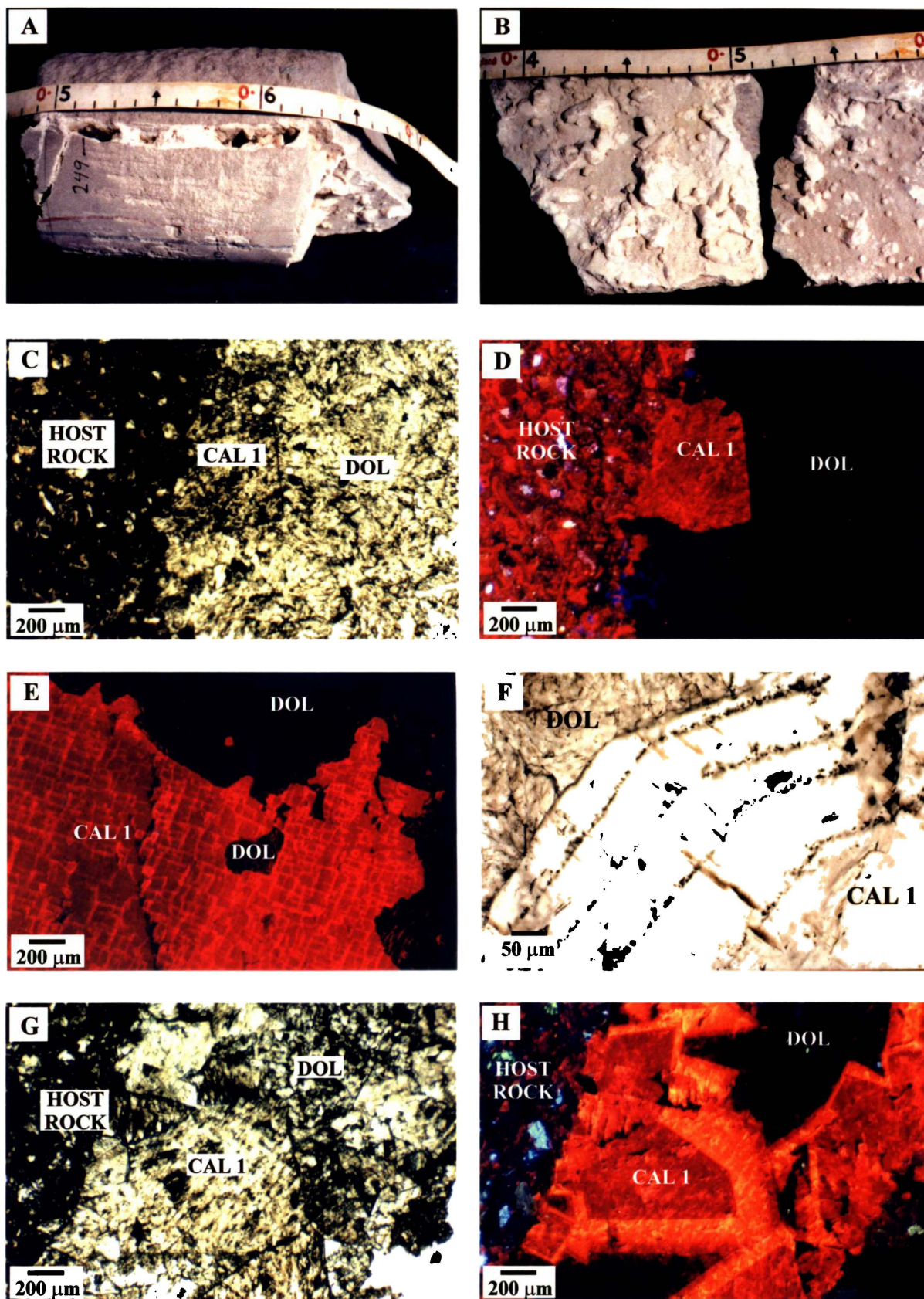


Plate 7.1 Core and thin section (PPL and CL) photographs of the major fracture porosity occluding carbonate phases, first generation calcite and baroque dolomite, in the Tikorangi Formation. (A) Fracture partially healed by coarse first generation calcite coated by fine baroque dolomite producing mammillary habit (sample W4.7.2B). (B) Fracture surface supporting large equant first generation calcite coated by very fine sucrosic dolomite (sample W4.7.2A). (C, D) Moderately ferroan dull luminescent first generation calcite cement precipitated at host rock boundary has been overgrown, but also partially replaced, by non-luminescent (black) ferroan baroque dolomite crust (evident in A, B). Note the very dirty appearance of calcite and generally cleaner dolomite (sample W2.9.12). (E) Dull luminescent first generation calcite showing evidence of partial dolomitisation by non-luminescent ferroan dolomite (sample W4.7.2B). (F) First generation calcite, seen in PPL containing primary fluid inclusions, overgrown by dolomite. (G, H) Zoned ferroan first generation calcite lining a vein with central porosity occluded by non-luminescent baroque dolomite (sample NG2.4.1B). CAL 1 = first generation calcite, DOL = dolomite. For sample details see Appendix 2.2. Scale divisions in A, B are in cm.

mineralisation may range from thin coatings (c. 0.5 mm) up to 40 mm-thick units involving multiple phases of movement and mineralisation. The maximum mineral thickness remaining on the sheared fracture surfaces is about 9 mm, but more typically it is 1-2 mm, and often slickensided with variable degrees of polishing and striation. Fracture systems range widely in their degree of mineral fill, from open non-mineralised to poorly healed to more commonly partially healed with preserved porosity. Few fractures are observed to be completely healed except those small scale systems up to a few mm wide. Residual porosity within the mineralised veins comprises vugs which range from <0.1 mm to +10 mm in size. Some porosity can exist along the vein fill contact with the host rock wall, probably a result of later minor movement.

7.6.3a First generation calcite

Two major vein calcite generations are evident in handspecimen. The first is variably textured, dog-tooth, drusy equant, white to grey calcite which constitutes the bulk of the vein filling (Plate 7.1A, B). This calcite may exhibit a pale yellow discolouration resulting from oil staining. Crystal textures range from fine (0.5-1 mm) to coarse (3-7 mm), rarely >20 mm size (Plate 7.1B). Crystal growths are often multi-directional and are not solely oriented porewards. Intercrystalline porosity occurs between the larger equant crystals. Multiple phases of movement and crystal growth are evident within this equant calcite phase. Less commonly more elongated crystal fabrics occur in association with slickensiding and may result from strain recrystallisation.

7.6.3b Second generation calcite

A second and much rarer generation of calcite visible in handspecimen comprises large (2-5+ mm) single or clustered, clear/translucent crystals. “Free growing” calcite crystals exhibit a range of equant, dog-tooth, and platey habits. This calcite phase post-dates the earlier first generation calcite mineralisation, and also the thin isopachous coatings of dolomite mineralisation (see below).

7.6.3c Dolomite

A hummocky or mamillary texture results from a dolomite crust coating much of the first generation calcite minerals which were precipitated upon fracture

surfaces (Plate 7.1B). This isopachous thin crust (up to 2.5 mm) comprises fine crystals (0.1-1 mm long). The dolomite may be stained yellow/brown by hydrocarbons. Within veins, dolomite can occur as a late fracture fill, occluding central porosity following first generation calcite, but less commonly as a fracture lining, typically 2-3 mm thick.

7.6.4 Other features

7.6.4a Slickensiding

Reactivation of movement along fault planes following mineralisation has often produced slickensiding (Plate 7.1A), strain recrystallisation, some smearing of mineralisation, and the shearing of some crystal tops. Less elevated areas with drusy calcite crystals have escaped slickensiding. Because of slickensiding, crystals are often dark grey to black and variably grooved or striated, often in different directions. The degree of surface polishing varies from dull to lustrous and is inferred to represent varying degrees of movement. In some instances the vein minerals have recrystallised to form elongated laths or needle-like crystals with intercrystalline porosity in the direction of slickensiding. The most recent phase of movement producing slickensides post-dates the formation of second generation calcite as evidenced by crystal shearing.

7.6.4b Stylolites

Accompanying fracture systems are similarly complex patterns of horsetail or flaser stylolites. They are distinct from hacksaw or toothed varieties commonly seen in exposed onland limestone equivalents associated with burial diagenesis (Hood & Nelson 1996). The stylolites are irregular, low amplitude, hummocky seams with wispy tails that represent discontinuous pressure-dissolution surfaces enriched in insoluble residue. They occur at a high angle to the presumed direction of original bedding and are not related to original depositional fabrics. The features have previously been misidentified as water escape structures and as fractures filled with muddy sediments (MacFarlan 1993), were correctly identified as stylolites by van der Lingen (1993). The Tikorangi Formation stylolites generally trend N-S, and are near vertical, and probably formed in response to strong E-W tectonic compression, just like the associated fracture systems.

7.7 PETROGRAPHY OF VEIN MINERALS

Fig. 7.5 provides a simplified schematic summary of the often complex petrographic relationships between the major carbonate vein minerals present within the Tikorangi Formation fractures. Two situations are shown, one for surface mineralisation and the other for fracture-filled vein systems. Table 7.1A, B provides summary petrographic characteristics of the vein minerals.

7.7.1 Ferroan calcite (first generation)

7.7.1a Standard petrography

Ferroan calcite (first generation) forms surface coatings and vein fills in handspecimen. It occurs as euhedral to subhedral, optically clear to very dirty inclusion-rich, moderately ferroan calcite (light blue stained) crystals which are typically equant to drusy in habit and of variable size, but often moderately coarse (up to 2 mm) (Fig. 7.5; Table 7.1A; Plate 7.1C-H). Uncommonly, large dog-tooth calcite crystals sometimes have grown across the entire fracture width and may reach up to several mm in length. The larger equant crystals are commonly twinned and associated with portions of a granulated texture. Crystal boundaries may also exhibit concavo-convex contacts suggestive of pressure-dissolution. In most cases first generation calcite is clearly the first formed vein precipitate, being in contact with the host rock, although it may infill more central portions of vein systems where dolomite has invaded the host rock wall-calcite contact (Fig. 7.5A).

First generation calcite crystals may be replaced by dolomite at a range of scales, including irregularly at the outer crystal boundaries ((Fig. 7.5B4; Plate 7.1C-E) or more pervasively as evidenced by small remnant calcite inclusions (Plate 7.2A, B). Coarser crystals have been generally less susceptible to dolomitisation than finer ones. Replaced calcite margins can be a mix of planar and non-planar surfaces, perhaps a result of the corrosive action of dolomitising fluids. Irregularly shaped relicts of ferroan calcite are often left poikilitically enclosed by dolomite (Fig. 7.5B4; Plate 7.1E), testament to a secondary replacive dolomite origin. Occasional replacement by perfect rhombohedra of dolomite occurs. However, in other samples dolomite appears to be a true precipitated cement (Fig. 7.5A1; Plate

7.1C, D) (see below) forming an outer coating on the first generation calcite crystals with little or no evidence of dolomitisation. First generation calcite commonly records some evidence of partial dolomitisation close to or at the host rock interface (Fig. 7.5A). Dolomite crystals range in size from 0.05-0.25 mm. Some minor porosity is evident within the dolomite, but may be a function of the thin-sectioning process.

7.7.1b CL petrography

First generation calcite exhibits an unzoned (Fig. 7.5A1; Plate 7.1, D), often patchy, non- to dull red/orange luminescence, slightly duller than that exhibited by the ferroan calcite cement within the host Tikorangi limestone. A general lack of zoning and dull- to non-luminescence are characteristic of Fe^{2+} -rich burial-derived cements, with elevated Fe concentrations quenching any Mn^{2+} -activated luminescence (Nelson et al. 1988). Rarely, coarse slightly ferroan drusy calcite may show a concentric zonation (Plate 7.5H) comprising an initial orange/red dull luminescence, with minor non-luminescent patches in the central portions of the crystals, followed by a brighter yellow/orange outer luminescent zone. The appearance of zoning may be a function of the relatively Fe-poor (dull as opposed to dark blue staining) nature of these crystals.

7.7.2 Ferroan calcite (second generation)

7.7.2a Standard petrography

These isolated, apparently free-standing dogtooths of blue stained and etched ferroan calcite crystals formed directly upon dolomite (Fig. 7.5A, A2; Table 7.1A; Plate 7.2C, D). In other cases where precipitative or replacement dolomite phases are absent, a similarly textured phase of large equant ferroan calcite crystals grew on the surface of the initial first generation calcite following a period of movement which produced a slickensided and striated base for second generation calcite growth. These coarse equant second generation calcite crystals have often grown in clusters, with individual crystals reaching up to 22 mm in length.

7.7.2b CL petrography

Crystals typically display a patchy non- to dull red/orange luminescence (Fig. 7.5A2; Plate 7.2D), identical to the first generation calcite. No evidence of zoning

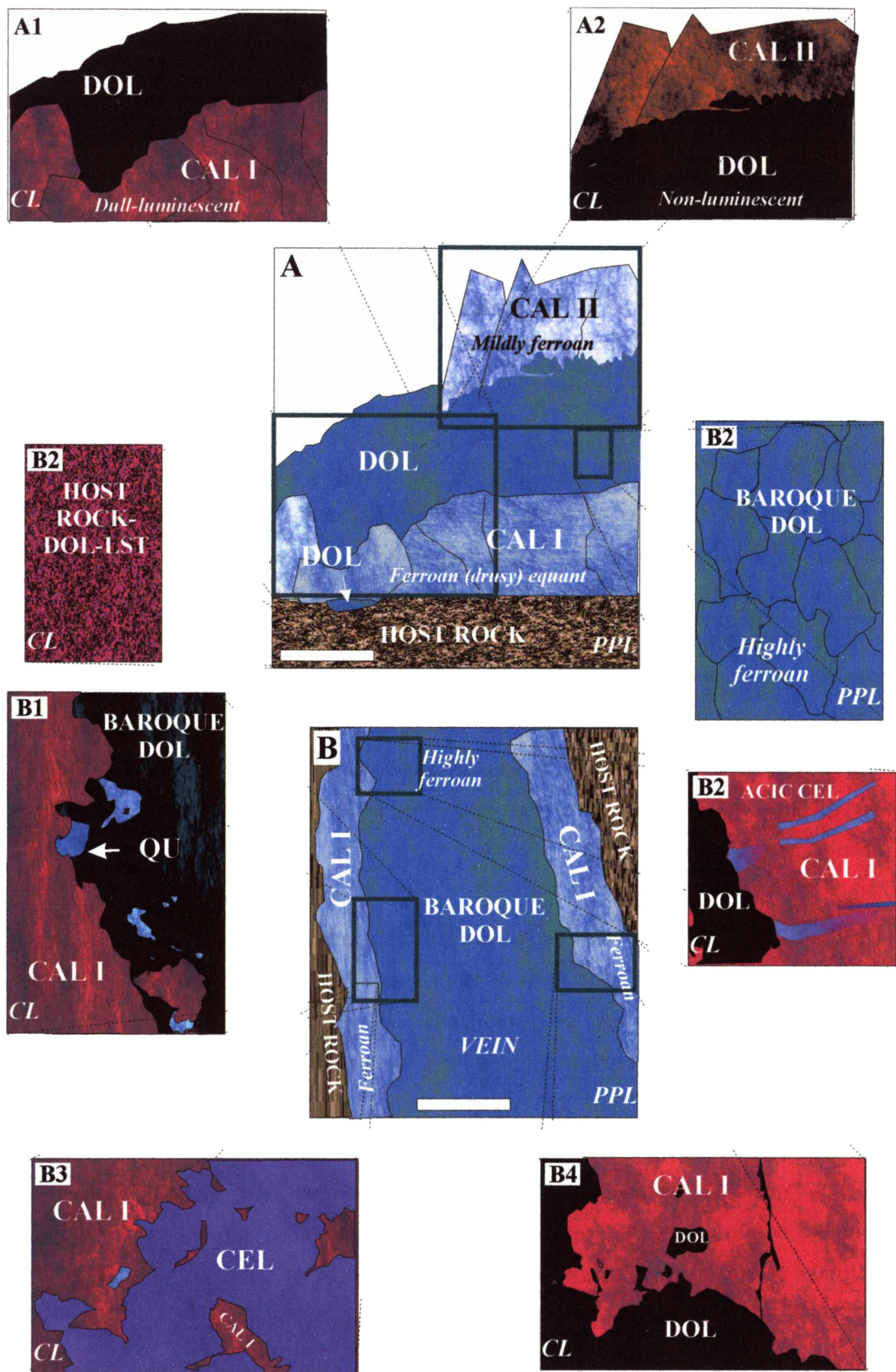


Fig. 7.5 Schematic summary of the major mineral relationships within the Tikorangi Formation vein material as modelled under cathodoluminescence (CL) and plane-polarised light (PPL). Colours in PPL result from staining and all carbonate minerals are typically Fe-rich (blue-green = ferroan). Under CL: calcite phases = dull-red, dolomite = black (non-luminescent), celestite = purple, quartzine = vivid blue. CAL 1 = first generation calcite, Cal II = second generation calcite, DOL = dolomite, CEL = celestite, ACIC = acicular, QU = quartzine, DOL-LST = dolomitic limestone. See text for detailed discussion. White scale bar in A, B = ~2-5 mm.

was seen in any second generation calcite crystals.

7.7.3 Baroque dolomite

7.7.3a *Standard petrography*

Dolomite [$\text{CaMg}(\text{CO}_3)_2$] formed after first generation calcite, and is the next most voluminous vein mineral type, occurring as both a primary precipitate (Fig. 7.5A, A1; Plate 7.1C, D and 7.2 C, D) and as a replacement phase of calcite (Fig. 7.5B4; Plate 7.1E and 7.2A, B). The dolomite is commonly relatively coarse-grained (to about 1 mm), and is mainly clean “sparry” in appearance compared to the commonly dirty calcite phases, although it is sometimes pale brown (Table 7.1A). Crystals often have a characteristic sweeping undulose extinction with distinctively warped crystal faces that appear as curved or saddle-like shapes forming a subhedral to typically hypidiotopic (nonplanar) fabric (Fig. 7.5A4), a feature of baroque dolomite (Gregg 1988; Tucker & Wright 1990). Dolomite occurs most commonly as deeply green/blue-stained ferroan dolomite [$\text{Ca}(\text{MgFe})(\text{CO}_3)_2$] (Fig. 7.5) which has an un-etched relief similar to that of siliciclastic grains. Late saddle dolomites are commonly iron-rich (Tucker & Wright 1990) like those in the Tikorangi Formation. Occasionally they may become less ferroan porewards.

Partial dolomite replacement at the margins of first generation calcite is common, and in some instances is restricted to an irregular zone (Fig. 7.5B4; Plate 7.1E and 7.2A, B) in contact with the host rock. Veins can be occasionally and partially lined or filled with replacement dolomite that may contain micro-porosity at the host rock wall contacts, but the original ferroan calcite has mainly resisted dolomitisation in the more central portions of veins where the coarsest drusy calcite crystals occur. Small relicts of ferroan calcite are often seen within the dolomite confirming a replacement origin for the dolomite in these instances. Dolomite rhombohedra with straight crystal faces may appear floating in ferroan calcite. Secondary (replacement) dolomite less commonly can be seen to have invaded small areas of the larger blue-stained ferroan calcite cement/fill. Relicts of ferroan calcite are irregularly shaped and are poikilitically enclosed within the replacement dolomite and remain suspended amid the dolomitisation products (Fig. 7.5B4). Within large calcite crystals multiple small dolomite nuclei can be

Table 7.1A Summary of main petrographic characteristics of the carbonate vein minerals within the Tikorangi Formation.

Carbonate mineral phases	Crystal habit	Crystal size	Occurrence	Relative abundance	Staining (after Dickson 1965)	Crystal clarity	CL signature	Intercrystalline porosity	Petrographic features	Timing/origin
<i>Calcite</i> (CaCO ₃)										
Ferroan calcite - first generation	Dog-tooth-drusy equant, euhedral-subhedral	Commonly 0.5 - 7 mm (rarely to 20 mm)	Major vein fill, thick coatings on fracture surfaces	Very common	Dull-deep blue, slightly-highly ferroan	Typically dirty brown, inclusion rich	Rarely concentrically zoned, patchy, non-dull red/orange	Common where associated with strain recrystallisation	Strain recrystallisation, sheared, slickensided, twinned, partially dolomitised	Phase I Primary cement
Ferroan calcite - second generation	Coarse equant-dogtooth-platey, clear-white sparry	2 - 5 mm, rarely >20 mm	Single crystals/clusters on: dolomite; slickensided phase I	Rare to some	Light blue moderately ferroan	Clear to dusty, primary inclusion trains	Unzoned, patchy non-dull red/orange	Absent	Clean, clear sparry, coarse	Phase II Primary cement
<i>Dolomite</i> [CaMg(CO ₃) ₂]										
Baroque (ferroan) dolomite	Sucrosic, subhedral to typically anhedral xenotopic (nonplanar) fabrics	Coarse up to 1 mm	Typically surface crust - coats phase I calcite- also vein fill	Common	Rarely unstained - typically deep green/blue. May become less ferroan outwards	Clean white sparry to pale brown	Dull - typically non (black)	Substantial porosity within central vein systems, minor resulting from dolomitisation	Partial replacement phase I calcite, undulose extinction, some warped crystal faces, calcite inclusions	Phase III commonly a precipitate, common calcite phase I partial replacement

Table 7.1B Summary of main petrographic characteristics of the non-carbonate vein minerals within the Tikorangi Formation.

Non-carbonate mineral phases	Crystal habit	Crystal size (mm)	Occurrence	Relative abundance	Staining (after Dickson 1965)	Crystal clarity	CL signature	Intercrystalline porosity	Petrographic features	Timing/origin
<i>Celestite</i> (SrSO ₄)										
Tabular celestite	Tabular plate-like anhedral to euhedral crystals, rarely prismatic	0.5 - 2.0 mm	Fracture fill	Some - locally common	N/A	Very dirty inclusion rich, often pale brown to yellow discolouration.	Dull-very dull purple/blue	Some intercrystalline porosity	High relief, fluid inclusion-rich, calcite inclusions, twinned	Phase IV Primary and replacement - some carbonate mineral relicts
Acicular celestite	Single needles, rarely intergrown radiating crystals	0.2 - 0.5 mm	Fracture fill	Rare	N/A	Clear-dirty	Very dull-dull purple/blue	Absent	Often ghost-like forms	Phase IV Replacement calcite ghosts
<i>Authigenic quartz</i> (SiO ₂)										
Fibrous quartzine	Fine, elongated fibres, some bundles	~0.1 mm	Fracture fill	Very rare	N/A	Dirty, micritic appearance	Moderate-bright blue	Absent	Often ghost-like forms, associated micritic-like calcite, felted	Phase ?IV Calcite replacement
Spherulitic quartzine	Irregular mass, containing scattered aggregated or spherulitic centres	Amorphous irregular patches in CL; pin-point sized crystals in CPL	Fracture fill	Some	N/A	Yellow/brown, clean to dirty and inclusion-rich	Amorphous moderate-bright vivid to darker blue	Absent	?Organic-bearing, relict inclusions, often associated dolomite/host rock contact	Phase ?IV Secondary - carbonate mineral relicts - commonly associated with dolomite

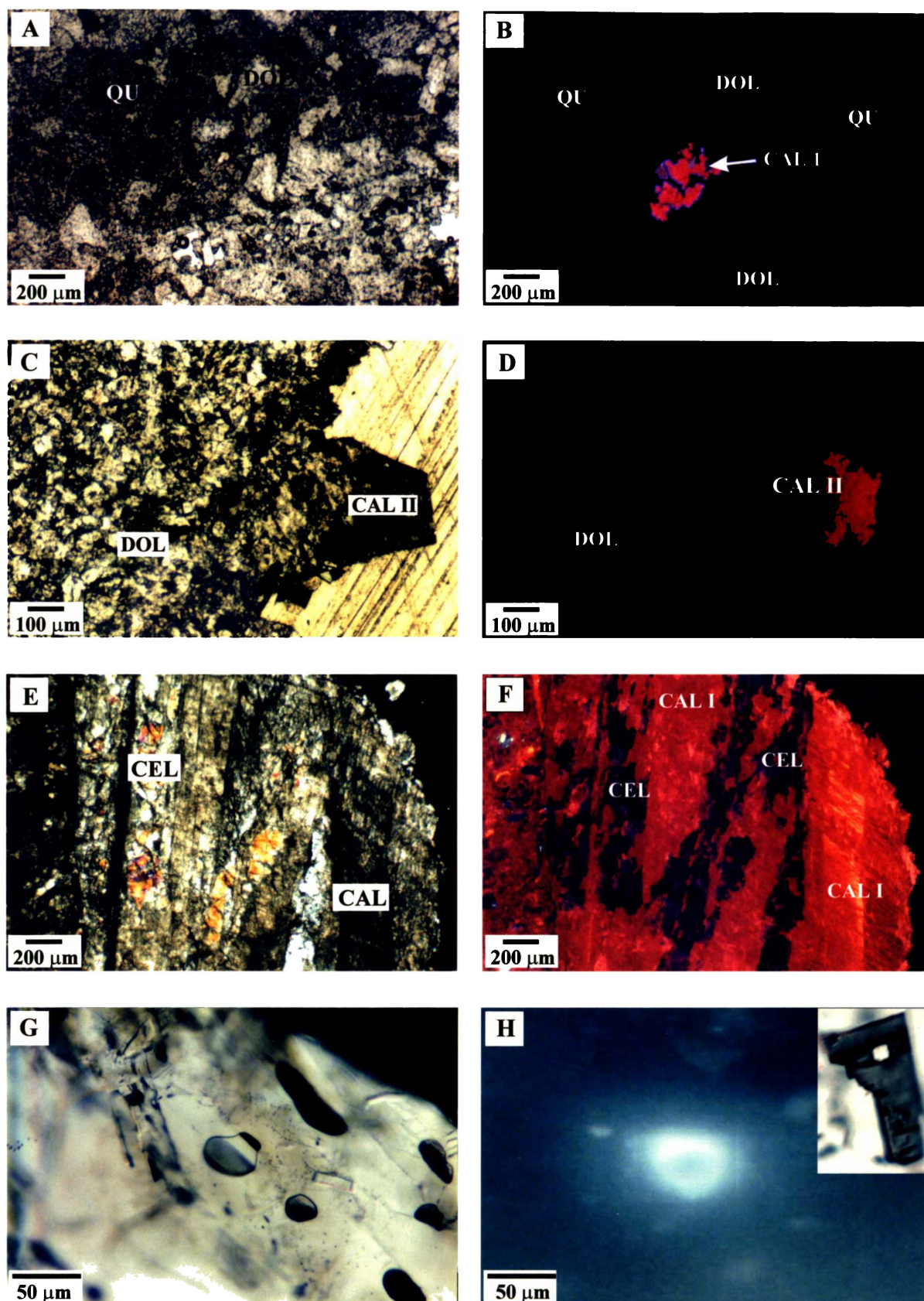


Plate 7.2 Photomicrographs showing several vein mineral types in the Tikorangi Formation as seen under PPL, CL, and UV. (A, B) Complex relationships between first generation calcite (dull red luminescent), and secondary (replacive) dolomite (non-luminescent) and quartzine (blue luminescent) phases (sample W4.7.4C, PPL & CL). (C, D) Second generation calcite has precipitated directly on dolomite phase (sample W2.9.12B, PPL & CL). (E, F) Celestite occurring as a replacement phase in first generation calcite exhibiting low 1st order interference colours and a dull purple/blue luminescence. Note the multiple generations of calcite separated by slickensided surfaces (sample NG2.4.3, CPL & CL). (G) Hydrocarbon-bearing fluid inclusions occurring within second generation calcite. (H) White luminescence is produced by hydrocarbon-bearing fluid inclusions under UV light. Inset shows inclusions containing high-pressure CH_4 , which has formed a solid gas-hydrate (clathrate), PPL (sample NG2.4.3). CAL I = first generation calcite, CAL II = second generation calcite, DOL = dolomite, CEL = celestite. For further sample details see Appendix 2.2.

seen to have formed as dolomite invaded the host crystals. Outer boundaries of replacement dolomite may exhibit a dog-toothed habit inherited from the original calcite cement. In other samples large drusy equant crystals have been partially replaced and are coated in primary ferroan dolomite which forms an isopachous outer rind (Fig. 7.5A, A1; Plate 7.1B-D). Dolomitisation has also occurred preferentially along crystal dislocation boundaries where Mg-rich fluids could penetrate.

7.7.3b CL petrography

CL in the Tikorangi Formation dolomite cements tends to be subdued and is typically non-luminescent (Plate 7.1D). Where the ferroan dolomite phase is transitional to nonferroan, as indicated by staining, a corresponding change from non-luminescence to dull luminescence occurs.

The replacement ferroan dolomite has mainly dull luminescence with non-luminescent patches. Relict non-luminescent calcite crystals are readily distinguished using CL and can be seen to be poikilitically enclosed in the generally dull luminescent dolomite (Plate 7.1E). Likewise patches of non-luminescent ferroan dolomite can be more easily seen invading portions of dull equant calcite crystals. Less ferroan dolomite has a tendency towards red/pink luminescence compared to the more orange/yellow/red luminescence of the associated calcite.

7.7.4 Tabular celestite

7.7.4a Standard petrography

Celestite (SrSO_4) appears in PPL as tabular, plate-like anhedral to euhedral crystals (Table 7.1B; Plate 7.2E, F), or as prismatic crystals with a high relief and an often dirty pale brown to yellow discolouration. Crystals are typically about 0.5 mm long, rarely as large as 2 mm. Celestite crystals are commonly fluid inclusion-rich, unstained and un-etched, and exhibit low first order grey and pale yellow interference colours, much like quartz, making them easily distinguishable from carbonate phases. The mineral was initially not identified in handspecimen due to its minor occurrence, but it has a definite yellow/brown resinous colour in handspecimen, possibly due to impurities and inclusions.

Celestite replacement can be confined to discrete thin calcite laminae separated by slickensided surfaces (Plate 7.2E, F). However, where multiple calcite layers are separated by slickensided surfaces, celestite replacement has sometimes occurred across slickensided boundaries and has partially replaced the adjacent calcite crystal(s). Some micro-porosity is apparent within the areas of celestite replacement. The celestite can poikilitically enclose relict inclusions of ferroan calcite (Fig. 7.5B3) and rarely dolomite rhombs, so that, much like dolomite, it is considered to have both a primary cement and secondary replacement origin. Crystals can have multiple fractures (typically 0.05 mm across) and be twinned probably due to pressure associated with crystal deformation. Fractures have been variably filled with ferroan calcite, possibly sourced directly from local pressure-dissolution.

7.7.4b CL petrography

Celestite is clearly identified under CL by its usually very dull but characteristic purple/blue luminescence (Fig. 7.5B3; Plate 7.2F), distinctive from the red/orange CL of calcite phases and the vivid blue CL shown by quartzine phases (see below). Dull red luminescent ferroan calcite/dolomite relict inclusions, where present, are easily distinguished using CL, but otherwise would be very difficult to identify.

7.7.5 Acicular celestite

7.7.5a Standard petrography

Celestite crystals occasionally appear as small, often bent or curved needle-like crystals typically 0.5 long, rarely larger (Fig. 7.5B2). Needles are typically single aligned crystals or rarely inter-grown crystals which radiate from a common centre. In PPL this form of celestite is difficult to distinguish and appears to be a mimic-type replacement of former calcite, including ghosts of the original calcite textures. Elongated crystals may be inter-fingered between phases of calcite mineralisation. In all cases the celestite does not contact the host rock but is poikilitically enclosed by ferroan calcite.

7.7.5b CL petrography

Acicular celestite exhibits similar dull purple/blue luminescence as the more

tabular crystal form discussed above.

7.7.6 Fibrous quartzine

7.7.6a Standard petrography

Non-detrital quartz appears in a few samples in two crystal forms. The first is fine, “length-slow chalcedony” or quartzine in which the elongation of the fibres is parallel to the crystallographic c-axis of the crystal, forming bundles of fibres/needles which may radiate from a common point. While characteristic of a void-filling cement it may also be a replacement fabric (Hesse 1990b).

7.7.6b CL petrography

Fibrous quartzine exhibits a moderately bright blue luminescence which aids its distinction.

7.7.7 Spherulitic quartzine

7.7.7a Standard petrography

Spherulitic quartzine in PPL often appears as a variably yellow/brown, clean to dirty and inclusion-rich irregular mass, containing scattered aggregated or spherulitic centres (Table 7.1B; Fig. 7.5B1; Plate 7.2A, B). This mineral may occur within the shape of possibly dissolved former carbonate crystals (Plate 7.2A, B). Under CPL a mass of equigranular microcrystalline quartzine crystals display pin-point extinction and low-order interference colours. Areas with a pale brown discolouration and inclusion-rich appearance may include organic matter related to hydrocarbons. Some areas of spherulitic quartzine include remnant carbonate phases, suggestive of a replacement origin by silica in some instances (Hesse 1990b). Clusters of variably corroded non-luminescent dolomite rhombs occur at the outer margins of quartzine patches (Plate 7.2A, B) or less typically as scattered dull luminescent free-floating rhombs poikilitically enclosed within microcrystalline quartzine. Calcite relicts may also be enclosed (Plate 7.2 A, B). There appears to be multiple generations of quartzine formation, earlier dirty varieties being fractured and then healed by later clear crystals. Often quartzine occurs at the vein – host-rock contact, a point of structural weakness (Fig. 7.5B1).

7.7.7b CL petrography

Crystals display a spectacularly vivid, generally moderately bright blue luminescence in which individual microcrystals are not distinguishable, so that the mass appears “amorphous” (Fig. 7.5B1; Plate 7.2B). Dolomite relicts are evident by their non-luminescent character, while calcite remnants have a dull red/orange CL.

7.8 GEOCHEMISTRY

Trace element data (Appendix 7.1) are summarized in Table 7.2 and graphically illustrated in Fig. 7.6. Stable isotope data (Appendix 7.2) are portrayed in Fig. 7.8.

7.8.1 Ferroan calcite (first and second generations)

XRD analysis has shown the ferroan calcite vein minerals are low-Mg calcite with Mg contents mainly <2 mol% MgCO_3 . Trace element analysis gives Mg values averaging about 6,900 ppm (Table 7.2; Fig. 7.6), but ranging from 750-19,000 ppm. The higher Mg values are probably due to partial dolomitisation of the calcite. Ca values are expectedly much higher in the calcite than in the dolomite phase (see below), averaging 295,000 ppm (range 157,100-371,200 ppm). Na levels near 800 ppm are also higher than in dolomite, but are significantly lower than in the host Tikorangi limestone. Fe levels range from 2,000 ppm to 12,600 ppm (av. 6,700 ppm) (Table 7.2; Fig. 7.6), but these values are significantly lower than the dolomite values and the majority of Tikorangi Formation host samples. Mn values range from 54-460 ppm (av. 200 ppm) and are less than half the dolomite average and comparable to the Tikorangi host samples. Sr values average 3,700 ppm, approximately half that of dolomite but similar to the average Tikorangi host (Table 7.2; Fig. 7.6).

Correlations between trace element concentrations in calcite and core sample depth show for all elements (not included here) except Sr an increasing concentration upcore. The opposite is the case for dolomite (see Section 7.8.2).

Summary trace elemental matrices and schematic pie diagrams possibly

Table 7.2 Summary trace element data for Tikorangi Formation vein samples including analysis of Tikorangi Formation and other New Zealand limestone averages. Data for the Tikorangi Formation are contained in Appendix 7.1.

PETROFACIES	No. of samples	Mg (ppm)	Ca (ppm)	Na (ppm)	Fe (ppm)	Sr (ppm)	Mn (ppm)
VEIN MINERALS							
Calcite - first generation	11	6,908	294,959	795	6,716	3,728	203
Dolomite	4	48,240	219,300	582	46,743	7,078	520
HOST ROCK							
Tikorangi Fm av.	65	15,515	325,040	4,589	12,647	3,483	273
OTHER NZ LIMESTONES							
NZ limestones av.	548	5,508	419,574	1,392	2,428	555	577

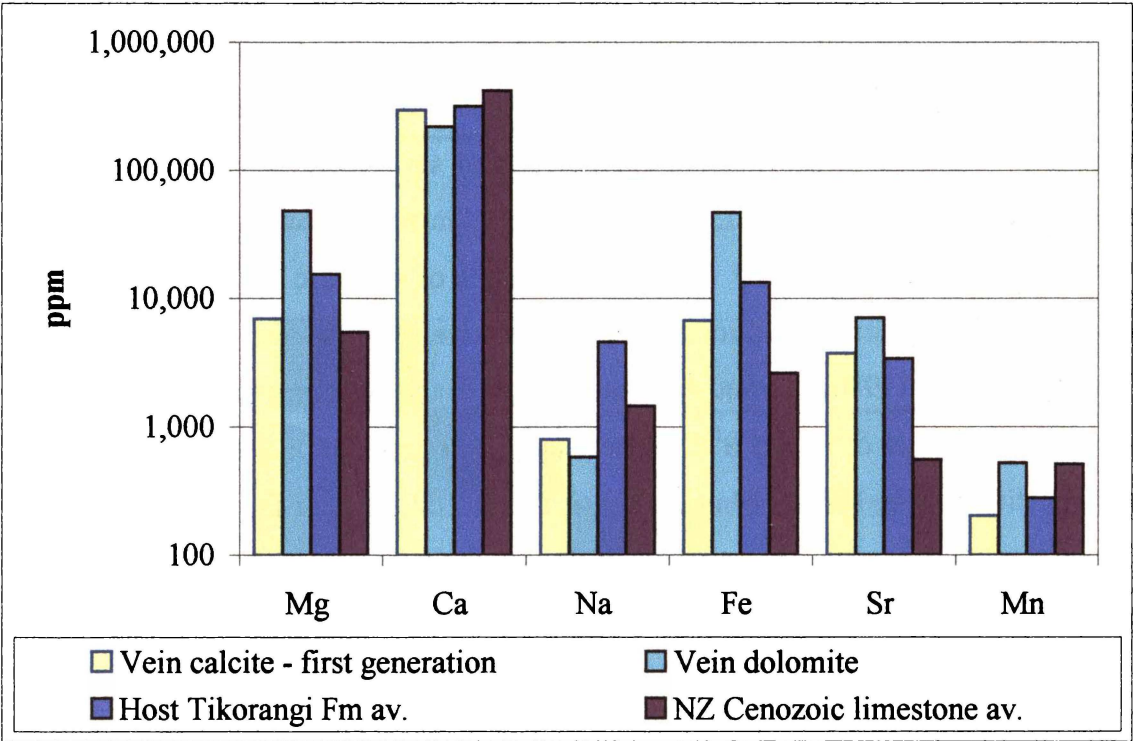


Fig. 7.6 Trace element average data for vein minerals first generation calcite and dolomite plotted in comparison to the host Tikorangi Formation and New Zealand Cenozoic limestone averages.

suggesting the relative influence of meteoric, shallow-burial, and deep burial pore fluids have been constructed (refer Topic 6) for both calcite and dolomite (Fig. 7.7). Taken at face value the diagram suggests a relatively strong meteoric signature associated with calcite vein mineralisation.

First generation calcite vein minerals have depleted $\delta^{18}\text{O}$ values ranging from -5.8 to -8.7‰ and averaging -7.4‰ (Fig. 7.8). Second generation calcite $\delta^{18}\text{O}$ values are generally slightly more depleted, ranging from -7.1 to -9.1‰ (av. -8.2‰). Both these Tikorangi calcite vein phase values compare well with New Zealand calcite vein studies by Nelson & Smith (1996) whose group 1 (burial) calcite ranged from -2.2 to -9.3‰ (av. -5.8‰) and group 2 (meteoric-influenced) calcite from -2.7 to -11.4‰ (av. -5.6‰).

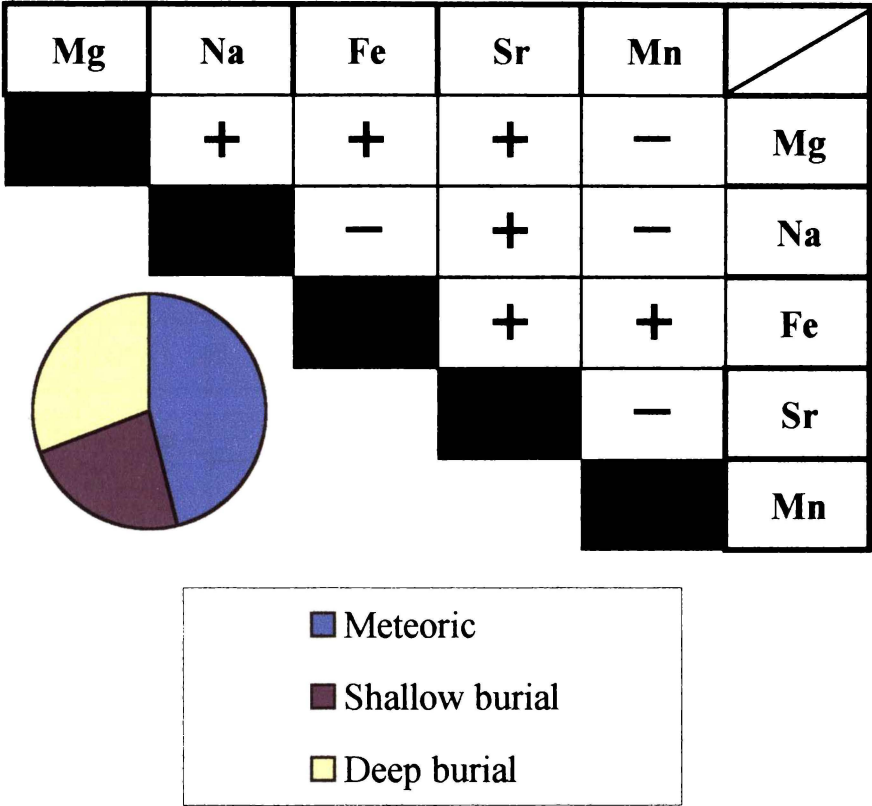
First generation calcite vein $\delta^{13}\text{C}$ values are similarly slightly to moderately depleted, ranging from -1.7 to -6.2‰ with an average of -3.84‰ (Fig. 7.8). Second generation calcite $\delta^{13}\text{C}$ values are slightly more depleted compared to first generation calcite values, averaging -4.6‰ and ranging from -0.5 to -6.2‰ .

Despite limited sample numbers, the Sr and Na concentrations in first generation calcite are correlated with $\delta^{18}\text{O}$ stable isotope data to assess potential indicators of meteoric diagenesis (Fig. 7.9A, B). This follows studies by Brand & Veizer (1980) and Aasm and Veizer (1986) who suggested increasing Sr and Na contents with increasingly heavier $\delta^{18}\text{O}$ values are indicative of meteoric diagenesis. Such a relationship appears to hold for Na, but the Sr correlation is poor. Additionally, Brand & Veizer (1980) showed that increasing Fe and Mn concentrations with increasingly lighter $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values supported meteoric diagenesis. This is the situation for Fe, but not Mn (Fig. 7.9C, D). Overall 75% of the geochemical trends support some degree of meteoric influence in the Tikorangi Formation first generation vein calcite.

7.8.2 Baroque dolomite

XRD shows the vein dolomite to be non-stoichiometric, calcian-rich dolomite (av. 58 mol% CaCO_3). Trace element analysis shows Mg values from 11,800 to 88,400 ppm and an average of 48,200 ppm (Fig. 7.6; Table 7.2). Dolomite is also

Calcite - first generation



Dolomite

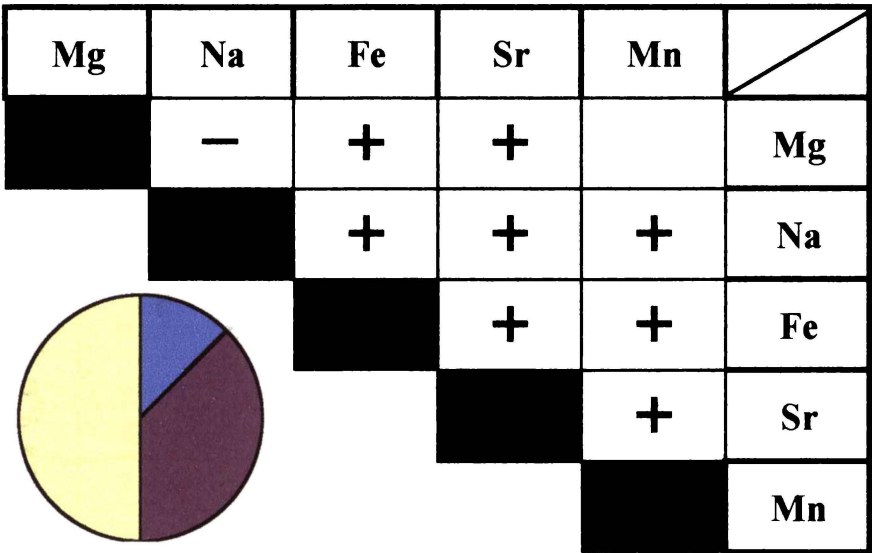


Fig. 7.7 Summary elemental matrices and pie diagrams for first generation calcite and dolomite vein minerals within the Tikorangi Formation fracture systems. See Topic 6 for details of methodology.

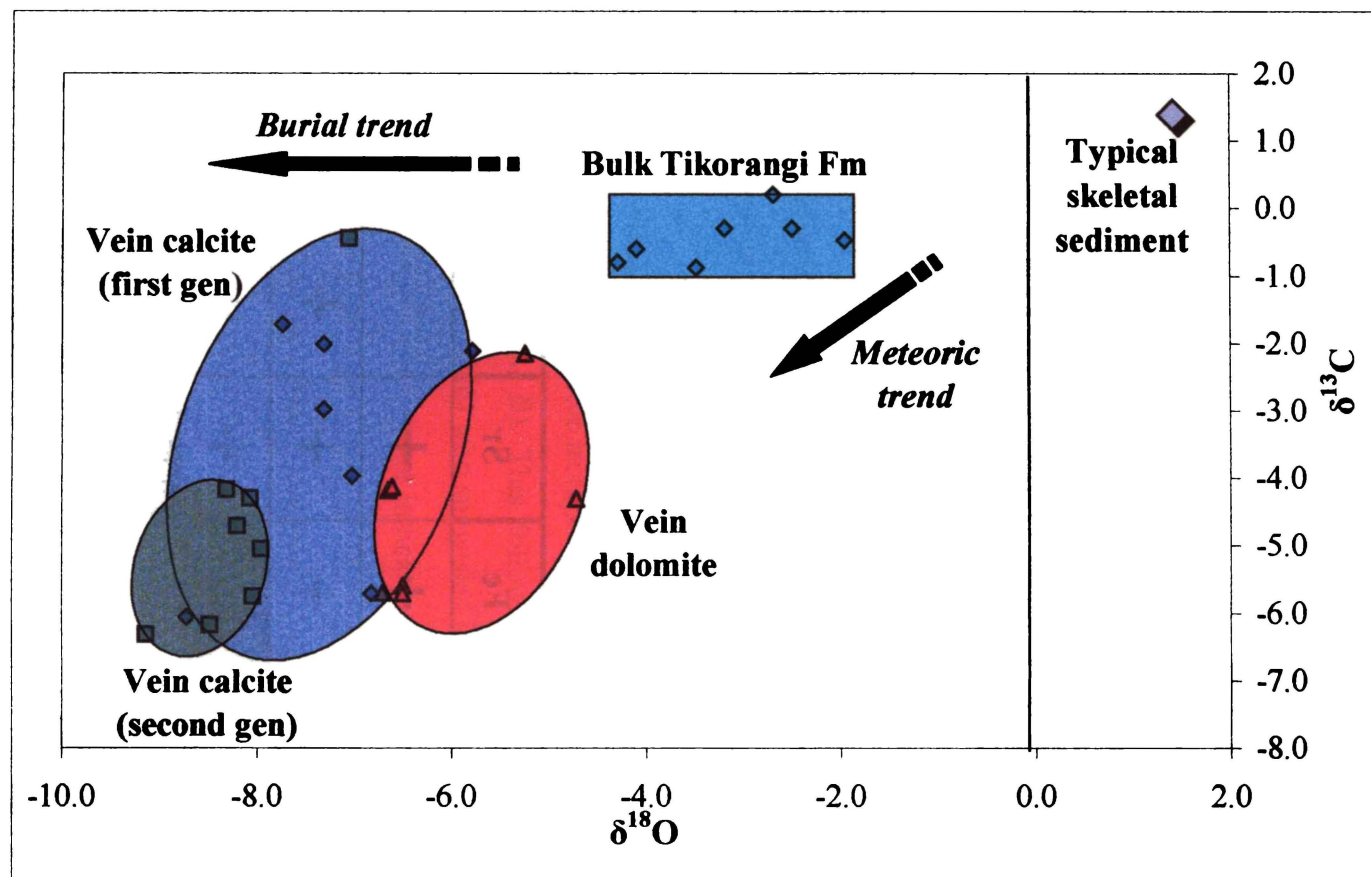
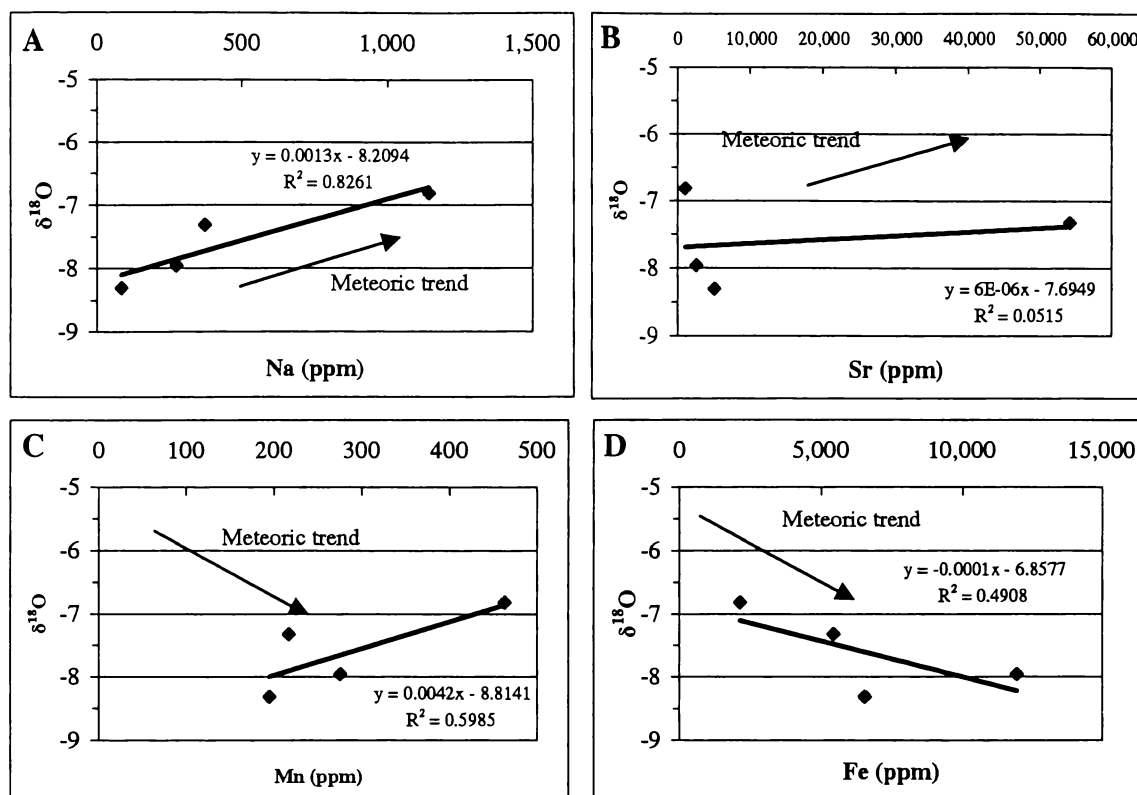


Fig. 7.8 $\delta^{18}\text{O}$ - $\delta^{13}\text{C}$ plot and generalised isotope fields for the host Tikorangi Formation and carbonate vein phases. A typical average New Zealand skeletal sediment value has been plotted as a reference (after Nelson & Smith 1996). gen = generation.

First generation calcite vein $\delta^{18}\text{O}$ versus elemental trends



Dolomite vein $\delta^{18}\text{O}$ versus elemental trends

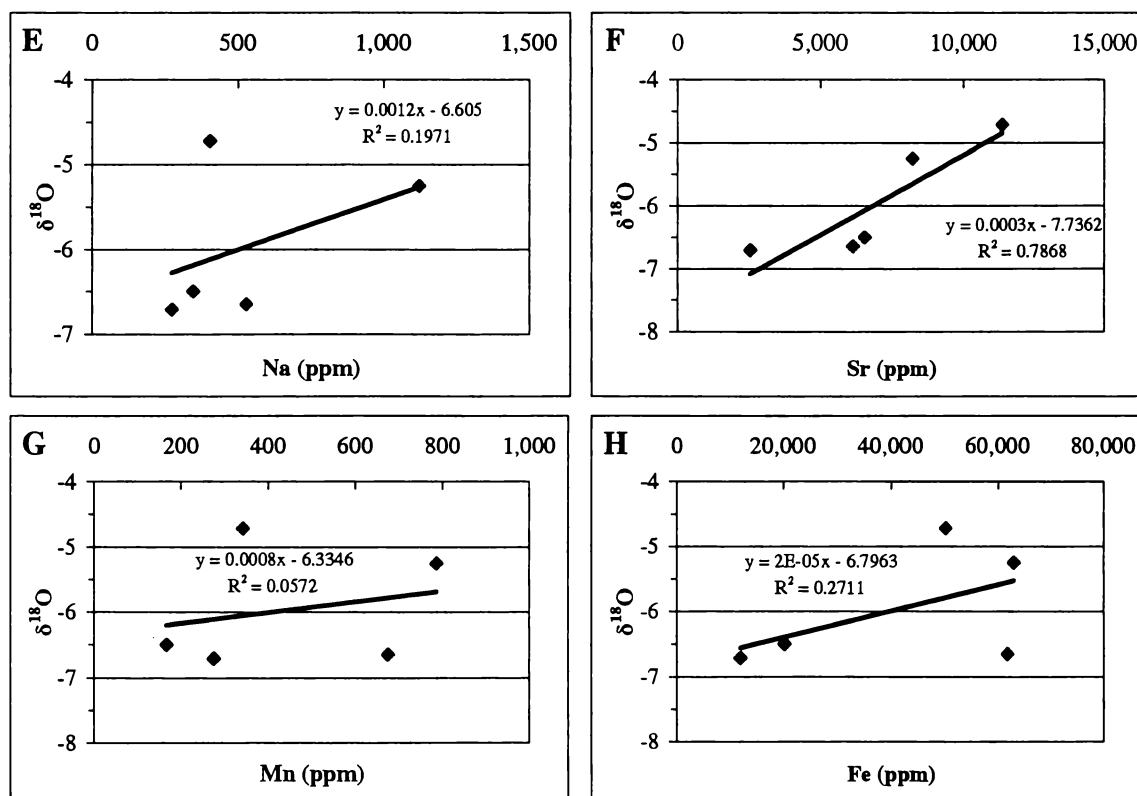


Fig. 7.9 Correlation plots of Na, Sr, Fe and Mn versus $\delta^{18}\text{O}$ for first generation calcite (A-D) and dolomite (E-H) in vein material from the Tikorangi Formation. Based on the meteoric trend lines shown, calcite shows some degree of meteoric influence in 75% of the correlations, reducing to 50% for dolomite.

commonly Fe-rich (12,000 to 63,000 ppm, av. 37,400 ppm) and lies within the ferroan dolomite-ankerite series. In comparison to the Tikorangi Formation average and New Zealand limestone average (Fig. 7.6; Table 7.2) dolomites contain substantially elevated Mg, Fe, and Sr values, the latter ranging from 2,600 to 11,400 ppm (av. 7,100 ppm). Mn levels are also higher than comparative databases. Conversely, Na levels from 270 to 1,100 ppm (av. 580 ppm) are depleted in relation to the Tikorangi Formation av. of 4,600 ppm. Ca values are also lower, averaging 219,300 ppm (range 179,700-309,600 ppm), and are substantially lower than for the calcite vein minerals, and the Tikorangi limestone averages (Fig. 7.6; Table 7.2). Correlations performed using sample depth versus trace element concentration in the dolomites (not included here) showed in all cases, with the exception of Ca, increasing concentrations downcore (see Section 7.10.4).

Vein dolomite shows a summary elemental matrix dominated by deep-burial and shallow-burial signatures, and only relatively minor meteoric influence (Fig. 7.7).

Dolomite vein samples show moderately depleted $\delta^{18}\text{O}$ values ranging from -4.7 to -6.7‰ (Fig. 7.8). $\delta^{13}\text{C}$ values are also similarly moderately depleted and range from -2.2 to -5.7‰ .

Combining stable isotope and trace element plots of $\delta^{18}\text{O}$ versus Na and Sr (Fig. 7.9E, F) as was done above for vein calcite, the vein dolomites show good (“meteoric”) correlation ($R^2 = 0.79$) for Sr only. The Mn and Fe trends do not suggest strong meteoric influence (Rao 1991). At best barely 50% of the geochemical trends suggest some degree of meteoric influence in the Tikorangi Formation vein dolomite, a reduced influence in comparison to that evident above for first generation vein calcite formation (Section 7.8.1).

7.9 FLUID INCLUSION GEOTHERMOMETRY

7.9.1 General characteristics

Fluid inclusions (FIs) abound in vein celestite, occur occasionally in vein calcite, and are rare in dolomite (Table 7.3). The celestite inclusions include liquid (L) with some mixed liquid + vapour (L+V) varieties, but there are generally few of a workable size. Primary single-phase liquid inclusions and the larger more vapour-rich inclusions are thought to be the result of necking down, a process whereby a fluid inclusion breaks down into multiple FIs, which can provide erroneous and elevated geothermometric (T_h) data (Shepherd 1985; Goldstein & Reynolds 1994). Two-phase liquid-vapour inclusions typically have small bubbles and poorly consistent L/V ratios (av. 4:1). Only rarely did some fields of view contain relatively consistent phase relationships required for microthermometric analysis. Dolomite crystals have few FIs, so that few analyses were possible.

7.9.2 Geothermometry

Geothermometry enables the minimum temperature of fluid entrapment in a two phase FI to be determined, as well as the salinity of the fluid. T_h or temperature of homogenisation is obtained by heating a two-phase FI from room temperature until the vapour phase disappears (i.e., liquid fills the FI). T_m , or temperature of final melting, is observed upon reheating a frozen FI and is recorded when all ice has returned to a liquid state. The freezing point depression is then related to the salinity of the FI (Shepherd 1985; Goldstein & Reynolds 1994). T_h minimum values are only discussed as this precludes the inclusion of higher temperature inclusions possibly formed from processes such as necking down or fracture and leakage, or those having a secondary origin. Tikorangi Formation fluid inclusion data are graphically summarised in Appendix 7.3.

7.9.2a T_h

T_h minimum values for first generation vein calcite samples range upwards from 90°C (Table 7.3). Second generation calcite samples generally provide slightly higher temperatures, ranging from a minimum of 101°C. The dolomite phase provides much less specific data. Dolomite T_h minimum values obtained from three samples range from 88°C (Table 7.3).

Celestite T_h values range upwards from 110°C for differing fluid inclusion assemblages with some measured inclusions reaching in excess of 200°C. Fluid inclusion homogenisation temperatures are thought to reflect the variability seen in phase ratios resulting from fracturing and leakage and necking down.

7.9.2b T_m ice

T_m values for first generation calcite range from –0.5 to –4°C and average –1.5°C, marginally higher than that for normal sea water at –1.9°C (Goldstein & Reynolds 1994) (Table 7.3; Appendix 7.3). These T_m values equate to values of 9-84 ppt NaCl and average 28 ppt NaCl (Table 7.3). Lower T_m values may be suggestive of higher salinity but may also be explained by later leakage and refilling of primary vacuoles (Goldstein & Reynolds 1994).

T_m values for second generation vein calcite range from –1.0 to –4°C and average –1.9°C, identical to that for normal sea water at –1.9°C (Goldstein & Reynolds 1994) (Table 7.3). These T_m values equate to values of 2-84 ppt NaCl and average 35 ppt NaCl (Table 7.3). Generally lower T_m values in comparison to first generation calcite may be suggestive of higher salinities.

Celestite T_m ice values range from –1.4 to –2.5°C and average –1.8°C (Table 7.3). Calculations of salinity show these temperatures equate to most commonly 26 ppt NaCl, but reach up to 47 ppt NaCl (av. 33 ppt NaCl) (Table 7.3). These data provide a range of meteorically-diluted to saline-enriched pore fluids whose average nears normal salinity.

7.9.3 Hydrocarbons

Coarse equant second generation calcite, formed on the earlier first generation calcite contains some evidence of hydrocarbon entrapment. Relatively large hydrocarbon-filled inclusions appear as dark inclusions, the result of internal reflection (Plate 7.2G), with regular curved morphologies. This contrasts with the usually more irregularly shaped inclusions associated with mineral-forming fluids, and also with trains of much smaller secondary inclusions. These hydrocarbon-bearing FI morphologies are suggestive of a single-phase methane fill (e.g., Goldstein & Reynolds 1994). Rarely inclusions may show evidence of

Table 7.3 Summary fluid inclusion data and inferred nature of geological fluids responsible for precipitating Tikorangi Formation vein minerals.

Mineral	Number measured	Total occurrence	Occurrence L+V	Th	Tm	Salinity (ppt)	SMOW $\delta^{18}O$	Fluid type	Fluid(s) origins	Hydrocarbons
<i>Calcite - first generation</i>	52	Many	Rare	90+	-0.5 to -4 (-1.5)	9 - 84 (28) Saline depleted to saline enriched with av. <normal marine	+5.5	Mixed: meteoric> shallow burial>deep burial	Largely influenced from meteoric fluids entering through cascade zones	Absent
<i>Calcite - second generation</i>	52	Many	Some	101+	-1 to -4 (-1.9)	2 - 84 (35) Slightly saline depleted to saline enriched. Av. > normal marine	+4.7	Mixed meteoric> shallow burial-deep burial	Mix of basinal brines, hydrocarbon-bearing and meteoric fluids	Present
<i>Dolomite</i>	18	Rare	Very rare	88 +	—	26 - 47 (33) Slightly saline depleted to saline enriched. Av. ~normal marine	+2.2	Mixed: deep burial (basinal)> shallow burial> meteoric	Influx of basinal brines precursory to hydrocarbon emplacement	Absent
<i>Celestite</i>	19	Common	Rare	110 +	-1.4 to -2.5 (1.8)	26 - 47 (33) Slightly saline depleted to saline enriched. Av. ~normal marine	n/a	Mixed: deep burial (basinal)> shallow burial> meteoric	Influx of basinal brines precursory to hydrocarbon emplacement	Absent

SMOW values were calculated from Th values (taken to be approximately 90°C and equivalent to Th min. values) and the oxygen isotope composition of the minerals using the isotope paleotemperature equation of Shackleton (1967) for calcite and of Fritz & Smith (1970) for dolomite.

heterogeneous entrapment and segregation of hydrocarbon and water phases. Some inclusions may represent entrapment of liquid phases also. Aqueous inclusions containing high-pressure bubbles of methane can be seen to have formed solid gas-hydrates (clathrates) (Plate 7.2H inset) within a fluid inclusion as it cooled. Clathrates alone are evidence of gas inclusion (Goldstein & Reynolds 1994). The hydrocarbon-rich nature of these inclusions was positively identified by their clearly visible and bright white fluorescence under blue UV light (Plate 7.2H).

Hydrocarbons have not been identified in the earlier first generation calcite or dolomite. However, hydrocarbons were commonly appear as brown films under PPL (white fluorescence under blue UV light) coating crystal boundaries and penetrating crystal dislocation surfaces where they have been introduced following vein mineralisation.

7.10 DISCUSSION

7.10.1 Fracture systems

Burial diagenesis of the Tikorangi calcitic carbonate sediments including dolomitisation, (see Topic 6; Section 7.10.5) produced a tight, dense, and well-lithified rock having negligible porosity and permeability. Miocene faulting, overthrusting, and folding associated with compression at the Australia/Pacific plate created extensive fracture systems within the Tikorangi Formation in the vicinity of the Tarata Thrust Zone. Brittle failure was enhanced by the rapid onset of a compressive stress regime in the Miocene, and by the fine-grained and dolomitic nature of the limestones, leading to the development of fracture-induced porosity. For the fractures to have remained open, the Tikorangi Formation rocks must have had sufficient shear strength to resist the outwards horizontal stress (Bjorlykke 1994), and burial diagenesis, Fractures may have opened and closed several times by a process of seismic pumping (e.g., Mann 1994). Open fractures became avenues of enhanced permeability with an ensuing history of ongoing displacement and episodic mineralisation prior to major hydrocarbon emplacement.

Fracture occurrence and spacing were determined by the small-scale variability in rock composition, and bed thickness and porosity, while the predominantly N-S fracture orientation relates to the general direction of E-W tectonic compression (King & Thrasher 1996). Fracture density is directly related to the strength or ductility of the rock, with the highest densities occurring in the least porous, most brittle, dolomitic-rich carbonates, and lesser densities in the more siliciclastic-rich facies.

Fracturing is likely to have suddenly, in geological terms, connected the deep-burial environment with meteoric fluids in the shallower subsurface, abruptly reducing locally the pore fluid pressure gradient into the fractures, and potentially drawing down meteoric fluids (e.g., Choquette & James 1990).

7.10.2 Vein mineralisation

7.10.2a Carbonate phases

Vein calcite (first and second generation) and dolomite are both late diagenetic minerals formed after fracturing of the Tikorangi Formation at significant burial depths and elevated temperatures (see Section 7.10.5). The ferroan nature of the carbonate minerals is consistent with burial derivation, they being precipitated under reducing conditions from Fe-rich pore fluids sourced from siliciclastic-rich interbeds, a situation typical of other mid-Tertiary New Zealand limestones experiencing burial diagenesis (Nelson et al. 1988; Hood & Nelson 1996). Poorly ordered Ca-rich baroque ferroan dolomite, also reflecting the large amount of iron present in the mixed carbonate-siliciclastic system (Land 1983), is typical of a very late burial diagenetic origin (Zenger & Dunham 1988). Baroque dolomite is suggested to form at elevated temperatures coincident with the oil window, from about 60-150°C, and is often associated with sulfate-bearing carbonates and hydrocarbons (Morrow 1990), which has implications for celestite formation and timing of hydrocarbon emplacement (see Section 7.10.5).

Baroque dolomite can be of replacement or, most commonly, very late pore-fill cement origin (Tucker & Wright 1990). A dominantly cement origin for dolomite is favoured in the Tikorangi Formation and is consistent with the isopachous coating it provides to first generation calcite. Other petrographic evidence also

supports a less voluminous replacement origin in the form of: calcite relicts poikilitically enclosed within dolomite (Plate 7.1E); preferential replacement of finer crystals; and partially dolomitised coarser calcite crystals. Relict calcite inclusions are commonplace in dolomite that has replaced calcite. The absence of fluid inclusions in the dolomite is indicative of slow crystal growth reducing the potential for numerous crystal imperfections (Goldstein & Reynolds 1994).

Fluids may have imported Mg from underlying shale sequences, partially dissolving the precursor calcite phase, precipitating dolomite, and exporting Ca and Sr (Scoffin 1987). Dolomite formation is suggested to have been terminated by a change in environmental conditions resulting from inversion (Fig. 7.10), after which the precipitation of second generation calcite occurred. Precipitation of carbonate minerals was eventually terminated by the introduction of hydrocarbon-bearing fluids.

7.10.2b Quartzine

Conditions surrounding the formation of quartzine phases in the Tikorangi Formation are less clear. Relatively little is known about the chertification of carbonates, especially pore fluid compositions and the chemical and physical conditions of precipitation (Hesse 1990b). The occurrence of minor amounts of spherulitic quartzine outside of chert nodules replacing evaporites is rarely documented in the literature. Chert is known to have replaced micrite infilling skeletons in the Amuri Limestone in northeastern South Island (Lawrence 1989). Chertification within the Tikorangi Formation may have involved precipitation of primary cements, but especially the replacement of both calcite and dolomite as evidenced by the poikilitic inclusion of carbonate relicts. The small grain size of quartzine suggests rapid and homogenous nucleation, while replacement fabrics suggest relatively low silicon concentrations.

Quartzine often occurs at the host rock/vein contact and may be a result of the weakening and fracturing at this contact allowing Si-rich fluid migration. Only minor and partial replacement of carbonate phases have occurred, presumably a function of pH, dissolved silicon activity, and the porosity and permeability of the rocks. Evidence of a relatively late stage origin may be provided by dirty areas

GEOHISTORY MODEL FOR THE TIKORANGI FORMATION AND VEIN MINERALISATION

Event 1 22->20 Ma
Tikorangi Formation cementation

Event 2 21-19 Ma
Tikorangi Formation partial
dolomitisation

Event 3 21-19 Ma
Tikorangi Formation brittle fracturing

Event 4 <20-18 Ma
First generation calcite precipitation

Event 5 17.5-6 Ma
Dolomite precipitation and partial
replacement first generation calcite

Event 6 (undifferentiated)
Celestite formation; cement
precipitation and replacement
Quartzine formation; dominantly
replacement

Event 7 8-5 Ma
Second generation calcite
precipitation

Event 8 <5 Ma
Major hydrocarbon emplacement

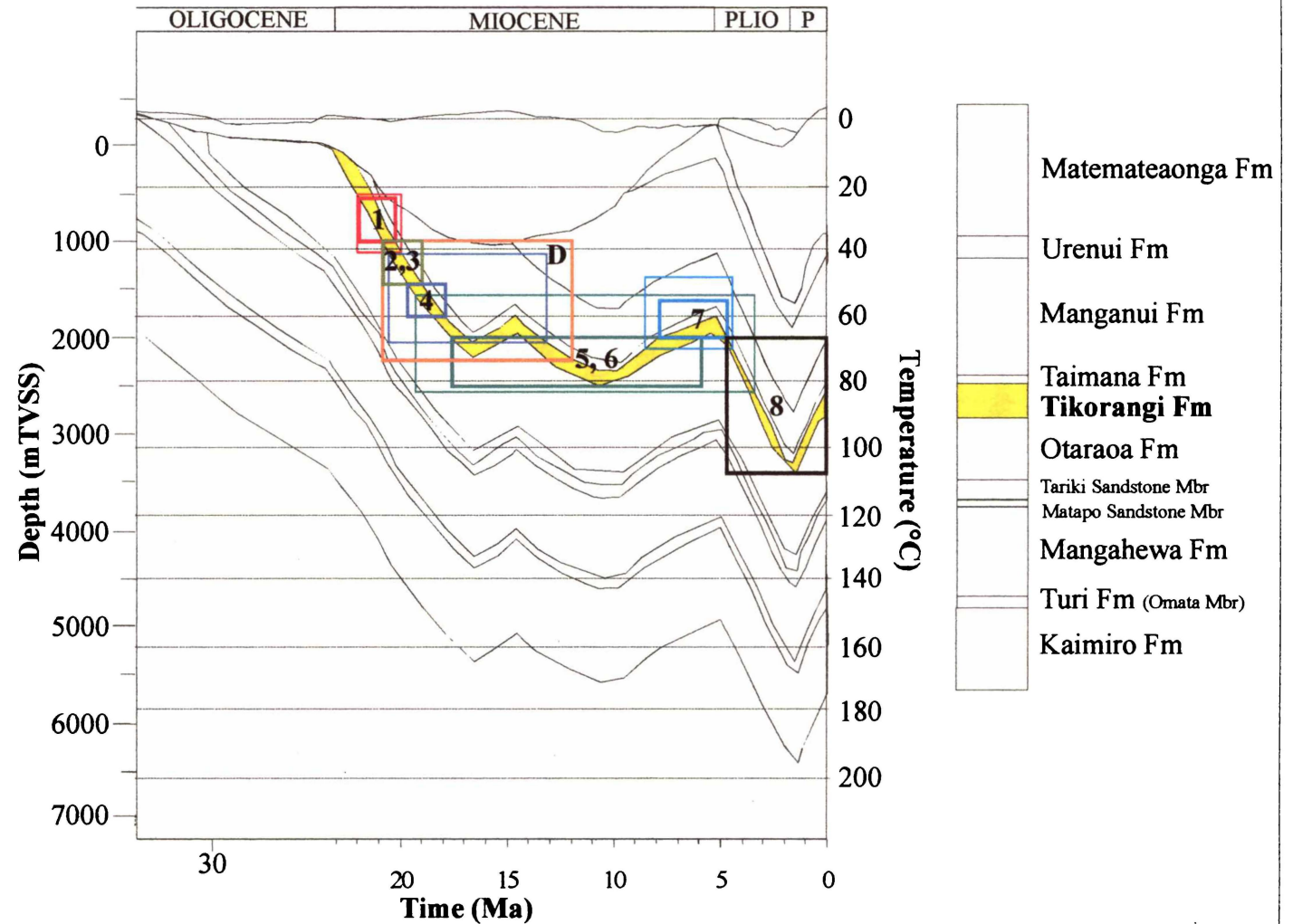


Fig. 7.10 Schematic summary showing the timing of major diagenetic events within the Tikorangi Formation and associated fracture systems based on the geohistory for Waihapa-1, Waihapa-Ngaere Field (see Fig. 7.1 for location). Geohistory plot based on Simpson (1992). Thicker event windows based on mean isotope temperatures while the thinner same coloured window denotes the broadest range for the event using isotope min. to max. temperatures shown in Table 7.4. MTVSS = metres true vertical sub-sea. D = previously broadly defined dolomitisation window in Topic 5.

thought to be organic-rich inclusions related to pre-cursor hydrocarbon-bearing fluids occurring after first generation calcite and the majority of dolomite carbonate mineralisation (cf. Hesse 1990b). Sources of silica are likely to have been biogenic, especially siliceous sponge spicules, with silica solubility increasing with burial depth (Hesse 1990a). For silicification during intermediate burial depths, pressure-dissolution of quartz together with smectite to illite transformation in associated shales have been invoked as additional silica sources (Hesse 1990b). Formation would have been promoted in the presence of Mg and high alkalinity, conditions similarly favourable for dolomitisation (Hesse 1990a). The close association of dolomite and quartzine phases is suggestive of formation within a similar time frame, and they are not considered to be mutually exclusive.

Elevated heat flow, generally regarded as necessary for a replacement origin, would have necessitated temperatures in the range of 60-100°C. However, rare fibrous forms in the Tikorangi Formation could be true precipitates that formed in the pressure shadows of rigid dolomite grains, in a fashion similar to pressure fringes in metamorphic rocks, and may be stress related (Hesse 1990b).

7.10.2c Celestite

Formation of celestite is likely to have resulted from the interaction of heated Sr-rich formation waters enriched in SO₄, possibly related to hydrocarbon-bearing fluids. At relatively modest burial depths (3,000 m or less) there is definite potential for highly variable sulfate concentrations in subsurface waters (Land 1997) conducive to celestite formation, for example as has been reported in DSDP cores (Baker 1986).

7.10.3 Fluid flow

It has been recognised for more than a decade that continental collisions may cause regional fluid migrations in foreland basins and in the adjacent hinterland (Wojcik et al. 1997). Migration of geological fluids was of fundamental importance to the systematic diagenetic evolution of the suite of vein minerals precipitated within the Tikorangi Formation. Fluid flow through the fractured rock would have required the fracture system to have a suitable geometry and for some threshold conditions to be exceeded in order that the system was linked into a

connected fluid migration pathway (Knipe & McCaig 1994). The effect on the permeability and fluid flow in the rock would have depended, and still depends today, upon the extent and duration that the fractures are interconnected and open (Knipe & McCaig 1994). Most fractures that have contributed to fluid flow during mineralisation in rocks are now at least partially healed. Episodic movement/fracturing is likely to have been a key to facilitating fluid migration (Parnell 1994). Evidence suggests that fluid flow in fault-related fracture systems is episodic where reverse faults, such as the Taranaki Fault marking the eastern boundary of the Tarata Thrust Zone, draw fluids into the crust (Parnell 1994). This may have been a mechanism for introducing meteoric fluids at depth.

7.10.4 Fluid sources and geochemistry

The occurrence of multiple vein mineral phases, collectively forming a calcite/dolomite-celestite-quartzine mineral assemblage, points to fluid compositions varying both spatially and with time. Burial diagenesis of carbonates generally is a complex process potentially involving a complex array of fluids (Heydari 1997). The fluids responsible for vein mineralisation in the Tikorangi Formation probably involved waters of diverse origins and compositions. Faulted reservoir rocks such as the Tikorangi Formation are often characterised by oilfield waters deficient in salinity (North 1985).

Studies have documented evidence for calcite and dolomite cements in environments where mixing of waters of widely varying salinity has occurred (Feng & Meyers 1998). However, there has been little study of the potential effects of fluid mixing on carbonate diagenesis under conditions of burial diagenesis (Morse et al. 1997). Various mixing models have proposed that mixtures of meteoric waters and sea water could be effective solutions for producing dolomite. The key to this type of model is that such mixing can result in undersaturation with respect to calcite but supersaturation with respect to dolomite (Morse & Mackenzie 1990).

Modelling suggests that meteoric water flow may reach 2-3 km into basins like the Gulf of Mexico (Bjorlykke 1994), while changes in base sealevel due to tectonic or eustatic changes must shift the interface between the relative positions

of the burial and meteoric fluid hydrological zones (Choquette & James 1990). In the south Louisiana Gulf Coast basin low salinity waters are being driven by variations in topographic elevation of 100 m or less to depths of up to 1 km into the subsurface (Land 1997). The question is then how deep can meteoric water penetrate beneath onshore Taranaki Basin? Allis et al. (1997) have calculated that from some 8 m of rainfall in the vicinity of Mount Taranaki onshore, and assuming a conservative 15% of rainfall becomes infiltration, meteoric recharge would be 3.8 million m³/day. They noted that sandstones at 2 km depth could be conduits for deeply circulating groundwater on a timescale in the order of 10⁴ to 10⁵ years.

For all except Ca, the trace element concentrations in the Tikorangi Formation vein dolomites show increasing values downcore. This is suggestive of dolomitising fluids being sourced generally from below the formation, and becoming more dilute as they move upcore. These fluids are thought to have been of a burial/basinal type and Mg- and Fe-rich, expelled from basinal mudrocks. Allis et al. (1997) have suggested that presently the Tikorangi Formation is charged by hydrocarbon and associated saline formation water leaking from sources within an underlying overpressurised zone.

Upon rising into shallower depths, mixing of basinal fluids with circulating groundwaters occurred, giving rise to a laterally and vertically variable range of fracture fluid compositions and salinities. Certainly T_m ice data and calculated salinity values show a range of salinity-depleted (2 ppt NaCl) and saline-enriched (84 ppt NaCl) fracture fluids which could be explained by mixing of connate burial fluids from below the Tikorangi Formation and meteoric fluids from above. Where there is an aquifer with strong hydraulic head and recharge descending into the deep subsurface, as in a cascade zone (Tucker & Wright 1990), then meteoric diagenesis could take place at significant depths.

The kinetic hindrances to precipitating dolomite from sea water could certainly have been overcome by meteoric dilution of sea water (Tucker & Wright 1990). Diluting sea water would have overcome the high ionic strength and the problem of rapid rates of precipitation. An important factor is that in solutions comprising

5-50% sea water, dolomite is supersaturated whereas calcite is undersaturated due to their solubility curves not being linear, and so dolomite should be capable of replacing calcite over this range of dilution (Tucker & Wright 1990). Dolomites that are not associated with evaporite deposits, and that are poorly ordered and Ca-rich, and depleted in Na and heavy isotopes, are commonly suggested to have a mixing model origin where Mg is derived from sea water whose circulation was induced by groundwater flow (Tucker & Wright 1990; Rao 1990). Dilution of saline solutions causes slow precipitation (Morrow 1990b), consistent with paucity of fluid inclusion entrapment as is the case for Tikorangi Formation vein dolomites. A mixing zone model for the Tikorangi Formation vein mineralisation would also support a geochemical environment conducive to calcite dissolution and simultaneous silica precipitation (Hesse 1990b).

Further evidence to support a fluid mixing model is provided by combining fluid inclusion and stable isotope data. Assuming calcite (first and second generation) and dolomite minerals precipitated in equilibrium with the ambient fluids, the oxygen isotope composition of the fluids can be calculated from the T_h min. values (e.g., Suchy et al. 2000), taken to be approximately 90°C, and the oxygen isotope composition of the minerals using the isotope paleotemperature equation of Shackleton (1967). At this temperature first and second generation calcite with $\delta^{18}\text{O}$ average values of -7.4‰ and -8.2‰ PDB precipitated from a fluid with $\delta^{18}\text{O}$ values of $+5.5\text{‰}$ and $+4.7\text{‰}$ SMOW, respectively (Table 7.3). Similar calculations for dolomite using the Fritz & Smith (1970) equation and a $\delta^{18}\text{O}$ average value of -6.1‰ PDB suggests precipitation from a fluid with a $\delta^{18}\text{O}$ value of $+2.2\text{‰}$ SMOW (Table 7.3). The highest $\delta^{18}\text{O}$ values for the calcite phases are close to the modern local Taranaki meteoric water of -5.5‰ (Smale et al. 1999), and the dolomite value shows some meteoric influence. Given that the T_h values used are higher than isotopically calculated paleotemperatures then some degree of forcing of SMOW values is a consequence, but these calculated values do suggest a significant degree of meteoric influence in the porewaters precipitating calcite phases, becoming less influential in the dolomite-forming pore fluids.

7.10.5 Paleodepths and paleotemperatures

Table 7.4 shows a range of paleotemperature calculations for mineral precipitation derived from $\delta^{18}\text{O}$ isotope data for calcite and dolomite vein minerals and Tikorangi Formation host rock samples. Given the previously discussed evidence for the possibility of mixed saline and meteoric fracture fluids, values assuming a range of slightly meteoric-influenced ($\delta^{18}\text{O}$ SMOW = -1), neutral ($\delta^{18}\text{O}$ SMOW = 0) and saline-enriched ($\delta^{18}\text{O}$ SMOW = +1) marine waters have been derived. These show increasing paleotemperatures with increasing salinity.

Bulk host rock samples have $\delta^{18}\text{O}$ values ranging from about -2.0‰ to -3.5‰ (Fig. 7.8; Table 7.3). To maximise the burial spar influence, paleotemperatures have been calculated using -4.3‰, which is close to Nelson and Smith's (1996) average burial spar value of -4.4‰. Average paleotemperatures for host rock spar cement are about 32°C, corresponding to about 0.8 km burial depth. Cementation of the limestone-dominated sequence may have commenced at temperatures as low as about 20°C, or 0.5 km burial depth, and was mainly complete by 1 km burial depth at which stage rock fabrics were tight and pressure-dissolved (Table 7.5; see Topic 5). This kind of burial diagenetic scenario is similar to that described by Nelson et al. (1988) for the age-equivalent limestones in neighbouring North Wanganui Basin. Using a geohistory plot (Fig. 7.10), average cementation depths of 0.8 km burial would have been reached after about 2 m.y., and slightly longer for 1 km burial. Brittle fracturing of an already lithified Tikorangi Formation rock must have therefore occurred at temperatures and depths equal to, or in excess of, 0.8 km burial depth, and/or 32°C, but below 1.4-1.8 km burial and/or 50-60°C associated with precipitation of first generation calcite (Table 7.4, 7.5).

The order of precipitation of vein carbonate mineral phases (first generation calcite, second generation calcite, dolomite) based on isotope temperatures is initially incompatible with the petrographically defined sequence (first generation calcite, dolomite, second generation calcite). However, upon integration with a geohistory plot, second generation calcite formed following uplift and subsequent cooling from the depths and temperatures associated with earlier dolomite formation (Fig. 7.10). First generation calcite temperatures of formation range

Table 7.4 Stable oxygen isotope paleotemperature calculations using a range of SMOW values and an average geothermal gradient of 29°C/km.

MINERAL PHASE	Stable Isotopes						Isotope <i>T</i> (°C)			Isotope <i>T</i> (°C)			Isotope <i>T</i> (°C)			Paleodepth (km)			Paleodepth (km)			Paleodepth (km)		
	$\delta^{13}\text{C}$			$\delta^{18}\text{O}$			$\delta^{18}\text{O}_{\text{SMOW}} = -1$			$\delta^{18}\text{O}_{\text{SMOW}} = 0$			$\delta^{18}\text{O}_{\text{SMOW}} = +1$			$\delta^{18}\text{O}_{\text{SMOW}} = -1$			$\delta^{18}\text{O}_{\text{SMOW}} = 0$			$\delta^{18}\text{O}_{\text{SMOW}} = +1$		
	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean
Host rock (*7) (Tikorangi Formation)	2.0	-0.9	-0.5	-2.0	-4.3	-3.2	21	32	27	26	38	32	31	43	37	0.5	0.8	0.7	0.6	1.0	0.8	0.8	1.2	1.0
Calcite - first generation (8)	-1.7	-6.2	-3.8	-5.8	-8.7	-7.4	40	57	49	46	63	55	51	69	61	1.1	1.7	1.4	1.3	1.9	1.6	1.5	2.1	1.8
Calcite - second generation (8)	-0.5	-6.3	-4.6	-7.1	-9.1	-8.2	47	59	53	53	65	59	59	72	65	1.3	1.8	1.6	1.5	2.0	1.8	1.7	2.2	2.0
Dolomite (7)	-2.2	-5.7	-4.5	-4.7	-6.7	-6.1	55	69	65	62	77	72	69	85	80	1.6	2.1	2.0	1.9	2.4	2.2	2.1	2.6	2.5

Note: Bracketed () value denotes number of samples. * Denotes inclusion of data for 5 samples from Smale et al. (1999).

from about 50-60°C, corresponding to burial depths of 1.4-1.8 km, and probably occurred at approximately <20-18 Ma (Fig. 7.10; Table 7.5). Fracturing and dolomitisation of the host Tikorangi Formation must have been complete by this time and was previously poorly constrained, but was believed to have occurred during the Early Miocene, coincident with a period of major tectonic compression (King & Thrasher 1996). The new data confine Tikorangi Formation dolomitisation and later fracturing to occurring between 21-19 Ma at paleotemperatures of 36-50°C corresponding to burial depths of 1.0 – 1.5 km (Fig. 7.10; Table 7.5). This is within the upper dolomitisation window (i.e. lowest temperatures and burial depths) proposed in Topics 5 and 6.

Baroque dolomite potentially formed over a 11.5 m.y. interval (17.5 – 6 Ma) as a primary precipitate and less commonly as a replacement of earlier first generation calcite at temperatures averaging 65-80°C, corresponding to 2-2.5 km burial depth (Fig. 7.10; Table 7.4; 7.5). This lies within the oil window temperature of 60-150°C, a range in which baroque dolomite is commonly formed in association with hydrocarbons (Tucker & Wright 1990). Second generation calcite potentially formed over a 3 m.y. period (8 –5 Ma) following a period of inversion, which may have begun during later dolomite formation when temperatures averaged 53-65°C, or burial depth of 1.6-2.0 km (Fig. 7.10; Table 7.4, and 7.5). Hydrocarbon emplacement *per se* is then inferred to have taken place relatively recently, post-second generation calcite formation, in the last 5 m.y. corresponding to burial temperatures and depths in the Tikorangi Formation fracture systems of 53-107°C and 2.0-3.5 km burial (Fig. 7.10; Table 7.5). Armstrong et al. (1996) and King & Thrasher (1996) suggest that Eocene source-rocks may have begun expelling hydrocarbons in the later Miocene, while this study suggests hydrocarbons entered the Tikorangi fracture systems from the Early Pliocene (Opoitian).

Fluid inclusion paleotemperatures derived from carbonate vein minerals (Appendix 7.3) are significantly higher than the temperatures calculated from the $\delta^{18}\text{O}$ data. Heat generated by friction during thrusting can also be significant and temperature is not simply a function of geothermal gradient (Heydari 1997). The discrepancy of higher paleotemperatures provided by T_h is also not surprising

Table 7.5 Summary of the major diagenetic events occurring within the Tikorangi Formation host rock and fracture systems based on stable oxygen paleotemperatures (Table 7.4) integrated with a geohistory plot (Fig. 7.10). New Zealand stage symbols defined in Appendix 1.2.

Diagenetic event		Description	Isotope temp. (°C mean range)	Paleodepth (km mean range)	Timing (Ma)	Timing (NZ Stage)	Duration of event (m.y.)
1	Host rock	Tikorangi Formation host rock cementation resulting from pressure dissolution associated with burial diagenesis	27 - 37	0.7 - 1.0	22->20	Lw-Po	~2
2		Tikorangi Formation host rock partial dolomitisation occurring in closed Mg-rich environments associated with micrite-clay rich facies.	36 - 50	1.0 - 1.5	21- 19	Po	~2
3		Tikorangi Formation thrusting, folding, brittle fracture and the creation of fracture porosity resulting from tectonic compression associated with the evolving Australia/Pacific plate boundary and Tarata Thrust Zone development	36 - 50	1.0 - 1.5	21- 19	Po	~2
4	Fracture systems	First generation vein calcite precipitation directly onto host rock fracture surfaces	49 - 61	1.4 - 1.8	<20 - 18	Po-Pl	~2
5		Vein dolomite formation dominantly as a precipitate coating but also partially replacing calcite first generation	65 - 80	2.0 - 2.5	17.5 - 6	Pl-Tk	~11.5
6		Vein celestite and quartzine formation associated with dolomite formation	65 - 80	2.0 - 2.5	17.5 - 6	Pl-Tk	~11.5
7		Second generation vein calcite precipitation atop dolomite and within central vein systems	53 - 65	1.6 - 2.0	8 - 5	Tt-Wo	~3
8		Major hydrocarbon emplacement into Tikorangi Formation fracture networks shutting off vein mineral formation	53 - 107	2.0 - 3.4	<5	Wo-?	?

given the majority of all fluid inclusion assemblages (FIAs) fell outside the 90% guideline of Goldstein & Reynolds (1994) occurring within 10-15°C. Outside this range FIAs could have experienced some degree of thermal re-equilibration. The high range of T_h is, however, strong evidence for a significant range of geologic conditions. Significantly different salinity fluids would have had to have existed at the same temperature to accommodate a wide range in T_h values and would require a complex mixing model explanation, as has been alluded to previously. The range of salinities has been calculated from measured T_m values and varies from reduced to enriched saline, lending further impetus to the argument for potential mixing of meteoric and marine fluids. More detailed fluid inclusion studies are required to provide a more definitive answer.

7.11 CONCLUSIONS

The distribution and productivity of hydrocarbon reservoirs, while often determined by tectonic configuration, are also dependent upon original depositional facies and diagenetic processes. The lithostratigraphic diversity of the carbonate-dominated Tikorangi Formation, coupled with superimposed burial diagenesis and tectonic fracturing, have resulted in a complex reservoir rock. Post-lithification processes in the Waihapa-Ngaere Field involved substantial compressional tectonics and thrust faulting (in the Tarata Thrust Zone), and extensive brittle fracturing of carbonate strata and episodic fluid flow in response to tectonic loading. Fracture systems provided significant fracture-induced porosity into which a suite of calcite-dolomite-celestite-quartzine minerals formed prior to hydrocarbon emplacement, as summarised in the paragenetic model presented in Fig. 7.11. Mineralisation substantially reduced fracture porosity and permeability.

Petrographic, trace element, stable isotope, and fluid inclusion data record a varied and complex history of changing pore fluid chemistry and heating during burial, punctuated by changes in input of downward circulating meteoric and upwelling basinal fluids. The initial ferroan low-Mg calcite first generation calcite formed from Fe-rich, meteorically modified, saline fluids in which mixing

SEQUENTIAL MODEL OF TIKORANGI FORMATION VEIN MINERALISATION

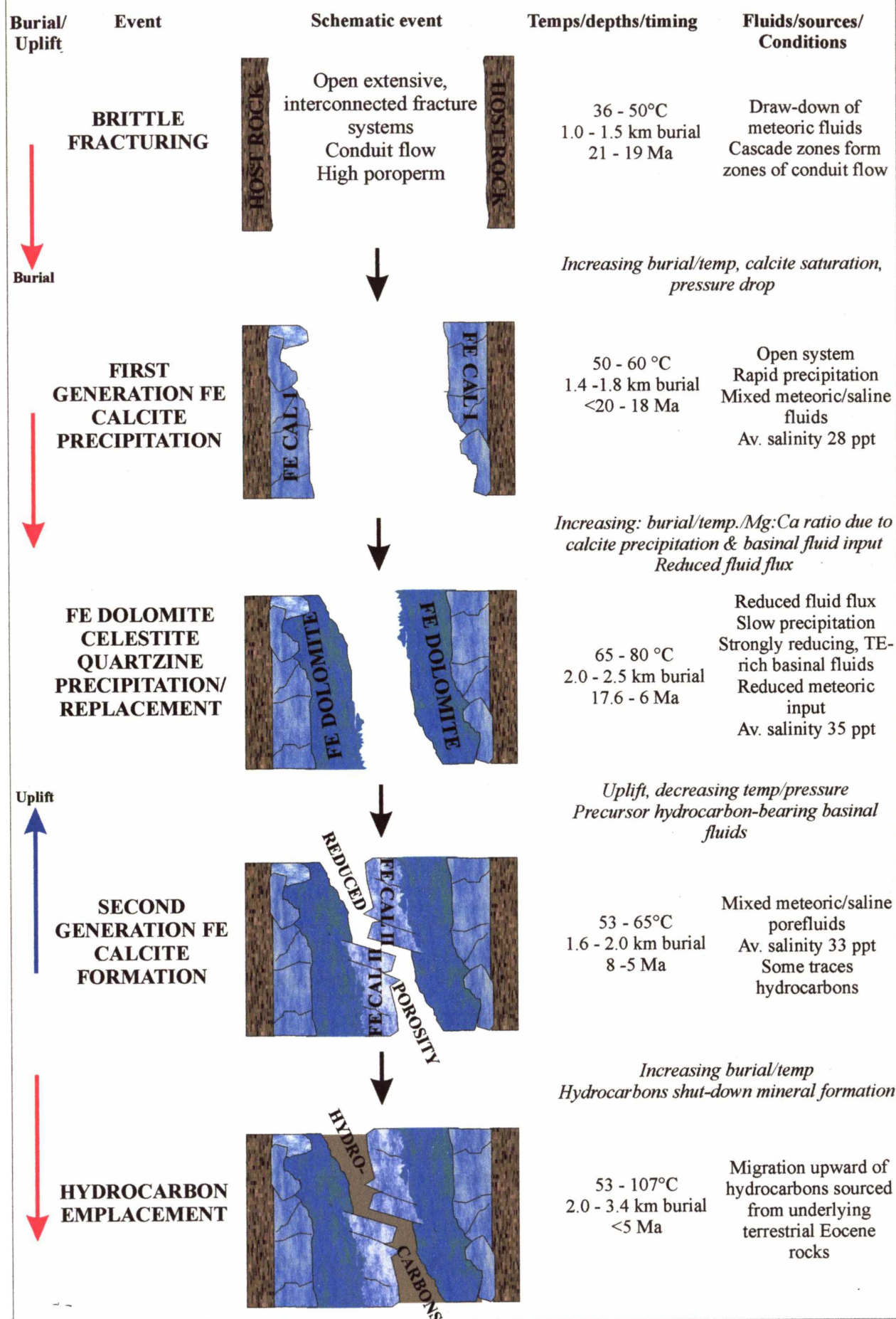


Fig. 7.11 Schematic model summarising major vein mineralisation events in the Tikorangi Formation. FE CAL I = first generation ferroan calcite, FE CAL II = second generation ferroan calcite.

occurred by percolation of deeply circulating groundwaters, particularly in cascade zones (Fig. 7.11). Baroque dolomite subsequently formed both as a primary cement and as a calcite replacement following onset of higher temperatures (65-80°C) and depths of burial (2-2.5 km) influenced by a change to more Mg-rich basinal fluid sources (Fig. 7.11), precursory to hydrocarbon emplacement *per se*. Celestite and quartzine phases coincided with, or marginally post-dated dolomite and formed as both spatially complex carbonate replacements and cements (Fig. 7.11). Ferroan second generation low-Mg calcite later formed at cooler temperatures (53-65°C) and shallower depths of burial (1.6-2.0 km) following a period of inversion. The presence of petroleum fluid inclusions in second generation calcite suggests in some cases precursory hydrocarbon-bearing fluids have migrated along with aqueous fluids from 8 Ma with major hydrocarbon emplacement occurring in the last 5 m.y. (Fig. 7.10, 7.11; Table 7.5). Throughout this complex mineralisation history continuing vein movement is recorded by shearing, recrystallisation, pressure-dissolution, twinning, and slickensiding on mineral surfaces.

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THE HYDROCARBON-PRODUCING CARBONATE-DOMINATED MID-TERTIARY TIKORANGI FORMATION, TARANAKI BASIN, NEW ZEALAND: A SUMMARY AND SYNTHESIS

8.1 NEW PERSPECTIVES

This study represents the first detailed geological study of the totally subsurface Tikorangi Formation, New Zealand's only commercially-producing carbonate and fracture reservoir. Previously the formation, often informally named the Tikorangi limestone, has been scantily documented and has remained poorly understood in comparison to most of the age-equivalent non-reservoir-bearing limestones exposed onshore (e.g., Nelson 1978a; Hayton et al. 1995; Hood & Nelson 1996). This scarcity of detailed published information about the Tikorangi Formation was the catalyst for the present study.

This investigation has shown the Oligocene-Early Miocene Tikorangi Formation records: (1) a complex history of mixed siliciclastic-carbonate-dominated deposition (Topic 2) including (2) a number of depositional sedimentary phases related to periods of aggradation, progradation, and retrogradation (Topic 3); (3) a shelf-to-basin depositional sequence encompassing near-situ shallow shelfal, mass redeposited foredeep, and pelagic basinal environments (Topic 4), formed during an important period of Taranaki Basin history, approaching the climax of a regional marine transgression (Topic 3); (4) at its onset a change from siliciclastic- to carbonate-dominated sedimentation and at its demise a return to siliciclastic sedimentation marking the uplift of source areas (Topics 3, 4); (5) a burial diagenetic history including dolomitisation that is not recorded in onshore and uplifted age-equivalent deposits (Topics 5, 6, 7); (6) the timing of onset of a major and fundamental change in tectonic style in Taranaki Basin associated with compression at the Australian-Pacific plate boundary, and evident in the formation by intense thrusting, folding/structuring, fracturing, and associated vein mineralisation responsible for the creation and modification of hydrocarbon-

producing fracture porosity; and (7) the timing of hydrocarbon emplacement within the formation reservoir (Topic 7).

Despite the constraints of the wholly subsurface position of the Tikorangi Formation, currently about 3 km below Taranaki Peninsula, and the discontinuous nature of available core material, this study has successfully employed a range of techniques to provide data which have contributed greatly to the scientific understanding of this important reservoir rock. The research has focused on the following aspects: history (Topic 1), stratigraphy (Topic 2), well-log trends and depositional setting (Topic 3), petrography, (Topic 4), diagenesis (Topic 5, 7), geochemistry (Topic 6), and fracture porosity and vein mineralisation. Topics are integrated here which together provide insight into a truly diverse and complex example of a cool-water carbonate-dominated sequence. The database for the Tikorangi Formation adds a new perspective to New Zealand carbonates more widely and extends aspects of currently developing global models for cool-water carbonate facies. The major findings of this study are highlighted below with an emphasis on graphically summarising interrelationships of key elements defined for the Tikorangi Formation (i.e., carbonate facies versus petrofacies), and illustrating differences between the three megafacies (shelfal, foredeep, basinal) from a shelf-to-basinal perspective, and their more specific petrofacies components. A brief paragenetic sequence of events for the Tikorangi Formation is presented. The relationship of the Tikorangi Formation to aspects of current temperate carbonate models, along with recommendations for further research and the future potential of hydrocarbon discovery within the Tikorangi Formation, are also commented upon.

8.2 TIKORANGI FORMATION PETROGENETIC ESSENTIALS

The basic framework for this study has centred around the definition of four major carbonate facies derived from the correlation of laboratory-determined carbonate data with geophysical Dt (sonic) and GR (gamma-ray) log data (Fig. 8.1), namely Facies A – calcareous siliciclastites, <25% carbonate; Facies B – very calcareous siliciclastites, 25-50% carbonate; Facies C – muddy limestones, 50-75%

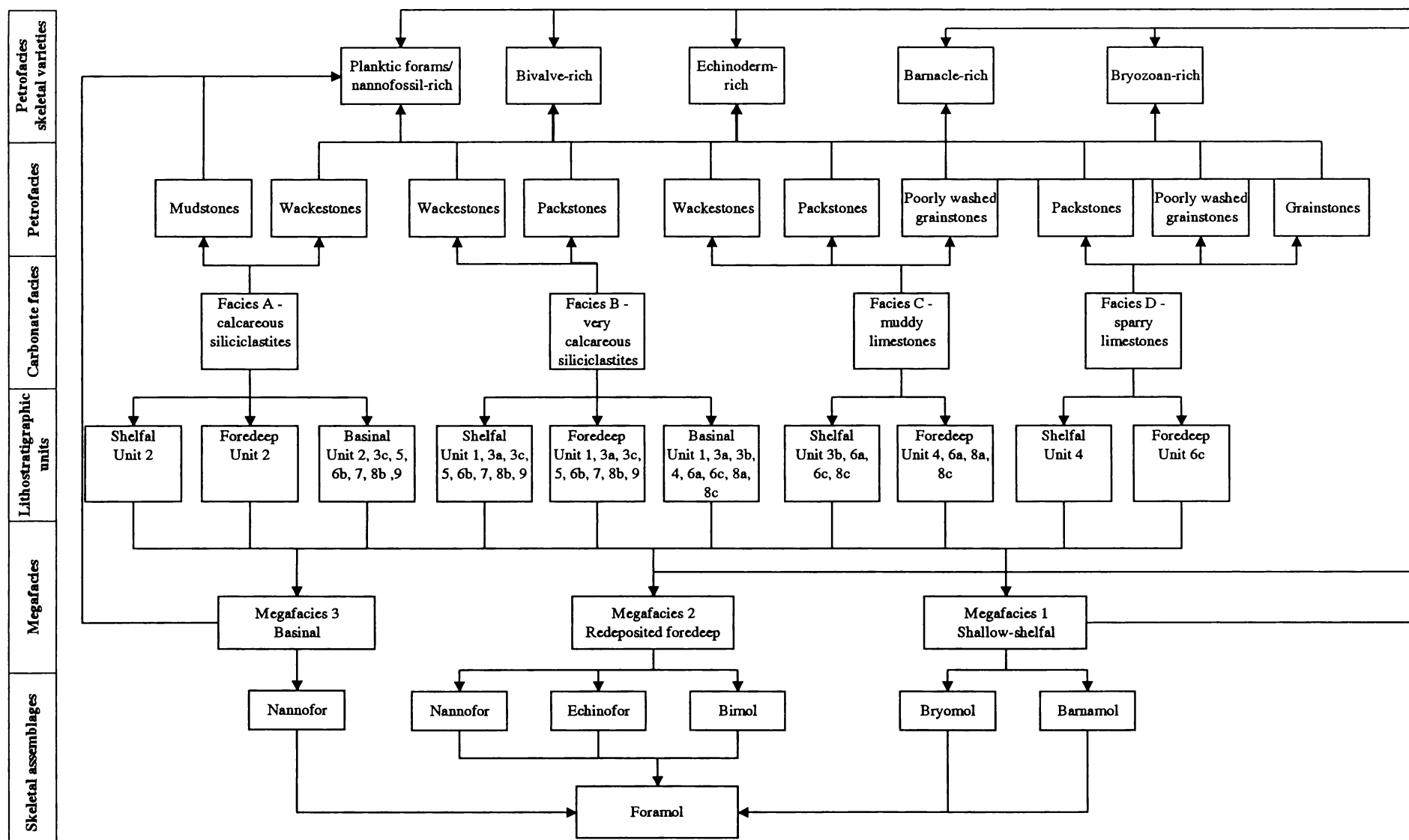


Fig. 8.1 Hierarchical lithological flowchart for the Tikorangi Formation showing the interrelationships amongst the various kinds of "facies" which underpin this study. Application of the cool-water skeletal assemblage classification scheme of Hayton et al. (1995) is also shown.

carbonate; and Facies D – sparry limestones, >75% carbonate. The major properties of the carbonate facies are schematically summarised in Fig. 8.2. The carbonate facies form the basic framework for identifying nine major lithostratigraphic units in the Tikorangi Formation (Fig. 8.1; Fig. 2.12) which have provided: a basis for the construction of a previously unavailable complete and detailed stratigraphy for the Tikorangi Formation; more appropriate formational boundaries based on compositional changes (see Table 2.2); a potential aid in delineating and correlating those particular facies most likely to be the key ones for hosting hydrocarbon reserves; and a sound stratigraphic framework and foundation for further detailed studies of the formation. The results highlight the utility of integrating geophysical log and laboratory data in stratigraphic analysis in subsurface studies where a limited and incomplete core record negates the opportunity for more traditional study using sedimentological methods.

Detailed petrography of the four carbonate facies (Topic 4) has delineated five petrofacies and shown the complex mixed siliciclastic-carbonate-rich nature of the deposits: I - mudstones; II – wackestones; III – packstones; IV - poorly washed grainstones; V - sparry grainstones (Fig. 8.1). Their relationships to the carbonate facies, and other key characteristics, are summarised in Fig. 8.3. Skeletal varieties within these petrofacies have aided in the identification of three texturally and compositionally distinctive megafacies for the Tikorangi Formation (Fig. 8.1; Fig. 4.26): (1) shelfal; (2) foredeep; and (3) basinal. Fig. 8.4 schematically summarises the key differences in age, thickness, carbonate facies make-up and stratigraphy for the three megafacies, while Fig. 8.5 portrays key textural and compositional differences from a shelf-to-basinal perspective.

Fig. 8.6 depicts the three megafacies within their depositional setting with key characteristics summarised in Table 8.1. Megafacies 1, an earliest Miocene (Waitakian), near-situ, shallow-shelfal limestone defined by, and limited to, Hu Rd-1A well, the southern- and easternmost well of the onshore Tarata Thrust Zone of the Eastern Mobile Belt, is placed on, or very near, variably exposed Mesozoic basement associated with the Patea-Tongaporutu-Herangi High. Megafacies 2 occurs further west in the Taranaki foredeep basin (Fig. 8.6; Table 8.1) and is an

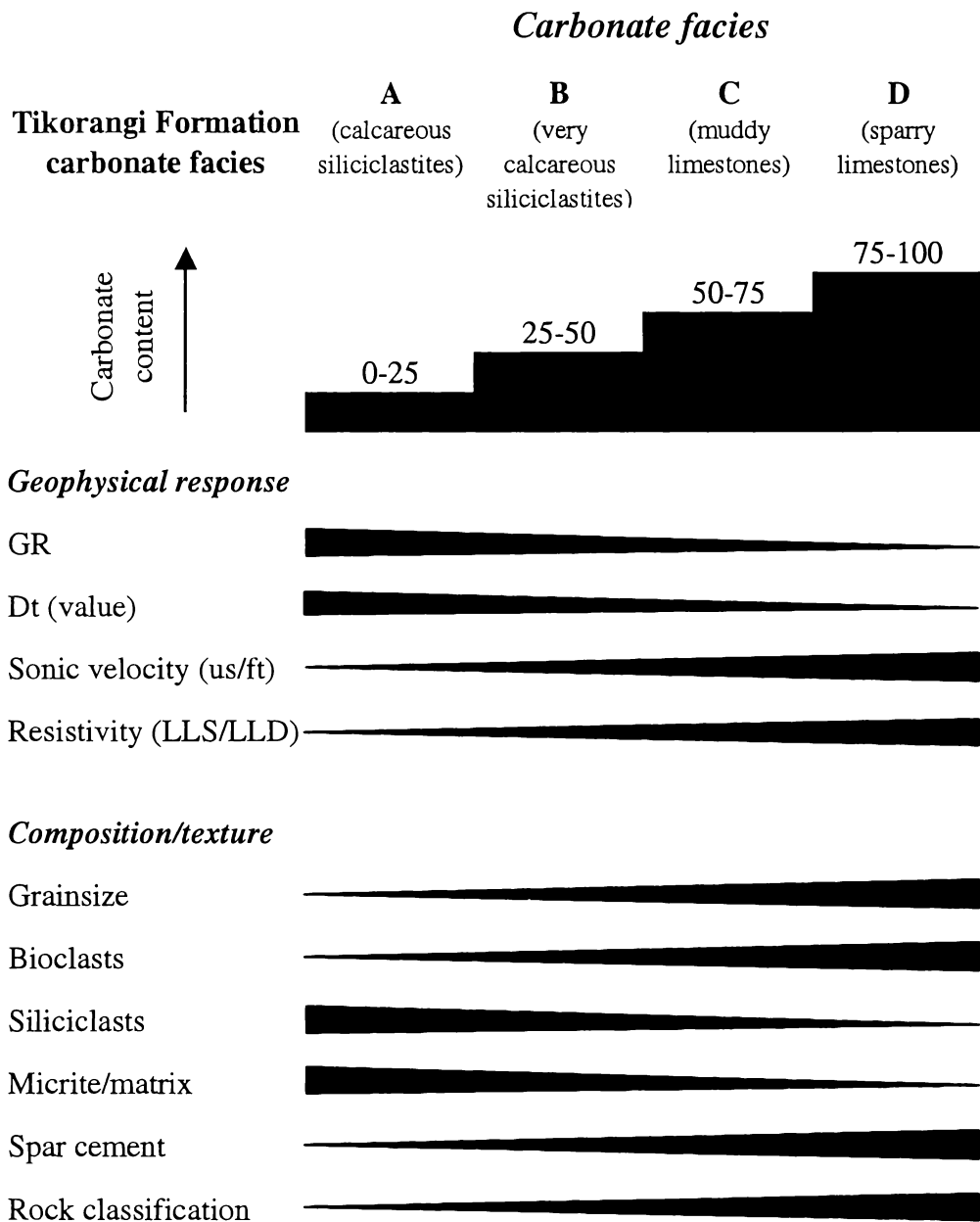


Fig. 8.2 Summary characteristics of the four carbonate facies (A-D) defined in the Tikorangi Formation, and their interrelationships. Thickening arrow denotes increasing value/content, and vice versa for thinning arrow. Rock classification refers to left = mudstones through to right = sparry grainstones (After Dunham 1962). LLS = laterolog shallow, LLD = laterolog deep.

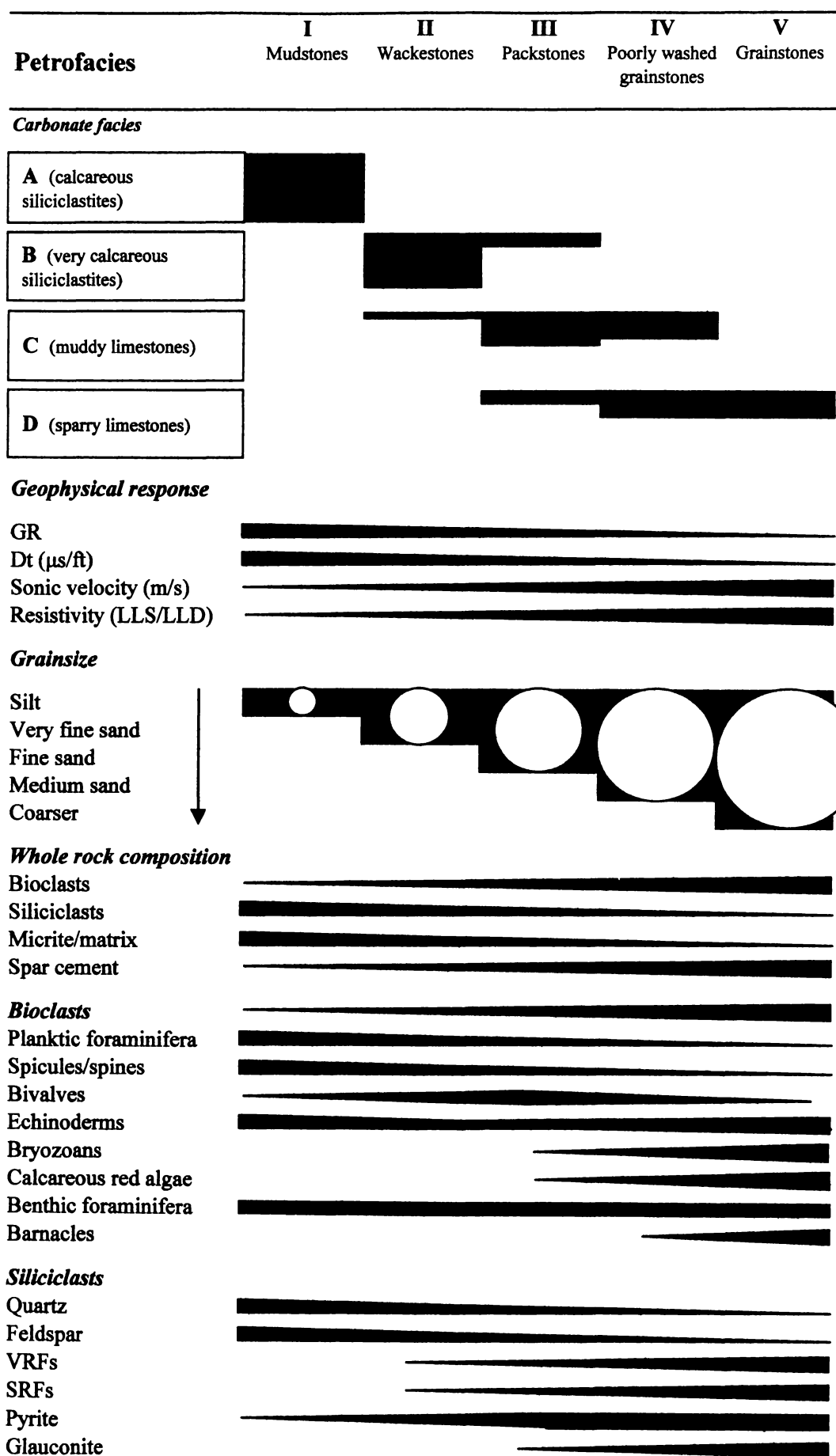


Fig. 8.3 Petrography and geophysical summary for the five Tikorangi Formation petrofacies (I-V) and their relationships with the four carbonate facies (A-D).

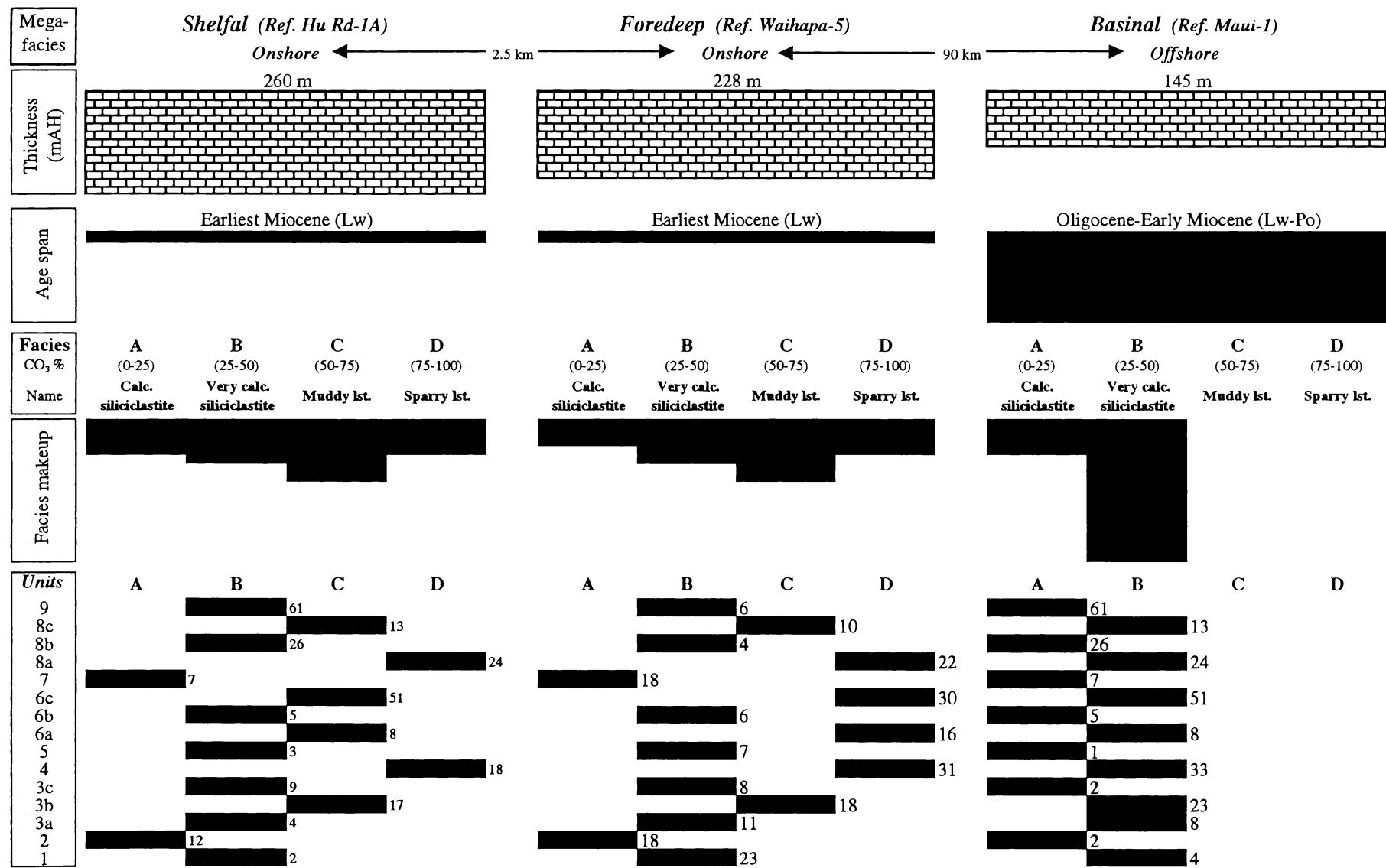


Fig. 8.4 Summary features of the three megafacies in the Tikorangi Formation and the interrelationships between carbonate facies and lithostratigraphic units. Av. unit thickness is shown in metres at the right side of the shaded box depicting the dominant carbonate facies occurring within each unit.

earliest Miocene (Waitakian) foredeep megafacies which comprises a spectrum of variably siliciclastic, generally carbonate-dominated rocks, including a prominent component of reworked and redeposited siliciclastics and shelfal bioclasts. Key indicators of mass-emplacement include the fragmental and highly abraded nature of the shelfal skeletons, including former photic dwellers such as calcareous red algae and large benthic foraminifera. The resulting skeletal mix of shelfal skeletons with background slope microfauna (pelagic foraminifera) and microflora (coccoliths) is unlike that in any of the age-equivalent limestones in the neighbouring onland North Wanganui Basin. Megafacies 3 occurs in more distal offshore basinal settings (Fig. 8.6; Table 8.1), as at Maui-1 on the Western Stable Platform, and is an Oligocene-Early Miocene (Whaingaroan-Otaian) basinal megafacies equivalent comprising very calcareous siliciclastites. Skeletal types are predominantly pelagically settled planktic foraminifera and coccoliths, while the siliciclastic fraction is dominated by clay- to fine silt-sized quartz and feldspar derived from Patea-Tongaporutu-Herangi High and South Island basement rocks, and possibly windblown Australian sources. The basinal megafacies was sufficiently removed from the foredeep trough to not be affected to any significant extent by those factors influencing the more landward well sites.

Depositional settings for the three contrasting megafacies were controlled largely by the interplay of the evolving and complex plate tectonic setting, including development of a foredeep trough, changes in relative sealevel and water depth within an overall transgressive regime, and the changing availability and sources of carbonate and siliciclastic supply (Fig. 8.7). Fig. 8.8 illustrates the changes in carbonate sediment composition occurring during deepening, characterised by a shift in the relative importance of shelfal-sourced mass redeposited components. This study of the Tikorangi Formation has captured through the three megafacies a shelf-to-basinal perspective of New Zealand's only hydrocarbon-producing limestone reservoir, at a time when many other New Zealand basins were accumulating dominantly shelfal non-producing carbonate-dominated deposits.

Geophysical well-log characterisation (Topic 3) has enabled a "sequence stratigraphy-type approach" that has provided a surrogate chronostratigraphic framework within which five major geophysical log sequences, representative of

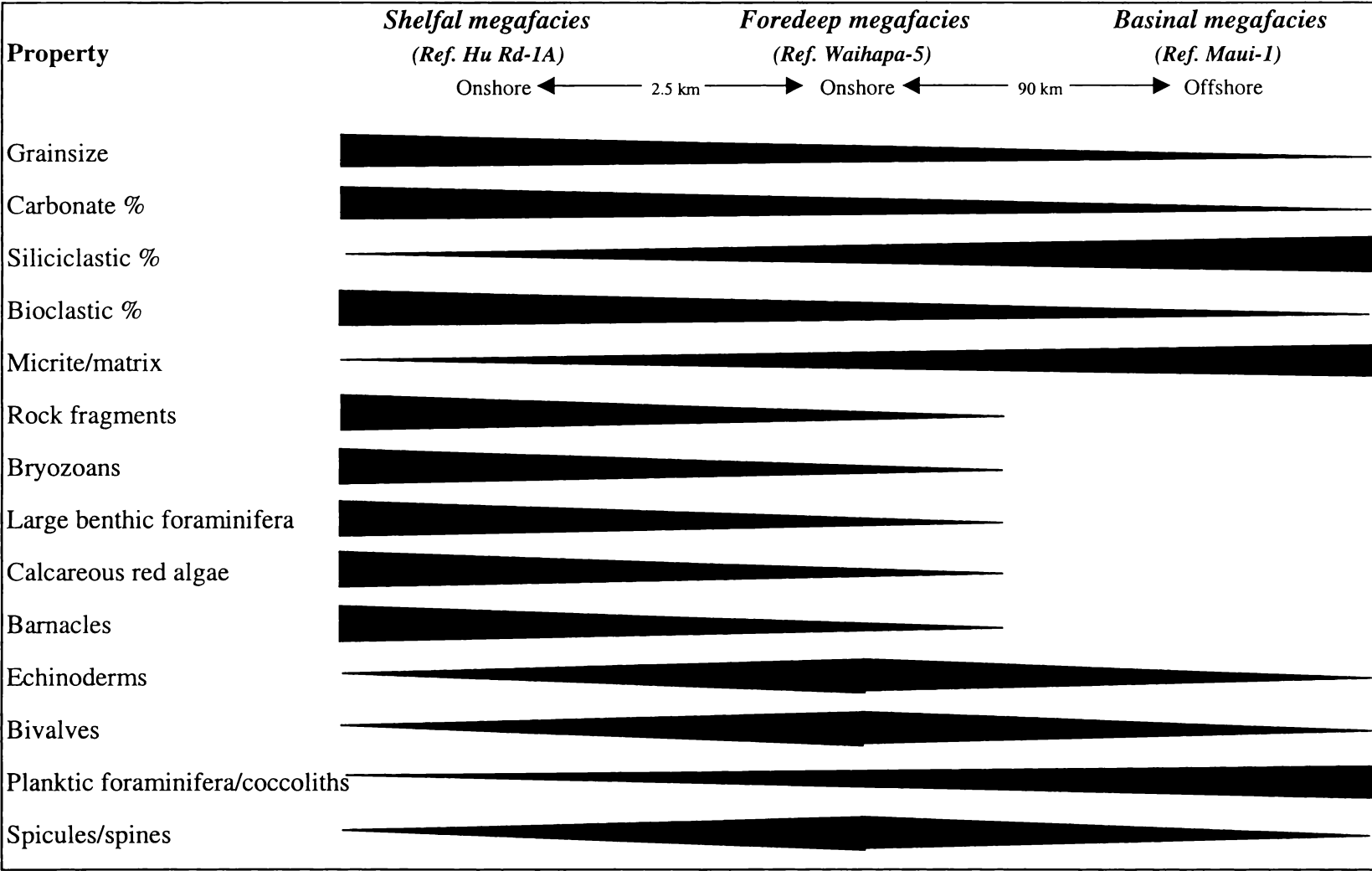


Fig. 8.5 Summary textural and compositional changes between the three Tikorangi Formation megafacies within a shelf-to-basin perspective. An increase or decrease in value/content from left or right is denoted by the changing thickness of the bars.

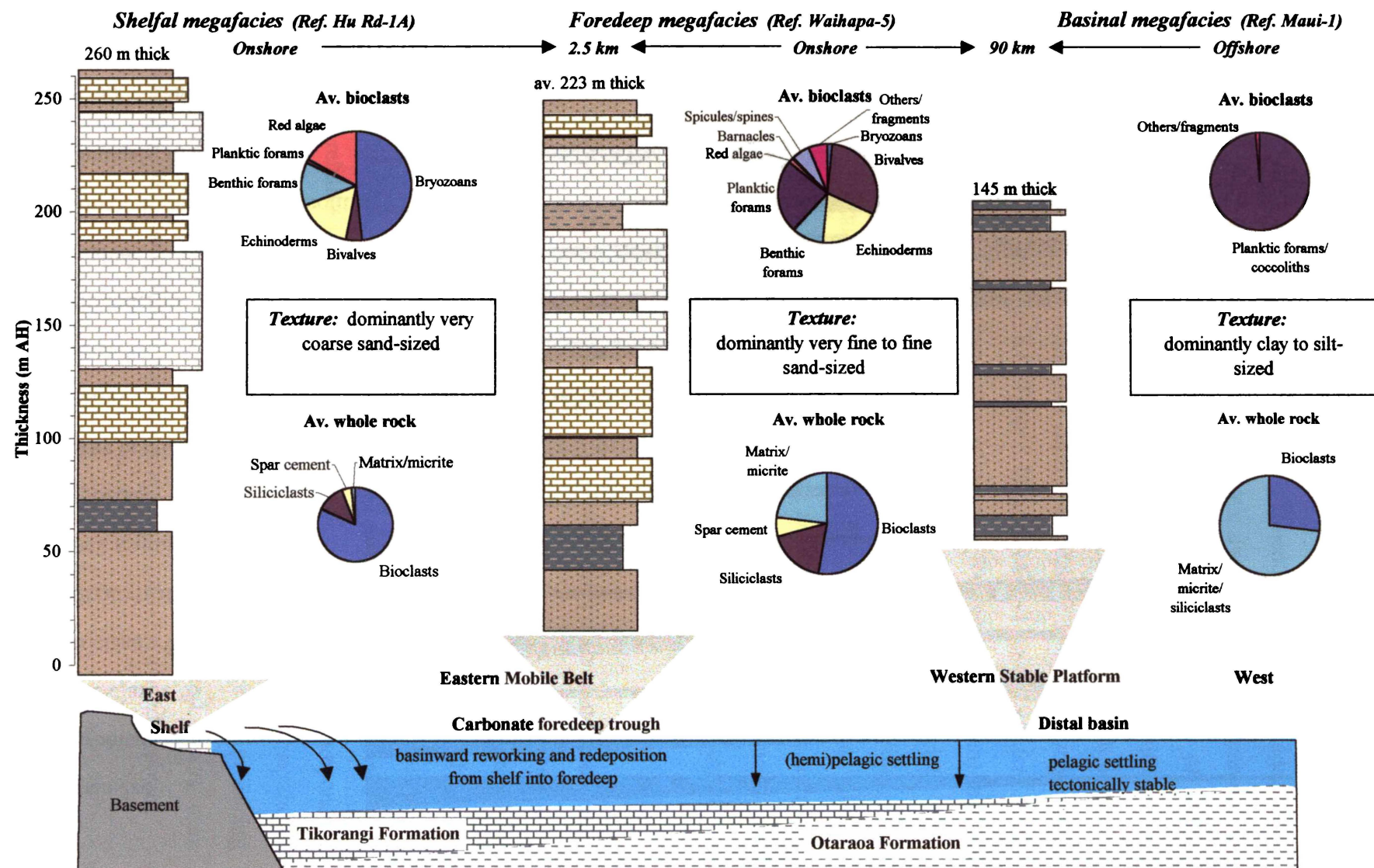


Fig. 8.6 Simplified stratigraphy showing the thickness, carbonate facies, and compositional and textural differences between the three shelf-foredeep-basin megafacies of the Tikorangi Formation in relation to their depositional settings. Facies A (calcareous siliciclastites), Facies B (highly calcareous siliciclastites), Facies C (muddy limestones), Facies D (sparry limestones).

Table 8.1 Summary characteristics distinguishing the three megafacies of the Tikorangi Formation.

Megafacies properties	Shelfal	Foredeep*	Basinal
<i>Present location</i>	Onshore, EMB	Onshore, EMB	Offshore, WSP
<i>Reference well</i>	Hu Rd-1/1A	Waihapa-5	Maui-1
<i>Thickness (mAH)</i>	260	184 - 278 (#210)	145
<i>Age</i>	Earliest Miocene (Waitakian)	Earliest Miocene (Waitakian)	Oligocene-Early Miocene (Whaingaroan-Otaian)
<i>Depositional environment</i>	Shallow shelf	Foredeep basin	Outer basin
<i>Dominant skeletal texture</i>	Very coarse sand	Fine sand	Clay to silt
<i>Dominant rock types</i>	Poorly washed grainstones, very pure grainstones	(Siliciclastic-rich) Wackestones, packstones, poorly washed grainstones	Siliciclastic-rich mudstones, wackestones
<i>Origin</i>	Near-situ accumulation	Mass redeposition basinward/pelagic settling	Pelagic settling
<i>Bioclasts</i>	Bryozoans, barnacles, calcareous red algae, benthic foraminifera, echinoderms, bivalves	Bivalves, planktic foraminifera, echinoderms, spicules/spines, fragments, calcareous red algae, bryozoans, barnacles	Planktic foraminifera, coccoliths
<i>Skeletal assemblages</i>	Echinofor, bimol, nannofor	Bryomol, barnamol	Nannofor
<i>Siliciclasts</i>	SRFs, quartz, feldspar	Quartz, feldspar	Quartz, feldspar
<i>Carbonate facies</i>	C>B>D=A	C>B>D>A	B>>A
<i>Dolomite occurrence</i>	Some (~10%)	Some to common (5 to 50%)	Absent
<i>Micrite/matrix</i>	Some	Common	Abundant
<i>Spar cement</i>	Common	Some to common	Rare to absent
<i>Fracturing/veining</i>	Some	Extensive	Absent
<i>Producing hydrocarbons</i>	No	Yes	No

*Foredeep data based on Ngaere-2, Waihapa-2, -4, -5, -6, and Toko-1 wells. mAH = metres along hole, EMB = Eastern Mobile Belt, WSP = Western Stable Platform. # = thickness in Waihapa-5. Note that Dunham textural names can apply to a spectrum of siliciclastic to carbonate-rich end members.

sedimentary phases within the Tikorangi Formation foredeep megafacies, have been identified and correlated (Fig. 8.7). These five phases formed during the climax of a major transgressive phase in Taranaki Basin, and record initially carbonate-poor sediments (Phase I comprising siliciclastic-dominated units), becoming more carbonate-rich with time (Phase II), and climaxing in deposition of Phases III and IV sediments characterised by mass-emplaced carbonate-rich units reflecting increased carbonate resedimentation basinward during the late transgression and highstand when the shelfal carbonate factory sites were most robust (e.g., Whalen et al. 2000) and minimal siliciclastics were entering the basin. The Phase V retrogradational sequence marks the reintroduction of siliciclastic material into the basin following uplift of Mesozoic basement associated with accentuated compressional tectonics along the Australia-Pacific plate boundary, initially diluting and ultimately extinguishing carbonate production factories. The correlation has been extended to the similarly-aged shelfal megafacies equivalent (Fig. 8.7). Comparable kinds of patterns are discernable within the much longer-lived basinal megafacies (Fig. 8.7), but clearly the age differences preclude any direct correlation.

This study documents for the first time the occurrence of dolomite within the temperate Tikorangi Formation (Topic 5). Dolomite is rare within New Zealand Cenozoic carbonates, and in cool-water carbonates more generally. The ubiquitous and persistent nature of Ca- and Fe-rich dolomite within the shelfal and foredeep megafacies of the Tikorangi Formation (Fig. 8.9) is distinct from well studied, uplifted and exposed age-equivalent New Zealand limestones which contain virtually no dolomite. Dolomite-bearing megafacies (Fig. 8.9) and petrofacies (Fig. 8.10) are trace element-enriched. The nonstoichiometric Ca- and Fe-rich nature of the dolomite is suggestive of a relatively “recent” late burial replacive diagenetic origin. Mg sources were probably from often bioturbated clay-rich micrite and the release of Mg from clay mineral structures. Pressure-dissolution of LMC/IMC skeletons may have been an additional source. Fe was supplied from siliciclastics and from within clay mineral structures. Dissolution during dolomitisation more or less balanced precipitation, preventing development of secondary porosity and permeability enhancement and so limiting the

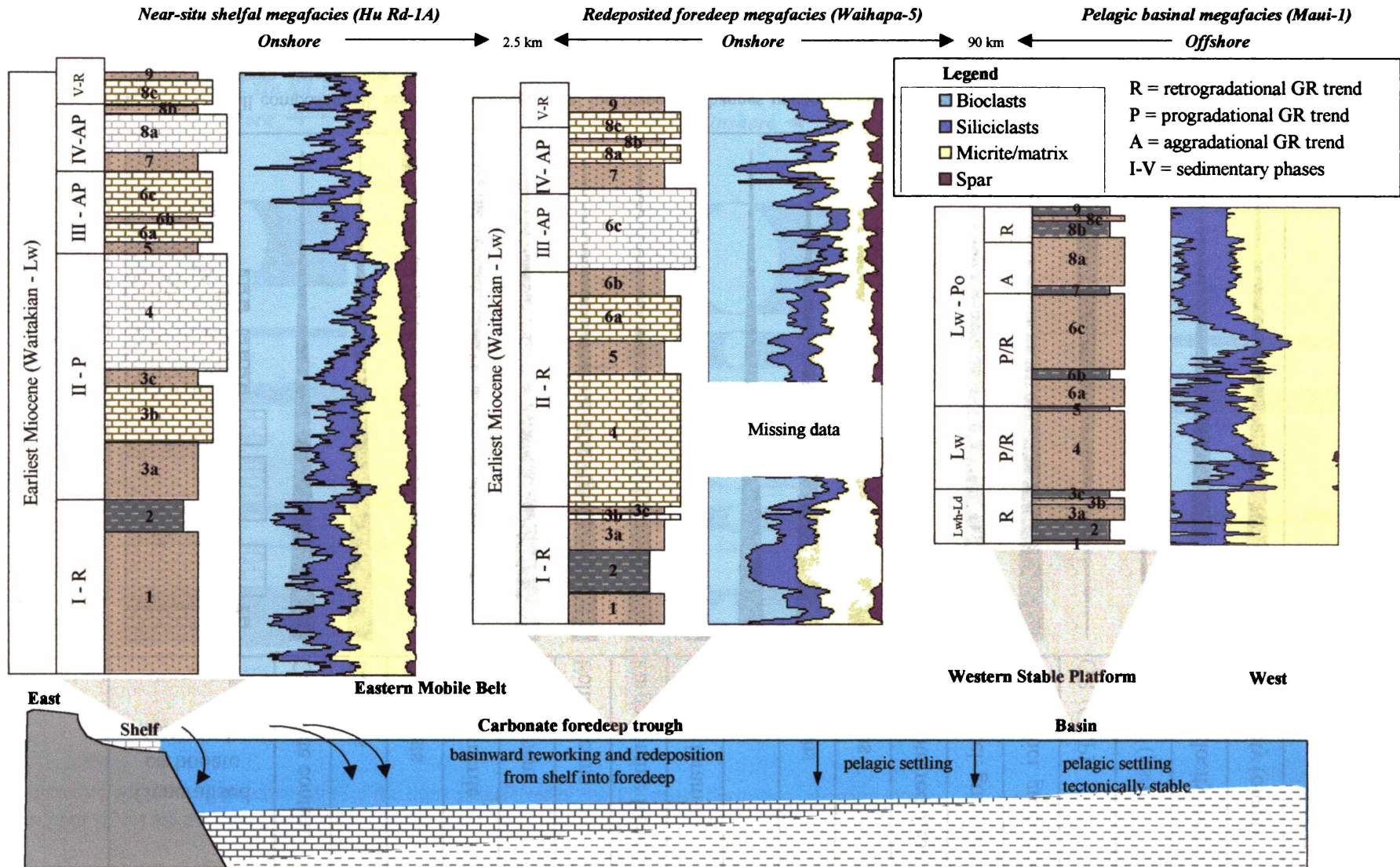


Fig. 8.7 Simplified stratigraphy showing the major carbonate facies and whole rock compositional changes associated with the five sedimentary phases (I-V) established for the shelfal and foredeep megafacies of the Tikorangi Formation. Lwh = Whaingaroan, Ld = Duntroonian, Lw = Waitakian, Po = Otaian. Facies A (calcareous siliciclastites), Facies B (highly calcareous siliciclastites), Facies C (muddy limestones), Facies D (sparry limestones).

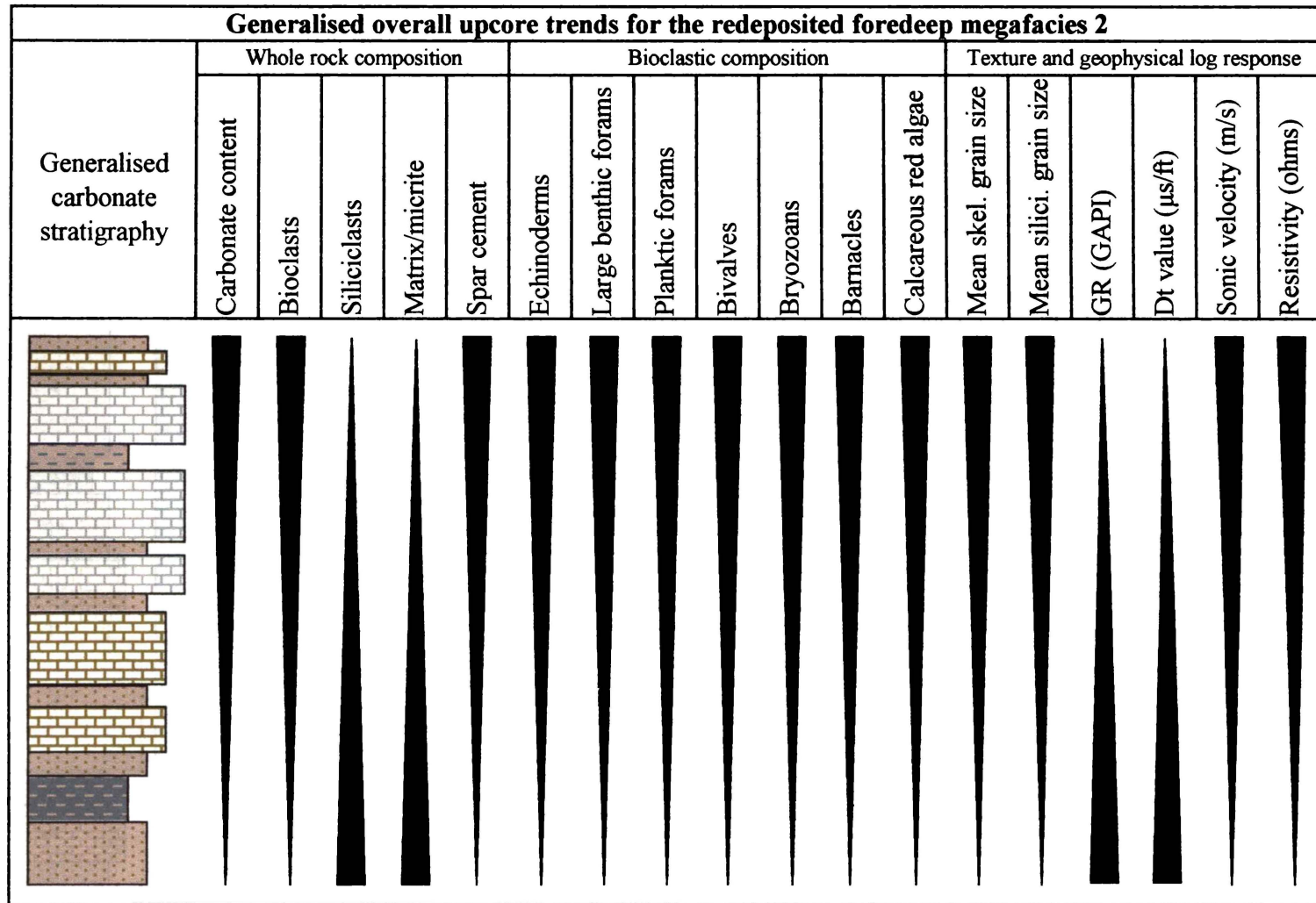


Fig. 8.8 Overall compositional, textural and geophysical log response changes upcore in the foredeep megafacies of the Tikorangi Formation reflecting increasing water depths, dwindling siliciclastic supply to the foredeep basin, and increasing frequency of mass emplacement events containing shelfal biota.

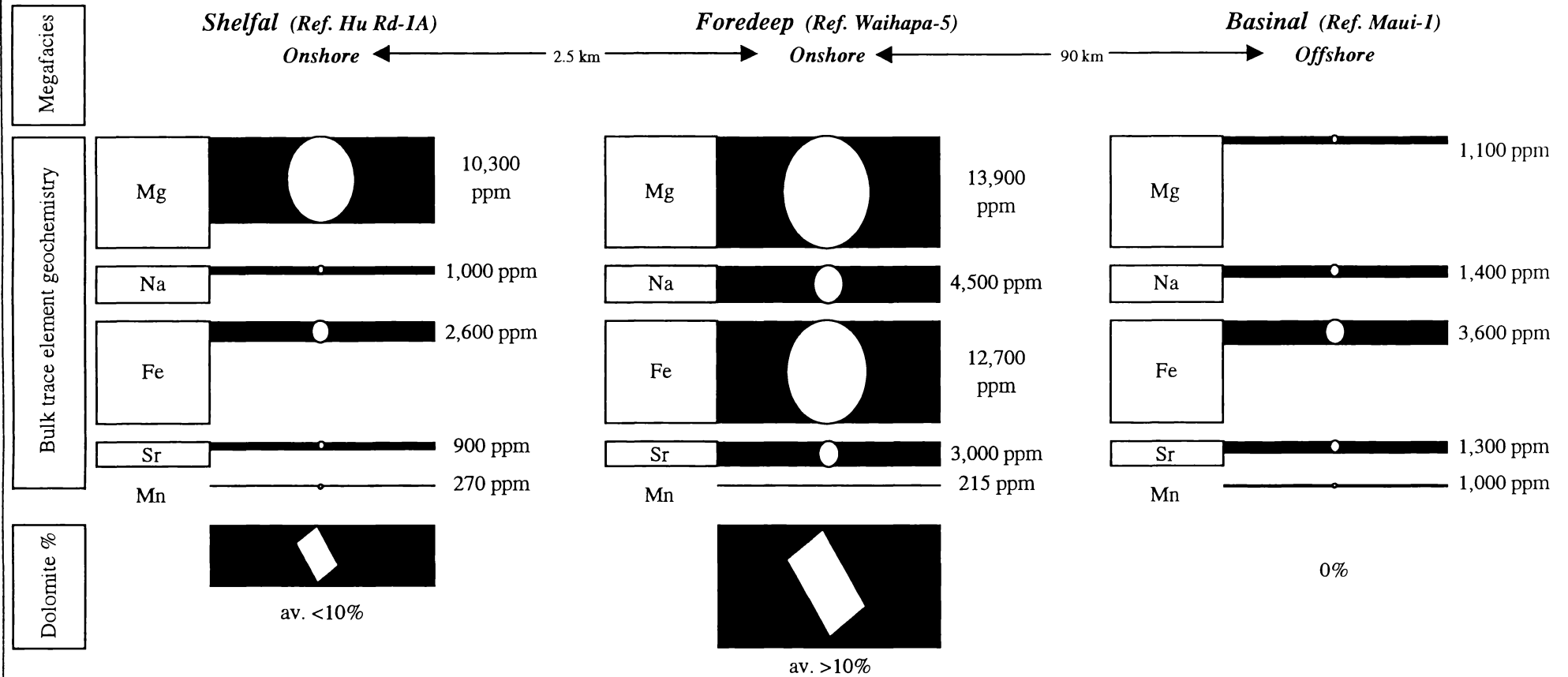


Fig. 8.9 Summary trace element geochemistry for the three megafacies of the Tikorangi Formation, showing increasing trace element concentrations within the more dolomite-rich deposits. ppm values are av. ones (Table 6.1).

Tikorangi Formation's ability to act directly as a hydrocarbon reservoir outside of fracture porosity.

Dolomite formation predates tectonically-induced pressure-dissolution and major fracturing and vein mineralisation associated with hydrocarbon-bearing fracture porosity. Dolomite-rich units are likely to have been more susceptible to brittle fracture during Miocene compressional tectonics, which could have implications for the location of fracture networks and therefore hydrocarbon prospectivity and production.

This study has contributed to the paucity of geochemical data for carbonates generally and for cool-water carbonates in particular, at the same time providing bulk trace element data for a mixed dolomite-calcite temperate sequence (Topic 6). Geochemical data are consistent with skeletal growth in a temperate cool-water paleoenvironment¹ followed by later burial cementation from pressure-dissolution of LMC/IMC skeletons under reducing conditions. The cement is ferroan LMC, characteristic of cool-water burial cements, and is typically enriched in Mn (>100 ppm) and depleted in Sr and Na in comparison with bulk skeletal values for modern Tasmanian cool-water carbonates, consistent with a burial-related origin.

Dolomite is shown here to have had a dramatic effect on the bulk rock elemental geochemistry of the Tikorangi Formation in comparison with most other cool-water calcitic carbonate occurrences (Fig. 8.11). The effect is also seen in Tikorangi Formation petrofacies (Fig. 8.10) and megafacies (Fig. 8.9). Element-element plots can show false affinities with modern Bahaman aragonitic and HMC-dominated carbonates rather than with cool-water examples, while the highest Mg values in Tikorangi samples are comparable to those in ancient warm-water Tasmanian carbonates involving elevated Mg, Na, and Sr values in relation to ancient LMC New Zealand limestones (Fig. 8.11). Enriched trace element values are directly attributable to the presence of burial-derived dolomites in the Tikorangi Formation, and is in contrast with the anticipated lowering of these element concentrations with progressive carbonate diagenesis in calcitic limestones. Fe levels in the Tikorangi Formation far exceed both modern and

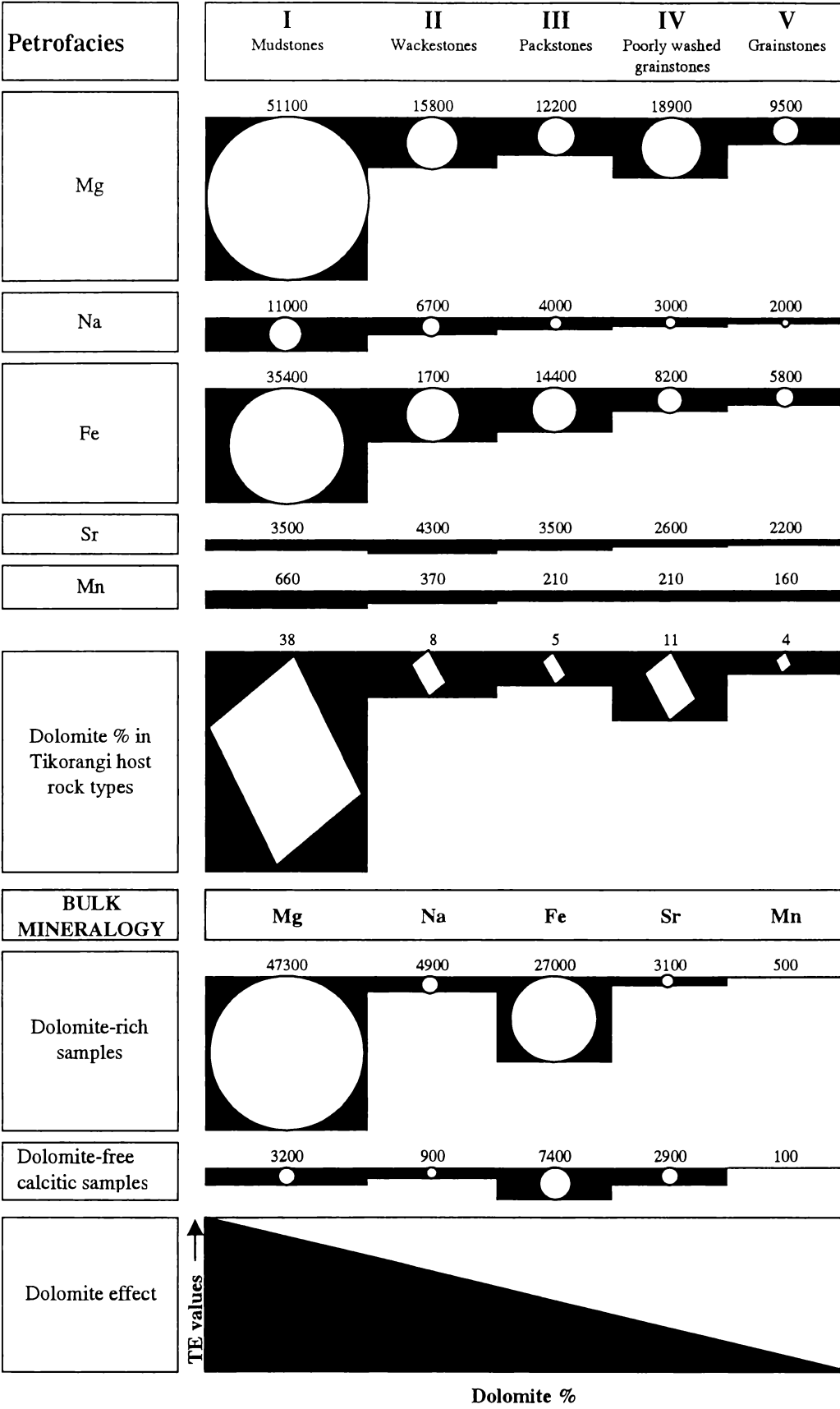


Fig. 8.10 Summary trace element geochemistry for the five petrofacies occurring within the Tikorangi Formation and the general effect dolomite content has in increasing trace element concentrations within the more dolomite-rich petrofacies.

ancient cool- and warm-water analogues (Fig. 8.11) and point to very Fe-rich pore fluids probably sourced from compaction in interbedded siliciclastic shale-like sequences. Given the modest proportion of tiny dolomite crystals with commonly intricate CL zoning, making micro-probing of specific crystal zones impossible, the bulk geochemical approach has been an effective technique for sample discrimination within the Tikorangi Formation.

8.3 TIKORANGI FORMATION PARAGENETIC SEQUENCE

The Oligocene-Early Miocene Tikorangi Formation formed in Taranaki Basin during a period of major tectonic change from a passive to an active margin setting linked with the development of the Australia-Pacific convergent plate boundary through New Zealand and associated foredeep development. Superimposed eustatic sea-level change has had little influence on the petrogenesis of the Tikorangi Formation in comparison with tectonically-controlled relative sea level change (Topic 3). The major events in the evolution of the Tikorangi Formation are schematically modelled in Fig. 8.12.

Basin foundering and the initiation of a basinwide marine transgression, caused by foreland thrust loading (Stern & Holt 1994), started at about 35 Ma in northern areas of Taranaki Basin and moved southwards (Fig. 8.12A). This was accompanied by a change from siliciclastic to carbonate-dominated sedimentation culminating with the deposition of the Tikorangi Formation (Fig. 8.12B). The basinal megafacies began accumulating on the passive western zone (Western Stable Platform) from the Early Oligocene (Whaingaroan) resulting from reduced siliciclastic supply to distal basinal areas, and continued through the Early Miocene. By the end of the Oligocene reduced siliciclastic input to proximal basin areas enabled accumulation during the earliest Miocene (Waitakian) of the near-situ shelfal megafacies on a narrow, probably fault-controlled shelf (King & Thrasher 1996), and formation of a mixed siliciclastic-carbonate-rich foredeep megafacies comprising redeposited shelf and slope biota within the developing asymmetric foreland basin, the Eastern Mobile Belt. Subsidence was especially pronounced immediately west of the Taranaki Fault where the thickest foredeep

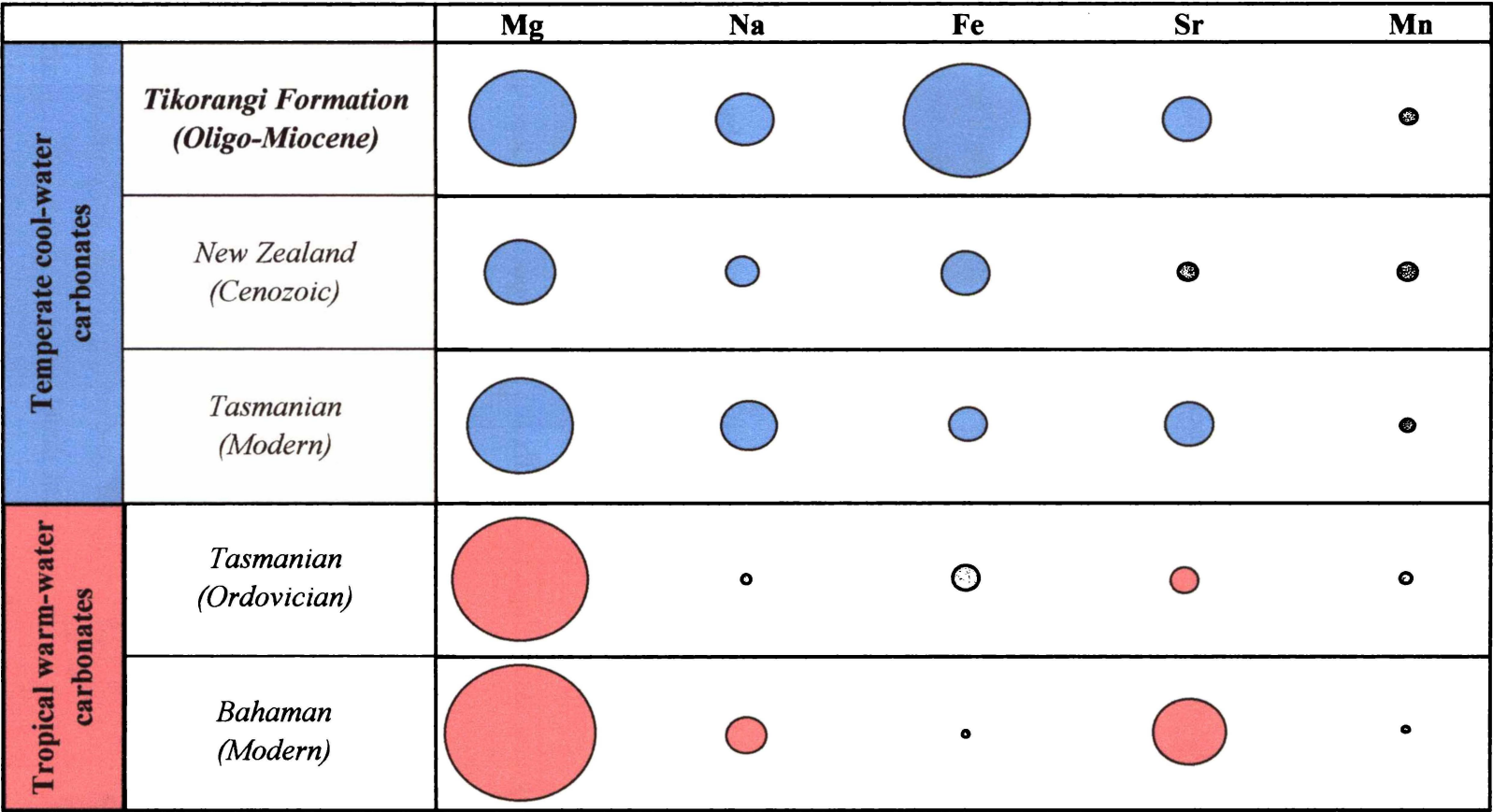


Fig. 8.11 Schematic summary of relative abundances of trace elements in the Tikorangi Formation and comparison with other temperate cool-water and tropical warm-water carbonates. The radius of the circles is roughly proportional to the average concentration of each element in the respective samples.

carbonates were deposited. While Tikorangi carbonates were forming in eastern areas of Taranaki Basin, southern margins of the basin experienced shallow shelfal conditions, with deposition of the laterally equivalent Takaka Limestone (Leask 1980), while extensive age-equivalent Te Kuiti Group limestones (Orahiri and Otorohanga Limestone) formed in the adjacent North Wanganui Basin (Nelson 1978a).

The shallow-shelfal megafacies formed from accumulation of biota on or very near variably exposed Mesozoic basement associated with the Patea-Tongaporutu-Herangi High (Fig. 8.12B). In contrast the foredeep megafacies formed from redeposition into the Taranaki foredeep (foreland basin) resulting in basinward displacement of shallow-water biota, production of highly fragmented fine sand-sized shelfal material, and intermixing of shelfal skeletons with background slope microfauna (pelagic foraminifera) and microflora (coccoliths). Carbonate supply into the foredeep basin was controlled by periodic mass-emplacement events, particularly evident in the upper parts of the formation. Trigger mechanisms probably included storms, seismic events, and over-steepening about bank margins. Background lower-volume carbonate input was also supplied by planktic foraminifera and nannofossils. Within the foredeep generally high levels of bioturbation of the sediment enhanced skeletal mixing and destroyed any original depositional bedding structures. The occurrence of a predominantly *Planolites-Chondrites-Zoophycos* assemblage (Appendix 4.5) is supportive of deposition at bathyal depths.

Formation of the Tikorangi deposits was fundamentally controlled by tectonism, the rate and type of sediment supply into the foredeep, foredeep accommodation, and the relative position of sealevel (Topic 3). Compositional and textural variability within the Tikorangi Formation megafacies has resulted from the complex interplay of a number of controlling factors: (1) the rapidly evolving tectonic setting which provided a range of co-existing shelfal, tectonically active foreland basinal, and tectonically quiescent distal basinal settings; (2) deposition during a number of relative sealevel changes within an overall transgressive or submergence regime; (3) the proximity to, and availability of, different siliciclastic sources to the east (Patea-Tongaporutu-Herangi High) and south

TIKORANGI FORMATION PARAGENETIC SEQUENCE

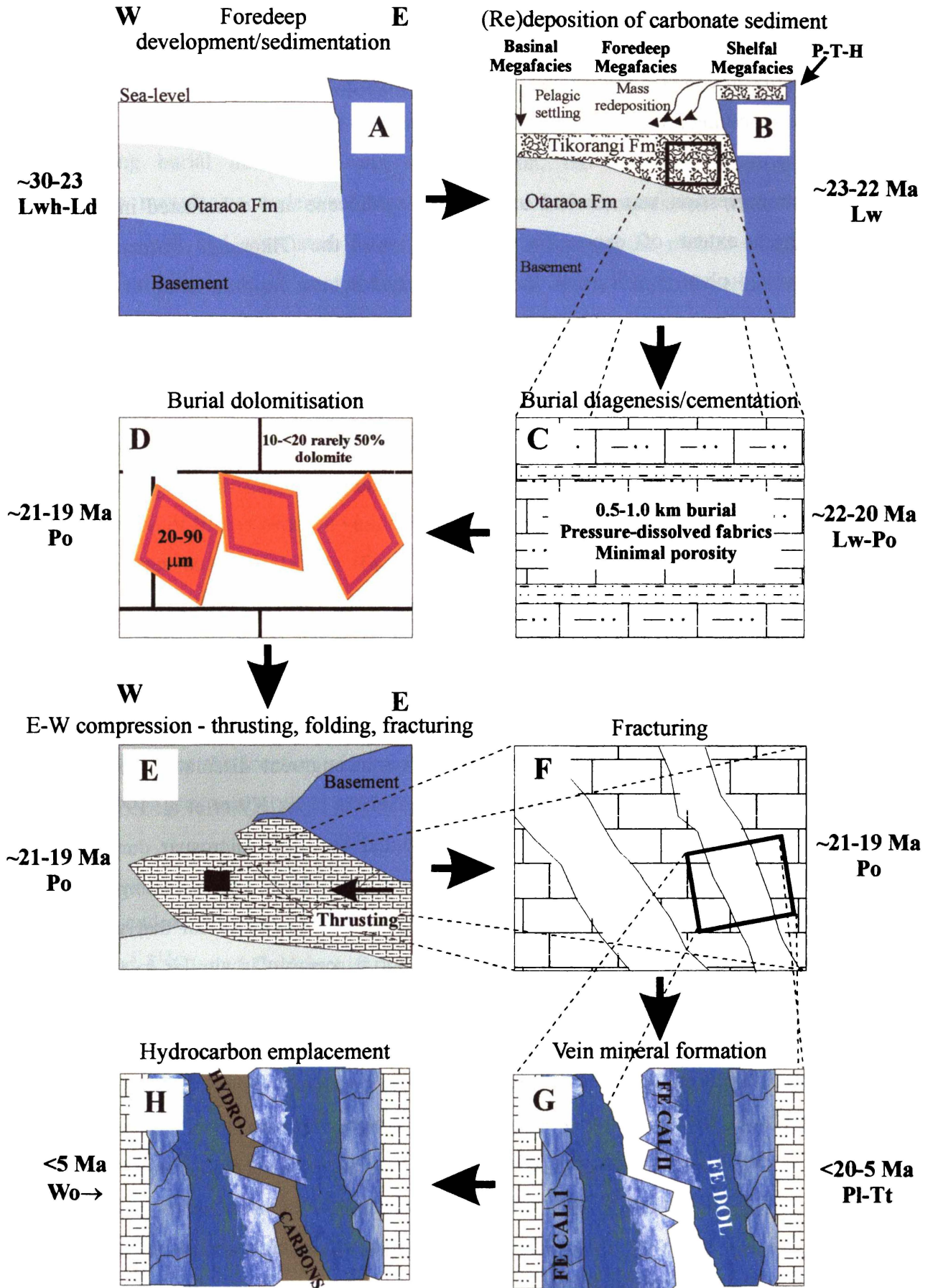


Fig. 8.12 Schematic summary paragenetic sequence for the carbonate-dominated Tikorangi Formation from deposition to hydrocarbon emplacement. Timing of events is shown in approximate Ma together with the corresponding New Zealand Stages (see Appendix 1.2 for geological time scale). P-T-H = Patea-Tongaporutu-Herangi High. FE CAL I = first generation ferroan calcite, FE CAL II = second generation ferroan calcite, FE DOL = ferroan (baroque) dolomite.

(South Island), and possibly even from the far west (Australia); and (4) the variability in composition, timing, and spatial distribution of mass redepositional events supplying sediment into the Taranaki foredeep basin.

Peak transgression was reached in the earliest Miocene and culminated in the maximum extent of deposition associated with the Tikorangi Formation. Accelerated plate convergence during the Early Miocene resulted in uplift and erosion of the basement Herangi-Patea-Tongaporutu High bringing to an end carbonate deposition in both Taranaki and neighbouring North Wanganui Basins (Nelson et al. 1994). The resulting increased rates of uplift adjacent to the plate boundary provided sources for a greatly increased siliciclastic supply, initiating major regression and subsequent progradation of the continental shelf edge north and northwestwards into Taranaki Basin.

Following deposition, early carbonate diagenesis in the Tikorangi Formation was dominantly destructive and saw (1) the dissolution of the majority of aragonitic skeletons prior to lithification (e.g., Beu et al. 1972; Nelson 1978b; Hood & Nelson 1996; Dodd & Nelson 1998), and (2) the stabilisation of metastable Mg-calcite (HMC and IMC) skeletons to LMC by incongruent dissolution (e.g., Nelson 1978b; Hood & Nelson 1996; Dodd & Nelson 1998; Kyser et al. 1998). The Tikorangi Formation host rock was cemented by LMC microspar during burial diagenesis, which began at temperatures of about 20°C, corresponding to about 0.5 km burial depth, and continued until about 1 km of burial that was reached in the Early Miocene (Otaian). This burial scenario is similar to that proposed by Nelson et al. (1988) for the same age limestones in the neighbouring North Wanganui Basin. By this stage the limestones had strongly pressure-dissolved fabrics and were tight with essentially zero porosity (Fig. 8.12C). They were partially dolomitised at burial depths and temperatures of 1.0–1.5 km and 36–50°C over a duration of some 2 m.y. during the Early Miocene (Otaian) (Fig. 8.12D). Dolomitisation occurred within diagenetically closed microenvironments by mimic non-pervasive and fabric-selective replacement of interparticle, and rarely intraparticle, micritic/clay-rich matrix. Micritic components provided an ideal substrate for dolomite nucleation and crystal growth because of its high

surface area and finely crystalline nature. Fe was largely supplied from the siliciclastic-rich units.

Following burial lithification and dolomitisation, the Tikorangi Formation foredeep megafacies underwent significant horizontal compression when the Taranaki Fault and associated Tarata Thrust Zone became the mobile western edge of a large area of contraction that formed in the foreland behind the propagating subduction zone (King & Thrasher 1996). The associated series of overthrust systems and structures, in which the onshore wells in this study are sited, have been instrumental in the development of the fractured Tikorangi Formation reservoir (Fig. 8.12E, F). Fracturing of the Tikorangi Formation is constrained here to a period following lithification and dolomitisation, but before precipitation of first generation vein calcite corresponding to burial depths of 1.0–1.5 km, from about 21–19 Ma (Early Miocene - Otaian). This timing is more definitive than the Early-Middle Miocene range previously suggested by King & Thrasher (1996). Dolomite-rich units would have been more susceptible to brittle fracture than non-dolomite-bearing units because of greater intact rock strength and therefore brittleness (e.g., Martindale & Boreen 1997). This could have implications for the location of extensive networks of fracture systems and for hydrocarbon prospectivity and production in the Tikorangi Formation.

Mineralisation within fracture systems has substantially reduced rock mass porosity and permeability (Fig. 8.12G). Petrographic, trace element, stable isotope ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$), and fluid inclusion data record a complex history of changing pore fluid chemistry and heating during burial, punctuated by changes in the relative input of downward circulating meteoric and upwelling basinal fluids. The initial first generation vein calcite was rapidly precipitated as ferroan LMC from Fe-rich, meteorically-modified marine fluids at temperatures of about 50–60°C at burial depths of 1.4–1.8 km, from about 20–18 Ma (Early Miocene). Mixing occurred by deep downward percolation of groundwaters, particularly in cascade zones during seismic pumping/draw-down events. Baroque dolomite formed atop first generation calcite following a period of Mg-enriched basinal fluid input. It occurs as a primary precipitate but also as a calcite replacement at temperatures of 65–80°C, corresponding to burial depths of 2–2.5 km. Volumetrically minor

amounts of quartzine and celestite precipitates/crystals are associated with the dolomite. The dolomite-quartzine-celestite mineral assemblage could have formed over a period spanning some 12 m.y. from 17.5–5 Ma (Early-Late Miocene). Second generation ferroan LMC formed at cooler temperatures (53–65°C) and shallower depths of burial (1.6–2.0 km) over a period of some 3 m.y. following a period of inversion. The presence of petroleum fluid inclusions in the second generation calcite suggests in some cases precursory hydrocarbon-bearing fluids, have migrated along with aqueous fluids since about 8 Ma (Late Miocene - Tongaporutuan), but the major hydrocarbon emplacement has occurred over the last 5 m.y. from the Early Pliocene (Opoitian) (Fig. 8.12H). This provides a more definitive timing for oil migration between Eocene terrestrial coal source rocks and the Tikorangi Formation reservoir rocks, which is generally poorly understood in Taranaki Basin (King & Thrasher 1996).

8.4 FORMAL STRATIGRAPHIC RECOMMENDATIONS

Formal stratigraphic nomenclature for the Tikorangi Formation has to date been inconsistent, with poorly defined upper and lower boundaries, and a largely unsatisfactory type section in the Mangahewa-1 well (designated by van Rijen & van der Abeele (1963) to be the 37 m-thick interval between 3213 m and 3250 m AHBKB (along hole below kelly bushing)) due to a lack of any core material. It is recommended here that the Waihapa-5 well (Fig. 1.4) becomes a designated reference section for the Tikorangi Formation because the over 112 m of available core material (see Appendix 2.1) provides a much firmer basis for lithological analysis. Core material is available through the Ministry of Commerce, Wellington, located at their rock store, Lower Hutt. A stratigraphic (mud) log is available in Young & Carter (1989), publicly available as report PR1851, housed in the Ministry of Commerce library, Wellington.

Having produced a carbonate-content-based lithostratigraphy for the Tikorangi Formation, it is suggested that the lower and upper boundaries of the formation be based on compositional changes rather than from geophysical log responses, as discussed in Topic 2 (Table 2.2).

8.5 THE COOL-WATER CARBONATE MODEL

While carbonates, both as limestones and dolomites, form globally important oil reservoirs, the Tikorangi Formation is fundamentally different in character from many of the world's well studied limestone reservoirs because it formed in a cool-water setting. Many studies based on New Zealand ancient (e.g., Nelson 1988; Hood 1993; Hayton et al. 1995; Hood & Nelson 1996; Winefield et al. 1996; Dodd & Nelson 1998; Nelson & James 2000) and modern carbonates (Gillespie & Nelson 1997; Gillespie et al. 1998), together with other overseas studies (e.g., Fornos & Ahr 1997; Nicolaides & Wallace 1997; Kyser et al. 1998; James et al. 1999; Randazzo et al. 1999; Betzler et al. 2000), have done much to further conceptual models for shallow-marine cool-water carbonates in recent times (Table 8.2). The Tikorangi Formation's mixed siliciclastic-carbonate nature, cool-water carbonate biotic make-up (echinoderms, planktic/benthic foraminifera, bivalves, calcareous red algae, bryozoans, barnacles), low-Mg calcite mineralogy of skeletons and cements, and delayed deep burial diagenetic history are key features characteristic of formation in temperate-latitude cool waters (Table 8.2).

While many of the features of the Tikorangi Formation are consistent with developing facies models for cool-water carbonates, others fall outside currently accepted model boundaries. The predominance of planktic foraminifera, echinoderms, and bivalve skeletons in the Tikorangi Formation carbonates can at the broadest level assign them to the foramol skeletal assemblage, which typifies cool-water carbonates generally (Fig. 8.1). More definitive skeletal assemblage classification, based on the three most common biotic contributors (Hayton et al. 1995), highlights the importance of the nannofor, echinofor and bimol assemblages (Fig. 8.1). In reality these assemblages oversimplify the range of skeletal varieties occurring in the Tikorangi Formation due to a lack of recognition of lesser but nevertheless important secondary components (i.e., redeposited shallower-water biota: bryozoans, calcareous red algae, large benthic foraminifera of a bryozoan-type assemblage; and upper slope sponge debris). Application of current skeletal assemblage terminology may therefore encounter problems when dealing with redeposited carbonates of mixed habitats, as occurs in the foredeep megafacies of the Tikorangi Formation. Application to the

compositionally simple basinal megafacies appears appropriate, involving only a nannofor assemblage, while the near-situ shelfal megafacies comprises typically bryomol and/or barnamol assemblages (Fig. 8.1).

The current understanding of carbonates redeposited beyond the shelf and mechanisms responsible for their formation have been little documented in the literature. Basinward redeposition of biota resulting in a complex suite of skeletal rocks such as occurs in the Tikorangi Formation foredeep megafacies is beginning to be recognised in the wider carbonate literature (e.g., Betzler et al. 1999; Gawenda et al. 1999; Pittet et al. 2000). However, in general the processes and products associated with mass redeposition of carbonate sediments are rather poorly understood compared to their siliciclastic counterparts. It is only in recent times that off shelf studies of tropical Bahaman Bank carbonates (e.g., Betzler et al. 1999) that have begun to document alternations of mass emplaced highstand shallow-water-dominated units with dominantly pelagic units, where the controls on the timing of mass redepositional events have been related to high frequency sea-level changes. Past study in the cool-water setting by Nelson et al. (1982) of the modern Three Kings Plateau, north of New Zealand, documents the widespread occurrence of coarse skeletal deposits dominated by fragments of shallow marine biota in deep waters, suggestive of present and/or past redeposition, especially active during the last glaciation, of skeletal material over the shelf edge. More recent studies by Coniglio & Dix (1992), Boreen & James (1993), Passlow (1997), and James (1997) have begun to appreciate more generally carbonate sedimentation basinward of the shelf. More specific to the cool-water setting at depths beyond the shelf, studies by Boreen & James (1993), Passlow (1997), and James (1997) begin to point to highstand pelagic deposition at these depths punctuated by redeposited shelf sediments during lowstands when the shelves were narrower and the high energy zone was nearer the shelf edge. Such a narrow fault-controlled shelf probably existed in Taranaki Basin at the time of Tikorangi Formation deposition (King & Thrasher 1996) and may have provided an “ideal” setting for mass redeposition of shelfal biota basinward. Clearly there is a need for cool-water carbonate models to incorporate not only shelfal but the more basinward settings and to especially provide more definitive controls, trigger mechanisms, timing in relation to sea level changes, and resultant

Table 8.2 Some contrasting environmental, compositional, and diagenetic features of the Tikorangi Formation in comparison to cool-water (nontropical) and tropical shelf carbonates (modified after Hood & Nelson 1996).

PROPERTY	TIKORANGI FORMATION	TEMPERATE (NONTROPICAL) SHELF CARBONATES	TROPICAL SHELF CARBONATES
<i>Setting</i>	Unrimmed open shelf, foredeep basin (slope/bathyal depths), outer basin floor	Unrimmed open shelves and ramps	Shallow rimmed shelves, open shelves, ramps, reefs
<i>Energy</i>	High (shelfal; mass flows into foredeep) to low energy (foredeep and basinal pelagic settling)	High energy	High to low energy
<i>Hermatypic reefs</i>	Absent	Absence of hermatypic reefs (polewards of 30°N to 30°S)	Common hermatypic coral reefs (from 30°N to 30°S)
<i>Skeletal assemblages</i>	Heterozoan (Foramol) skeletal types - complex mix of echinoderms, foraminifera, bivalve molluscs, bryozoans, barnacles, calcareous red algae	Heterozoan (Foramol) skeletal types - bryozoans (bryomol), echinoderms (echinofor), bivalve molluscs (bimol), foraminifera (nannofor)	Photozoan (Chlorozoan) skeletal types - Corals, calcareous green algae, molluscs, benthic foraminifera
<i>Sediment texture</i>	Gravel (shelf) to sand/mud (foredeep) to mud (basinal)	Gravel and sand textures dominate	Sand and mud textures dominate
<i>Water temperature</i>	Cool water	Cool water (10-18°C bottom water)	Warm water (>22°C bottom water)
<i>Carbonate saturation</i>	Saturated/undersaturated	Saturated/undersaturated	Saturated/supersaturated
<i>Non-skeletal grains</i>	Absence of non-skeletal grains	Absence of non-skeletal grains	Common non-skeletal grains (ooids, aggregates)
<i>Cementation</i>	Early to late burial ferroan calcite cements, replacement dolomite rhombs	Minor early cementation; late burial cements dominate	Extensive early cementation by marine and meteoric cements
<i>Carbonate mud</i>	Minor to common (physical maceration, erosion resulting from mass redeposition)	Minor carbonate mud (bioerosion)	Abundant carbonate mud (micritisation, precipitation, bioerosion)
<i>Mineralogy</i>	Low-Mg calcite, dolomite	Low- and intermediate-Mg calcite mineralogies dominate	Aragonite and high-Mg calcite mineralogies dominate
<i>Diagenesis</i>	Destructive early diagenesis (dissolution, maceration), late burial cementation, partial replacement dolomitisation	Destructive early diagenesis (dissolution, maceration), late burial cementation	Constructive diagenesis (early cementation)
<i>Sedimentation rates</i>	Low to high (high in mass redeposited units)	Typically low accumulation rates	Typically high accumulation rates

characteristic dispositional and compositional details for mass emplaced deposits at depths beyond the shelf. Much work remains to be undertaken not only on modern and ancient mass emplaced cool-water deposits such as the Tikorangi Formation, but also on tropical redeposited carbonates.

As a further result of its redeposited nature and generally deeper water setting, the Tikorangi Formation diverges from current cool-water carbonate models not only in terms of its diversity of skeletal compositions, but also in terms of texture (Table 8.2). Coarse arenites to rudites are typical textures in cool-water carbonates (Gillespie & Nelson 1997), whereas the Tikorangi Formation includes substantial mud to fine sand-sized skeletal debris. Carbonate mud or matrix (siliciclastic material)-dominated rock types (wackestones, packstones) are generally reported to be rare or absent within shallow-marine cool-water deposits (e.g., Jones 1992), but are relatively common in the Tikorangi Formation. This reflects shelf-to-basin redeposition and incorporation of nannofossil debris not otherwise commonly associated with shelfal environments. Pittet et al. (2000) have suggested that in deep-shelf carbonate deposits of southern Germany and Spain carbonate mud is similarly sourced and exported from shallow shelfal areas where carbonate productivity is high.

Other than dolomitisation, the diagenesis of the carbonate-dominated Tikorangi Formation proceeded similarly to that recorded in other age-equivalent New Zealand limestones and cool-water examples generally. A temperate depositional setting (Appendix 8.1) (45-50° S paleolatitude during the Oligocene-Early Miocene period (Nelson & Cooke 1999)) fostered a predominantly destructive early diagenetic history, including the loss of metastable aragonitic skeletons. A paucity of early cement sources in the Tikorangi Formation has negated the development of all but scant syntaxial rim cement overgrowths, otherwise generally common in New Zealand age-equivalent limestones, despite an abundance of echinoderm fragments. Major cementation was delayed and only occurred after substantial mechanical and chemical compaction associated with pressure dissolution, and the formation of tight pressure-dissolved and fitted fabrics with substantially reduced pore volumes. Cementation occurred at depths of burial from 0.5-1.0 km during which ferroan, dull-luminescent equant LMC

spar formed. Such a diagenetic scenario is typical of many cool-water New Zealand Oligo-Miocene limestones (e.g., Nelson et al. 1988; Hood & Nelson 1996), as well as in tropical aragonite-poor limestones (e.g., Mississippian limestones, Indiana (Dodd & Nelson 1998)).

Dolomite is ubiquitous throughout the Tikorangi Formation but is absent or rare in other New Zealand mid-Tertiary limestones and in temperate carbonates generally (Table 8.2). While high concentrations of Mg are common in warm tropical fluids, a specialised set of microenvironmental conditions was necessary to form Mg-rich fluids within the Tikorangi pore spaces from which replacive dolomite developed. Major controls on the dolomitisation of the Tikorangi Formation have been: the rapid transition into, and continued residency at, significant burial depths (> 1 km; see Fig. 7.10); the matrix/micritic-rich nature of many of the original sediments; and the formation of diagenetically closed microenvironments within micrite by destructive burial diagenesis, with substantial porosity/permeability reduction by physical/chemical compaction and late stage burial cementation. Dolomite has resulted in trace element enrichment in the Tikorangi dolomitic limestones and has falsely brought these rocks more in line with elemental geochemistries more typical of warm-water carbonates.

A paucity of dolomite in age-equivalent limestone exposed onland in comparison to the Tikorangi Formation may be explained by: a paucity of suitable micritic and clay-rich substrates for nucleation and for provision of a Mg-rich microenvironment (the limestones are typically clean grainstones); a lack of associated shale-like lithologies for providing a Mg source; and lower burial depths and therefore insufficiently elevated temperatures (cf. 36-50°C and 1.0-1.5 km burial depths for Tikorangi Formation dolomitisation), pressures, and salinity to overcome the kinetic constraints on dolomitisation.

While the complex sedimentary and diagenetic history of the Tikorangi Formation is broadly appreciated, much work remains to be able to better understand not only this hydrocarbon reservoir, but temperate-latitude carbonates more generally. Evolving temperate carbonate facies models do not easily incorporate much of the diversity and complexity of a broad spectrum of skeletal facies and diagenetic

features such as identified in this study. Features such as redeposition, dolomitisation and tectonic fracturing enabling them to host hydrocarbons will necessitate an expansion and greater diversification of the shallow-marine temperate carbonate model in the future. Further development of the temperate carbonate facies model will require considerably more extensive and detailed studies in order to continue to better understand the complexities of the burial diagenetic realm, dolomitisation, and the geochemical changes involved with uplift and exposure to meteoric pore fluids. Moreover the potential of cool-water carbonate facies to form petroleum host rocks remains to be properly evaluated.

8.6 FURTHER WORK

Application of the lithologic correlations made in this study could be extended to other wells in Taranaki Basin where geophysical logs have been recorded through the Tikorangi Formation, but for which no core material exists. This would provide additional impetus for the study of the Tikorangi Formation as an oil-producing reservoir by allowing a fuller delineation and correlation of units throughout the eastern Taranaki Basin. The optimum units for fracture development would probably be those predisposed to brittle fracture, namely those dolomite-rich limestones.

Current facies models for cool-water carbonates remain under development, especially from a diagenetic and geochemical viewpoint. Very little work has been published on temperate dolomitic carbonates remaining in the subsurface, and rocks such as the Tikorangi Formation provide an important window into the deep burial environment unaltered by uplift and subaerial exposure. Much work remains to explore the application of bulk trace element geochemistry to carbonates for elucidating diagenetic environments, not only in temperate carbonates but also for modern and ancient carbonates in general. Further investigations of the conditions and constraints surrounding dolomitisation in the Tikorangi Formation are required to explore why there appears to be a paucity of dolomite in most other temperate carbonate occurrences. While this study has mentioned the likelihood of a meteoric influence within the deep burial

environment beneath Taranaki Peninsula, work is needed on the nature of modern-day fluids circulating at depth to begin to test this scenario and its implications.

Much work remains to be undertaken to ascertain the provenance of the considerable quantities of fine siliciclastic material supplied to the Tikorangi depocentres basin during a peak transgressive event with minimal source rock areas exposed to the east. The potential sources suggested here, including South Island basement rocks and Australian provenances, are worthy of consideration.

8.7 FUTURE PROSPECTIVITY

In the context of the projected decline of currently producing oil fields in New Zealand, there is an obvious need to establish new petroleum reserves. Clearly Taranaki Basin remains a focus of exploration attention. An understanding of already discovered hydrocarbon systems will greatly aid in the identification and evaluation of new prospects within the basin. While the Tikorangi Formation must continue to be seen as an important potential hydrocarbon reservoir within Taranaki Basin, the improved understanding of its stratigraphy and lithologic properties provided by this research should aid in increasing its potential prospectivity.

Proposed drilling programmes in Taranaki Basin for the end of year 2000 include three wells which plan to target the Tikorangi Formation, testimony to the formation's ongoing hydrocarbon prospectivity. Canadian-based company Pacific Tiger Energy (NZ) Ltd has confirmed plans to drill the Awakino South-1 well in offshore north Taranaki. Indo-Pacific will be drilling the Kahili-1 well immediately north of the Tariki mining licence to test limestones of the Tikorangi Formation and the Tariki sandstones. Fletcher Challenge Energy Ltd proposes to drill Tuihu-1 well near the end of year 2000 to the east of the Tariki Field in central onshore Taranaki. The primary objective is the Tariki sandstones, while secondary objectives are the Tikorangi limestones and the Kapuni Group sands (MOC 2000). Future hydrocarbon discoveries within the Tikorangi Formation will

emphasise its unique position as being currently the only fracture-controlled and carbonate reservoir in the Taranaki Basin.

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APPENDIX 1.1

Stratigraphic data for onshore wells penetrating the Tikorangi Formation

Well	Top (mAH)	Top (mTVSS)	Base (mAH)	Base (mTVSS)	AHT (m)	TV (m)	TST (m)	Isocore (m)	Northing	Easting
Ahuroa-1	2083.14	1870.60	2314.83	2101.10	231.69	230.50	224.12	237.04	6214669.10	2626567.60
Ahuroa-1A	2083.40	1870.90	2314.16	2100.40	230.77	229.50	223.50	236.38	6214669.00	2626567.00
Ahuroa-2	1780.64	1574.70	1964.07	1758.10	183.43	183.40	180.97	183.76	6214613.20	2625649.40
Ahuroa-2A	1781.20	1575.30	1976.84	1767.60	195.64	192.30	194.97	196.89	6214613.20	2625649.30
Awakino-1	1915.00	1892.70	1956.00	1933.70	41.00	41.00	40.82	40.98	6293128.90	2646657.00
Cardiff-1	3229.98	2923.50	3243.68	2937.10	13.71	13.60	13.68	13.68	6203649.50	2620506.20
Hu Road-1A	3035.22	2781.90	3220.65	2967.00	185.43	185.10	158.79	183.36	6197744.20	2629915.40
Makara-1	2129.80	1981.70	2282.64	2133.60	152.83	151.90	150.29	156.35	6229216.60	2623753.20
Mangahewa-1	3214.63	3036.70	3250.40	3072.50	35.77	35.80	35.77	35.77	6236761.00	2623649.90
Manganui-1	3304.03	3146.30	3313.88	3156.10	9.84	9.80	9.84	9.86	6232159.00	2622645.00
Manganui-2	3387.92	3111.60	3397.00	3120.40	9.08	8.80	8.89	8.90	6232552.00	2623086.00
McKee-1	1738.00	1642.40	1828.00	1732.10	90.00	89.70	81.55	92.36	6232715.00	2625260.00
McKee-10	1787.35	1634.00	1854.63	1649.90	67.28	15.90	62.68	67.50	6231444.00	2625170.50
McKee-11	1726.15	1555.00	1798.67	1617.40	72.52	62.40	59.66	62.90	6234266.50	2625413.20
McKee-14	1806.44	1651.20	1910.99	1750.90	104.56	99.70	88.16	92.70	6233986.50	2625484.80
McKee-15	1693.80	1559.40	1762.72	1622.30	68.92	62.90	64.29	68.00	6234146.50	2625388.00
McKee-16	1705.22	1551.00	1756.05	1597.10	50.83	46.10	49.56	50.86	6234260.00	2625393.10
McKee-2	1814.69	1660.80	1919.88	1765.90	105.19	105.10	102.12	106.23	6233669.00	2625391.00
McKee-2A	1815.72	1662.00	1920.35	1766.60	104.63	104.60	101.33	105.41	6233671.00	2625396.00
McKee-3	1726.08	1392.10	1791.72	1451.00	65.65	58.90	64.76	65.76	6233770.00	2624686.00
McKee-3A	1680.97	1448.30	1745.82	1513.00	64.85	64.70	64.22	65.66	6233727.00	2624987.90

Well	Top (mAH)	Top (mTVSS)	Base (mAH)	Base (mTVSS)	AHT (m)	TV (m)	TST (m)	Isocore (m)	Northing	Easting
McKee-4	1904.00	1649.10	1980.32	1723.60	76.32	74.50	74.28	75.94	6233204.10	2625227.40
McKee-5	1851.34	1674.20	1925.44	1748.00	74.10	73.80	70.43	72.29	6234216.00	2625635.20
McKee-5A	1847.18	1670.10	1917.03	1739.20	69.85	69.10	68.83	71.97	6234213.00	2625629.00
McKee-7A	1685.97	1553.60	1759.54	1623.30	73.56	69.70	73.18	76.53	6234110.00	2625371.80
McKee-8	1815.17	1643.50	1899.36	1713.70	84.18	70.20	75.93	77.63	6233629.00	2625314.80
McKee-9	1856.91	1644.90	1930.23	1702.70	73.31	57.80	56.44	59.93	6233559.00	2625301.10
Mokau-1	2525.00	2490.50	2551.00	2516.40	26.00	25.90	25.95	26.21	6275490.30	2638725.90
Ngaere-1	2978.76	2596.00	3283.52	2826.80	304.76	230.80	205.39	208.56	6204731.60	2627202.20
Ngaere-2	2857.62	2607.70	3133.05	2836.60	275.43	228.90	219.55	220.76	6205924.50	2627614.00
Ngaere-3	3048.95	2724.30			N/A	-	-	-	6207636.10	2627171.10
Ohanga-1	2575.65	2500.40	2621.40	2546.10	45.75	45.70	45.66	45.75	6241150.50	2627145.60
Onaero-1	2510.13	2459.30	2551.46	2500.60	41.33	41.30	39.46	41.99	6243636.40	2628941.90
Piakau-1	2010.12	1733.00	2255.17	1978.00	245.05	245.00	242.62	245.00	6211052.10	2625278.90
Pouri-1	1648.38	1543.10	1739.93	1631.20	91.55	88.10	86.71	88.65	6235136.00	2625426.90
Pouri-1A	1633.88	1527.30	1701.22	1589.20	67.34	61.90	66.11	67.59	6235130.50	2625438.50
Pukemai-1	1726.42	1562.60	1769.05	1605.20	42.63	42.60	42.50	42.66	6235923.80	2626183.10
Pukemai-1B	1735.15	1566.50	1795.00	1623.10	59.85	56.60	54.29	54.50	6235927.30	2626235.00
Pukemai-2A	1956.10	1641.90	2003.05	1687.40	46.95	45.50	45.82	45.99	6235371.00	2626118.60
Pukemai-3	1732.16	1567.00	1788.45	1620.90	56.30	53.90	54.66	54.87	6235908.90	2626203.20
Stratford-1	3338.13	2991.70	3388.96	3042.50	50.84	50.80	50.76	50.80	6210437.50	2619537.70
Tariki North-1A	2715.22	2341.60	2752.39	2367.30	37.17	25.70	29.41	39.58	6222947.50	2628487.00
Tariki-1	2202.17	1990.10	2304.08	2091.90	101.91	101.80	80.11	104.58	6219921.70	2626665.60
Taraki-1A	2092.95	1834.20	2217.61	1946.00	124.66	111.80	118.56	139.80	6219854.70	2626961.70
Tariki-2	2223.00	1978.80	2476.65	2219.10	253.65	240.30	242.13	242.46	6221931.70	2628000.60
Tariki-2A	2264.50	1883.10	2468.62	2064.70	204.12	181.60	184.32	186.62	6221301.40	2627803.70
Tariki-4A	2196.44	1907.20	2291.74	1985.40	95.29	78.20	62.54	81.64	6220194.40	2626822.80

Well	Top (mAH)	Top (mTVSS)	Base (mAH)	Base (mTVSS)	AHT (m)	TV (m)	TST (m)	Isocore (m)	Northing	Easting
Tirua-1	1688.00	1655.70	1740.00	1707.20	52.00	51.50	52.00	52.00	6316307.70	2651456.90
Toetoe-1	1608.52	1484.50	1696.66	1572.50	88.14	88.00	78.71	90.00	6231427.00	2624602.80
Toetoe-1A	1607.30	1483.20	1698.77	1574.60	91.47	91.40	81.64	93.34	6231427.00	2624602.90
Toetoe-2	1709.00	1502.90	1799.00	1583.20	90.00	80.30	84.26	85.56	6232388.00	2624909.40
Toetoe-4	1785.16	1617.40	1893.78	1710.90	108.63	93.50	82.88	89.39	6230351.50	2623756.80
Toetoe-4A	1720.66	1557.00	1778.08	1611.00	57.42	54.00	53.02	57.18	6230424.40	2623756.10
Toetoe-5	1768.20	1539.10	1939.66	1687.30	171.45	148.20	138.11	152.39	6230491.50	2623935.60
Toetoe-7	1562.95	1435.00	1638.63	1507.90	75.68	72.90	65.71	73.74	6231475.90	2624488.20
Toetoe-7A	1562.40	1434.50	1635.16	1504.30	72.76	69.80	66.05	74.13	6231477.60	2624487.40
Toetoe-8	1646.33	1565.10	1729.30	1647.80	82.97	82.70	77.91	84.03	6232133.90	2624962.50
Toetoe-8A	1646.83	1565.60	1736.62	1655.10	89.79	89.50	84.16	90.77	6232133.90	2624962.40
Toetoe-9	1623.46	1499.20	1696.59	1572.10	73.13	72.90	60.99	73.57	6231419.60	2624619.30
Toko-1	2980.62	2772.20	3149.72	2941.40	169.10	169.20	168.92	169.85	6208704.40	2627883.30
Toko-2	2966.76	2678.30	3258.51	2911.10	291.75	232.80	128.04	154.44	6208819.10	2626875.90
Toko-2A	3023.85	2627.20			N/A	-	-	-	6209239.60	2626398.60
Totara-1	3244.53	3104.60	3362.69	3222.60	118.16	118.00	117.98	117.98	6226226.10	2624549.70
Tuhua-1					N/A	-	-	-	6236587.00	2626977.20
Tuhua-2A	1804.26	1619.80	1863.10	1672.80	58.83	53.00	54.35	54.48	6236995.00	2627154.00
Tuhua-2B	1803.42	1622.30	1859.48	1677.30	56.06	55.00	54.86	54.91	6236961.00	2627177.00
Tuhua-3	2070.80	1811.70	2128.84	1856.90	58.04	45.20	53.53	56.61	6236286.10	2627402.00
Tuhua-3C	2074.67	1742.30	2131.23	1787.30	56.56	45.00	50.14	51.46	6236229.00	2627076.00
Tuhua-3D	2073.01	1741.10	2130.47	1786.70	57.46	45.60	50.94	52.28	6236229.00	2627076.00
Tuhua-4	1892.17	1692.40	1954.62	1752.30	62.45	59.90	58.10	59.88	6235753.00	2626534.00
Tuhua-5	1839.50	1606.40	1886.00	1646.70	46.50	40.30	40.15	40.65	6237176.00	2627044.00
Tuhua-5A	1847.17	1615.80	1885.67	1650.80	38.50	35.00	33.68	34.10	6237176.00	2627054.00
Tuhua-6	1886.56	1593.70	1962.66	1660.30	76.10	66.60	67.68	67.85	6237302.00	2626941.00

Well	Top (mAH)	Top (mTVSS)	Base (mAH)	Base (mTVSS)	AHT (m)	TV (m)	TST (m)	Isocore (m)	Northing	Easting
Tuhua-7	1809.49	1620.30	1866.64	1673.40	57.15	53.10	53.94	54.07	6236944.00	2627127.00
Tuhua-8	1860.00	1664.10	1908.00	1710.10	48.00	46.00	43.12	43.93	6236786.00	2627191.00
Tuhua-9	1814.41	1630.40	1866.51	1679.70	52.10	49.30	47.24	47.50	6236871.00	2627150.00
Turi-1	3063.00	3030.70	3086.00	3053.70	23.00	23.00	22.99	22.99	6300602.10	2634428.80
Uurenui-1	2549.77	2479.20	2596.75	2526.20	46.98	47.00	46.82	46.94	6241772.50	2627525.80
Waihapa-1	2878.23	2638.40	3110.55	2870.40	232.32	232.00	231.69	233.43	6201263.30	2628223.10
Waihapa-2	2902.11	2654.60	3145.26	2897.30	243.15	242.70	242.27	244.65	6201310.90	2627660.20
Waihapa-4	2802.02	2574.90	3043.98	2816.60	241.96	241.70	241.46	242.79	6203855.30	2627752.00
Waihapa-5	2995.22	2744.50	3195.28	2944.20	200.06	199.70	197.55	200.60	6199942.60	2628040.60
Waihapa-6	3003.92	2772.70			N/A	-	-	-	6202372.60	2626810.20
Waihapa-6A	2885.02	2614.80			N/A	-	-	-	6202559.40	2627087.90
Waihapa-8	3252.13	2677.00	3502.24	2870.90	250.11	193.90	161.57	165.18	6202303.30	2628339.00
Waihi-1	2225.00	2213.50	2251.00	2239.50	26.00	26.00	25.92	25.95	6282129.40	2639803.50
Wharehuia-1	2243.14	1962.90	2489.93	2209.70	246.79	246.80	245.44	246.79	6211615.00	2626127.00

1) Formation top and base (where penetrated) in both AH (along hole) and TVSS (true vertical sub sea).

2) AHT (along hole thickness) - thickness penetrated in well.

3) mTV (metres true vertical).

4) TST (true stratigraphic thickness) - i.e. the isopach thickness.

5) Isocore - the thickness that would be encountered if a vertical well was drilled at the well location (many TAWN wells are deviated).

6) Eastings and northings for the intersection of the top of the Tikorangi Formation. Again, as many wells are deviated to high angles, the surface location is not necessarily where the Tikorangi Formation was penetrated.

Note: Data kindly supplied by Petrocorp Exploration Ltd/Fletcher Challenge Energy, New Plymouth.

APPENDIX 1.2

New Zealand Oligocene-Recent geological time scale(after Crampton et al. 1995)

INTER.		NEW ZEALAND				
Series		Series	Stage	Symbol	Age	
PLEISTOCENE	M-L					
PLIOCENE	E	WANGANUI	Haweran	Wq	0.37	
	LATE		Castlecliffian	Wc	1.6	
			Nukumaruan	Wn	2.6	
			Mangapanian	Wm	3.2	
			Waipipian	Wp	3.6	
EARLY	Opoitian	Wo	5.3			
MIOCENE	LATE	TARANAKI	Kapitean	Tk	6.6	
			Tongaporutuan	Tt	10.9	
	MIDDLE	LONDON	Waiauan	Sw	13	
			Lillburnian	Sl	15.1	
			Clifdenian	Sc	16.3	
	EARLY		Altonian	Pl	18.5	
			Otaian	Po	21.8	
			Waitakian	Lw	23.2	
			Duntroonian	Ld	27.0	
OLIGOCENE	LATE		Whaingaroan	Lwh	33.5	
	EARLY					

APPENDIX 2.1

Tikorangi Formation drill core data

Well	Core number	Percent recovered	Box numbers	Depth (m) (top)	Depth (m) (bottom)	Total length (m)
Hu Rd-1A	1	84	1	2961.00	2962.00	1.00
Hu Rd-1A	2	94	2-8	2962.00	2969.00	7.00
				Total cored length		8.00
Maui-1	1		1-9	2515	2524.00	9.00
				Total cored length		9.00
Toko-1	1		1	3099.20	3101.40	2.20
				Total cored length		2.20
Waihapa-2	1	100	1-7	2913.00	2918.56	5.56
Waihapa-2	2	95	1-12	2919.00	2929.70	10.70
Waihapa-2	3	93	1-8	2930.30	2937.32	7.02
Waihapa-2	4	94	1-12	2977.62	2988.75	11.13
Waihapa-2	5	94	1-2	2989.30	2990.90	1.60
Waihapa-2	6	100	1-5	2990.90	2995.00	4.10
Waihapa-2	7	90	1-5	2995.00	2999.76	4.76
Waihapa-2	8	78	1-2	3076.00	3077.97	1.97
Waihapa-2	9	100	1-12	3078.50	3089.70	11.20
				Total cored length		58.04
Waihapa-4	1	100	1-10	2819.00	2828.00	9.00
Waihapa-4	2	100	1-7	2828.04	2834.08	6.04
Waihapa-4	3	100	1-20	2834.08	2852.38	18.30
Waihapa-4	4	87	1-11	2883.00	2892.98	9.98
Waihapa-4	5	100	1-2	2894.00	2895.50	1.50
Waihapa-4	6	72	1-16	2895.50	2908.54	13.04
Waihapa-4	7	62	1-7	3004.00	3010.80	6.80
Waihapa-4	8	16	1-3	3060.00	3062.91	2.91
				Total cored length		67.57

Well	Core number	Percent recovered	Box numbers	Depth (m) (top)	Depth (m) (bottom)	Total length (m)
Waihapa-5	1	77	1-9	3005.00	3013.00	8.00
Waihapa-5	2	97	1-12	3015.00	3025.40	10.40
Waihapa-5	3	100	1-19	3025.50	3044.25	18.75
Waihapa-5	4	100	1-21	3073.00	3091.80	18.80
Waihapa-5	5	100	1-21	3091.70	3110.60	18.90
Waihapa-5	6	100	1-20	3140.00	3158.80	18.80
Waihapa-5	7	100	1-18	3158.80	3177.65	18.85
				<i>Total cored length</i>		<i>112.50</i>
Waihapa-6	4	100	1-22	3109.50	3128.00	18.50
				<i>Total cored length</i>		<i>18.50</i>
Ngaere-2	1	?	1-10	2905.50	2914.30	8.80
Ngaere-2	2	?	1-11	2914.30	2923.40	9.10
Ngaere-2	3	?	1-19	2926.00	2944.50	18.50
Ngaere-2	4	?	1-18	2984.50	3000.70	16.20
Ngaere-2	5	?	1-20	3001.30	3019.80	18.50
Ngaere-2	6	?	1-14	3049.80	3062.10	12.30
Ngaere-2	7	?	1-21	3062.10	3080.70	18.60
				<i>Total cored length</i>		<i>102.00</i>

APPENDIX 2.2

Catalogue of Tikorangi Formation samples used in this study

E. Sc. store number	Running number	Sample number	Well	Core number	Box number	Depth (mAH)
W00501	1	Hu.2.1A	Hu Rd-1A	2	1A	2962.00
W00502	2	Hu.2.3	Hu Rd-1A	2	3	2963.50
W00503	3	Hu.2.4	Hu Rd-1A	2	4	2966.50
W00504	4	Hu.2.6A	Hu Rd-1A	2	6	2967.00
W00505	5	Hu.2.6B	Hu Rd-1A	2	6	2967.00
W00506	6	Hu.2.7	Hu Rd-1A	2	7	2968.50
W00507	7	K1	Kea-1	Side-wall core		2825.00
W00508	8	K2	Kea-1	Side-wall core		2895.00
W00509	9	K3	Kea-1	Side-wall core		2902.00
W00510	10	Mau1	Maui-1	1	9	2522.10
W00511	11	Mau2	Maui-1	1	5	2519.10
W00512	12	Mau3	Maui-1	1	3	2517.00
W00513	13	Mau4	Maui-1	1	1	2515.80
W00514	14	NG2.1.3	Ngaere-2	1	3	2907.90
W00515	15	NG2.1.5	Ngaere-2	1	5	2909.20
W00516	16	NG2.1.8	Ngaere-2	1	8	2912.40
W00517	17	NG2.1.10	Ngaere-2	1	10	2914.30
W00518	18	NG2.2.2	Ngaere-2	2	2	2915.10
W00519	19	NG2.2.3	Ngaere-2	2	3	2916.20
W00520	20	NG2.2.7	Ngaere-2	2	7	2919.90
W00521	21	NG2.2.9	Ngaere-2	2	9	2921.80
W00522	22	NG2.3.1	Ngaere-2	3	1	2926.70
W00523	23	NG2.3.2	Ngaere-2	3	2	2927.40
W00524	24	NG2.3.4	Ngaere-2	3	4	2930.85
W00525	25	NG2.3.6	Ngaere-2	3	6	2931.80
W00526	26	NG2.3.8	Ngaere-2	3	8	2934.40
W00527	27	NG2.3.10	Ngaere-2	3	10	2936.20
W00528	28	NG2.3.14	Ngaere-2	3	14	2940.20
W00529	29	NG2.3.16	Ngaere-2	3	16	2941.75
W00530	30	NG2.3.18	Ngaere-2	3	18	2944.00
W00531	31	NG2.4.1	Ngaere-2	4	1	2984.50
W00532	32	NG2.4.1A	Ngaere-2	4	1	2984.60
W00533	33	NG2.4.1B	Ngaere-2	4	1	2984.90

E. Sc. store number	Running number	Sample number	Well	Core number	Box number	Depth (mAH)
W00534	34	NG2.4.2A	Ngaere-2	4	2	2985.45
W00535	35	NG2.4.2B	Ngaere-2	4	2	2985.50
W00536	36	NG2.4.3	Ngaere-2	4	3	2986.98
W00537	37	NG2.4.5	Ngaere-2	4	5	2988.70
W00538	38	NG2.4.6	Ngaere-2	4	6	2989.80
W00539	39	NG2.4.9	Ngaere-2	4	9	2992.35
W00540	40	NG2.4.11A	Ngaere-2	4	11	2993.75
W00541	41	NG2.4.11B	Ngaere-2	4	11	2993.80
W00542	42	NG2.4.13A	Ngaere-2	4	13	2996.10
W00543	43	NG2.4.13B	Ngaere-2	4	13	2996.30
W00544	44	NG2.4.15	Ngaere-2	4	15	2998.30
W00545	45	NG2.4.16B	Ngaere-2	4	16B	2998.70
W00546	46	NG2.4.16	Ngaere-2	4	16	2998.80
W00547	47	NG2.4.18	Ngaere-2	4	18	3000.25
W00548	48	NG2.5.1A	Ngaere-2	5	1	3001.50
W00549	49	NG2.5.1B	Ngaere-2	5	1	3001.95
W00550	50	NG2.5.2	Ngaere-2	5	2	3001.95
W00551	51	NG2.5.3	Ngaere-2	5	3	3003.55
W00552	52	NG2.5.6	Ngaere-2	5	6	3006.50
W00553	53	NG2.5.8	Ngaere-2	5	8	3007.80
W00554	54	NG2.5.10	Ngaere-2	5	10	3010.20
W00555	55	NG2.5.14	Ngaere-2	5	14	3014.00
W00556	56	NG2.5.18	Ngaere-2	5	18	3017.75
W00557	57	NG2.5.20	Ngaere-2	5	20	3019.40
W00558	58	NG2.6.1	Ngaere-2	6	1	3050.20
W00559	59	NG2.6.2A	Ngaere-2	6	2	3051.10
W00560	60	NG2.6.2B	Ngaere-2	6	2	3051.10
W00561	61	NG2.6.7	Ngaere-2	6	7	3055.55
W00562	62	NG2.6.8	Ngaere-2	6	8	3057.00
W00563	63	NG2.6.10A	Ngaere-2	6	10	3058.95
W00564	64	NG2.6.10B	Ngaere-2	6	10	3059.2-3
W00565	65	NG2.6.11A	Ngaere-2	6	11	3059.35
W00566	66	NG2.6.11B	Ngaere-2	6	11	3059.50
W00567	67	NG2.6.12	Ngaere-2	6	12	3060.75
W00568	68	NG2.6.13	Ngaere-2	6	13	3061.12
W00569	69	NG2.7.2	Ngaere-2	7	2	3063.75
W00570	70	NG2.7.3A	Ngaere-2	7	3	3064.25
W00571	71	NG2.7.3B	Ngaere-2	7	3	3064.60
W00572	72	NG2.7.6	Ngaere-2	7	6	3067.40
W00573	73	NG2.7.8	Ngaere-2	7	8	3068.55
W00574	74	NG2.7.13A	Ngaere-2	7	13	3073.15

E. Sc. store number	Running number	Sample number	Well	Core number	Box number	Depth (mAH)
W00575	75	NG2.7.13B	Ngaere-2	7	13	3073.75
W00576	76	NG2.7.16A	Ngaere-2	7	16	3076.00
W00577	77	NG2.7.19	Ngaere-2	7	19	3079.10
W00578	78	NT1	N. Tasman-1	Side-wall core		1939.40
W00579	79	NT2	N. Tasman-1	Side-wall core		1968.20
W00580	80	S1	Surville	Side-wall core		1513.00
W00581	81	Tok1	Toko-1	1	1	3099.50
W00582	82	Tok2	Toko-1	1	1	3100.40
W00583	83	Tok3	Toko-1	1	1	3101.40
W00584	84	W2.1.1	Waihapa-2	1	1	2913.50
W00585	85	W2.1.5	Waihapa-2	1	5	2916.60
W00586	86	W2.1.6	Waihapa-2	1	6	2917.14
W00587	87	W2.1.6A	Waihapa-2	1	6	2917.00
W00588	88	W2.1.7	Waihapa-2	1	7	2918.00
W00589	89	W2.2.1	Waihapa-2	2	1	2919.40
W00590	90	W2.2.3	Waihapa-2	2	3	2921.25
W00591	91	W2.2.5	Waihapa-2	2	5	2923.60
W00592	92	W2.2.6	Waihapa-2	2	6	2924.00
W00593	93	W2.2.7A	Waihapa-2	2	7	2924.10
W00594	94	W2.2.7B	Waihapa-2	2	7	2924.70
W00595	95	W2.2.7C	Waihapa-2	2	7	2925.00
W00596	96	W2.2.9	Waihapa-2	2	9	2927.07
W00597	97	W2.2.11	Waihapa-2	2	11	2928.65
W00598	98	W2.3.1	Waihapa-2	3	1	2930.40
W00599	99	W2.3.2	Waihapa-2	3	2	2931.50
W00600	100	W2.3.4	Waihapa-2	3	4	2935.40
W00601	101	W2.3.7	Waihapa-2	3	7	2936.73
W00602	102	W2.3.8	Waihapa-2	3	8	2937.20
W00603	103	W2.4.1	Waihapa-2	4	1	2978.60
W00604	104	W2.4.5	Waihapa-2	4	5	2981.30
W00605	105	W2.4.6	Waihapa-2	4	6	2982.18
W00606	106	W2.4.10A	Waihapa-2	4	10	2986.25
W00607	107	W2.4.10B	Waihapa-2	4	10	2986.81
W00608	108	W2.4.11A	Waihapa-2	4	11	2987.25
W00609	109	W2.4.11B	Waihapa-2	4	11	2987.34
W00610	110	W2.4.11C	Waihapa-2	4	11	2988.06
W00611	111	W2.5.1	Waihapa-2	5	1	2989.50

E. Sc. store number	Running number	Sample number	Well	Core number	Box number	Depth (mAH)
W00612	112	W2.5.2	Waihapa-2	5	2	2990.50
W00613	113	W2.6.2	Waihapa-2	6	2	2992.00
W00614	114	W2.6.3	Waihapa-2	6	3	2993.55
W00615	115	W2.7.1	Waihapa-2	7	1	2995.20
W00616	116	W2.7.2	Waihapa-2	7	2	2996.00
W00617	117	W2.7.4A	Waihapa-2	7	4	2998.20
W00618	118	W2.7.4B	Waihapa-2	7	4	2998.70
W00619	119	W2.8.1A	Waihapa-2	8	1	3076.00
W00620	120	W2.8.1B	Waihapa-2	8	1	3076.35
W00621	121	W2.8.2	Waihapa-2	8	2	3077.00
W00622	122	W2.9.1	Waihapa-2	9	1	3079.10
W00623	123	W2.9.6A	Waihapa-2	9	6	3083.50
W00624	124	W2.9.6B	Waihapa-2	9	6	3083.75
W00625	125	W2.9.6C	Waihapa-2	9	6	3084.00
W00626	126	W2.9.9	Waihapa-2	9	9	3088.72
W00627	127	W2.9.12A	Waihapa-2	9	12	3089.30
W00628	128	W2.9.12B	Waihapa-2	9	12	3089.40
W00629	129	W4.1.1	Waihapa-4	1	1	2820.20
W00630	130	W4.1.4	Waihapa-4	1	4	2822.40
W00631	131	W4.1.5	Waihapa-4	1	5	2823.00
W00632	132	W4.1.7	Waihapa-4	1	7	2824.80
W00633	133	W4.1.8	Waihapa-4	1	8	2826.00
W00634	134	W4.1.10	Waihapa-4	1	10	2827.50
W00635	135	W4.2.2	Waihapa-4	2	2	2829.60
W00636	136	W4.2.4	Waihapa-4	2	4	2831.40
W00637	137	W4.3.3	Waihapa-4	3	3	2836.41
W00638	138	W4.3.9	Waihapa-4	3	9	2842.60
W00639	139	W4.3.13	Waihapa-4	3	13	2845.60
W00640	140	W4.3.14	Waihapa-4	3	14	2846.00
W00641	141	W4.3.20	Waihapa-4	3	20	2852.00
W00642	142	W4.4.1A	Waihapa-4	4	1	2883.40
W00643	143	W4.4.1B	Waihapa-4	4	1	2883.80
W00644	144	W4.4.2A	Waihapa-4	4	2	2884.20
W00645	145	W4.4.2B	Waihapa-4	4	2	2884.50
W00646	146	W4.4.3	Waihapa-4	4	3	2884.90
W00647	147	W4.4.5	Waihapa-4	4	5	2886.10
W00648	148	W4.4.8	Waihapa-4	4	8	2889.70
W00649	149	W4.4.10A	Waihapa-4	4	10	2891.45
W00650	150	W4.4.10B	Waihapa-4	4	10	2892.00
W00651	151	W4.4.11A	Waihapa-4	4	11	2892.50

E. Sc. store number	Running number	Sample number	Well	Core number	Box number	Depth (mAH)
W00652	152	W4.4.11B	Waihapa-4	4	11	2892.50
W00653	153	W4.5.1A	Waihapa-4	5	1	2894.10
W00654	154	W4.5.1B	Waihapa-4	5	1	2894.60
W00655	155	W4.5.2	Waihapa-4	5	2	2895.00
W00656	156	W4.6.1	Waihapa-4	6	1	2896.00
W00657	157	W4.6.3	Waihapa-4	6	3	2897.00
W00658	158	W4.6.4	Waihapa-4	6	4	2898.70
W00659	159	W4.6.9	Waihapa-4	6	9	2902.40
W00660	160	W4.6.13	Waihapa-4	6	13	2905.00
W00661	161	W4.6.14	Waihapa-4	6	14	2906.00
W00662	162	W4.7.1	Waihapa-4	7	1	3004.10
W00663	163	W4.7.2A	Waihapa-4	7	2	3005.30
W00664	164	W4.7.2B	Waihapa-4	7	2	3005.60
W00665	165	W4.7.4A	Waihapa-4	7	4	3006.70
W00666	166	W4.7.4B	Waihapa-4	7	4	3007.00
W00667	167	W4.7.4C	Waihapa-4	7	4	3007.00
W00668	168	W4.7.5	Waihapa-4	7	5	3007.70
W00669	169	W4.8.2	Waihapa-4	8	2	3061.00
W00670	170	W5.1.2	Waihapa-5	1	2	3006.00
W00671	171	W5.1.3	Waihapa-5	1	3	3007.00
W00672	172	W5.1.4A	Waihapa-5	1	4	3008.50
W00673	173	W5.1.4B	Waihapa-5	1	4	3008.40
W00674	174	W5.1.7	Waihapa-5	1	7	3011.20
W00675	175	W5.1.8	Waihapa-5	1	8	3012.30
W00676	176	W5.1.9	Waihapa-5	1	9	3013.00
W00677	177	W5.2.1A	Waihapa-5	2	1	3015.25
W00678	178	W5.2.1B	Waihapa-5	2	1	3015.25
W00679	179	W5.2.1C	Waihapa-5	2	1	3015.75
W00680	180	W5.2.1D	Waihapa-5	2	1	3015.85
W00681	181	W5.2.5	Waihapa-5	2	5	3019.00
W00682	182	W5.2.7	Waihapa-5	2	7	3021.00
W00683	183	W5.2.11	Waihapa-5	2	11	3024.90
W00684	184	W5.3.3	Waihapa-5	3	3	3028.52
W00685	185	W5.3.5	Waihapa-5	3	5	3029.50
W00686	186	W5.3.6	Waihapa-5	3	6	3031.00
W00687	187	W5.3.9	Waihapa-5	3	9	3034.30
W00688	188	W5.3.11	Waihapa-5	3	11	3036.00
W00689	189	W5.3.14	Waihapa-5	3	14	3038.90
W00690	190	W5.3.15	Waihapa-5	3	15	3040.50
W00691	191	W5.3.19	Waihapa-5	3	19	3043.90

E. Sc. store number	Running number	Sample number	Well	Core number	Box number	Depth (mAH)
W00692	192	W5.4.4	Waihapa-5	4	4	3075.20
W00693	193	W5.4.6	Waihapa-5	4	6	3077.15
W00694	194	W5.4.11	Waihapa-5	4	11	3082.20
W00695	195	W5.4.17	Waihapa-5	4	17	3087.50
W00696	196	W5.4.21	Waihapa-5	4	21	3091.70
W00697	197	W5.5.4	Waihapa-5	5	4	3094.70
W00698	198	W5.5.9	Waihapa-5	5	9	3099.00
W00699	199	W5.5.10	Waihapa-5	5	10	3100.00
W00700	200	W5.5.13	Waihapa-5	5	13	3103.00
W00701	201	W5.5.14	Waihapa-5	5	14	3104.60
W00702	202	W5.5.17	Waihapa-5	5	17	3107.00
W00703	203	W5.5.19A	Waihapa-5	5	19	3109.00
W00704	204	W5.5.19B	Waihapa-5	5	19	3109.40
W00705	205	W5.5.20	Waihapa-5	5	20	3109.70
W00706	206	W5.5.21	Waihapa-5	5	21	3110.40
W00707	207	W5.6.1A	Waihapa-5	6	1	3140.75
W00708	208	W5.6.1B	Waihapa-5	6	1	3141.00
W00709	209	W5.6.2	Waihapa-5	6	2	3141.40
W00710	210	W5.6.3	Waihapa-5	6	3	3142.40
W00711	211	W5.6.4	Waihapa-5	6	4	3143.00
W00712	212	W5.6.5	Waihapa-5	6	5	3145.00
W00713	213	W5.6.7	Waihapa-5	6	7	3146.70
W00714	214	W5.6.11	Waihapa-5	6	11	3150.70
W00715	215	W5.6.13	Waihapa-5	6	13	3152.60
W00716	216	W5.6.19	Waihapa-5	6	19	3158.50
W00717	217	W5.7.4	Waihapa-5	7	4	3162.00
W00718	218	W5.7.4B	Waihapa-5	7	4B	3163.50
W00719	219	W5.7.6	Waihapa-5	7	6	3165.70
W00720	220	W5.7.9A	Waihapa-5	7	9	3169.00
W00721	221	W5.7.9B	Waihapa-5	7	9	3169.00
W00722	222	W5.7.14	Waihapa-5	7	14	3173.60
W00723	223	W5.7.17	Waihapa-5	7	17	3177.00
W00724	224	W6.3.1	Waihapa-6	3	1	2871.60
W00725	225	W6.3.2A	Waihapa-6	3	2	2872.30
W00726	226	W6.3.2B	Waihapa-6	3	2	2872.45
W00727	227	W6.3.4	Waihapa-6	3	4	2874.00
W00728	228	W6.3.5	Waihapa-6	3	5	2874.90
W00729	229	W6.3.8	Waihapa-6	3	8	2877.70
W00730	230	W6.3.9	Waihapa-6	3	9	2878.50
W00731	231	W6.3.11	Waihapa-6	3	11	2980.00

E. Sc. store number	Running number	Sample number	Well	Core number	Box number	Depth (mAH)
W00732	232	W6.4.1	Waihapa-6	4	1	3110.18
W00733	233	W6.4.2	Waihapa-6	4	2	3111.00
W00734	234	W6.4.6	Waihapa-6	4	6	3114.00
W00735	235	W6.4.12	Waihapa-6	4	12	3119.60
W00736	236	W6.4.20	Waihapa-6	4	20	3126.60

Note: Sidewall core sampled from wells outside of the Waihapa-Ngaere Field are included here for completeness, but due to their residual nature and poor quality were not further analysed in this study. mAH = metres along hole.

APPENDIX 2.3

Carbonate percentage data (running numbers from Appendix 2.2)

Running number	Sample number	Weight carbonate (g)	Weight residual (g)	Carbonate %
2	Hu2.3	0.8018	0.2006	80.0
3	Hu2.4	0.5073	0.0497	91.1
4	Hu2.6A	0.4517	0.5522	45.0
6	Hu2.7	1.0002	0.0022	99.8
10	Mau1	0.4055	0.5937	40.6
11	Mau2	0.3218	0.6854	31.9
12	Mau4	0.3704	0.633	36.9
14	NG2.1.3	0.7569	0.2486	75.3
15	NG2.1.5	0.4369	0.5625	43.7
16	NG2.1.8	0.1911	0.8202	18.9
19	NG2.2.3	0.7059	0.3014	70.1
20	NG2.2.7	0.3972	0.5949	40.0
22	NG2.3.1	0.4813	0.5232	47.9
23	NG2.3.2	0.1486	0.8539	14.8
26	NG2.3.8	0.2217	0.7782	22.2
39	NG2.4.9	0.2950	0.7143	29.2
46	NG2.4.16	0.5944	0.4037	59.6
51	NG2.5.3	0.6504	0.3546	64.7
52	NG2.5.6	0.3300	0.6761	32.8
58	NG2.6.1	0.4665	0.5336	46.6
61	NG2.6.7	0.5255	0.4824	52.1
69	NG2.7.2	0.5026	0.5036	50.0
73	NG2.7.8	0.2389	0.7601	23.9
74	NG2.7.13A	0.4911	0.5178	48.7
77	NG2.7.19	0.4319	0.5709	43.1
81	Tok1	0.5252	0.4804	52.2
82	Tok2	0.6702	0.4118	61.9
83	Tok3	0.6912	0.3089	69.1
84	W2.1.1	0.7079	0.2982	70.4
90	W2.2.3	0.811	0.1858	81.4
97	W2.2.11	0.6016	0.3968	60.3
101	W2.3.7	0.6496	0.3516	64.9
104	W2.4.5	0.3727	0.6323	37.1
106	W2.4.10A	0.6260	0.3769	62.4
113	W2.6.2	0.5218	0.4770	52.2

Running number	Sample number	Weight carbonate (g)	Weight residual (g)	Carbonate %
117	W2.7.4A	0.6170	0.3823	61.7
121	W2.8.2	0.4708	0.4708	50.0
128	W2.9.12B	0.5297	0.4703	53.0
131	W4.1.5	0.8690	0.1359	86.5
134	W4.1.10	0.8679	0.1452	85.7
141	W4.3.20	0.6902	0.3138	68.7
146	W4.4.3	0.2037	0.7988	20.3
148	W4.4.8	0.4949	0.5072	49.4
158	W4.6.4	0.5826	0.4144	58.4
161	W4.6.14	0.5835	0.4208	58.1
169	W4.8.2	0.3439	0.6631	34.2
170	W5.1.2	0.6855	0.314	68.6
174	W5.1.7	0.4780	0.5267	47.6
176	W5.1.9	0.3040	0.6967	30.4
177	W5.2.1A	0.5312	0.4626	53.5
182	W5.2.7	0.5194	0.4863	51.6
184	W5.3.3	0.3058	0.6963	30.5
188	W5.3.11	0.6633	0.3346	66.5
190	W5.3.15	0.2468	0.7480	24.8
191	W5.3.19	0.6151	0.3863	61.4
192	W5.4.4	0.5605	0.4456	55.7
195	W5.4.17	0.5048	0.4960	50.4
196	W5.4.21	0.4130	0.5919	41.1
199	W5.5.10	0.5088	0.4978	50.5
202	W5.5.17	0.7375	0.2638	73.7
203	W5.5.19A	0.6116	0.3812	61.6
206	W5.5.21	0.7885	0.2118	78.8
207	W5.6.1A	0.7719	0.2298	77.1
211	W5.6.4	0.8108	0.1906	81.0
213	W5.6.7	0.5225	0.4757	52.3
215	W5.6.13	0.4166	0.5807	41.8
216	W5.6.19	0.4803	0.5229	47.9
221	W5.7.9B	0.3686	0.6283	37.0
223	W5.7.17	0.4139	0.5886	41.3
229	W6.3.8	0.2574	0.7471	25.6
231	W6.3.11	0.2339	0.7703	23.3
236	W6.4.20	0.3800	0.6314	37.6

APPENDIX 2.4

Well stratigraphic and log summary sheets

A2.4.1. Maui-1

A2.4.2. Toko-1

A2.4.3. Ngaere-2

A2.4.4. Waihapa-4

A2.4.5. Waihapa-6

A2.4.6. Waihapa-2

A2.4.7. Waihapa-5

A2.4.8. Hu Rd-1

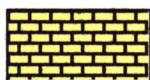
Key:



Facies A - Calcareous siliciclastites (<25% carbonate)



Facies B - Very calcareous siliciclastites (25-50% carbonate)



Facies C - Muddy limestones (50-75% carbonate)



Facies D - Sparry limestones (>75% carbonate)



Changed upper and/or lower Tikorangi Formation boundary from those defined in Well Completion Reports



Dashed blue line denotes existing formation boundary

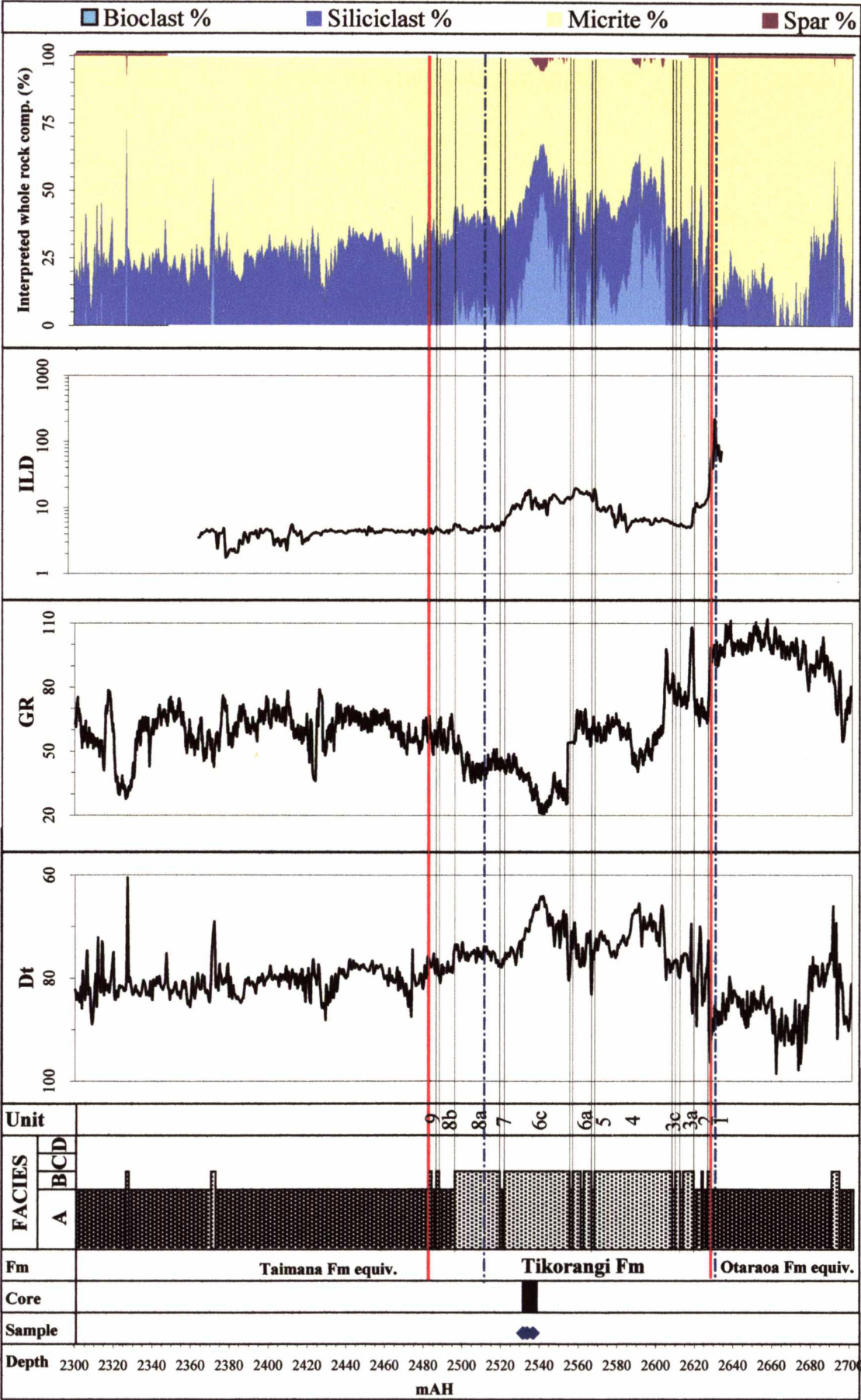


Major stratigraphic unit boundary lines (Unit 6)

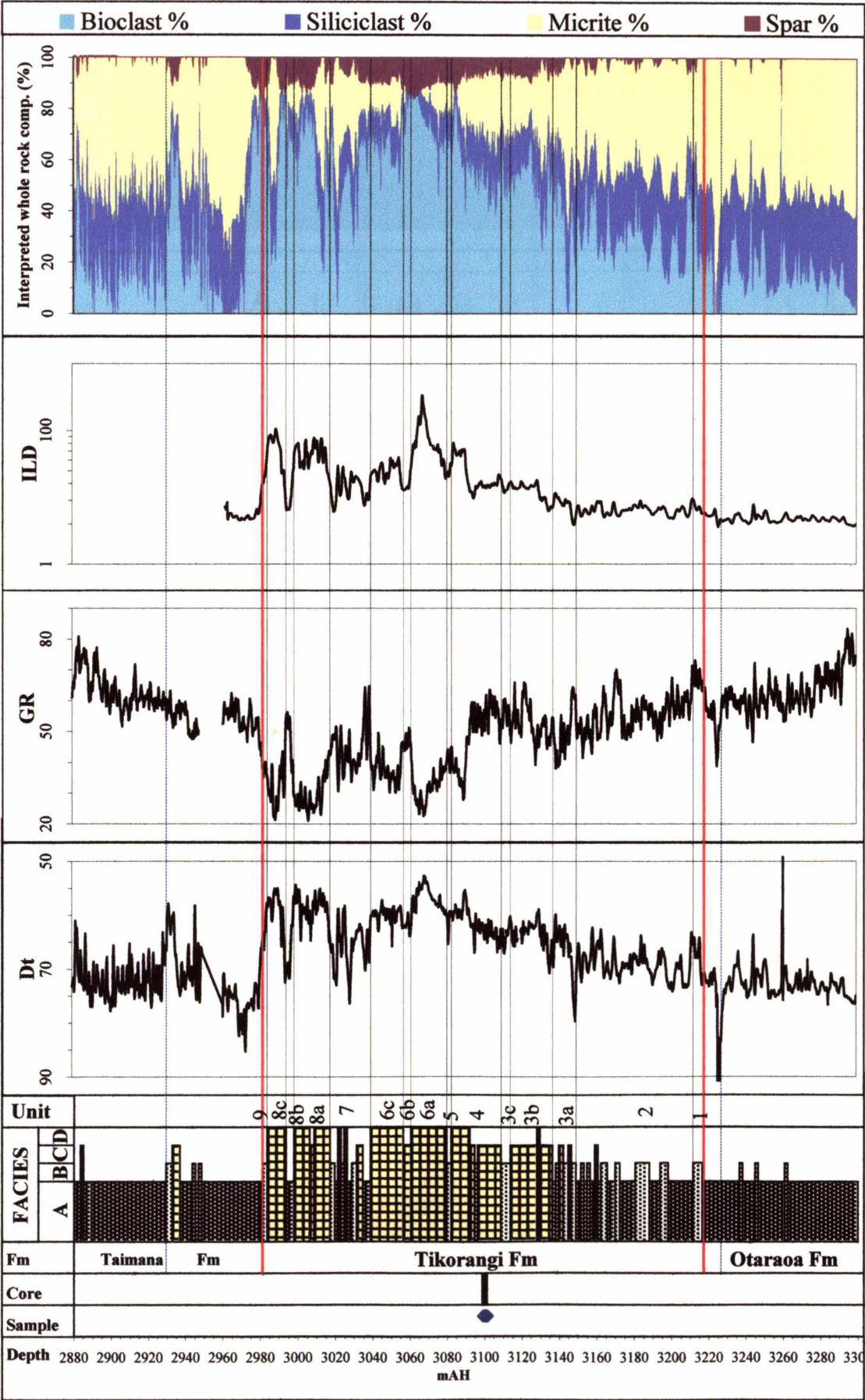


Sub-stratigraphic unit boundary lines (i.e. Unit 6c)

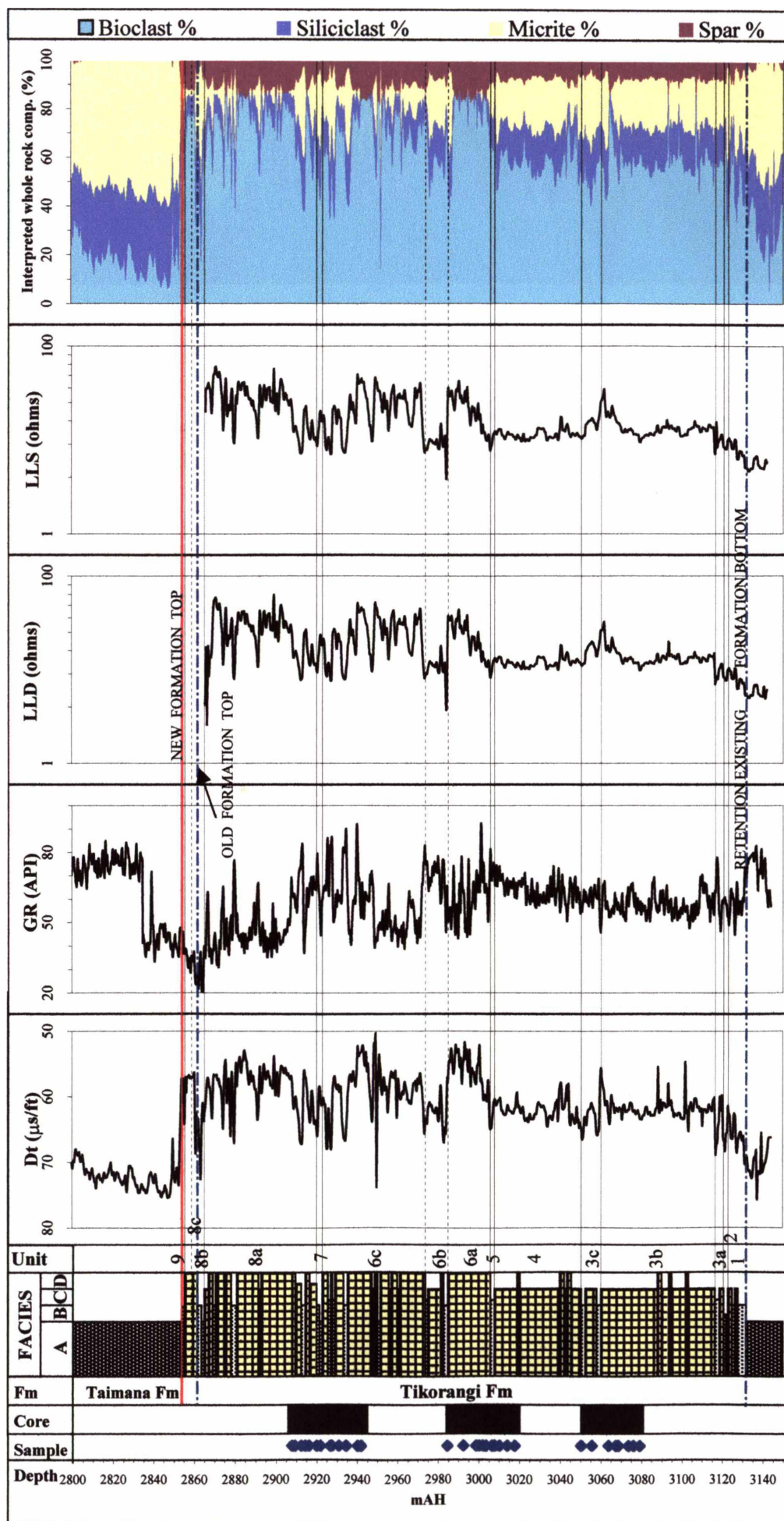
Core and sample locations and depths are shown in mAH (metres along hole). Dt = sonic log ($\mu\text{s}/\text{ft}$), GR = Gamma-ray log (GAPI). Resistivity logs (Rt) (ohms) - LLD = Laterolog deep, LLS = Laterolog shallow; ILD = induction log deep; ILM = induction log shallow.



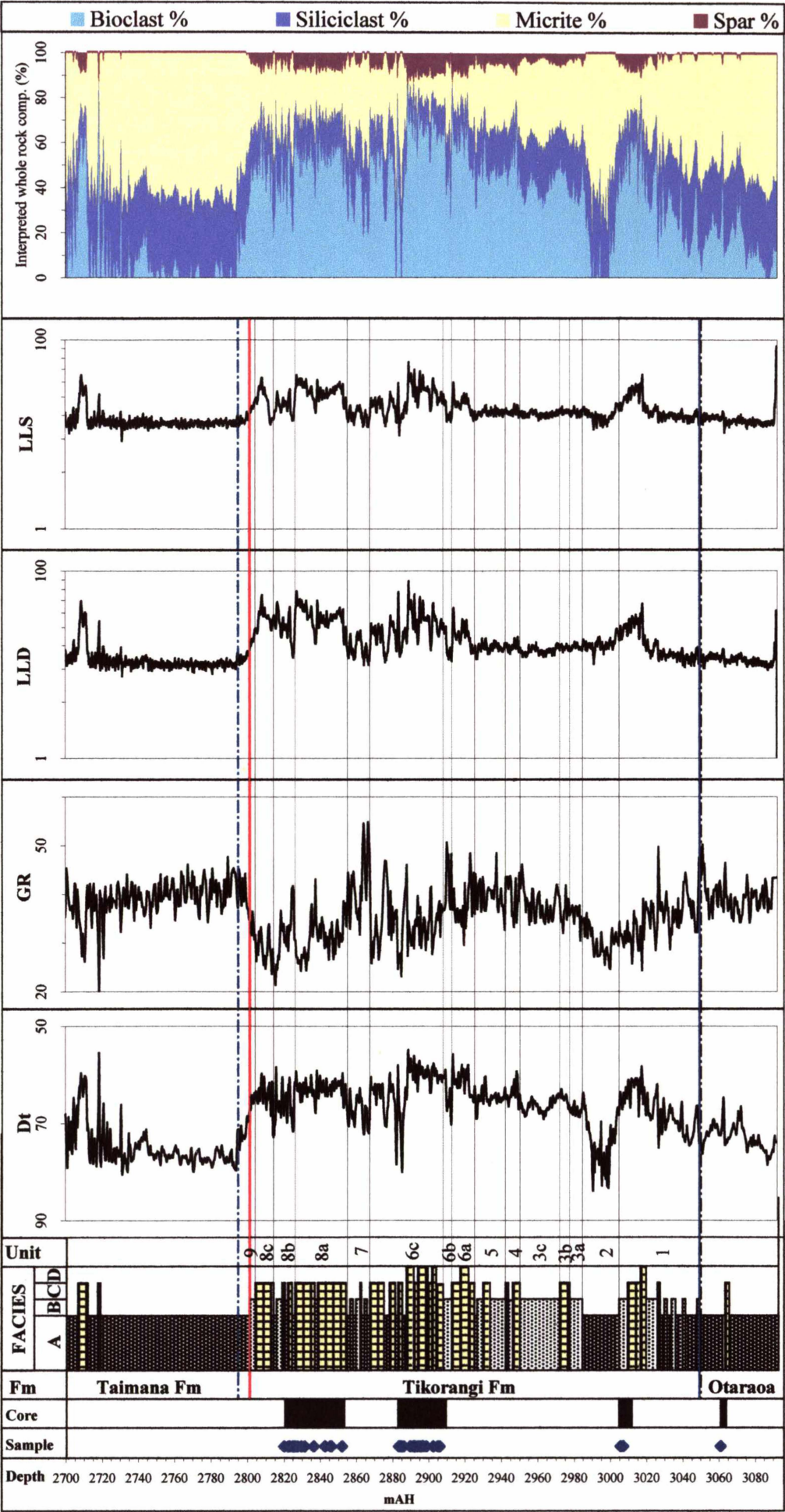
A2.4.1 Maui-1 well stratigraphic log summary.



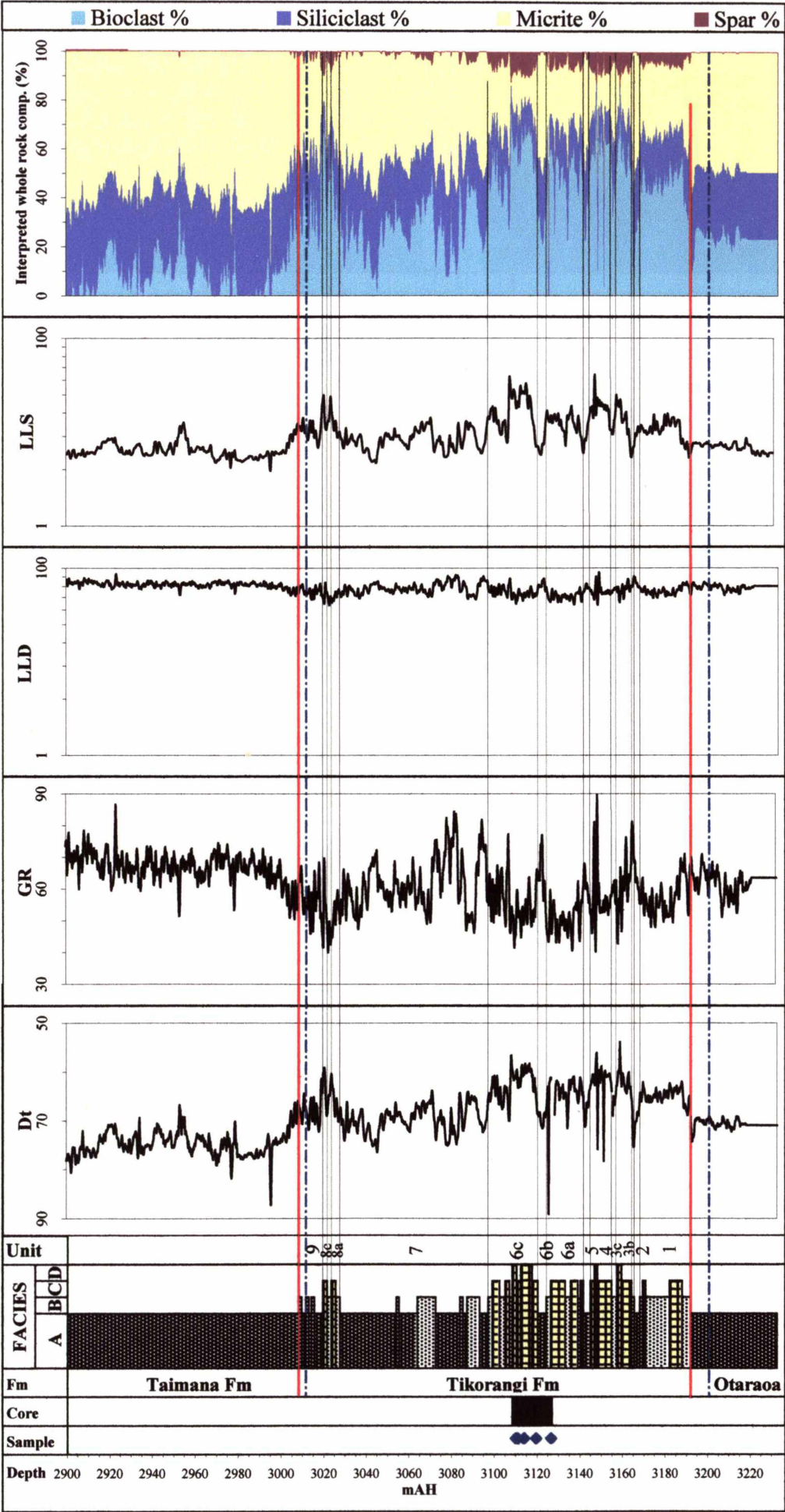
A2.4.2 Toko-1 well stratigraphic log summary.



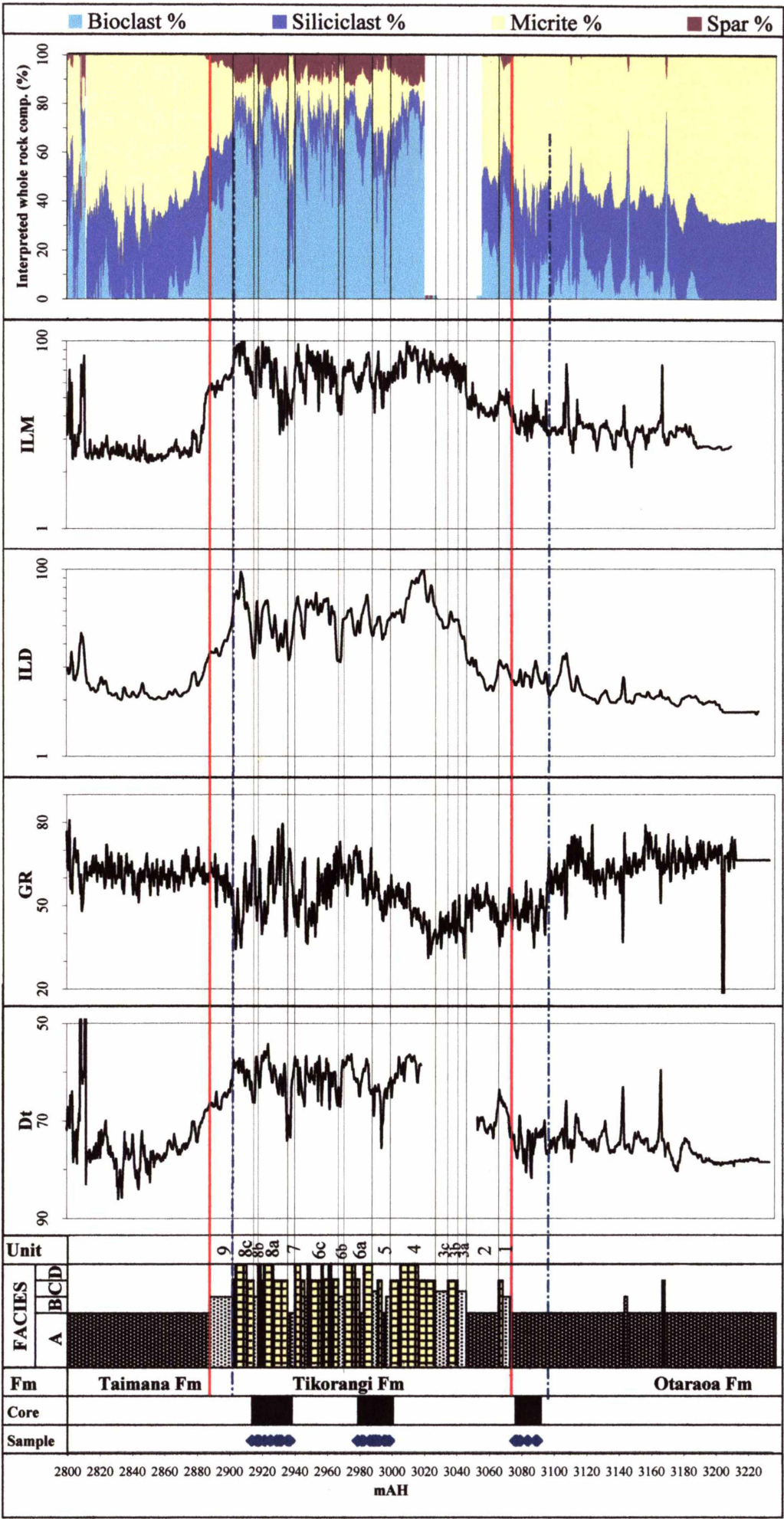
A2.4.3 Ngaere-2 well stratigraphic log summary.



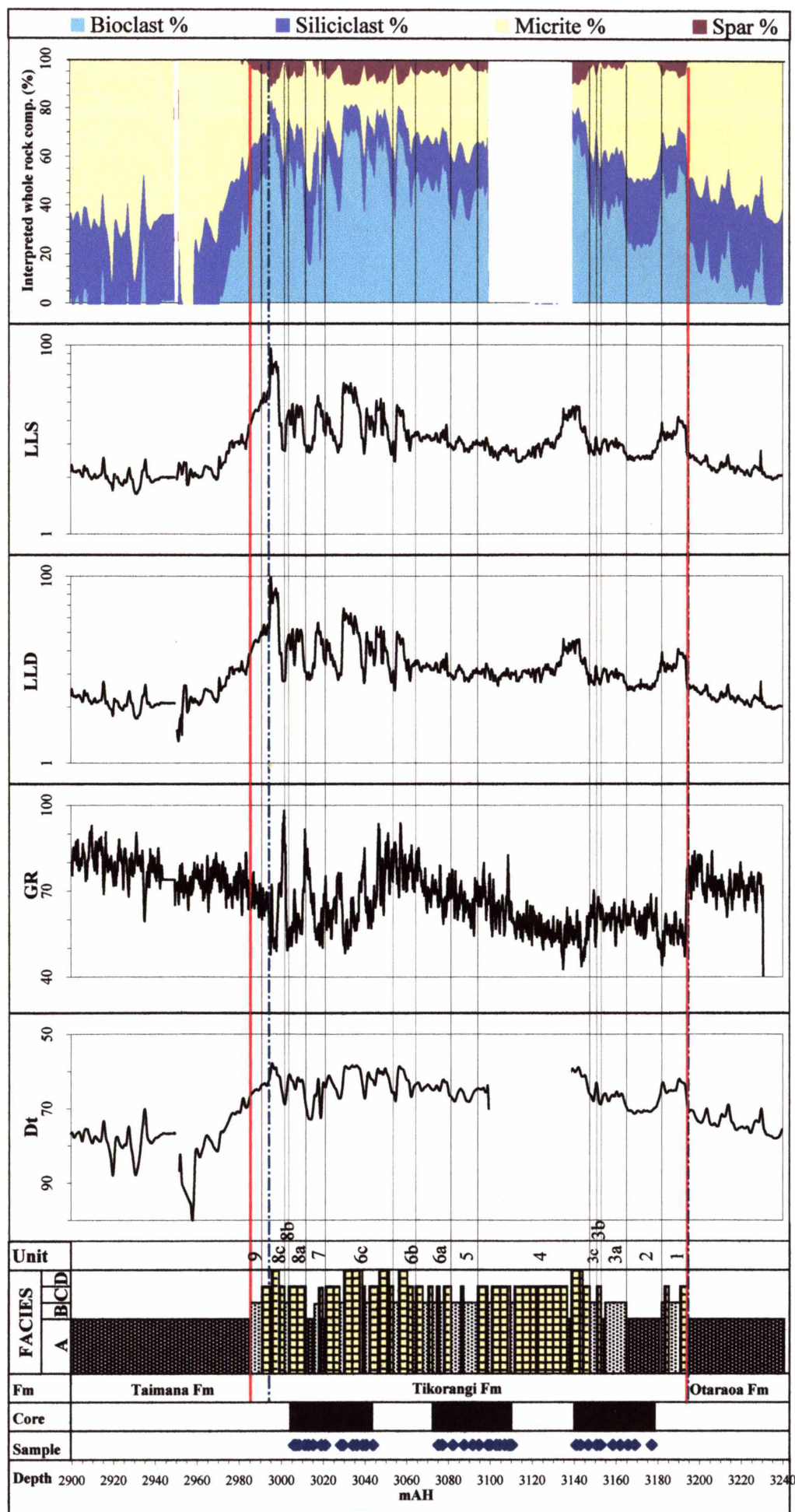
A2.4.4 Waihapā-4 well stratigraphic log summary.



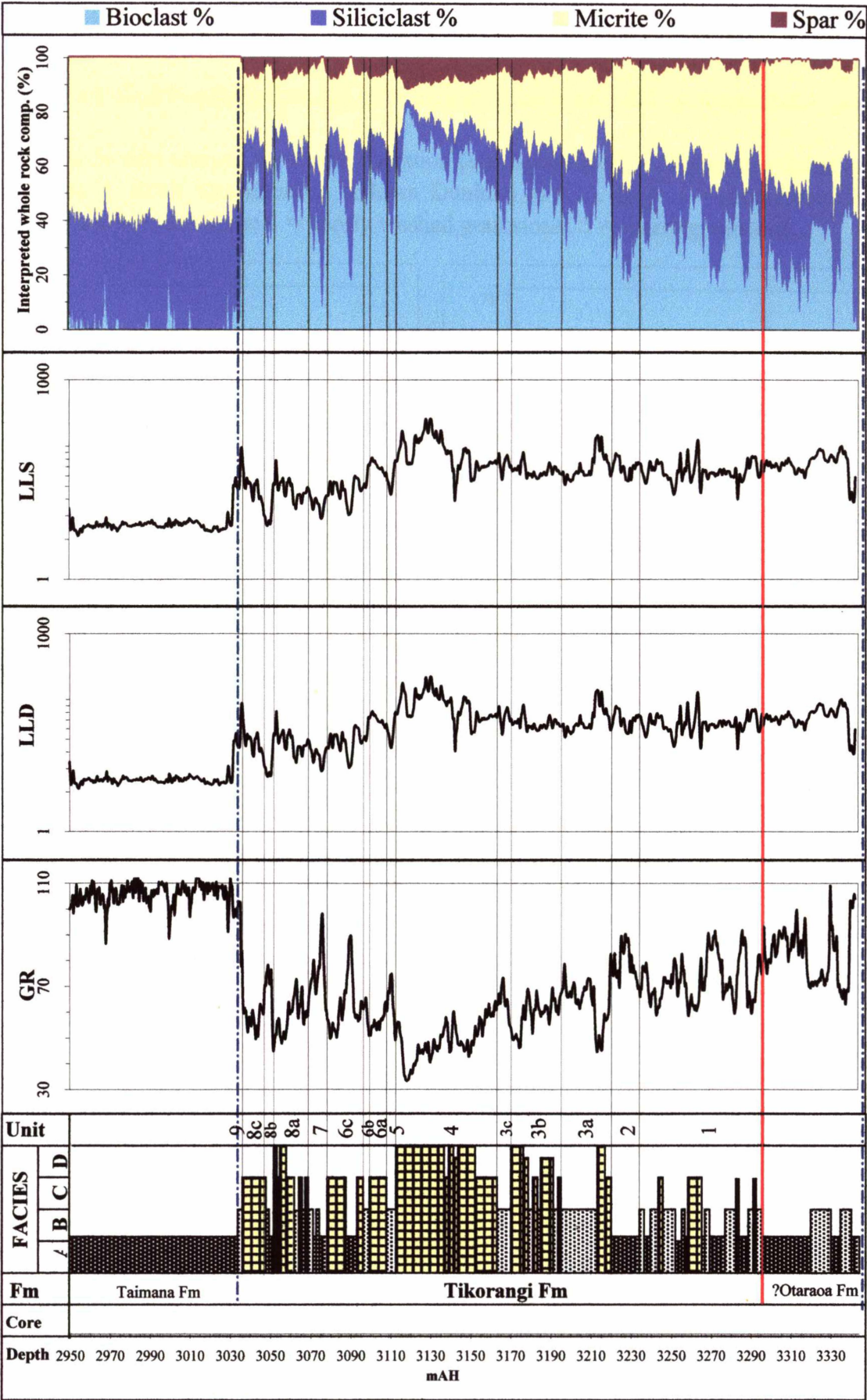
A2.4.5 Waihapa-6 well stratigraphic log summary.



A2.4.6 Waihapa-2 well stratigraphic log summary.



A2.4.7 Waihapa-5 well stratigraphic log summary.

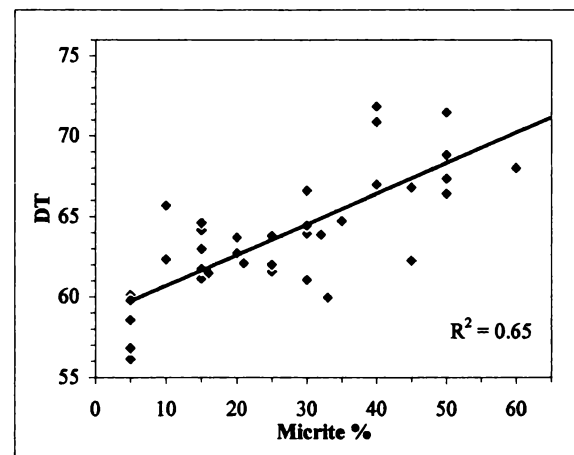
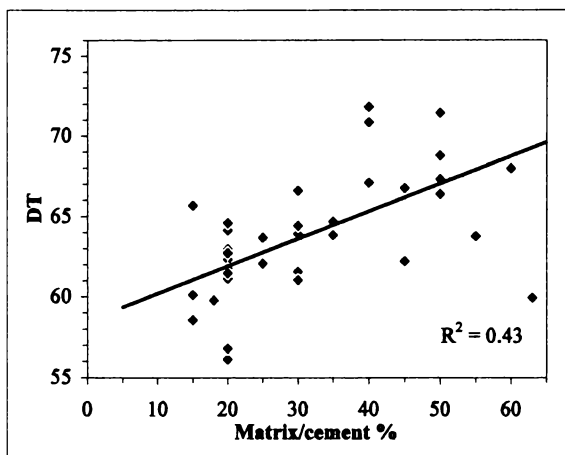
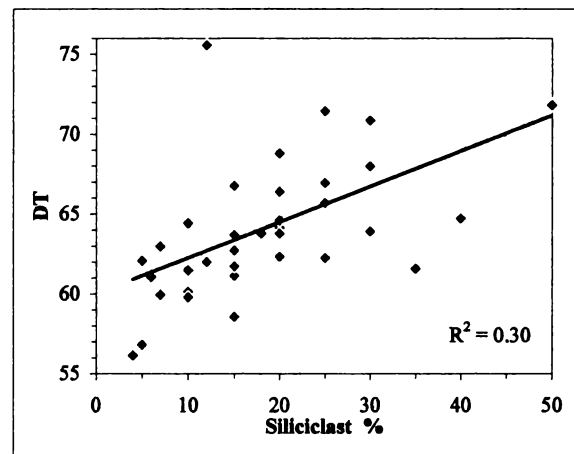
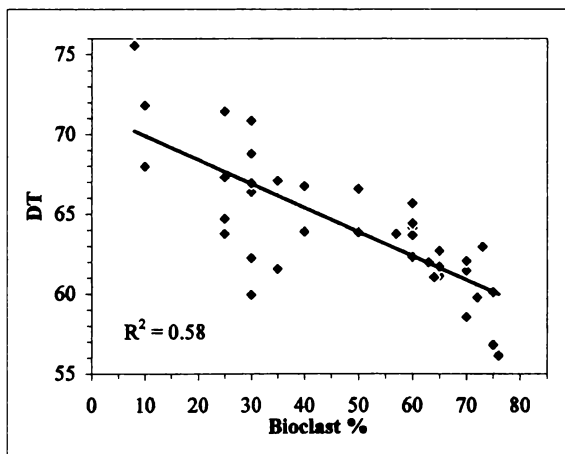
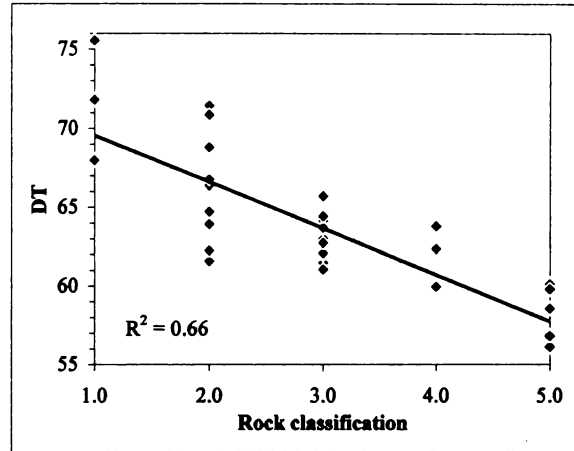
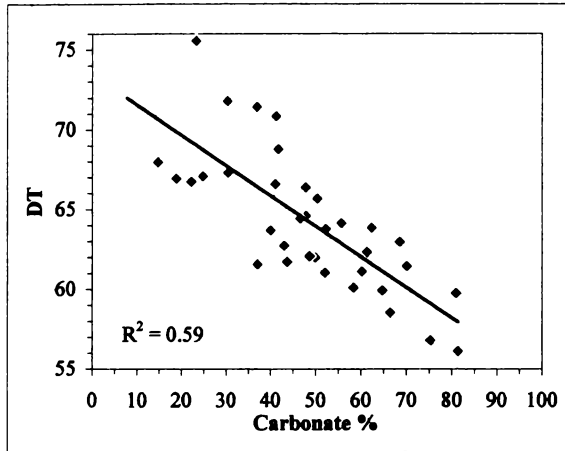


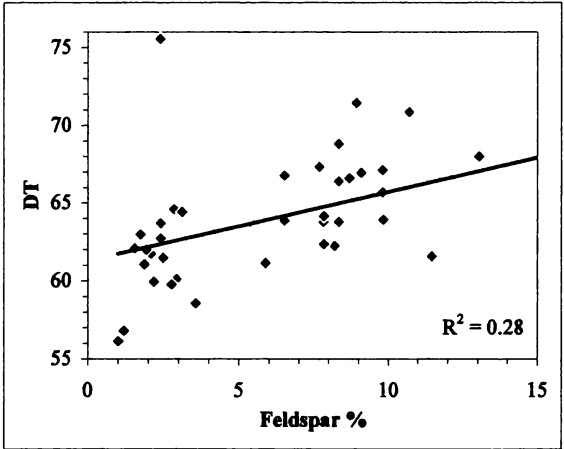
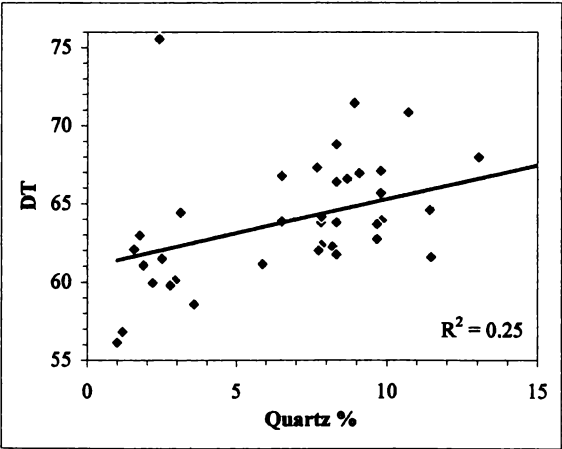
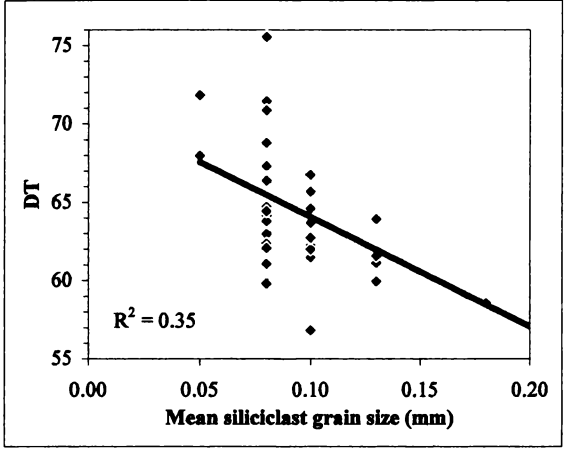
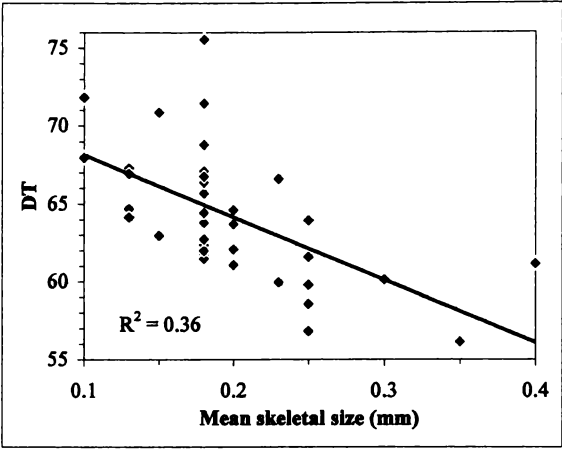
A2.4.8 Hu Rd-1 well stratigraphic log summary.

APPENDIX 2.6

Correlations of carbonate % data and petrographic % data with DT (sonic velocity - $\mu\text{s}/\text{ft}$)

Carbonate % data derived from acid digestion (see Appendix 2.3). For petrographic data see Topic 4. Rock classification follows Dunham (1962). Key: 1 = mudstone; 2 = wackestone; 3 = packstone; 4 = poorly washed grainstone; 5 = sparry grainstone.

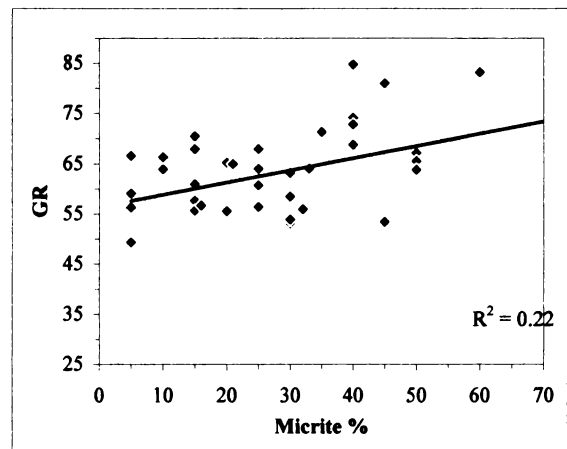
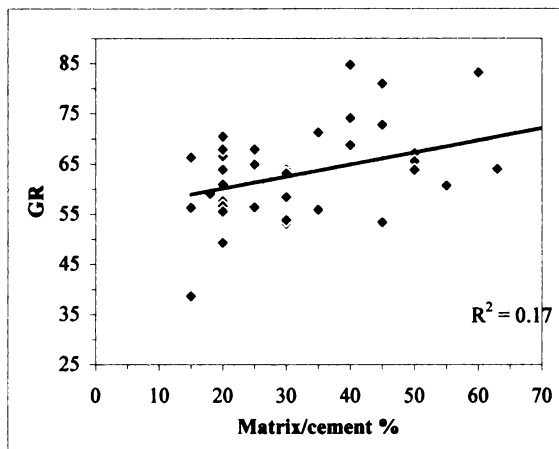
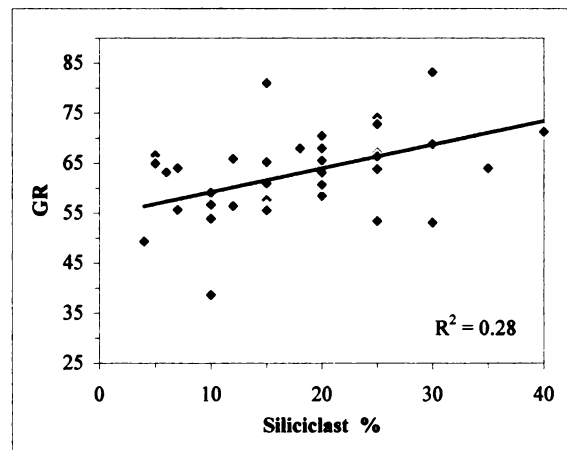
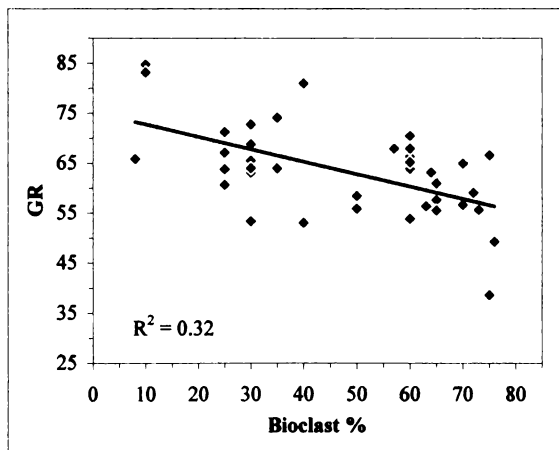
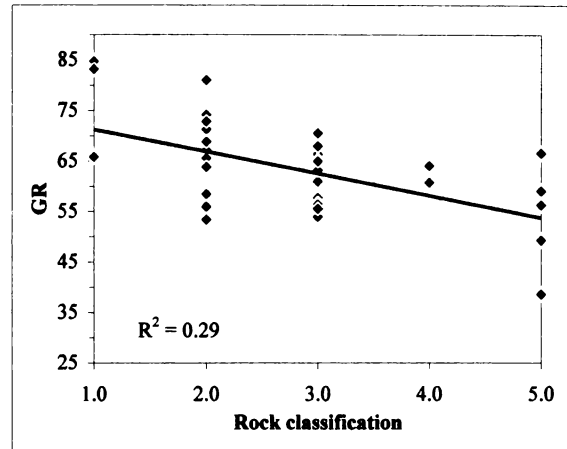
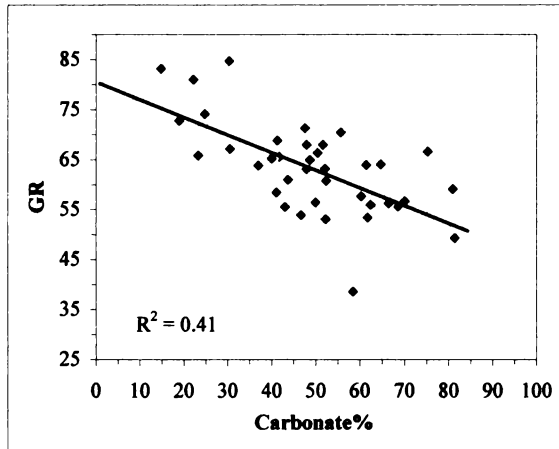


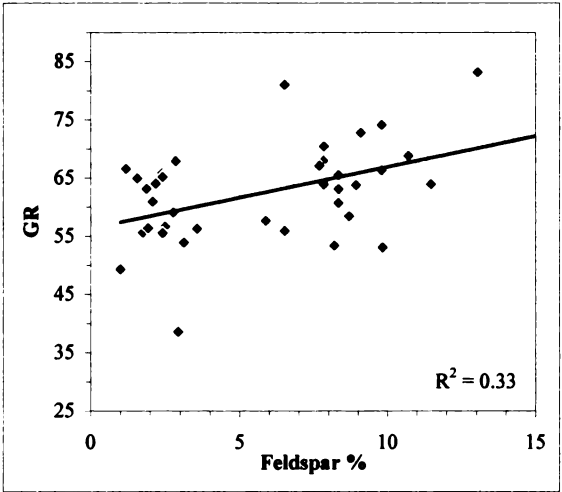
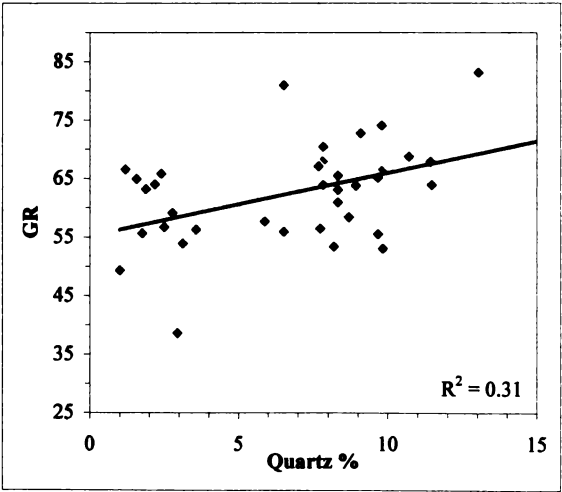
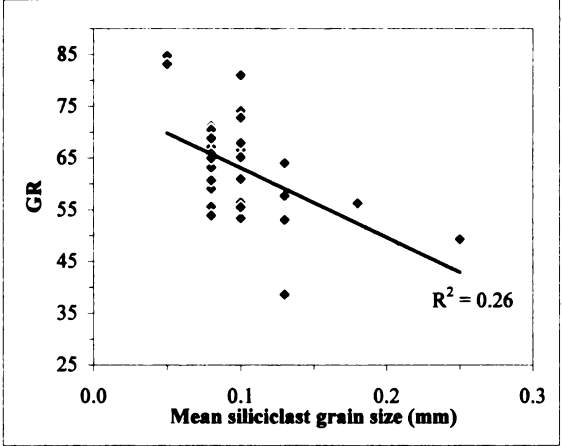
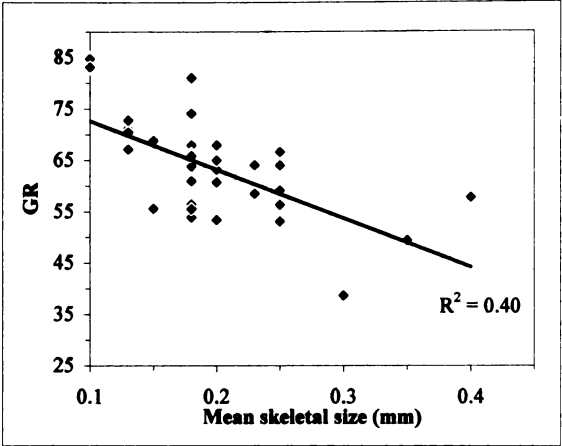


APPENDIX 2.7

Correlations of carbonate % data and petrographic % data with GR (Gamma-ray - GAPI)

Carbonate % data derived from acid digestion (see Appendix 2.3). For petrographic data see Topic 4. Rock classification follows Dunham (1962). Key: 1 = mudstone; 2 = wackestone; 3 = packstone; 4 = poorly washed grainstone; 5 = sparry grainstone.





APPENDIX 2.8

General mudlog descriptions of the Tikorangi and underlying Otaraoa and overlying Taimana Formations

General and brief mudlog descriptions are provided here for the Tikorangi Formation, as well as for both the underlying Otaraoa and overlying Taimana Formations for the eight wells in this study. Wells are listed under each formation from and in order from offshore Maui-1 and from south to north onshore.

The meaning of certain terminology used in the petroleum industry reports sometimes had to be interpreted here. Argillaceous is taken to mean clay (mineral) -rich whereas in well completion reports it appears to simply mean very fine grained (or muddy). The use of the term crystalline is taken to mean sparry or spar cement-rich. Reports also use terms such as calcirudites, calcarenites, or calcilutites to describe rocks that occur along with limestones, when in fact these names are simply different-textured limestones (e.g., NZ Oil & Gas 1992). It is inferred that their use of this terminology refers to calcareous rocks of varying textures.

UNDERLYING OTARAOA FORMATION OR EQUIVALENTS

Maui-1

In Maui-1 the underlying formation equivalent occurs as a dark brown-grey, hard, fissile, calcareous shale with thin siltstone streaks. Below are medium to very fine friable sandstone beds which dominate the sequence (Shell BP Todd 1969).

Hu Rd-1/1A

Base of Tikorangi Formation and therefore underlying formation not penetrated according to the well completion report (NZ Oil & Gas 1992).

Waihapa-5

The upper boundary is distinctive with much higher gamma and sonic values than overlying Tikorangi Limestone. Only the top of the Otaraoa Formation was penetrated where the formation is brown-grey, hard, cryptocrystalline, argillaceous/muddy, silty limestone with traces of glauconite and foraminifera. Contains interbeds of grey to olive grey, soft to firm, massive, silty, calcareous mudstone (Young & Carter 1989).

Waihapa-2

Otaraoa Formation is gradational with the Tikorangi Limestone with limestone lenses gradually decreasing with depth. The upper Otaraoa Formation consists of interbedded limestone and siltstone. The limestone is medium grey to light grey to dark yellow brown, firm to hard, crystalline (sparry) to cryptocrystalline, moderately to very argillaceous/muddy, with common glauconite, which grades to siltstone in part which is light brown, soft to firm, blocky, very calcareous and becomes increasingly argillaceous/muddy with depth (Carter et al. 1988).

Waihapa-6

Only the very top part of the Otaraoa Formation was drilled. Logs show the Otaraoa Formation to be significantly less calcareous than the overlying Tikorangi Limestone. The formation consists of brown to grey, friable to firm, massive, calcareous siltstone (Carter & Kelly 1989b).

Waihapa-4

Otaraoa Formation is less calcareous than overlying Tikorangi Formation, and is composed of siltstone interbedded with and grading to mudstone. The siltstone is generally light to medium olive grey, hard, very calcareous, argillaceous/muddy, and contains abundant disseminated carbonaceous material, and traces of pyrite, glauconite, and foraminifera. The mudstone is firm to hard, very calcareous, olive brown to medium brown-grey with abundant silt and traces of very fine sand, glauconite, and foraminifera (Carter & Kelly 1989a).

Ngaere-2

Calcareous argillaceous/muddy, dark brown, soft to firm siltstone grading into highly calcareous, pale to dark brown, very soft to soft claystone (PEL 1995).

Toko-1

The formation is composed of grey-brown calcareous mudstone interbedded with calcareous siltstone and minor sandy glauconitic limestone (Adams et al. 1980).

TIKORANGI FORMATION

Maui-1

The top of the limestone is hard, dense, light brown to yellowish brown coccolith-foraminifera lime packstone grading into a blue-grey coccolith-foraminifera lime packstone. At depth the formation is generally a light grey to white, hard, generally sparry cemented coccolith-foraminifera lime packstone with increasing amounts of glauconite towards the base (Shell BP Todd 1969).

Hu Rd-1/1A

The Tikorangi is interpreted near the top of the section in Hu Rd-1A to comprise interbedded limestone and calcareous sandstone (rudites to lutites). The limestone is off-white, brittle, contains common fine quartz and is sparry, becoming more muddy throughout the lower sections (NZ Oil & Gas 1992).

Hu Rd-1 becomes more calcareous upwards and from mudlog data has been divided into three zones. A lower zone comprising interbedded calcareous sandstones and claystones; a mid-zone of interbedded limestone and calcareous sandstones; and an upper limestone-dominated zone with some calcareous siltstone. The top of the Tikorangi Limestone at Hu Rd-1 is well defined on electric logs as a sharp increase in resistivity, sonic velocity, and density and a decrease in gamma ray values. Changes interpreted from cuttings are not well expressed in the electric log suite (NZ Oil & Gas 1992). The upper limestone is mottled grey-white, slightly to very sandy, calcite cemented, moderately hard with no porosity, grading in places to calcareous sandstone or siltstone. The lower

section comprises grey to buff crystalline (sparry) to microcrystalline, clean to moderately sandy, fine to coarsely fragmental limestone with traces of glauconite interbedded with calcareous, light to medium grey, fine to very coarse grained, calcareous to very calcareous sandstone with occasional, poorly sorted, larger subrounded grains (NZ Oil & Gas 1992).

Waihapa-5

The Tikorangi Formation is predominantly limestone with interbeds of mudstone and siltstone. The limestone is off-white to medium to light grey to grey/brown and argillaceous/muddy becoming more argillaceous/muddy towards the base with traces of foraminifera, glauconite, and skeletal fragments. Occasional silt and very fine sand occur. The mudstone is grey, blue grey, hard, calcareous and contains occasional silt. The siltstone is light to medium brown-grey, hard, argillaceous/muddy, calcareous, and contains common very fine sand (Young & Carter 1989).

Waihapa-2

Mudlogs show predominantly limestone with thin interbeds of mudstone, siltstone, and sandstone. Upper sections of the limestone are off white/light grey but below it is more olive grey to brown grey brown and varies from moderately to very argillaceous/muddy. The sandstone is fine, moderately to very calcareous, and very argillaceous/muddy with common lithics and traces of glauconite (Carter et al. 1988).

Waihapa-6/6A

Both upper and lower boundaries of the Tikorangi Formation are gradational. The formation consists dominantly above 3174 m of limestone with interbeds of mudstone and rare siltstones with siltstone predominating in the lower sections. The limestone varies from white to olive grey to brown, friable to firm, crystalline (sparry) to cryptocrystalline, non to moderately argillaceous/muddy with trace to common quartz. The mudstone is medium to light grey. Below 3174 m siltstone predominates and is olive-grey, very hard and moderately calcareous (Carter & Kelly 1989b).

Waihapa-4

On logs the upper boundary of the Tikorangi Formation is definite with both low DT and GR values. The lower boundary is harder to pick with the lower calcareous (generally) siltstones merging with the underlying siltstones/mudstones of the Otaraoa Formation. Log correlation with Waihapa-2 is extremely good over the upper part of the formation (Carter & Kelly 1989a).

In the upper formation limestone predominates with minor interbeds of siltstone and mudstone, while in the lower sections siltstone predominates and is interbedded with and grades into mudstone. The limestone is very light grey to grey brown, firm to hard, argillaceous/muddy with traces of shell, glauconite, lithics, and major calcite veins. In places the limestone grades to siltstone and mudstone. The mudstone is light brown-grey, firm to hard, and moderately to very calcareous. Siltstones are medium grey-brown, hard, very calcareous with common lithic fragments (Carter & Kelly 1989a).

Ngaere-2

Crystalline or sparry limestone with minor sandstone and highly calcareous claystone. The limestone is described as a grainstone with a trace of clay and fine quartz lithic sand, with very poor to nil intergranular porosity becoming generally darker with depth with increasing quartz-lithic sand and clay content (PEL 1995). The sandstone is medium grey, soft, very fine to fine, while the claystone is grey, soft, and highly calcareous (PEL 1995).

Toko-1

The upper formation comprises interbedded limestone, calcareous sandstone, and siltstone. Below more massive limestone grades into siltstone and sandstone in lower part. In upper sections the limestone is a cream to light grey brown, fine to coarse grainstone. Grains are angular to subrounded and moderately to poorly sorted, comprising foraminifera and quartz with occasional traces of glauconite. Samples are firm to hard, and crystalline or sparry in part that grades into calcareous sandstone in places. Sandstones are mainly quartz, soft to firm, and calcareous. The lower section consists of a more massive coarse limestone composed of echinoderms and bivalves, angular to subangular, poorly sorted with

minor quartz, glauconite, pyrite, and influxes of volcanic rock fragments which become finer with depth (Adams et al. 1980).

OVERLYING TAIMANA FORMATION OR EQUIVALENTS

Maui-1

The lithology is a well consolidated, dark grey, slightly silty, calcareous mudstone (Shell BP Todd 1969).

Hu Rd-1/1A

The Taimana Formation was not encountered in Hu Rd-1A due to overthrust contact with Mesozoic basement (NZ Oil & Gas 1992) but was encountered in Hu-Rd-1.

Waihapa-5

The lower boundary is gradational with increasing carbonate content with depth towards the Tikorangi Limestone. The Taimana consists mainly of olive grey to brown-grey, soft to firm, calcareous mudstone. It is silty in part and contains occasional sand. Rare light grey, hard, argillaceous/muddy limestone and grey-blue, hard, argillaceous/muddy, calcareous siltstone occur also (Young & Carter 1989).

Waihapa-2

The Taimana Formation is regarded as the gradational unit between mudstones of the Manganui Formation and the limestone of the Tikorangi Formation. The Taimana has a distinctive log character, as carbonate content gradually increases towards the Tikorangi Limestone, sonic values decrease and gamma ray values increase upcore. The Taimana consists of finely interbedded limestone, mudstone, and siltstone. The limestone is off-white to very light grey, firm to moderately hard, cryptocrystalline to crystalline (sparry) limestone with trace to common amounts of quartz grains, and traces of glauconite and pyrite. The mudstone is medium to dark grey, hard, massive to blocky, slightly calcareous and silty in part. The siltstone is olive grey to olive blue, firm to moderately hard, massive to

blocky, very calcareous with traces of lithics, glauconite, and mica (Carter et al. 1988).

Waihapa-6

The Taimana is difficult to recognise on logs. Higher sonic and dual laterolog values are a characteristic with limestone percentages gradually increasing toward the base (gradational boundary with Tikorangi Limestone). The formation consists of predominantly mudstone with interbeds of siltstone and limestone. The limestone is argillaceous/muddy, light brown-grey, soft to firm, and argillaceous and occasionally crystalline (sparry). Siltstones are moderately calcareous and brown-grey in colour (Carter & Kelly 1989b).

Waihapa-4

The Taimana Formation consists of mudstone with minor limestone. The mudstone is medium to dark grey which becomes lighter grey with depth, is firm to hard, moderately calcareous, and moderately to very silty in part. The limestone is green-grey, hard, and contains some fine sand, common glauconite, and rare shell fragments (Carter & Kelly 1989a).

Ngaere-2

Formation consists of highly calcareous, brown, soft to firm, silty clay that grades into calcareous siltstone with minor bioclastic sandy limestone and soft to firm, very fine sandstone (PEL 1995).

Toko-1

The formation consists of predominantly grey-brown soft siltstone with occasional interbeds of sandstone, mudstone, and limestone that becomes firmer with depth (Adams et al. 1980).

APPENDIX 2.9

Discussion of carbonate facies distribution within individual wells

This appendix briefly outlines the distribution of the four carbonate facies identified within the Tikorangi Formation in this study for the eight study wells. Wells are discussed from offshore to onshore south to north.

Maui-1

The base of the Tikorangi interval in Maui-1 is marked by a change upward from the equivalent underlying Facies A of the Otaraoa Formation into Facies B of the Tikorangi Formation. The key feature of Maui-1 is the dominance of very calcareous siliciclastites - Facies B (some 80% of the Tikorangi interval) when compared to the onshore study wells. Thick Facies B units are separated by thin Facies A – calcareous siliciclastites. Given the restriction of only a short core interval, limited samples provide carbonate data in the range of 32-41% consistent with very calcareous calcilutites defined here as having carbonate contents of 25-50%. At no time do carbonate or geophysical correlation data provide evidence for the presence of any carbonate Facies C (>50% carbonate). The top of the Tikorangi interval is marked by a change upwards from Facies B in the uppermost Tikorangi Formation to an overlying Taimana Formation Facies A equivalent.

Hu Rd-1

The basal contact of the underlying Otaraoa Formation with the Tikorangi Formation is marked by a change upward from Facies A to Facies B. The lower section of the Tikorangi comprises a mix of Facies A through to Facies C with Facies C becoming more common upcore. Central sections of the interval are the most carbonate-rich and are Facies D sparry limestones. Carbonate content declines in the upper section to generally 50-75% (Facies C) separated by thin Facies A and B units. The top of the Tikorangi is marked by a change from Facies B of the Tikorangi to Facies A equivalent in the overlying Taimana Formation.

Waihapa-5

The base of the Tikorangi is marked by an abrupt change upward from the Facies A equivalent in the underlying Otaraoa Formation to a Facies C unit 5 m thick. The lowermost section is dominated by Facies B and A before moving upwards into Facies C units which dominate much of the Tikorangi interval. Commonly Facies C is interbedded with thin interbeds of Facies B (less than 5 m thick), with Facies A interbeds becoming more common in the upper formation. Overall 55% of Tikorangi interval in Waihapa-5 comprises Facies C, 15% Facies A, and 30% Facies B. The top of the Tikorangi Formation is marked by a change from Facies B upward into Facies A equivalent in the overlying Taimana Formation.

Waihapa-2

The base of the Tikorangi Formation is marked as in many of the study wells by a change from Facies A equivalent in the underlying Otaraoa Formation upward to Facies B of the Tikorangi Formation. Facies A dominates the lowermost section of the Tikorangi interval before carbonate content increases upward into Facies B then Facies C limestones. Facies C and D limestones dominate the upper two thirds of the Tikorangi interval and are typically >5 to 35 m thick, with interbeds being generally less than 5 m thick. Commonly thick Facies C units are separated by thin Facies B and less commonly Facies A. The top of the Tikorangi Formation in Waihapa-2 is marked by a change from Facies B upward into Facies A of the overlying Taimana Formation. Overall 55% of the Tikorangi Formation in Waihapa-2 comprises Facies C, 30% Facies B, and 15% Facies A.

Waihapa-6

The base of the Tikorangi Formation is marked in Waihapa-6 by a change from Facies A equivalent in the underlying Otaraoa Formation upward into a Facies B unit of the Tikorangi Formation. Facies B dominates the lower section of the Tikorangi interval while Facies C units become most common upcore, commonly separated by single interbeds of Facies A and Facies B units. Facies C units are generally 5 to <15 m thick while interbeds are less than 5 m. The upper Tikorangi interval is dominated by Facies A with unevenly spaced interbeds of Facies B and thin Facies C. Waihapa-6 is the least limestone-like of all the onshore study wells with only some 40% of the interval comprising Facies C, a limestone. Facies A is

slightly higher in occurrence with less than 20% Facies B. The top of the Tikorangi Formation is marked a change from Facies B to Facies A equivalent in the overlying Taimana Formation.

Waihapa-4

The base of the Tikorangi Formation in Waihapa-4 is marked by a change from Facies A equivalent in the underlying Otaraoa Formation upward into Facies B of the Tikorangi interval. The lowermost Tikorangi interval is dominated by Facies A with thin interbeds of B. Facies B becomes more dominant upcore and also sees the introduction of Facies C which dominates the upper 50% of the section. Facies C is interspersed with thin units of Facies B which changes to alternating thin Facies A and thicker Facies C units in the upper section. Facies C units are typically 5-25 m thick with Facies A and B interbeds commonly about 5 m thick. A general trend of increasing carbonate upcore occurs. Some 50% of Waihapa-4 comprises Facies C, 30% Facies B, and 20% Facies A. The top of the Tikorangi Formation is marked by a change upward from Facies B of the Tikorangi into Facies A equivalent in the overlying Taimana Formation.

Ngaere-2

The Tikorangi Formation in the Ngaere-2 well is the most limestone-rich of the onshore study wells with well developed Facies D (sparry) units. The base of the Tikorangi interval is marked by a change from Facies A equivalent of the underlying Otaraoa Formation upward into Facies B of the Tikorangi Formation. The lowermost section of the Tikorangi comprises a series of thin alternating units of Facies B and C before changing upwards into a lower Facies C dominated section. Facies C units are separated by thin interbeds of Facies B (generally less than 4 m thick) occurring roughly at 20 m intervals. With the exception of a thin 2 m Facies A interbed near the top of the Tikorangi all interbeds are Facies B units. A change to Facies D dominance occurs in the upper section which continues to within close proximity of the formation top. The top is marked by a thin Facies B unit after which an upward change into the Facies A equivalent of the overlying Taimana Formation occurs. Facies C and D together form over 80% of the Tikorangi interval in Ngaere-2, with some 10% each of Facies A and B.

Toko-1

The base of the Tikorangi Formation in Toko-1 is marked by a change from Facies A equivalent in the underlying Otaraoa Formation upward into Facies B of the Tikorangi interval. The lower Tikorangi is dominated by Facies A containing interbeds of Facies B generally 5-10 m thick which become more frequent and thicker upcore at the expense of Facies A. Facies C becomes dominant in the mid-section with purer Facies D limestones dominating the mid-upper sections. The top of the Formation is marked by a change upwards from Facies B of the Tikorangi Formation into Facies A equivalent in the overlying Taimana Formation. Toko-1 is dominated by Facies C comprising 50% of the Tikorangi interval with 15% Facies B, and 35% Facies A.

APPENDIX 2.10

Discussion of interpreted whole rock compositions within individual study wells

This appendix discusses briefly the interpreted whole rock compositions for the Tikorangi Formation in the eight wells used in this study. Wells are discussed from offshore to onshore south to north.

Maui-1

The upper contact of the underlying Otaraoa Formation with the base of the Tikorangi Formation is marked by a decrease in micrite/matrix content and a corresponding increase in siliciclastic content. Compositionally Maui-1 is a siliciclastic/micrite/matrix-dominated succession hosting only two major bioclastic-rich units which occur mid-formation. These purer units are some 20 m in thickness with bioclastic contents of up to 45%, otherwise they are commonly less than 10%. The lower section of the Tikorangi interval is marked by decreasing micrite/matrix contents upcore which again become important mid-section and in the uppermost formation. Despite a gradually increasing bioclastic content upcore to the first major bioclastic unit, the siliciclastic component remains high. Siliciclastic contents reach as low as 15% but may be as high as 40%. Matrix contents range from a low of 30% to as high as 65%. Bioclastic content decreases mid-section before increasing in the upper of the two more bioclastic-rich units. Spar cement contents are very low with the exception of the two more calcareous-rich units where maximum values of 5% are reached. The contact of the Tikorangi Formation and overlying Taimana Formation is marked by increased matrix/micrite contents.

Hu Rd-1

The contact of the underlying Otaraoa Formation with the basal Tikorangi Formation is marked by an increase in bioclastic and spar cement content upcore with a corresponding decrease in micrite/matrix content. From near the base of the Tikorangi Formation, an overall increase in bioclastic content occurs which reaches a maximum 3/5 upsection at some 85%. The upper 1/3 section sees an initial decrease then another short increase in bioclastic content. Siliciclastic

contents may be as high as 40% in lower section and less than 5% at its most purest. Micrite/matrix comprises up to 50% in the lower formation and then gradual decreases upcore. This trend is mirrored by a gradual increase in spar cement contents which rise from generally <5% in the lower sections to reach near 15% in the upper sections. Bioclastic-rich units are separated by comparatively thin siliciclastic-rich units, particularly in the lower and upper sections of the formation. The top of the Tikorangi Formation is marked by a dramatic drop in bioclastic content and increased siliciclastic and micrite/matrix components.

Waihapa-5

The base of the Tikorangi Formation is marked by a sharp increase in bioclastic content which rises to 55%, mirrored by a corresponding decrease in matrix and siliciclastic components. Bioclast contents reaches a maximum of 70% in the upper formation before a sharp decline marking the top of the Tikorangi Formation. Thick bioclastic-rich units are separated by thin siliciclastic-rich units in the upper formation. The trend upcore is for siliciclastic contents to drop from 30% in the lower sections to 10% or less in the upper Formation. Matrix shows a similar trend, declining from 50% in lower to 10% in upper sections. Spar cement is present throughout most of the section but generally constitutes less than 10% of the whole rock composition. The contact of the Tikorangi Formation with the overlying Taimana Formation is marked by a decrease in bioclastic content and an increase in matrix/micrite and siliciclastic components.

Waihapa-2

The base of the Tikorangi Formation in Waihapa-2 is marked by an increase in bioclastic and spar cement contents with a corresponding decrease in micrite/matrix and siliciclastic components. The lower formation is dominated by micrite/matrix and siliciclastic components. By mid-formation bioclasts dominate to reach a maximum of some 80% in the limestone units while non-carbonate-rich interbeds typically contains 40-50% bioclastic material. Siliciclastic contents are generally in the range of 5-15% while spar cement forms generally less than 10% of the rock. The top of the Tikorangi interval is marked by a rapidly declining

bioclastic content which is replaced by increasing siliciclastic and micrite/matrix contents.

Waihapa-6

The base of the Tikorangi Formation is marked by an increase in bioclastic content and decrease in the micrite/matrix component. Bioclast contents reach a maximum of 65% in carbonate-rich units and fall to below 20% in carbonate-poor intervals. From just below mid-formation bioclastic contents gradually decline to the top of the Tikorangi Formation. Siliciclastic contents are typically 15-35%, with the siliciclastic component becoming important in the upper sections as bioclastic contents decline. This is a feature uncharacteristic of other more carbonate-rich onshore wells. Micrite/matrix is the dominant component in the upper sections, reaching up to 60%, but may be as low as 10% in the most carbonate-rich limestones that are best developed in the lower to mid section of the formation. Thin siliciclastic-rich units often separate the more carbonate-rich units. Spar cement contents are generally low and reach a maximum of 10% in the purer carbonate-rich sections. The top of the Tikorangi Formation marks a rapid decline in bioclastic content and a change to siliciclastic and micrite/matrix-dominated rocks of the overlying Taimana Formation.

Waihapa-4

The basal section of the Tikorangi Formation is marked by an upward increasing bioclastic content which increases at the expense of reducing siliciclastic and micrite/matrix contents. A low bioclastic interval is encountered between 2805 m and 3005 m before again increasing to reach a maximum post-mid-formation of some 75%. Siliciclastic contents are generally less than 15% in the upper formation and reach highest values of some 20% in the lower sections. Spar cement contents generally range from 5-10% throughout the Tikorangi interval. The upper section is marked by a rapid upward decrease in bioclastic content and increasing siliciclastic and micrite/matrix contents marking the contact with the overlying Taimana Formation.

Ngaere-2

The base of the Tikorangi Formation is marked by an increase in total bioclastic content, although siliciclastic contents do not correspondingly decrease but rather uncharacteristically remain at similar levels until mid-formation. Micrite/matrix dominates the lower formation but declines markedly upcore by mid-formation. The upper Tikorangi Formation exhibits generally lower siliciclastic contents. Spar cement contents are negligible at the base and reach maximum values from mid-formation and generally remain below 15%. Bioclast contents peak at about 80% through the mid- to upper-formation although they can drop to below 40%. The matrix/micrite component ranges from 40% at the base to near 0% in places in the upper carbonate-rich sections. The lower sections remain compositionally more consistent in comparison with the greater fluctuations occurring in the upper sections. The top of the Tikorangi Formation is marked by a dramatic drop in bioclastic content together with large increases in siliciclastic and micrite/matrix contents which mark the contact with the overlying Taimana Formation.

Toko-1

The base of the Tikorangi Formation is marked by a matrix- dominated unit with a very low bioclastic content, after which a gradual increase in bioclastic content occurs upcore punctuated by less bioclastic-rich interbeds. Bioclastic contents reach a maximum 2/3 up section at some 85%. The bioclastic component then steeply decreases before another influx of bioclastic material occurs. A sharp drop to near 0% bioclasts occurs near the top of the formation before a final thin bioclastic-rich unit marks the upper boundary. Siliciclastic contents near the base average some 30% which decrease to less than 5% over short (5m) intervals where limestones are very pure. Matrix contents decreases from 60% near the base to near 0% at most carbonate-rich. Spar cement contents increase markedly by mid-section to reach a maximum of 15% but generally remain at less than 10%. The base of the overlying Taimana Formation is marked by large increases in siliciclastic and micrite/matrix contents.

APPENDIX 3.1

Individual well geophysical log descriptions

Wells are discussed from offshore to onshore south to north.

Toko-1

The sedimentation pattern in the basal section of Toko-1 depicts an upward decelerating cleaning-upward bow-trend which changes into a slight dirtying-upward retrogradational trend in the lower-mid Tikorangi Formation. Mid-formation a step down in GR results in a change to a aggradational sequence comprising thick carbonate units separated a much thinner mudstones. Some of the major carbonate units exhibit a hacksaw geometry and may indicate a mass emplacement origin. The upper Tikorangi log response shows a change to a dirtying upwards sequence.

Ngaere-2

The lower Tikorangi Formation displays a dirtying upward or retrogradational trend which becomes more aggradational mid-formation with a number interbedded thicker carbonates separated by thinner mudstone units. This then changes into a cleaning upward or progradational sequence which contain thick barrel perhaps mass-emplaced carbonate units separated by sonic spikes indicative of pauses in resedimentation events and continued background sedimentation. A dirtying up sequence begins just before the top of the Tikorangi formation.

Waihapa-4

A similar sedimentation pattern can be seen in Waihapa-4 as occurs in Ngaere-2 with the base of the Tikorangi displaying a cleaning upwards trend which once established in the more carbonate rich facies becomes a decelerating progradational dirtying up sequence which at about two-thirds up formation gradually changes into a retrogradational cleaning upward sequence. Some of the upper carbonate units are well developed with barrel like appearances on GR and

may be indicative of mass emplacement. Carbonate units appear to thin nearer the formation top while some may exhibit a hacksaw appearance.

Waihapa-2

Waihapa-2 shows a very similar pattern of sedimentation to that of Waihapa-5 although a short lived cleaning-upward trend in the top of the underlying Otaraoa Formation occurs before entering the Tikorangi formation. This may be a result of perhaps an early established carbonate supply source. The Tikorangi base is marked by a dirtying-upward-trend followed by a cleaning-upward interval not seen in Waihapa-5 before returning to general retrogradational pattern. This sequence, as occurs in Waihapa-5, is overlain by a progradational sequence which becomes more aggradational near the top with increasingly thicker carbonate units.

Waihapa-6

The pattern of sedimentation shown by Waihapa-6 is less definitive. The lower retrogradational sequence is not so well defined and comprises a stacked aggradational sequence of carbonates separated by thinner siliciclastic units. Many of these carbonates have a barrel type appearance on GR and may be indicative of mass emplaced turbidite-type deposits. There is a slight dirtying-upward trend which may be indicative of a retrogradational sequence. However the top of the Tikorangi as ascertained in this study sees an obvious change to a progradational cleaning up sequence and may mark the position of the maximum flooding surface. In what this study considers to be lower Taimana Formation (justified by the high gamma ray and low carbonate) a decelerating increase in GR marks the potential maximum progradation surface.

Waihapa-5

Upwards of the base of the Tikorangi an initial dirtying upwards parasequence set contains three small scale dirtying up trends. This lower sequence ends with a step down in GR to the start of a more prolonged dirtying upward sequence. This implies a decrease in grain size associated with a decrease in energy which is thought to be associated with the accelerating subsidence and significant deepening of the foreland basin. This retrogradational trend/geometry occurs

when the sediment supply is less than the rate of creation of accommodation volume resulting in facies belts migrating landward. This trend can in other circumstances be associated with a change from carbonate to clastic sedimentation which is clearly not the case with carbonate sedimentation in its peak at this time in Taranaki Basin history. This trend can also be associated with a thinning in carbonate rich beds changing to a more shaley dominance. This could represent the waning of a mixed carbonate-siliciclastic submarine fan depositional system. This retrogradational sequence reaches its GR maximum some 2/3 up the Formation possibly marking the maximum flooding surface.

A cleaning-upwards sequence follows and is associated with the beginning of a progradational sequence now that sediment supply exceeds that of accommodation volume. This is usually associated with an increase in energy and grain size (decrease in clay mineral content) and progradation of the depositional system associated with regression but is more likely to be the result of removal of the siliciclastic source to the west with the transgression at its maxima. Cleaner carbonates may represent the peak of carbonate production during a period of minimal siliciclastic input. The maximum progradational surface is marked by a gamma ray minimum which occurs near the top of the Tikorangi. After this point increasing siliciclastic input saw the demise of carbonate production. This progradational sequence is marked by a number of small scale cleaning upwards parasequences which may relate to the increase in thickness of carbonate beds verses thinning of more siliciclastic rich beds with carbonate factory in the peak of production. Units may be indicative of mass emplacement with fine siliciclastic background sedimentation units separated by influxes of coarser carbonate material. In the upper section a couple of major sonic spikes which may represent pauses in or switching off periods of submarine fan deposition contain an abundance of planktic forams and are more shale like units. This progradation changes to an aggradational type geometry when sediment supply and rate of creation of accommodation volume are roughly balanced with a more vertical stack of these bedded carbonate and siltstone/mudstone units. Once established in the Taimana Formation, logs indicate a general retrogradational pattern indicative of influx of clay rich siliciclastic material associated with uplift along the Taranaki and Alpine Faults.

Hu Rd-1

Hu Rd-1 shows a very contradictory pattern of sedimentation to that of the other onshore wells. A clear cleaning upward or progradational sequence is seen to occur upwards to more than 2/3 up the formation after which a switch to a more aggradational or slight dirtying upwards sequence occurs. There appears to be some very thick mass-emplaced carbonate units in the upper midsection which decrease in the upper section accounting perhaps for a increase in the thickness of mudstone interbeds causing the decreasing trend in GR. This major progradational trend over much of the formation may be due to a dwindling siliciclastic supply or local progradation associated with a bryozoan mound type deposit formed on a basement high away from the influence of the general subsidence associated with the foreland basin.

Maui-1

The upper Kapuni group shows an decelerating dirtying upwards trend implying decreasing shale rich facies to the base of the Tikorangi marking a dropping off in siliciclastic supply. The base of the Tikorangi sees a general change to an overall cleaning upward stacked parasequences set which comprises four cyclic parasequences with a general decline in siliciclastic supply and a change from siliciclastic to carbonate dominated sedimentation. A basal dirtying up trend could represent a decrease in coarser more sandier beds, followed by a cleaning up a waning in siliciclastic supply and a thickening of coarser more sandy units, followed by a slight dirtying up, may be box ca and final another cleaning up cycle. Two thirds up the Formation a major change to another dirtying up parasequence set. Initially this is an decelerating trend followed by a further more lineal dirtying up trend marking the renew supply of siliciclastic sediment which once established ends the formation of the carbonate dominated Tikorangi into the base of the Mahoenui Fm equivalent.

APPENDIX 4.1

Key to petrographic data sheets

ABUNDANCE (as % of whole rock composition)

R = rare	<1%
S = some	1-5%
M = many	5-15%
C = common	15-25%
VC = very common	25-50%
A = abundant	50-75%
VA = very abundant	>75%

SHAPE

Calclasts

SA = slightly abraded
MA = moderately abraded
A = abraded
VA = very abraded

Siliciclasts

A = angular
SA = subangular
SR = subrounded
R = rounded

SORTING (in relation to visible grain sizes)

P = poorly sorted
PM = poorly to moderately sorted
M = moderately sorted
MW = moderately to well sorted
W = well sorted
VW = very well sorted

ABBREVIATIONS

ARA = formerly aragonitic (either bivalves/gastropods) locally important
SPIN = echinoderm spines locally important
FRA = unidentified skeletal fragments/debris locally important
SPO = siliceous sponge debris locally important
SPI = spicules locally important
SER = serpulids locally important
BRA = brachiopods locally important
OST = ostracods locally important

Well		H	H	H	H	H		K	K	K		M	M
Core number		U	U	U	U	U		1	2	3		A	A
		2	2	2	2	2						U	U
Box number		1A	3	4	6A	7						1	2
C a l c i c l a s s	Total bioclast %	85	82	87	66	90		10	20	15		25	25
	Bryozoans	C	C	VC	M	VC		-	-	-		-	-
	Bivalves	S	S	S	S	S		-	R	R		-	-
	Echinoderms	S	M	M	M	M		-	-	-		-	-
	Benthic foraminifera	S	S	S	M	C		-	R	-		-	-
	Planktic foraminifera	R	S	-	-	-		M	C	M		C	C
	Gastropods	-	-	-	-	-		-	-	-		-	-
	Calcareous algae	M	S	M	S	C		-	-	-		-	-
	Barnacles	C	VC	S	C	C		-	-	-		-	-
	Spicules & spines	-	-	-	-	-		R	-	-		-	-
	Others	R	R	R	R	R		R	-	R		R	R
	Maximum size (mm)	2.50	3.00	2.25	2.00	3.00		0.20	0.50	0.50		0.50	0.50
	Mean size (mm)	1.50	0.80	0.75	1.25	1.50		0.20	0.20	0.20		0.20	0.20
	Shape	MA	MA	MA	MA	MA		MA	MA	A		SA	SA
S i l i c i c l a s s	Sorting	PM	MW	MW	MW	MW		VW	W	W		VW	VW
	Intraclast %	-	-	-	-	-		-	-	-		-	-
	Terrigenous grain %	10	12	2	30	5		3	5	5		1	1
	Quartz	S	S	R	M	S		-	R	R		R	R
	Feldspar	S	R	R	M	R		-	-	-		-	-
	VRFs	M	S	R	R	S		-	-	-		-	-
	SRFs	S	S	R	M	R		-	-	-		-	-
	Micas	-	-	-	-	-		-	-	-		-	-
	Pyrite grains	R	R	R	R	R		S	S	S		R	R
	Pyrite infills	-	-	-	-	-		-	S	-		-	-
	Glauconite pellets	R	-	R	R	R		-	-	S		-	-
	Glauconite infills	R	-	S	-	S		-	-	-		-	-
	Maximum size (mm)	1.50	1.50	0.50	12	1.25		-	0.07	0.25		0.03	0.03
	Mean size (mm)	0.75	0.50	0.50	0.25	1.00		-	0.07	0.20		0.03	0.03
	Shape	SR	SR-R	SR	SR	SR-R		-	SR	R		SR	SR
	Sorting	M	W	W	PM	W		-	VW	W		VW	VW
	Matrix-cement %	5	5	10	4	5		87	75	80		74	74
	Spar cement %	4	4	7	2	4		-	-	-		-	-
	Micrite %	1	1	3	2	1		87	75	80		74	74
	Pore Space %	-	1	1	-	-		-	-	-		-	-

Well		M	M		N	N		S		T	T	T	
Core number		A	A		T	T		1		O	O	O	
Box number		U	U		1	2				K	K	K	
		3	4							1	2	3	
C a l c i c l a s t	Total bioclast %	30			40	Q		20		40	45	45	
	Bryozoans	-			M	U		S		-	-	-	
	Bivalves	-			R	A		-		S	S	S	
	Echinoderms	-			M	R		-		-	S	-	
	Benthic foraminifera	-			S	T		-		S	M	S	
	Planktic foraminifera	VC			-	Z		-		M	S	M	
	Gastropods	-			-			-		-	-	-	
	Calcareous algae	-			-	S		-		-	-	-	
	Barnacles	-			-	A		-		-	-	-	
	Spicules & spines	-			-	N		-		-	-	-	
	Others	R			M	D		M		VC	VC	VC	
						S							
	Maximum size (mm)	0.50			1.50	T				1.75	13	2.00	
	Mean size (mm)	0.20			1.00	O				0.25	0.15	0.20	
	Shape	SA			MA	N				VA	VA	VA	
S i l i c l a s t	Sorting	VW			M	E				MW	MW	MW	
	Intraclast %	-			-					-	-	-	
	Terrigenous grain %	1			25			40		20	20	20	
	Quartz	R			C			VC		M	M	M	
	Feldspar	-			S			M		M	M	M	
	VRFs	-			-			-		-	-	-	
	SRFs	-			R			-		-	-	-	
	Micas	-			-			-		-	-	-	
	Pyrite grains	R			R			S		S	S	S	
	Pyrite infills	-			-			-		S	S	S	
	Glaucinite pellets	-			R			R		R	S	R	
	Glaucinite infills	-			R			-		-	-	-	
	Maximum size (mm)	0.03			0.60			0.50		0.13	0.15	0.14	
	Mean size (mm)	0.30			0.25			0.25		0.13	0.10	0.14	
	Shape	SR			SR			SR		SA	SR	SA	
	Sorting	VW			MW			W		VW	W	VW	
	Matrix-cement %	69			35			40		40	35	40	
	Spar cement %	-			-			-		20	20	20	
	Micrite %	69			35			40		20	15	20	
	Pore Space %	-			-			-		-	-	-	

Well		W 2	W 2	W 2	W 2	W 2	W 2	W 2	W 2	W 2	W 2	W 2	W 2
Core number		.	.	.	.	.	.	.	.	.	.	.	.
Box number		1	1	1	1	1	2	2	2	2	2	2	2
		.	.	.	.	.	.	.	.	.	.	.	.
		1	5	6	6A	7	1	3	5	6	7A	7B	7C
C a l c i c l a s t s	Total bioclast %	70	20	80	65	80		76				75	76
	Bryozoans	-	-	R	R	-		R				-	-
	Bivalves	M	S	C	C	VC		VC				C	C
	Echinoderms	S	-	S	S	S		C				R	S
	Benthic foraminifera	S	R	M	M	M		S				S	S
	Planktic foraminifera	VC	M	C	VC	C		VC				VC	VC
	Gastropods	-	-	R	R	-		-				-	-
	Calcareous algae	-	-	-	-	-		-				-	-
	Barnacles	-	-	-	-	-		-				-	-
	Spicules & spines	M	S	S	S	S		S				R	R
	Others	R	R	R	-	-		R				-	-
	Maximum size (mm)	1.75	0.50	1.75	2.50	0.75		5.00				0.75	3.00
	Mean size (mm)	0.50	0.10	0.30	0.37	0.37		0.35				0.25	0.20
	Shape	MA	MA	MA	MA	MA		MA				MA	MA
	Sorting	MW	MW	M	MW	MW		PM				MW	MW
	Intraclast %	-	-	-	-	-		-				-	-
S i l i c i c l a s t s	Terrigenous grain %	5	25	7	5	5		4				5	4
	Quartz	S	M	S	S	S		S				S	S
	Feldspar	S	S	S	S	S		S				S	S
	VRFs	-	-	-	-	-		-				-	-
	SRFs	-	-	-	-	-		-				-	-
	Micas	-	-	-	-	-		-				-	-
	Pyrite grains	S	M	S	S	S		S				S	S
	Pyrite infills	S	-	S	S	S		S				S	S
	Glauconite pellets	R	R	R	R	R		S				R	R
	Glauconite infills	R	-	-	-	-		-				-	-
	Maximum size (mm)	0.13	0.30	0.30	0.30	0.25		0.25				0.25	0.25
	Mean size (mm)	0.13	0.25	0.25	0.25	0.20		0.25				0.25	0.25
	Shape	SA	SR	SR	SA	SR		SR				SA	SA
	Sorting	VW	W	W	VW	VW		VW				VW	VW
	Matrix-cement %	25	55	13	20	15		20				20	20
	Spar cement %	10	-	6	13	5		15				5	5
	Micrite %	15	55	6	7	10		5				15	15
	Pore Space %	-	-	-	-	-		-				-	-

Well		W	W	W	W	W	W	W	W	W	W	W	W
Core number		2	2	2	2	2	2	2	2	2	2	2	2
Box number		2	2	3	3	3	3	4	4	4	4	4	5
		9	11	1	2	4	7	1	5	6	10A	11C	1
C a l c i c l a s t	Total bioclast %		65	70	45	55	70	45	35	50	50	40	30
	Bryozoans		-	-	-	-	-	-	-	-	-	-	-
	Bivalves		VC	M	S	M	C	M	S	M	M	C	M
	Echinoderms		C	C	S	S	S	C	M	M	M	M	S
	Benthic foraminifera		M	C	M	M	M	S	M	M	M	S	S
	Planktic foraminifera		C	C	C	C	VC	C	C	M	M	M	M
	Gastropods		R	-	-	-	-	-	-	-	-	-	-
	Calcareous algae		-	-	-	-	-	-	-	-	-	-	-
	Barnacles		-	-	-	-	-	-	-	-	-	-	-
	Spicules & spines		S	M	S	S	S	C	M	M	S	S	S
	Others		-	R	-	-	-	-	-	-	-	-	-
			ARA	SPI									
	Maximum size (mm)		14	2.50	1.75	1.75	1.00	9.00	2.00	1.50	2.50	2.50	0.50
	Mean size (mm)		0.40	0.25	0.15	0.25	0.25	0.30	0.25	0.20	0.25	0.13	0.13
	Shape		A	A	A	A	A	A	A	A	A	A	A
Sorting		P	P	PM	PM	W	P	W	W	MW	M	W	
Intraclast %		-	-	-	-	-	-	-	-	-	-	-	
S i l i c l a s t	Terrigenous grain %		15	10	25	15	5	25	35	20	15	25	25
	Quartz		M	M	M	M	S	M	M	M	M	M	M
	Feldspar		M	S	M	M	S	M	M	M	M	M	M
	VRFs		R	-	-	-	-	-	-	-	-	-	-
	SRFs		-	-	-	R	-	-	-	-	-	-	-
	Micas		-	-	-	-	-	-	-	-	-	-	-
	Pyrite grains		S	S	M	S	M	M	M	M	S	S	M
	Pyrite infills		S	S	S	S	M	S	S	S	S	S	S
	Glaucinite pellets		S	S	R	R	S	R	R	R	R	R	R
	Glaucinite infills		-	-	-	-	-	-	-	-	-	-	-
	Maximum size (mm)		0.70	0.20	0	0.75	0.13	0.10	0.25	0.13	0.10	0.25	0.20
	Mean size (mm)		0.13	0.13	0.13	0.13	0.13	0.10	0.13	0.13	0.10	0.13	0.08
	Shape		SA	SA	SA	SA	SA	SA	SA	SA	SA	SA	SA
	Sorting		MW	VW	VW	MW	VW	VW	VW	VW	VW	W	MW
	Matrix-cement %		20	20	30	30	25	30	30	30	35	35	45
	Spar cement %		5	5	5	5	5	5	5	3	3	3	-
	Micrite %		15	15	25	25	20	25	25	27	32	32	45
	Pore Space %		-	-	-	-	-	-	-	-	-	-	-

Well		W	W	W	W	W	W	W	W	W	W	W	W
Core number		2	2	2	2	2	2	2	2	2	2	2	2
Box number		5	6	7	7	7	8	8	8	9	9	9	9
		.	.	.	.	.	.	.	.	.	.	.	.
		2	2	1	2	4	1A	1B	2	1	6B	9	12B
C a l c i c l a s s	Total bioclast %	30	40	15	25	30	40	45	30	60	45	20	40
	Bryozoans	-	-	-	-	-	-	-	-	-	-	-	-
	Bivalves	S	M	S	M	M	M	M	M	C	S	S	S
	Echinoderms	S	C	M	S	S	S	M	M	S	S	S	S
	Benthic foraminifera	S	S	S	S	S	M	S	S	S	M	S	S
	Planktic foraminifera	M	M	S	M	S	M	S	S	C	M	S	M
	Gastropods	-	-	-	-	-	-	R	-	-	-	-	-
	Calcareous algae	-	-	-	-	-	-	-	-	-	-	-	-
	Barnacles	-	-	-	-	-	-	-	-	-	-	-	-
	Spicules & spines	S	S	S	R	S	M	S	S	S	M	S	M
	Others	-	-	-	-	-	-	M	-	-	-	S	-
								FRA				FRA	
	Maximum size (mm)	1.00	3.00	0.50	0.30	1.00	1.00	2.50	0.25	0.75	2.50	0.50	0.50
	Mean size (mm)	0.20	0.25	0.20	0.13	0.20	0.20	0.18	0.20	0.18	0.18	0.18	0.18
	Shape	A	A	A	A	A	A	A	A	A	A	A	A
S i l i c i c l a s s	Sorting	W	MW	MW	MW	W	W	M	VW	W	MW	MV	W
	Intraclast %	-	-	-	-	-	-		-	-	-	-	-
								SPO					
	Terrigenous grain %	30	30	45	25	25	30	30	30	15	15	40	20
	Quartz	M	M	C	M	M	M	M	M	M	M	C	M
	Feldspar	M	M	M	M	M	M	M	M	M	M	C	M
	VRFs	-	-	-	-	-	-	-	-	-	-	-	-
	SRFs	-	-	-	-	-	-	-	-	-	-	-	-
	Micas	-	-	-	-	-	-	-	-	-	-	-	-
	Pyrite grains	S	M	M	M	M	S	S	S	S	S	S	S
	Pyrite infills	S	S	S	S	S	S	S	S	S	S	S	S
	Glauconite pellets	R	R	R	R	R	R	R	R	R	R	R	R
	Glauconite infills	-	-	-	-	-	-	-	-	-	-	-	-
	Maximum size (mm)	0.20	0.20	0.10	0.10	0.12	0.10	0.13	0.10	0.10	0.15	0.10	0.10
	Mean size (mm)	0.13	0.13	0.07	0.07	0.10	0.10	0.13	0.07	0.07	0.07	0.07	0.08
	Shape	SA	SA	SA	SA	SA	SA	SA	SA	SA	SA	SA	SA
	Sorting	W	W	W	W	VW	VW	VW	VW	VW	VW	VW	VW
	Matrix-cement %	40	30	40	50	45	30	25	40	25	40	40	40
	Spar cement %	-	-	-	-	-	-	-	-	-	12	-	-
	Micrite %	40	30	40	50	45	30	25	40	25	28	40	40
	Pore Space %	-	-	-	-	-	-	-	-	-	-	-	-

Well		W 4	W 4	W 4	W 4	W 4	W 4	W 4	W 4	W 4	W 4	W 4	W 4
Core number		.	.	.	.	.	.	.	.	.	.	.	.
Box number		1	1	1	1	1	1	1	2	2	3	3	3
		.	.	.	.	.	.	.	.	.	.	.	.
		1	4	5	7	7A	8	10	2	4	3	9	13
C a l c i c l a s s	Total bioclast %	70	80	78	81	79	80	73	63	65	76	78	25
	Bryozoans	-	-	R	-	-	-	-	-	-	-	R	-
	Bivalves	C	C	C	C	M	VC	C	C	C	C	VC	M
	Echinoderms	VC	VC	VC	VC	VC	M	M	M	M	C	M	S
	Benthic foraminifera	S	S	S	S	S	S	S	S	S	M	S	S
	Planktic foraminifera	C	S	C	C	C	C	VC	VC	VC	C	C	M
	Gastropods	-	-	-	-	-	-	-	-	-	-	-	-
	Calcareous algae	-	-	-	-	-	-	-	-	-	-	-	-
	Barnacles	-	-	-	-	-	-	-	-	-	-	-	-
	Spicules & spines	S	C	S	M	S	S	M	M	M	S	S	S
	Others	-	-		-	-	-	-	-	-	-	-	-
			SPI										
	Maximum size (mm)	0.50	30	2.50	1.50	5.00	0.60	2.00	1.25	2.50	0.75	1.60	0.50
	Mean size (mm)	0.25	0.30	0.30	0.25	0.30	0.18	0.20	0.20	0.20	0.18	0.18	0.20
	Shape	MA	A	A	A	A	A	A	A	A	A	A	A
	Sorting	W	P	MW	W	M	W	MW	MW	MW	W	MW	W
	Intraclast %	-	-	-	-	-	-	-	-	-	-	-	-
S i l i c l a s s	Terrigenous grain %	10	5	7	7	6	5	2	7	10	4	7	25
	Quartz	S	S	S	S	S	S	S	S	S	S	S	M
	Feldspar	S	S	S	S	S	S	R	S	S	S	S	M
	VRFs	-	-	-	-	-	-	-	-	-	-	-	-
	SRFs	-	-	-	-	-	-	-	-	-	-	-	-
	Micas	-	-	-	-	-	-	-	-	-	-	-	-
	Pyrite grains	S	S	S	S	S	S	S	S	S	S	S	M
	Pyrite infills	R	R	S	S	S	S	R	S	S	R	S	S
	Glauconite pellets	S	R	R	S	S	R	R	R	R	R	R	R
	Glauconite infills	-	-	-	-	-	-	-	-	-	-	-	-
	Maximum size (mm)	0.20	0.13	0.13	0	0.18	0.20	0.10	0.20	0.20	0.10	0.10	0.10
	Mean size (mm)	0.08	0.13	0.13	0.10	0.10	0.10	0.10	0.08	0.08	0.08	0.08	0.08
	Shape	SR	SR	SR	SA	SA	SA	SA	SA	SA	SA	SA	SR
Sorting	VW	VW	VW	VW	VW	VW	VW	VW	VW	VW	VW	VW	
	Matrix-cement %	20	15	15	12	15	15	25	30	25	20	15	50
	Spar cement %	-	8	10	6	9	5	20	10	5	10	5	5
	Micrite %	20	7	5	6	6	10	5	20	20	10	10	45
	Pore Space %	-	-	-	-	-	-	-	-	-	-	-	-

Well		W 4	W 4	W 4	W 4	W 4	W 4	W 4	W 4	W 4	W 4	W 4	W 4
Core number		.	.	.	.	.	.	.	.	.	.	.	.
Box number		3	3	4	4	4	4	4	4	4	4	5	5
.		.	.	.	.	.	.	.	.	.	.	.	.
		14	20	1A	2A	3	5	8	10A	10B	11A	1B	2
C a l c i c l a s s	Total bioclast %	77	65	60	65	25	35	62	40	75	60	45	43
	Bryozoans	S	R	R	-	-	-	-	-	-	R	-	-
	Bivalves	VC	C	S	C	-	C	VC	S	C	M	R	R
	Echinoderms	C	M	M	M	-	M	C	S	VC	VC	C	C
	Benthic foraminifera	S	M	S	M	R	S	S	M	M	M	S	S
	Planktic foraminifera	C	C	M	VC	S	M	S	M	S	R	R	R
	Gastropods	-	-	-	-	-	-	-	-	-	-	-	-
	Calcareous algae	-	-	-	-	-	-	-	-	-	-	-	-
	Barnacles	-	R	-	-	-	-	-	-	-	-	-	-
	Spicules & spines	S	R	S	M	R	S	M	R	R	S	R	S
	Others	-	-	C	-	M	-	-	-	-	-	M	-
				FRA		FRA						FRA	
	Maximum size (mm)	0.38	25	0.43	1.50	0.38	0.63	1.25	0.75	1.00	2.00	1.00	1.25
	Mean size (mm)	0.25	0.18	0.13	0.25	0.18	0.20	0.20	0.20	0.18	0.15	0.25	0.20
	Shape	A	A	A	A	A	A	A	A	A	A	A	A
Sorting	VW	P	W	W	VW	W	W	W	M	M	W	W	
Intraclast %	-	-	-	-	-	-	3	-	-	-	-	-	
S i l i c l a s s	Terrigenous grain %	3	20	20	5	35	25	20	20	5	20	40	45
	Quartz	S	M	M	S	C	M	M	M	S	S	M	M
	Feldspar	S	M	M	S	M	M	M	M	S	S	M	M
	VRFs	-	-	-	-	-	-	-	-	-	S	M	M
	SRFs	-	-	-	-	-	-	-	-	-	-	-	-
	Micas	-	-	-	-	-	-	-	-	-	-	-	-
	Pyrite grains	S	S	S	S	S	S	S	S	S	S	S	S
	Pyrite infills	R	S	S	S	S	S	S	S	S	S	S	R
	Glaucinite pellets	R	S	R	R	-	-	-	-	-	R	R	R
	Glaucinite infills	-	-	-	-	-	-	-	-	-	-	-	-
	Maximum size (mm)	0.13	0.18	0.18	0.13	0.15	0.13	0.13	0.13	0.20	0.20	0.30	0.20
Mean size (mm)	0.08	0.08	0.10	0.08	0.05	0.08	0.08	0.08	0.13	0.13	0.13	0.13	
Shape	SA	SA	SA	SA	SA	SA	SA	SA	SA	SA	SA	SA	
Sorting	VW	VW	VW	VW	VW	VW	VW	VW	VW	VW	VW	VW	
	Matrix-cement %	20	15	20	30	40	40	15	40	20	20	15	12
	Spar cement %	15	5	5	10	-	-	-	-	15	15	5	5
	Micrite %	5	10	15	20	40	40	15	40	5	5	10	7
	Pore Space %	-	-	-	-	-	-	-	-	-	-	-	-

Well		W	W	W	W	W	W	W	W	W		W	W
Core number		4	4	4	4	4	4	4	4	4		5	5
Box number		6	6	6	6	6	6	7	7	8		1	1
		1	3	?	9	13	14	2B	4C	2		2	3
C a l c i c l a s t	Total bioclast %	15	69	75	55	45	65	65	65	30		73	70
	Bryozoans	-	S	R	-	R	-	-	-	-		-	-
	Bivalves	-	C	C	M	M	C	S	S	M		C	C
	Echinoderms	S	C	VC	C	M	C	M	M	S		C	C
	Benthic foraminifera	M	M	S	S	M	C	M	S	S		S	S
	Planktic foraminifera	M	S	S	S	M	S	S	M	S		M	M
	Gastropods	R	-	-	-	-	-	-	-	R		-	-
	Calcareous algae	-	-	-	-	-	-	-	-	-		-	-
	Barnacles	-	-	-	-	-	-	-	-	-		-	-
	Spicules & spines	R	S	R	R	R	R	S	M	S		M	S
	Others	-	-	-	-	-	M	M	M	M		C	M
				SER			FRA	FRA	FRA	FRA		FRA	FRA
	Maximum size (mm)	2.00	0.60	1.25	2.50	2.00	1.00	0.50	0.50	1.50		1.50	1.25
	Mean size (mm)	0.13	0.20	0.30	0.13	0.13	0.20	0.18	0.18	0.15		0.15	0.18
	Shape	A	A	A	A	A	A	A	A	A		A	A
	Sorting	MW	VW	W	MW	MW	W	VW	VW	W		W	W
	Intraclast %	-	-	-	-	-	-	-	-	-		-	-
S i l i c i c l a s t	Terrigenous grain %	40	6	10	30	40	20	20	20	25		7	15
	Quartz	M	S	S	M	M	M	M	M	M		S	S
	Feldspar	M	S	S	M	M	M	M	M	M		S	S
	VRFs	S	R	R	S	M	S	S	M	M		S	S
	SRFs	-	-	-	-	-	-	-	-	-		-	-
	Micas	-	-	-	-	-	-	-	-	-		-	-
	Pyrite grains	S	R	S	S	S	S	S	S	S		S	S
	Pyrite infills	R	-	S	R	R	S	S	S	S		S	S
	Glauconite pellets	-	-	R	-	R	R	R	R	R		-	R
	Glauconite infills	-	-	-	-	-	-	-	-	-		-	-
	Maximum size (mm)	0.20	0.20	0.25	0.20	0.20	0.25	0.25	0.20	0.13		0.13	0.13
s	Mean size (mm)	0.10	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.08		0.08	0.08
	Shape	SA	SR	SR	SA	SA	SA	SA	SA	SA		SA	SA
	Sorting	VW	VW	VW	VW	VW	VW	VW	VW	VW		VW	VW
	Matrix-cement %	45	25	15	15	15	15	15	15	45		20	15
	Spar cement %	-	20	10	5	5	10	10	5	5		5	5
	Micrite %	45	10	5	10	10	5	5	10	40		15	10
	Pore Space %	-	-	-	-	-	-	-	-	-		-	-

Well		W 5	W 5	W 5	W 5	W 5	W 5	W 5	W 5	W 5	W 5	W 5	W 5
Core number		.	.	.	.	.	.	.	.	.	.	.	.
Box number		1	1	1	2	2	2	2	3	3	3	3	3
		.	.	.	.	.	.	.	.	.	.	.	.
		4A	7	9	1B	5	7	11	3	5	6	9	11
C a l c i c l a s s	Total bioclast %	70	25	10	75	75	57		25	35		80	70
	Bryozoans	-	-	-	-	-	-		-	-		-	-
	Bivalves	C	S	-	VC	VC	C		M	S		C	C
	Echinoderms	M	S	S	C	C	S		-	M		M	C
	Benthic foraminifera	S	S	R	S	S	S		S	S		S	S
	Planktic foraminifera	M	M	S	C	C	C		M	M		C	C
	Gastropods	-	R	-	-	-	-		-	-		-	-
	Calcareous algae	-	-	-	-	-	-		-	-		-	-
	Barnacles	-	-	-	-	-	-		-	-		-	-
	Spicules & spines	S	S	S	S	S	S		S	S		M	M
	Others	M	M	S	-	-	M		M	M		M	S
		FRA	FRA				FRA		FRA	FRA		FRA	
	Maximum size (mm)	2.00	0.63	2.50	0.75	1.00	1.50		0.50	2.50		3.50	1.75
	Mean size (mm)	0.13	0.13	0.10	0.13	0.18	0.18		0.13	0.18		0.25	0.25
	Shape	A	A	A	A	A	A		A	A		A	A
	Sorting	VW	VW	M	VW	W	P		VW	M		P	M
	Intraclast %	-	-	-	-	-	-		-	-		-	-
S i l i c l a s s	Terrigenous grain %	10	40	50	10	5	18		25	25		5	15
	Quartz	S	C	C	S	S	M		M	M		S	S
	Feldspar	S	C	C	S	S	M		M	M		S	S
	VRFs	S	-	-	-	-	-		-	-		-	S
	SRFs	-	-	-	-	-	-		S	-		-	-
	Micas	-	-	-	-	-	-		-	-		-	-
	Pyrite grains	S	S	S	S	S	S		M	M		S	S
	Pyrite infills	S	S	S	R	S	S		S	S		S	S
	Glaucinite pellets	-	-	-	-	-	R		-	-		R	R
	Glaucinite infills	-	-	-	-	-	-		-	-		-	-
	Maximum size (mm)	0.13	0.13	0.10	0	0.13	0.25		0.75	0.18		0.18	0.25
	Mean size (mm)	0.08	0.08	0.05	0.08	0.08	0.08		0.08	0.08		0.08	0.18
Shape	SA	SA	SA	SA	SA	SR		SR	SR		SR	SR	
Sorting	VW	VW	VW	VW	VW	W		W	VW		VW	VW	
	Matrix-cement %	20	35	40	15	20	25		50	40		15	15
	Spar cement %	5	-	-	7	5	-		-	-		7	10
	Micrite %	15	35	40	8	15	25		50	40		8	5
	Pore Space %	-	-	-	-	-	-		-	-		-	-

Well		W	W	W	W	W	W	W	W	W	W	W	W
Core number		5	5	5	5	5	5	5	5	5	5	5	5
Box number		3	3	3	4	4	4	4	5	5	5	5	6
		.	.	.	.	.	.	.	.	.	.	.	.
		14	15	19	4	6	11	17	19A	19B	20	21	1B
C a l i c l a s s	Total bioclast %	65	35	60	60	65	50	60	60	35	30	65	60
	Bryozoans	-	-	-	-	-	-	-	-	-	-	R	S
	Bivalves	C	M	VC	M	C	C	C	C	S	C	C	C
	Echinoderms	S	S	C	M	M	S	S	M	R	R	M	S
	Benthic foraminifera	S	S	M	S	S	S	S	S	S	S	S	M
	Planktic foraminifera	M	M	M	S	C	M	M	M	M	M	S	M
	Gastropods	-	-	-	-	-	-	-	-	-	-	-	-
	Calcareous algae	-	-	-	-	-	-	-	-	-	-	-	-
	Barnacles	-	-	-	-	-	-	-	-	-	-	-	-
	Spicules & spines	S	S	S	S	S	S	S	S	R	R	S	S
	Others	M	-	-	M	M	R	-	-	-	-	S	-
		FRA			FRA	SPO	SPO						
	Maximum size (mm)	3.50	1.50	7.00	1.50	3.00	1.00	0.50	2.50	1.00	2.50	0.50	1.40
	Mean size (mm)	0.20	0.18	0.18	0.13	0.20	0.10	0.18	0.20	0.15	0.18	0.18	0.18
	Shape	A	A	A	A	A	A	A	A	A	A	A	A
	Sorting	M	M	P	M	PM	W	VW	W	W	W	VW	W
	Intraclast %	-	-	-	-		-	-	-	-	-	-	-
						BRA SER							
S i l i c l a s s	Terrigenous grain %	20	25	20	20	15	30	25	20	40	40	10	10
	Quartz	S	M	M	M	S	M	M	M	C	C	S	S
	Feldspar	S	M	M	M	S	M	M	M	C	C	S	S
	VRFs	S	S	S	S	S	S	S	S	M	S	S	R
	SRFs	-	-	-	-	-		-	-	-		-	-
	Micas	-	-	-	-	-	-	-	-	-	-	-	-
	Pyrite grains	S	S	S	S	S	S	S	S	S	S	S	S
	Pyrite infills	S	S	S	S	S	S	S	S	S	S	S	S
	Glauconite pellets	R	R	R	R	R	-	R	R	R	R	R	R
	Glauconite infills	-	-	-	-	-	-	-	-	-	-	-	-
	Maximum size (mm)	0.20	0.20	0.20	0.13	0.15	0.18	0.13	0.13	0.13	0.13	0.18	0.18
	Mean size (mm)	0.10	0.10	0.08	0.08	0.08	0.10	0.10	0.10	0.10	0.10	0.10	0.10
	Shape	SA	SR	SR	SR	SA	SR	SR	SA	SA	SA	SA	SR
	Sorting	VW	VW	VW	VW	VW	VW	VW	VW	VW	VW	VW	VW
	Matrix-cement %	15	40	20	20	20	20	15	20	25	30	25	30
	Spar cement %	7	-	10	5	10	5	5	10	5	5	20	15
	Micrite %	8	40	10	15	10	15	10	10	20	25	5	15
	Pore Space %	-	-	-	-	-	-	-	-	-	-	-	-

Well		W	W	W	W	W	W	W	W	W	W	W	W
Core number		5	5	5	5	5	5	5	5	5	6	6	6
Box number		6	6	6	6	6	7	7	7	7	3	3	3
		4	7	11	13	19	4	6	9B	17	1	2A	2B
C a l c i c l a s t	Total bioclast %	72	25	40	30	30	30	30	25	30	2	75	25
	Bryozoans	S	-	-	-	-	-	-	-	-	R	VC	C
	Bivalves	C	M	C	C	C	C	VC	C	M	-	M	S
	Echinoderms	M	S	S	S	S	R	S	M	-	R	S	S
	Benthic foraminifera	M	S	S	S	S	M	S	S	S	R	C	M
	Planktic foraminifera	M	S	S	S	M	S	S	S	M	R	-	-
	Gastropods	-	-	-	-	-	-	-	-	-	-	-	-
	Calcareous algae	S	-	R	-	-	-	-	-	-	-	S	S
	Barnacles	-	-	-	-	-	-	-	-	-	-	M	S
	Spicules & spines	S	R	S	S	S	S	S	S	S	-	-	-
	Others	-	-	S	M	-	R	-	-	S	-	-	-
				SPO	FRA		SPO			SPO			
	Maximum size (mm)	0.50	20.0	1.50	0.50	0.63	1.00	0.75	0.75	0.63	0.35	2.50	2.25
	Mean size (mm)	0.25	0.20	0.20	0.18	0.18	0.15	0.15	0.18	0.15	0.10	1.20	1.00
	Shape	A	A	A	A	A	A	A	A	A	A	MA	MA
	Sorting	VW	P	W	VW	W	W	W	W	W	VW	MW	MW
	Intraclast %	-	-	-	-	-	-	-	-	-	-	-	-
			BIV							FRA			
S i l i c l a s t	Terrigenous grain %	10	20	20	20	20	25	30	25	30	25	15	65
	Quartz	S	M	M	M	M	M	M	M	M	M	R	S
	Feldspar	S	M	M	M	M	M	M	M	M	M	-	S
	VRFs	R	R	R	R	R	R	S	S	S	-	-	M
	SRFs	R	R	R	R	R	S	S	S	S	-	M	VC
	Micas	-	-	-	-	-	-	-	-	-	-	-	-
	Pyrite grains	S	S	S	S	S	S	S	S	S	S	R	R
	Pyrite infills	S	S	S	S	S	S	S	S	S	-	-	-
	Glauconite pellets	R	R	R	R	R	R	R	R	R	R	R	R
	Glauconite infills	-	-	-	-	-	-	-	-	-	-	R	-
	Maximum size (mm)	0.13	0.13	0.13	0.20	0.20	0.30	0.20	0.20	0.20	0.20	4.00	12.0
s	Mean size (mm)	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	1.50	1.00
	Shape	SA	SA	SA	SR	SA	SR	SR	SR	SR	SR	SR	SR
	Sorting	VW	VW	VW	VW	VW	W	VW	VW	VW	VW	M	PM
	Matrix-cement %	18	55	40	50	50	45	40	50	40	73	10	10
	Spar cement %	13	30	5	-	-	-	-	-	-	-	2	-
	Micrite %	5	25	35	50	50	45	40	50	40	73	8	10
	Pore Space %	-	-	-	-	-	-	-	-	-	-	-	-

Well		W	W	W	W	W	W	W	W	W	W	W	W
Core number		6	6	6	6	6	6	6	6	6	6	6	6
Box number		3	3	3	3	3	3	3	4	4	4	4	4
		4	5	8	9A	9B	2A	11	1	2	6	12	20
C a l i c l a s s	Total bioclast %	78	70	30	40	10	5	7	65	25	65	68	25
	Bryozoans	M	VC	C	R	-	-	-	-	-	-	-	-
	Bivalves	S	M	S	C	S	-	R	M	S	C	C	S
	Echinoderms	S	S	S	-	-	-	-	S	S	S	M	S
	Benthic foraminifera	VC	C	M	S	S	-	R	S	S	S	S	S
	Planktic foraminifera	-	-	-	C	S	-	S	C	C	C	C	M
	Gastropods	-	-	-	-	-	-	-	-	-	-	-	-
	Calcareous algae	S	S	S	R	-	-	-	-	-	-	-	-
	Barnacles	S	M	M	-	-	-	-	-	-	-	-	-
	Spicules & spines	-	-	-	-	S	-	R	S	S	M	S	S
	Others	-	-	-	-	-	S	R	M	R	-	-	-
							FRA		FRA	SPO	OST		
	Maximum size (mm)	2.50	8.00	5.00	0.25	0.25	0.10	0.50	0.33	4.00	0.75	0.88	1.40
	Mean size (mm)	1.00	1.00	2.00	0.15	0.13	0.13	0.18	0.18	0.20	0.18	0.17	0.13
	Shape	MA	MA	MA	A	A	A	SA	A	SA	A	VA	VA
	Sorting	W	M	MW	W	W	VW	VW	VW	M	W	W	M
	Intraclast %	-	-	-	-	-	-	1.00	-	1.00	-	-	-
										SPI			
S i l i c l a s s	Terrigenous grain %	10	20	60	25	20	40	12	5	12	5	7	25
	Quartz	S	S	S	M	M	C	S	S	S	S	S	M
	Feldspar	S	S	S	M	M	C	S	S	S	S	S	M
	VRFs	S	S	C	S	S	M	S	R	R	R	R	S
	SRFs	M	M	VC	S	S	-	S	R	R	R	R	S
	Micas	-	-	-	-	-	-	-	-	-	-	-	-
	Pyrite grains	S	S	S	M	S	S	S	S	M	S	S	M
	Pyrite infills	R	R	M	S	S	-	R	S	S	S	S	S
	Glauconite pellets	R	S	R	R	R	-	-	-	R	-	R	-
	Glauconite infills	S	S	-	-	-	-	-	-	-	-	-	-
	Maximum size (mm)	1.50	6.00	4.00	0.18	0.20	0.10	0.38	0.28	0.30	0.10	0.10	0.18
	Mean size (mm)	0.50	2.00	2.50	0.10	0.05	0.08	0.08	0.09	0.08	0.08	0.08	0.08
	Shape	R	SR	SR	SA	SR	SA	SR	SA	SR	SR	SA	SA
Sorting	W	MW	W	VW	VW	VW	W	VW	VW	VW	VW	VW	
	Matrix-cement %	12	10	10	35	70	55	80	30	63	30	25	50
	Spar cement %	7	4	4	10	-	-	-	-	-	15	15	-
	Micrite %	5	6	6	25	70	55	80	30	63	15	10	50
	Pore Space %	-	-	-	-	-	-	-	-	-	-	-	-

Well		W	W	W	W	W	W	W	W				
Core number		N	5	5	5	5	5	5	5				
Box number		1	4	5	5	5	5	5	5				
			21	4	9	10	13	14	17				
C a l c i c l a s s	Total bioclast %	7	50	65	55	30	45	25	47				
	Bryozoans	-	-	-	-	-	-	-	-				
	Bivalves	-	M	C	C	M	C	M	M				
	Echinoderms	-	C	M	C	M	C	-	C				
	Benthic foraminifera	-	S	S	M	S	S	S	S				
	Planktic foraminifera	S	M	M	M	S	S	S	S				
	Gastropods	-	-	-	-	-	-	-	-				
	Calcareous algae	-	-	-	-	-	-	-	-				
	Barnacles	-	-	-	-	-	-	-	-				
	Spicules & spines	-	M	S	S	S	S	-	S				
	Others	-	S	-	-	S	-	M	M				
						SPO		FRA	FRA				
	Maximum size (mm)	0.10		1.75	2.50	3.50	22	0.25	20.0				
	Mean size (mm)	0.10		0.20	0.25	0.18	0.18	0.13	0.18				
	Shape	A		A	A	A	A	A	A				
	Sorting	VW		W	M	M	P	VW	P				
	Intraclast %	-		-	-	-	-	-	-				
S i l i c i c l a s s	Terrigenous grain %	2		15	15	15	15	30	18				
	Quartz	S		M	M	M	M	M	M				
	Feldspar	-		M	M	M	M	M	M				
	VRFs	-		S	S	R	R	R	R				
	SRFs	-		S	S	S	R	R	R				
	Micas	-		-	-	-	-	-	-				
	Pyrite grains	S		S	S	S	S	S	S				
	Pyrite infills	-		S	S	S	S	S	S				
	Glaucinite pellets	-		R	R	R	R	R	R				
	Glaucinite infills	-		-	-	-	-	-	-				
	Maximum size (mm)	0.10		0.18	0.18	1.50	0.13	0.10	0.13				
	Mean size (mm)	0.08		1.00	0.10	0.10	0.08	0.08	0.08				
	Shape	SA		SA	SA	SR	SR	SR	SR				
	Sorting	VW		VW	VW	W	VW	VW	VW				
	Matrix-cement %	91		20	30	55	40	45	35				
	Spar cement %	-		5	15	20	15	-	15				
	Micrite %	91		15	15	35	25	45	20				
	Pore Space %	-		-	-	-	-	-	-				

APPENDIX 4.2 - Petrographic percentage data calculated as that part of the whole rock composition

Sample	Depth (m)	Total bioclast %	Bryozoans %	Bivalves %	Echinoderms %	Benthic forams %	Planktic forams %	Gastropods %	Calcareous red algae %	Barnacles %	Spicules & spines %
Hu2.1A	2962.00	85	29	4	4	4	1	0	15	29	0
Hu2.3	2963.50	82	21	3	11	3	3	0	3	39	0
Hu2.4	2966.50	87	50	3	13	3	0	0	13	3	0
Hu2.6A	2967.00	66	12	3	12	12	0	0	3	24	0
Hu2.7	2968.50	90	31	2	8	16	0	0	16	16	0
Mau1	8323 ft	25	0	0	0	0	24	0	0	0	0
Mau2	8313 ft	25	0	0	0	0	24	0	0	0	0
Mau3	8306 ft	30	0	0	0	0	30	0	0	0	0
NG2.1.10	2914.3	77	4	29	4	4	29	1	4	0	4
NG2.1.3	2907.90	75	0	34	18	2	18	0	2	0	0
NG2.1.5	2909.20	65	1	26	3	3	26	0	3	1	1
NG2.1.8	2912.4	30	0	5	1	5	18	0	0	0	1
NG2.2.3	2916.20	70	0	17	8	8	32	0	2	0	2
NG2.2.7	2919.90	60	1	14	14	3	28	0	0	0	0
NG2.2.9	2921.80	70	0	19	9	2	35	0	2	0	2
NG2.3.1	2926.70	60	0	8	8	8	32	0	0	0	2
NG2.3.14	2940.20	86	2	17	31	8	8	0	17	0	2
NG2.3.16	2941.75	86	0	20	37	10	10	0	10	0	0
NG2.3.2	2927.4	10	0	1	1	1	6	0	0	0	0
NG2.3.4	2930.85	75	1	25	3	12	25	3	3	0	3
NG2.3.8	2934.4	40	1	3	3	3	10	1	0	0	1
NG2.4.1	2984.5	75	3	23	23	11	11	1	3	1	0
NG2.4.16B	2998.7	35	0	9	0	9	9	0	0	0	0
NG2.4.18	3000.25	76	1	42	5	5	21	0	1	0	1
NG2.4.9	2992.35	50	0	29	4	14	4	0	0	0	0
NG2.5.10	3010.20	65	0	16	32	4	4	4	1	0	0

Sample	Depth (m)	Total bioclast %	Bryozoans %	Bivalves %	Echinoderms %	Benthic forams %	Planktic forams %	Gastropods %	Calcareous red algae %	Barnacles %	Spicules & spines %
NG2.5.14	3014.00	65	0	43	5	5	5	0	1	0	0
NG2.5.18	3017.75	75	0	30	15	4	15	1	4	0	4
NG2.5.2A	3001.95	60	1	45	1	6	0	6	0	0	1
NG2.5.2B	3001.95?	25	0	8	2	2	2	2	0	0	0
NG2.5.3	3003.55	30	0	10	2	2	2	0	0	0	2
NG2.5.6	3006.5	30	0	3	3	12	0	0	0	0	12
NG2.5.8	3007.80	60	1	13	25	3	3	3	0	0	0
NG2.6.1	3050.20	60	0	30	4	4	15	0	0	0	4
NG2.6.7	3055.55	64	0	13	27	3	3	1	0	0	13
NG2.7.13	3073.15	70	0	15	29	4	4	0	15	0	0
NG2.7.16A	3076.00	65	0	8	31	2	8	2	8	0	2
NG2.7.16B	3076?	63	0	26	3	3	13	1	13	0	3
NG2.7.19	3079.1	65	0	24	12	3	12	0	12	0	0
NG2.7.2	3063.75	63	0	23	11	3	11	1	11	0	0
NG2.7.6	3067.40	62	0	31	4	4	16	0	4	0	4
NG2.7.8	3068.55	63	0	17	32	2	9	0	2	0	0
Tok1	3099.50	40	0	2	0	2	8	0	0	0	0
Tok2	3100.40	45	0	2	2	8	2	0	0	0	0
Tok3	3101.40	43	0	2	0	2	8	0	0	0	0
W2.1.1	2913.50	70	0	11	3	3	42	0	0	0	11
W2.1.5	2916.60	20	0	3	0	1	13	0	0	0	3
W2.1.6	2917.14	80	1	28	4	14	28	1	0	0	4
W2.1.6A	2917.00	75	1	20	3	10	38	1	0	0	3
W2.1.7	2918.00	80	0	41	3	11	22	0	0	0	3
W2.2.11	2928.65	65	0	27	14	7	14	0	0	0	2
W2.2.3	2921.25	76	0	28	15	2	28	0	0	0	2

Sample	Depth (m)	Total bioclast %	Bryozoans %	Bivalves %	Echinoderms %	Benthic forams %	Planktic forams %	Gastropods %	Calcareous red algae %	Barnacles %	Spicules & spines %
W2.2.7B	2924.70	75	0	25	1	3	46	0	0	0	1
W2.2.7C	2925.00	76	0	24	3	3	45	0	0	0	1
W2.3.1	2930.40	70	0	9	17	17	17	0	0	0	9
W2.3.2	2931.50	45	0	3	3	12	24	0	0	0	3
W2.3.4	2935.40	55	0	12	3	12	24	0	0	0	3
W2.3.7	2936.73	70	0	19	2	10	36	0	0	0	2
W2.4.1	2978.60	45	0	6	12	2	12	0	0	0	12
W2.4.10A	2986.25	50	0	12	12	12	12	0	0	0	3
W2.4.11C	2988.06	40	0	18	9	2	9	0	0	0	2
W2.4.5	2981.30	35	0	2	7	7	13	0	0	0	7
W2.4.6	2982.18	50	0	10	10	10	10	0	0	0	10
W2.5.1	2989.50	30	0	11	3	3	11	0	0	0	3
W2.5.2	2990.50	30	0	4	4	4	15	0	0	0	4
W2.6.2	2992.00	40	0	9	18	2	9	0	0	0	2
W2.7.1	2995.20	15	0	2	8	2	2	0	0	0	2
W2.7.2	2996.00	25	0	10	2	2	10	0	0	0	0
W2.7.4	2998.20	30	0	15	4	4	4	0	0	0	4
W2.8.1A	3076.00	40	0	9	2	9	9	0	0	0	9
W2.8.1B	3076.35	45	0	12	12	3	3	1	0	0	3
W2.8.2	3077.00	30	0	11	11	3	3	0	0	0	3
W2.9.1	3079.10	60	0	25	3	3	25	0	0	0	3
W2.9.12B	3089.40	40	0	4	4	4	15	0	0	0	15
W2.9.6B	3083.75	45	0	3	3	13	13	0	0	0	13
W2.9.9	3088.72	20	0	3	3	3	3	0	0	0	3
W4.1.1	2820.20	70	0	17	32	2	17	0	0	0	2
W4.1.10	2827.50	73	0	18	9	2	34	0	0	0	9

Sample	Depth (m)	Total bioclast %	Bryozoans %	Bivalves %	Echinoderms %	Benthic forams %	Planktic forams %	Gastropods %	Calcareous red algae %	Barnacles %	Spicules & spines %
W4.1.4	2822.40	80	0	19	36	2	2	0	0	0	19
W4.1.5	2823.00	78	0	19	35	2	19	0	0	0	2
W4.1.7	2824.80	81	0	18	34	2	18	0	0	0	9
W4.1.7A	2824.8?	79	0	11	41	3	22	0	0	0	3
W4.1.8	2826.00	80	0	41	11	3	22	0	0	0	3
W4.2.2	2829.60	63	0	16	8	2	30	0	0	0	8
W4.2.4	2831.40	65	0	16	8	2	30	0	0	0	8
W4.3.13	2845.60	25	0	9	2	2	9	0	0	0	2
W4.3.14	2846.00	77	2	34	18	2	18	0	0	0	2
W4.3.20	2852.00	65	1	21	11	11	21	0	0	1	1
W4.3.3	2836.41	76	0	21	21	10	21	0	0	0	3
W4.3.9	2842.60	78	1	40	11	3	21	0	0	0	3
W4.4.10A	2891.45	40	0	4	4	16	16	0	0	0	1
W4.4.10B	2892.00	75	0	21	40	11	3	0	0	0	1
W4.4.11A	2892.50	60	0	10	37	10	0	0	0	0	2
W4.4.1A	2883.40	60	1	3	13	3	13	0	0	0	3
W4.4.2A	2884.20	65	0	15	7	7	28	0	0	0	7
W4.4.3	2884.90	25	0	0	0	1	5	0	0	0	1
W4.4.5	2886.10	35	0	16	8	2	8	0	0	0	2
W4.4.8	2889.70	62	0	32	17	2	2	0	0	0	9
W4.5.1B	2892.50	45	0	1	26	3	1	0	0	0	1
W4.5.2	2895.00	43	0	1	33	4	1	0	0	0	4
W4.6.?	2898.70	75	1	24	44	3	3	0	0	0	1
W4.6.1	2896.00	15	0	0	2	6	6	0	0	0	0
W4.6.13	2905.00	45	1	11	11	11	11	0	0	0	1
W4.6.14	2906.00	65	0	18	18	18	2	0	0	0	0

Sample	Depth (m)	Total bioclast %	Bryozoans %	Bivalves %	Echinoderms %	Benthic forams %	Planktic forams %	Gastropods %	Calcareous red algae %	Barnacles %	Spicules & spines %
W4.6.3	2897.00	69	3	24	24	12	3	0	0	0	3
W4.6.9	2902.40	55	0	15	31	4	4	0	0	0	1
W4.7.2B	3005.60	65	0	4	17	17	4	0	0	0	4
W4.7.4C	3007.00	65	0	4	14	4	14	0	0	0	14
W4.8.2	3061.00	30	0	10	2	2	2	0	0	0	2
W5.1.2	3006.00	73	0	18	18	2	9	0	0	0	9
W5.1.3	3007.00	70	0	22	22	3	11	0	0	0	3
W5.1.4A	3008.50	70	0	25	13	3	13	0	0	0	3
W5.1.7	3011.20	25	0	2	2	2	8	0	0	0	2
W5.1.9	3013.00	10	0	0	2	0	2	0	0	0	2
W5.2.1B	3015.25	75	0	34	18	2	18	0	0	0	2
W5.2.5	3019.00	75	0	34	18	2	18	0	0	0	2
W5.2.7	3021.00	57	0	20	2	2	20	0	0	0	2
W5.3.11	3036.00	70	0	19	19	2	19	0	0	0	9
W5.3.14	3038.90	65	0	27	3	3	14	0	0	0	3
W5.3.15	3040.50	35	0	13	3	3	13	0	0	0	3
W5.3.19	3043.90	60	0	28	15	8	8	0	0	0	2
W5.3.3	3028.52	25	0	7	0	2	7	0	0	0	2
W5.3.5	3029.50	35	0	2	9	2	9	0	0	0	2
W5.3.9	3034.30	80	0	22	11	3	22	0	0	0	11
W5.4.11	3082.20	50	0	26	3	3	13	0	0	0	3
W5.4.17	3087.50	60	0	32	4	4	16	0	0	0	4
W5.4.21	3091.70	50	0	9	18	2	9	0	0	0	9
W5.4.4	3075.20	60	0	16	16	4	4	0	0	0	4
W5.4.6	3077.15	65	0	20	10	3	20	0	0	0	3
W5.5.10	3100.00	30	0	10	10	3	3	0	0	0	3

Sample	Depth (m)	Total bioclast %	Bryozoans %	Bivalves %	Echinoderms %	Benthic forams %	Planktic forams %	Gastropods %	Calcareous red algae %	Barnacles %	Spicules & spines %
W5.5.13	3103.00	45	0	19	19	2	2	0	0	0	2
W5.5.14	3104.60	25	0	10	0	3	3	0	0	0	0
W5.5.17	3107.00	47	0	10	20	2	2	0	0	0	2
W5.5.19A	3109.00	60	0	27	13	3	13	0	0	0	3
W5.5.19B	3109.40	35	0	5	1	5	22	0	0	0	1
W5.5.20	3109.70	30	0	18	0	2	9	0	0	0	0
W5.5.21	3110.40	65	1	32	16	4	4	0	0	0	4
W5.5.4	3094.70	65	0	29	14	4	14	0	0	0	4
W5.5.9	3099.00	55	0	18	18	9	9	0	0	0	2
W5.6.11	3150.70	40	0	24	3	3	3	0	1	0	3
W5.6.13	3152.60	30	0	15	2	2	2	0	0	0	2
W5.6.19	3158.50	30	0	16	2	2	8	0	0	0	2
W5.6.1b	3141.00	60	3	25	3	13	13	0	0	0	3
W5.6.4	3143.00	72	3	25	13	13	13	0	3	0	3
W5.6.7	3146.70	25	0	14	3	3	3	0	0	0	1
W5.7.17	3177.00	30	0	11	0	3	11	0	0	0	3
W5.7.4	3162.00	30	0	17	0	8	2	0	0	0	2
W5.7.6	3165.70	30	0	24	2	2	2	0	0	0	2
W5.7.9B	3169.00	25	0	13	7	2	2	0	0	0	2
W6.3.1	2871.60	2	1	0	1	1	1	0	0	0	0
W6.3.11	2980.00	8	0	1	0	1	4	0	0	0	1
W6.3.2A	2872.30	75	34	9	2	18	0	0	2	9	0
W6.3.2B	2872.45	25	13	2	2	6	0	0	2	2	0
W6.3.4	2874.00	78	14	3	3	51	0	0	3	3	0
W6.3.5	2874.90	70	32	8	2	17	0	0	2	8	0
W6.3.8	2877.70	30	13	2	2	6	0	0	2	6	0

Sample	Depth (m)	Total bioclast %	Bryozoans %	Bivalves %	Echinoderms %	Benthic forams %	Planktic forams %	Gastropods %	Calcareous red algae %	Barnacles %	Spicules & spines %
W6.3.9A	2878.50	40	0	18	0	2	18	0	0	0	0
W6.3.9B	2878.50	10	0	3	0	3	3	0	0	0	3
W6.4.1	3110.18	65	0	14	3	3	27	0	0	0	3
W6.4.12	3119.60	68	0	25	12	3	25	0	0	0	3
W6.4.2	3111.00	25	0	2	2	2	16	0	0	0	2
W6.4.20	3126.60	25	0	3	3	3	13	0	0	0	3
W6.4.6	3114.00	65	0	24	3	3	24	0	0	0	12

Sample	Others/ fragments	Maximum size (mm)	Mean size (mm)	Shape	Sorting	Terrigenous grain %	Quartz %	Feldspar %	VRFs %	SRFs %	Pyrite %
Hu2.1A	1	2.50	1.50	MA	MP	10	1	1	5	1	0
Hu2.3	1	3.00	0.80	MA	MW	13	4	1	4	4	1
Hu2.4	1	2.25	0.75	MA	MW	3	1	1	1	1	1
Hu2.6A	1	2.00	1.25	MA	MW	30	10	10	0	10	0
Hu2.7	0	3.00	1.50	MA	MW	5	2	0	2	0	0
Mau1	1	0.50	0.20	SA	VW	1	1	0	0	0	1
Mau2	1	0.50	0.20	SA	VW	1	1	0	0	0	1
Mau3	0	0.50	0.20	SA	VW	1	1	0	0	0	1
NG2.1.10	0	0.50	0.25	MA	VW	3	1	1	0	0	1
NG2.1.3	0	3.50	0.25	A	MW	5	1	1	0	0	1
NG2.1.5	1	1.10	0.18	MA	W	15	8	2	0	0	2
NG2.1.8	1	0.50	0.13	VA	W	25	9	9	2	0	2
NG2.2.3	0	7.00	0.18	MA	M	10	3	3	0	0	3
NG2.2.7	1	3.00	0.20	MA	M	15	10	2	0	0	2
NG2.2.9	0	3.50	0.20	MA	M	15	4	4	0	0	4
NG2.3.1	0	5.00	0.20	A	M	20	11	3	0	0	3
NG2.3.14	0	1.25	0.25	A	W	4	1	1	0	0	0
NG2.3.16	0	30.00	0.20	A	M	4	1	1	1	0	0
NG2.3.2	0	1.00	0.10	A	MW	30	13	13	0	0	3
NG2.3.4	0	2.50	0.25	A	W	5	2	2	0	0	2
NG2.3.8	21	0.90	0.18	VA	W	15	7	7	0	0	2
NG2.4.1	0	0.38	0.18	A	VW	5	2	2	0	0	2
NG2.4.16B	9	1.00	0.20	A	VW	30	13	13	0	0	3
NG2.4.18	0	3.00	0.20	A	VW	4	1	1	0	0	1
NG2.4.9	0	1.10	0.20	A	VW	30	13	13	0	0	3
NG2.5.10	4	11.00	0.20	A	M	10	3	3	0	0	3

Sample	Others/ fragments	Maximum size (mm)	Mean size (mm)	Shape	Sorting	Terrigenous grain %	Quartz %	Feldspar %	VRFs %	SRFs %	Pyrite %
NG2.5.14	5	2.75	0.18	A	W	10	3	3	0	0	3
NG2.5.18	4	3.50	0.18	A	W	7	2	2	0	0	2
NG2.5.2A	0	12.00	0.18	A	M	15	10	2	0	0	2
NG2.5.2B	8	1.75	0.20	A	W	10	3	3	0	0	3
NG2.5.3	10	5.00	0.23	A	W	7	2	2	0	0	2
NG2.5.6	1	0.75	0.15	A	W	25	11	11	0	0	3
NG2.5.8	13	20.25	0.25	A	M	10	3	3	0	0	3
NG2.6.1	4	1.50	0.18	A	W	10	3	3	0	0	3
NG2.6.7	3	12.00	0.20	A	M	6	2	2	0	0	2
NG2.7.13	4	25.00	0.20	A	P/M	5	2	2	0	0	2
NG2.7.16A	2	20.00	0.20	A	M/P	10	3	3	0	0	3
NG2.7.16B	0	25.00	0.18	A	M/P	7	2	2	0	0	2
NG2.7.19	3	1.80	0.18	A	W	15	10	2	0	0	2
NG2.7.2	3	6.00	0.18	A	W	12	8	2	0	0	2
NG2.7.6	0	4.00	0.18	A	W	8	3	3	0	0	3
NG2.7.8	0	10.00	0.18	A	M	12	4	4	0	0	4
Tok1	29	1.75	0.25	VA	MW	20	9	9	0	0	2
Tok2	31	13.00	0.15	VA	MW	20	8	8	0	0	2
Tok3	31	2.00	0.20	VA	MW	17	7	7	0	0	2
W2.1.1	1	1.75	0.50	MA	MW	5	2	2	0	0	2
W2.1.5	1	0.50	0.10	MA	MW	25	11	3	0	0	11
W2.1.6	1	1.75	0.30	MA	M	7	2	2	0	0	2
W2.1.6A	0	2.50	0.37	MA	MW	5	2	2	0	0	2
W2.1.7	0	0.75	0.37	MA	MW	5	2	2	0	0	2
W2.2.11	0	14.00	0.40	A	P	15	6	6	0	0	1
W2.2.3	0	5.00	0.35	MA	MP	4	1	1	0	0	1

Sample	Others/ fragments	Maximum size (mm)	Mean size (mm)	Shape	Sorting	Terrigenous grain %	Quartz %	Feldspar %	VRFs %	SRFs %	Pyrite %
W2.2.7B	0	0.75	0.25	MA	MW	5	2	2	0	0	2
W2.2.7C	0	3.00	0.20	MA	MW	4	1	1	0	0	1
W2.3.1	0	2.50	0.25	A	P	10	6	1	0	0	1
W2.3.2	0	1.75	0.15	A	PM	25	8	8	0	0	8
W2.3.4	0	1.75	0.25	A	PM	15	6	6	0	0	2
W2.3.7	0	1.00	0.25	A	W	5	1	1	0	0	3
W2.4.1	0	9.00	0.30	A	P	25	8	8	0	0	8
W2.4.10A	0	2.50	0.25	A	MW	15	7	7	0	0	2
W2.4.11C	0	2.50	0.13	A	M	25	11	11	0	0	3
W2.4.5	0	2.00	0.25	A	W	35	11	11	0	0	11
W2.4.6	0	1.50	0.20	A	W	20	7	7	0	0	7
W2.5.1	0	0.50	0.13	A	W	25	8	8	0	0	8
W2.5.2	0	1.00	0.20	A	W	30	13	13	0	0	3
W2.6.2	0	3.00	0.25	A	MW	30	10	10	0	0	10
W2.7.1	0	0.50	0.20	A	MW	45	22	11	0	0	11
W2.7.2	0	0.30	0.13	A	MW	25	8	8	0	0	8
W2.7.4	0	1.00	0.20	A	W	25	8	8	0	0	8
W2.8.1A	0	1.00	0.20	A	W	30	13	13	0	0	3
W2.8.1B	12	2.50	0.18	A	M	30	13	13	0	0	3
W2.8.2	0	0.25	0.20	A	VW	30	13	13	0	0	3
W2.9.1	0	0.75	0.18	A	W	15	7	7	0	0	2
W2.9.12B	0	0.50	0.18	A	W	20	9	9	0	0	2
W2.9.6B	0	2.50	0.18	A	MW	15	7	7	0	0	2
W2.9.9	3	0.50	0.18	A	MV	40	19	19	0	0	2
W4.1.1	0	0.50	0.25	MA	W	10	3	3	0	0	3
W4.1.10	0	2.00	0.20	A	MW	2	1	0	0	0	1

Sample	Others/ fragments	Maximum size (mm)	Mean size (mm)	Shape	Sorting	Terrigenous grain %	Quartz %	Feldspar %	VRFs %	SRFs %	Pyrite %
W4.1.4	0	30.00	0.30	A	P	5	2	2	0	0	2
W4.1.5	0	2.50	0.30	A	MW	7	2	2	0	0	2
W4.1.7	0	1.50	0.25	A	W	7	2	2	0	0	2
W4.1.7A	0	5.00	0.30	A	M	6	2	2	0	0	2
W4.1.8	0	0.60	0.18	A	W	5	2	2	0	0	2
W4.2.2	0	1.25	0.20	A	MW	7	2	2	0	0	2
W4.2.4	0	2.50	0.20	A	MW	10	3	3	0	0	3
W4.3.13	0	0.50	0.20	A	W	25	8	8	0	0	8
W4.3.14	0	0.38	0.25	A	VW	3	1	1	0	0	1
W4.3.20	0	25.00	0.18	A	P	20	8	8	0	0	2
W4.3.3	0	0.75	0.18	A	W	4	1	1	0	0	1
W4.3.9	0	1.60	0.18	A	MW	7	2	2	0	0	2
W4.4.10A	0	0.75	0.20	A	W	20	9	9	0	0	2
W4.4.10B	0	1.00	0.18	A	M	5	2	2	0	0	2
W4.4.11A	0	2.00	0.15	A	M	20	5	5	5	0	5
W4.4.1A	25	0.43	0.13	A	W	20	9	9	0	0	2
W4.4.2A	0	1.50	0.25	A	W	5	2	2	0	0	2
W4.4.3	19	0.38	0.18	A	VW	35	22	11	0	0	3
W4.4.5	0	0.63	0.20	A	W	25	11	11	0	0	3
W4.4.8	0	1.25	0.20	A	W	20	9	9	0	0	2
W4.5.1B	13	1.00	0.25	A	W	40	12	12	12	0	3
W4.5.2	0	1.25	0.20	A	W	45	14	14	14	0	3
W4.6.?	0	1.25	0.30	A	W	10	3	3	1	0	3
W4.6.1	0	2.00	0.13	A	MW	40	16	16	4	0	4
W4.6.13	0	2.00	0.13	A	MW	40	12	12	12	0	3
W4.6.14	9	1.00	0.20	A	W	20	8	8	2	0	2

Sample	Others/ fragments	Maximum size (mm)	Mean size (mm)	Shape	Sorting	Terrigenous grain %	Quartz %	Feldspar %	VRFs %	SRFs %	Pyrite %
W4.6.3	0	0.60	0.20	A	VW	6	3	3	1	0	1
W4.6.9	0	2.50	0.13	A	MW	30	12	12	3	0	3
W4.7.2B	17	0.50	0.18	A	VW	20	8	8	2	0	2
W4.7.4C	14	0.50	0.18	A	VW	20	6	6	6	0	2
W4.8.2	10	1.50	0.15	A	W	25	8	8	8	0	2
W5.1.2	18	1.50	0.15	A	W	7	2	2	2	0	2
W5.1.3	11	1.25	0.18	A	W	15	4	4	4	0	4
W5.1.4A	13	2.00	0.13	A	VW	10	3	3	3	0	3
W5.1.7	8	0.63	0.13	A	VW	40	19	19	0	0	2
W5.1.9	2	2.50	0.10	A	M	50	24	24	0	0	3
W5.2.1B	0	0.75	0.13	A	VW	10	3	3	0	0	3
W5.2.5	0	1.00	0.18	A	W	5	2	2	0	0	2
W5.2.7	10	1.50	0.18	A	P	18	8	8	0	0	2
W5.3.11	2	1.75	0.25	A	M	15	4	4	4	0	4
W5.3.14	14	3.50	0.20	A	M	20	5	5	5	0	5
W5.3.15	0	1.50	0.18	A	M	25	10	10	2	0	2
W5.3.19	0	7.00	0.18	A	P	20	8	8	2	0	2
W5.3.3	7	0.50	0.13	A	VW	25	8	8	0	2	8
W5.3.5	9	2.50	0.18	A	M	25	8	8	0	0	8
W5.3.9	11	3.50	0.25	A	P	5	2	2	0	0	2
W5.4.11	1	1.00	0.10	A	W	30	12	12	3	0	3
W5.4.17	0	0.50	0.18	A	VW	25	10	10	2	0	2
W5.4.21	2	4.00	0.23	A	M	20	9	9	0	0	2
W5.4.4	16	1.50	0.13	A	M	20	8	8	2	0	2
W5.4.6	10	3.00	0.20	A	MP	15	4	4	4	0	4
W5.5.10	3	3.50	0.18	A	M	15	6	6	0	1	1

Sample	Others/ fragments	Maximum size (mm)	Mean size (mm)	Shape	Sorting	Terrigenous grain %	Quartz %	Feldspar %	VRFs %	SRFs %	Pyrite %
W5.5.13	0	22.00	0.18	A	P	15	6	6	0	0	2
W5.5.14	10	0.25	0.13	A	VW	30	13	13	1	1	3
W5.5.17	10	20.00	0.18	A	P	18	8	8	0	0	2
W5.5.19A	0	2.50	0.20	A	W	20	8	8	2	0	2
W5.5.19B	0	1.00	0.15	A	W	40	15	15	8	0	2
W5.5.20	0	2.50	0.18	A	W	40	18	18	2	0	2
W5.5.21	4	0.50	0.18	A	VW	10	2	2	2	0	2
W5.5.4	0	1.75	0.20	A	W	15	5	5	1	1	1
W5.5.9	0	2.50	0.25	A	M	15	5	5	1	1	1
W5.6.11	3	1.50	0.20	A	W	20	8	8	0	0	2
W5.6.13	8	0.50	0.18	A	VW	20	8	8	0	0	2
W5.6.19	0	0.63	0.18	A	W	20	8	8	0	0	2
W5.6.1b	0	1.40	0.18	A	W	10	3	3	1	0	3
W5.6.4	0	0.50	0.25	A	VW	10	3	3	1	1	3
W5.6.7	0	20.00	0.20	A	P	20	8	8	0	0	2
W5.7.17	3	0.63	0.15	A	W	30	11	11	3	3	3
W5.7.4	0	1.00	0.15	A	W	25	10	10	0	2	2
W5.7.6	0	0.75	0.15	A	W	30	11	11	3	3	3
W5.7.9B	0	0.75	0.18	A	W	25	9	9	2	2	2
W6.3.1	0	0.35	0.10	A	VW	25	11	11	0	0	3
W6.3.11	1	0.50	0.18	SA	VW	12	2	2	2	2	2
W6.3.2A	0	2.50	1.20	MA	MW	15	1	0	0	13	1
W6.3.2B	0	2.25	1.00	MA	MW	65	3	3	12	46	1
W6.3.4	0	2.50	1.00	MA	W	10	1	1	1	5	1
W6.3.5	0	8.00	1.00	MA	M	20	2	2	2	9	2
W6.3.8	0	5.00	2.00	MA	MW	60	2	2	18	34	2

Sample	Others/ fragments	Maximum size (mm)	Mean size (mm)	Shape	Sorting	Terrigenous grain %	Quartz %	Feldspar %	VRFs %	SRFs %	Pyrite %
W6.3.9A	0	0.25	0.15	A	W	25	7	7	2	2	7
W6.3.9B	0	0.25	0.13	A	W	20	7	7	2	2	2
W6.4.1	14	0.33	0.18	A	VW	5	1	1	0	0	1
W6.4.12	0	0.88	0.17	VA	W	7	2	2	0	0	2
W6.4.2	0	4.00	0.20	SA	M	12	2	2	0	0	7
W6.4.20	0	1.40	0.13	VA	M	25	7	7	2	2	7
W6.4.6	0	0.75	0.18	A	W	5	1	1	0	0	1

Sample	Glauconite %	Maximum size (mm)	Mean size (mm)	Shape	Sorting	Matrix- cement %	Spar cement %	Micrite %
Hu2.1A	0	1.50	0.75	SR	M	5	4	1
Hu2.3	0	1.50	0.50	SR-R	W	5	4	1
Hu2.4	1	0.50	0.50	SR	W	10	7	3
Hu2.6A	0	12.00	0.25	SR	MP	4	2	2
Hu2.7	0	1.25	1.00	SR-R	W	5	4	1
Mau1	0	0.03	0.03	SR	VW	74	0	74
Mau2	0	0.03	0.03	SR	VW	74	0	74
Mau3	0	0.03	0.30	SR	VW	69	0	69
NG2.1.10	0	0.10	0.10	SA	VW	20	4	16
NG2.1.3	1	0.13	0.10	SR	VW	20	15	5
NG2.1.5	2	0.15	0.10	SA	VW	20	5	15
NG2.1.8	2	0.30	0.10	SA	W	45	5	40
NG2.2.3	3	0.15	0.10	SA	VW	20	4	16
NG2.2.7	0	0.15	0.10	SA	VW	25	5	20
NG2.2.9	4	0.15	0.10	SA	VW	15	3	12
NG2.3.1	3	0.15	0.10	SR	VW	20	5	15
NG2.3.14	1	0.18	0.10	SA	VW	10	8	2
NG2.3.16	0	0.15	0.10	SA	VW	10	8	2
NG2.3.2	1	0.10	0.05	SA	VW	60	0	60
NG2.3.4	0	0.15	0.10	SA	VW	20	5	15
NG2.3.8	0	0.13	0.10	SA	VW	45	0	45
NG2.4.1	0	0.15	0.10	SA	VW	20	15	5
NG2.4.16B	1	0.30	0.10	SA	VW	35	0	35
NG2.4.18	0	0.18	0.10	SA	VW	20	10	10
NG2.4.9	1	0.20	0.10	SA	VW	20	3	17
NG2.5.10	1	0.13	0.10	SA	VW	25	5	20

Sample	Glauconite %	Maximum size (mm)	Mean size (mm)	Shape	Sorting	Matrix- cement %	Spar cement %	Micrite %
NG2.5.14	1	0.18	0.10	SA	VW	25	5	20
NG2.5.18	0	0.13	0.08	SR	VW	18	3	15
NG2.5.2A	0	0.18	0.13	SA	VW	25	15	10
NG2.5.2B	1	0.18	0.13	SA	VW	65	25	40
NG2.5.3	0	0.18	0.13	SA	VW	63	30	33
NG2.5.6	1	0.18	0.10	SA	VW	45	20	25
NG2.5.8	1	0.18	0.10	SA	VW	30	5	25
NG2.6.1	1	0.14	0.08	SR	VW	30	0	30
NG2.6.7	0	0.13	0.08	SR	VW	30	0	30
NG2.7.13	0	0.13	0.08	SR	VW	25	4	21
NG2.7.16A	1	0.15	0.10	SR	VW	25	0	25
NG2.7.16B	0	0.15	0.10	SR	VW	30	10	20
NG2.7.19	0	0.15	0.10	SR	VW	20	0	20
NG2.7.2	0	0.17	0.10	SR	VW	25	0	25
NG2.7.6	1	0.13	0.08	SR	VW	30	0	30
NG2.7.8	1	0.13	0.08	SR	VW	25	0	25
Tok1	0	0.13	0.13	SA	VW	40	20	20
Tok2	2	0.15	0.10	SR	W	35	20	15
Tok3	0	0.14	0.14	SA	VW	40	20	20
W2.1.1	0	0.13	0.13	SA	VW	25	10	15
W2.1.5	1	0.30	0.25	SR	W	55	0	55
W2.1.6	0	0.30	0.25	SR	W	13	6	6
W2.1.6A	0	0.30	0.25	SA	VW	20	13	7
W2.1.7	0	0.25	0.20	SR	VW	15	5	10
W2.2.11	1	0.70	0.13	SA	MW	20	5	15
W2.2.3	1	0.25	0.25	SR	VW	20	15	5

Sample	Glauconite %	Maximum size (mm)	Mean size (mm)	Shape	Sorting	Matrix- cement %	Spar cement %	Micrite %
W2.2.7B	0	0.25	0.25	SA	VW	20	5	15
W2.2.7C	0	0.25	0.25	SA	VW	20	5	15
W2.3.1	1	0.20	0.13	SA	VW	20	5	15
W2.3.2	0	0.25	0.13	SA	VW	30	5	25
W2.3.4	0	0.75	0.13	SA	MW	30	5	25
W2.3.7	1	0.13	0.13	SA	VW	25	5	20
W2.4.1	0	0.10	0.10	SA	VW	30	5	25
W2.4.10A	0	0.10	0.10	SA	VW	35	3	32
W2.4.11C	1	0.25	0.13	SA	W	35	3	32
W2.4.5	1	0.25	0.13	SA	VW	30	5	25
W2.4.6	0	0.13	0.13	SA	VW	30	3	27
W2.5.1	0	0.20	0.08	SA	MW	45	0	45
W2.5.2	1	0.20	0.13	SA	W	40	0	40
W2.6.2	0	0.20	0.13	SA	W	30	0	30
W2.7.1	1	0.10	0.07	SA	W	40	0	40
W2.7.2	0	0.10	0.07	SA	W	50	0	50
W2.7.4	0	0.12	0.10	SA	VW	45	0	45
W2.8.1A	1	0.10	0.10	SA	VW	30	0	30
W2.8.1B	1	0.13	0.13	SA	VW	25	0	25
W2.8.2	1	0.10	0.07	SA	VW	40	0	40
W2.9.1	0	0.10	0.07	SA	VW	25	0	25
W2.9.12B	0	0.10	0.08	SA	VW	40	0	40
W2.9.6B	0	0.15	0.07	SA	VW	40	25	15
W2.9.9	0	0.10	0.07	SA	VW	40	0	40
W4.1.1	3	0.20	0.08	SR	VW	20	0	20
W4.1.10	0	0.10	0.10	SA	VW	25	20	5

Sample	Glauconite %	Maximum size (mm)	Mean size (mm)	Shape	Sorting	Matrix- cement %	Spar cement %	Micrite %
W4.1.4	0	0.13	0.13	SR	VW	15	8	7
W4.1.5	0	0.13	0.13	SR	VW	15	10	5
W4.1.7	2	0.18	0.10	SA	VW	12	6	6
W4.1.7A	2	0.18	0.10	SA	VW	15	9	6
W4.1.8	0	0.20	0.10	SA	VW	15	5	10
W4.2.2	0	0.20	0.08	SA	VW	30	10	20
W4.2.4	1	0.20	0.08	SA	VW	25	5	20
W4.3.13	0	0.10	0.08	SR	VW	50	5	45
W4.3.14	0	0.13	0.08	SA	VW	20	15	5
W4.3.20	2	0.18	0.08	SA	VW	15	5	10
W4.3.3	0	0.10	0.08	SA	VW	20	10	10
W4.3.9	0	0.10	0.08	SA	VW	15	5	10
W4.4.10A	0	0.13	0.08	SA	VW	40	0	40
W4.4.10B	0	0.20	0.13	SA	VW	20	15	5
W4.4.11A	1	0.20	0.13	SA	VW	20	15	5
W4.4.1A	0	0.18	0.10	SA	VW	20	5	15
W4.4.2A	0	0.13	0.08	SA	VW	30	10	20
W4.4.3	0	0.15	0.05	SA	VW	40	0	40
W4.4.5	0	0.13	0.08	SA	VW	40	0	40
W4.4.8	0	0.13	0.08	SA	VW	18	0	18
W4.5.1B	1	0.30	0.13	SA	VW	15	5	10
W4.5.2	1	0.20	0.13	SA	VW	12	5	7
W4.6.?	1	0.25	0.13	SR	VW	15	10	5
W4.6.1	0	0.20	0.10	SA	VW	45	0	45
W4.6.13	1	0.20	0.13	SA	VW	15	5	10
W4.6.14	0	0.25	0.13	SA	VW	15	10	5

Sample	Glauconite %	Maximum size (mm)	Mean size (mm)	Shape	Sorting	Matrix- cement %	Spar cement %	Micrite %
W4.6.3	0	0.20	0.13	SR	VW	25	20	10
W4.6.9	0	0.20	0.13	SA	VW	15	5	10
W4.7.2B	0	0.25	0.13	SA	VW	15	10	5
W4.7.4C	0	0.20	0.13	SA	VW	15	5	10
W4.8.2	0	0.13	0.08	SA	VW	45	5	40
W5.1.2	0	0.13	0.08	SA	VW	20	5	15
W5.1.3	1	1.25	0.08	SA	VW	15	5	10
W5.1.4A	0	0.13	0.08	SA	VW	20	5	15
W5.1.7	0	0.13	0.08	SA	VW	35	0	35
W5.1.9	0	0.10	0.05	SA	VW	40	0	40
W5.2.1B	0	0.13	0.08	SA	VW	15	7	8
W5.2.5	0	0.13	0.08	SA	VW	20	5	15
W5.2.7	0	0.25	0.08	SR	W	25	0	25
W5.3.11	1	0.25	0.18	SR	VW	15	10	5
W5.3.14	1	0.20	0.10	SA	VW	15	7	8
W5.3.15	0	0.20	0.10	SR	VW	40	0	40
W5.3.19	0	0.20	0.08	SR	VW	20	10	10
W5.3.3	0	0.75	0.08	SR	W	50	0	50
W5.3.5	0	0.18	0.08	SR	VW	40	0	40
W5.3.9	0	0.18	0.08	SR	VW	15	7	8
W5.4.11	0	0.18	0.10	SR	VW	20	5	15
W5.4.17	0	0.13	0.10	SR	VW	15	5	10
W5.4.21	0	1.20	0.08	SR	M	30	0	30
W5.4.4	0	0.13	0.08	SR	VW	20	5	15
W5.4.6	1	0.15	0.08	SA	VW	20	10	10
W5.5.10	0	1.50	0.10	SR	W	55	20	35

Sample	Glauconite %	Maximum size (mm)	Mean size (mm)	Shape	Sorting	Matrix- cement %	Spar cement %	Micrite %
W5.5.13	0	0.13	0.08	SR	VW	40	15	25
W5.5.14	1	0.10	0.08	SR	VW	45	0	45
W5.5.17	0	0.13	0.08	SR	VW	35	15	20
W5.5.19A	0	0.13	0.10	SA	VW	20	10	10
W5.5.19B	0	0.13	0.10	SA	VW	25	5	20
W5.5.20	0	0.13	0.10	SA	VW	30	5	25
W5.5.21	0	0.18	0.10	SA	VW	25	20	5
W5.5.4	0	0.18	1.00	SA	VW	20	5	15
W5.5.9	0	0.18	0.10	SA	VW	30	15	15
W5.6.11	0	0.13	0.08	SA	VW	40	5	35
W5.6.13	0	0.20	0.08	SR	VW	50	0	50
W5.6.19	0	0.20	0.08	SA	VW	50	0	50
W5.6.1b	1	0.18	0.10	SR	VW	30	15	15
W5.6.4	1	0.13	0.08	SA	VW	18	13	5
W5.6.7	0	0.13	0.08	SA	VW	55	30	25
W5.7.17	1	0.20	0.08	SR	VW	40	0	40
W5.7.4	0	0.30	0.08	SR	W	45	0	45
W5.7.6	1	0.20	0.08	SR	VW	40	0	40
W5.7.9B	0	0.20	0.08	SR	VW	50	0	50
W6.3.1	1	0.20	0.08	SR	VW	73	0	73
W6.3.11	0	0.38	0.08	SR	W	80	0	80
W6.3.2A	1	4.00	1.50	SR	M	10	2	8
W6.3.2B	1	12.00	1.00	SR	MP	10	0	10
W6.3.4	0	1.50	0.50	R	W	12	7	5
W6.3.5	2	6.00	2.00	SR	MW	10	4	6
W6.3.8	0	4.00	2.50	SR	W	10	4	6

Sample	Glauconite %	Maximum size (mm)	Mean size (mm)	Shape	Sorting	Matrix- cement %	Spar cement %	Micrite %
W6.3.9A	0	0.18	0.10	SA	VW	35	10	25
W6.3.9B	0	0.20	0.05	SR	VW	70	0	70
W6.4.1	0	0.28	0.09	SA	VW	30	0	30
W6.4.12	0	0.10	0.08	SA	VW	25	15	10
W6.4.2	0	0.30	0.08	SR	VW	63	0	63
W6.4.20	0	0.18	0.08	SA	VW	50	0	50
W6.4.6	0	0.10	0.08	SR	VW	30	15	15

APPENDIX 4.3

Detailed petrofacies descriptions

PETROFACIES II - WACKESTONES

Skeletal varieties

Bivalve wackestones

Bivalve-dominated, fine skeletal sand-sized rocks are the most abundant variety of wackestone. Bivalve fragments are usually the sole dominant skeletal type, although in some samples planktic foraminifera co-dominate. Rarely echinoderm and benthic foraminifera fragments also co-dominate, but they are mainly the two subdominant skeletal groups. Of the three wackestone skeletal varieties bivalve wackestones have intermediate carbonate contents (about 41%) with high siliciclastic (av. 27%) and matrix (425) contents. Bivalve wackestones are most common in Waihapa-5 and Waihapa-2, and also occur in Waihapa-4.

Planktic foraminifera wackestones

Planktic foraminifera-dominated, fine sand-sized wackestones are the least pure (av. 35% carbonate) and most matrix-rich (av. 46%) of the wackestone skeletal varieties (Plate 4.1B). Most of these rocks are dominated solely by planktic foraminifera, although occasionally spicules and spines, benthic foraminifera, or echinoderms may be equally important. Subdominant skeletons, where present, are usually benthic foraminifera or echinoderms. Rocks mainly belong in carbonate Facies B (very calcareous siliciclastites), but sometimes Facies C (muddy limestones). This rock type is characteristic of the offshore well Maui-1, but is also found within some Waihapa wells and Ngaere-2.

Echinoderm wackestones

This limited variety of wackestone is cleaner and more carbonate-rich (av. 52%) than the other two skeletal varieties. Echinoderm fragments are the dominant skeletal type with minor bivalve fragments and planktic foraminifera (Plate 4.1G-H). Mean skeletal grain size is slightly coarser than in the other varieties. Matrix

is typically non-carbonate material which is less abundant (av. 35%) than in the other two wackestone varieties. Rocks are solely associated with carbonate Facies B and are limited in occurrence to Waihapa-2.

PETROFACIES III - PACKSTONES

Skeletal varieties

Bivalve packstones

Among the packstone skeletal varieties, bivalve-dominated packstones (Plate 4.1C) have slightly lower carbonate contents (av. 51%), and the highest siliciclastic content (av. 15%). Skeletal material is dominated by fine sand-sized bivalve fragments with subdominant amounts of planktic foraminifera and echinoderms. Benthic foraminifera, spicules and spines, and calcareous red algae are minor components. This skeletal variety is most common in Ngaere-2 and also occurs in Waihapa-2, Waihapa-4, and Waihapa-5.

Echinoderm packstones

These fine sand-sized limestones are dominated by echinoderm material with subdominant bivalves. Benthic and planktic foraminifera and spicules and spines are present in small quantities, together with rare calcareous red algae. This skeletal variety is common in Ngaere-2, and also in Waihapa-4 and Waihapa-5, and is rare in Waihapa-2.

Planktic foraminifera packstones

These fine sand-sized planktic foraminifera-dominated limestones have the highest carbonate contents of this petrofacies (av. 55%) reflecting their increased bioclastic content (av. 66%). Planktic foraminifera are the dominant skeletal type, with occasional bivalve, echinoderm and benthic foraminifera, and rare spicule and spine and calcareous red algae grains. These rocks occur in Ngaere-2, Waihapa-2, Waihapa-4, and Waihapa-6, but are absent in Waihapa-5.

PETROFACIES IV - POORLY WASHED GRAINSTONES

Skeletal varieties

Bivalve poorly washed grainstones

Fragmental bivalve material dominates this fine sand-sized skeletal variety of Petrofacies IV, with planktic foraminifera being important secondary components along with some echinoderms and benthic foraminifera material (Plate 4.1E). Calcareous red algae and bryozoans are rare. These bivalve-dominated rocks are limestones which have the lowest siliciclastic contents (10%) of the poorly washed grainstone skeletal varieties and the highest matrix/cement contents (28%). The latter comprises sub-equal amounts of spar cement and matrix/micrite. These rocks commonly occur in Waihapa-5, with some in Ngaere-2 and rare occurrences in Waihapa-2, Waihapa-4, and Waihapa-6.

Echinoderm poorly washed grainstones

These fine sandy echinoderm-dominated limestones have the lowest bioclastic content (av. 56%) of the Petrofacies IV skeletal varieties. These rocks contain moderate to high siliciclastic and matrix/cement contents at 20% and 25%, respectively. Bivalves are the second most common skeletal grain type, with some benthic and planktic foraminifera, spicules and spines, and very rare bryozoans. These echinoderm-dominated rocks are commonly found in Waihapa-4, with some in Waihapa-5 and rare occurrences in Ngaere-2 and Toko-1.

Planktic foraminifera poorly washed grainstones

These uncharacteristically coarser, medium sand-sized limestones are the purest of the poorly washed grainstones, av. 69% carbonate. Bivalves are the subdominant skeletal fragment type, with some spicules and spines, echinoderms, and benthic foraminifera. These rocks are found in, and limited to, Toko-1, Waihapa-2, and Waihapa-4.

Barnacle poorly washed grainstones

This very uncharacteristic coarse barnacle-rich calcareous sandstone is dominated by 30% siliciclastics, including a large number of subrounded to rounded sedimentary rock fragments (greywacke). The variety is restricted to an 8 m

interval of core from Hu Rd-1A. Bryozoans, echinoderms, and benthic foraminifera form the subdominant skeletal types, along with rare bivalves and calcareous red algae. This variety has low matrix/cement contents at 4%.

PETROFACIES V - GRAINSTONES

Skeletal varieties

Bivalve grainstones

These fine sand-sized limestones are classified as bivalve-rich grainstones which exhibit the highest cement/matrix quantities (av. 21%) of any Tikorangi Formation facies, most of which (av. 15%) is spar cement. Total bioclastic content (73%) is the lowest of the four grainstone skeletal varieties, with echinoderms and planktic foraminifera occurring as secondary skeletal components. These rocks are the finest of the grainstone varieties, the skeletal material being dominantly fine sand-size and the siliciclastics very fine sand-sized. These rocks occur in Waihapa-5, Ngaere-2 and Waihapa-2 wells.

Echinoderm grainstones

These fine sand-sized echinoderm-dominated limestones (Plate 4.1F) include subdominant amounts of bivalves, benthic foraminifera and calcareous red algae grains, and contain relatively high quantities (av. 12%) of spar cement. These rocks are limited to Ngaere-2 and Waihapa-4.

Bryozoan grainstones

These very coarse sand-sized grainstones are the purest limestones within the Tikorangi Formation, av. 95% carbonate. Bioclastic contents are the highest of any rocks at 89%, and although singularly dominated by bryozoans, they also contain important shallow-water biota such as calcareous red algae (17% of bioclasts), barnacles (11%), and large benthic foraminifera (11%). Siliciclastic contents are low (av. 4%). These rocks only occur in Hu Rd-1A.

Barnacle grainstones

These pure (av. 80% carbonate) barnacle-rich grainstones are very coarse sand-sized and contain subdominant amounts of bryozoans with some calcareous red algae (Plate 4.2B). Siliciclastic grain contents are higher than in any other grainstones, and include coarse sand-sized volcanic and sedimentary rock fragments sourced from basement greywackes. Cement/matrix content is uncharacteristically low at 5% and is dominated by spar cement. These rocks are limited to Hu Rd-1A.

APPENDIX 4.4

Individual study well petrographic summaries.

A4.4.1. Maui-1

A4.4.2. Toko-1

A4.4.3. Ngaere-2

A4.4.4. Waihapa-4

A4.4.5. Waihapa-6

A4.4.6. Waihapa-2

A4.4.7. Waihapa-5

A4.4.8. Hu Rd-1

For each well:

Graph A = Average whole rock composition

Graph B = Average bioclastic composition

Graph C = Average siliciclastic composition

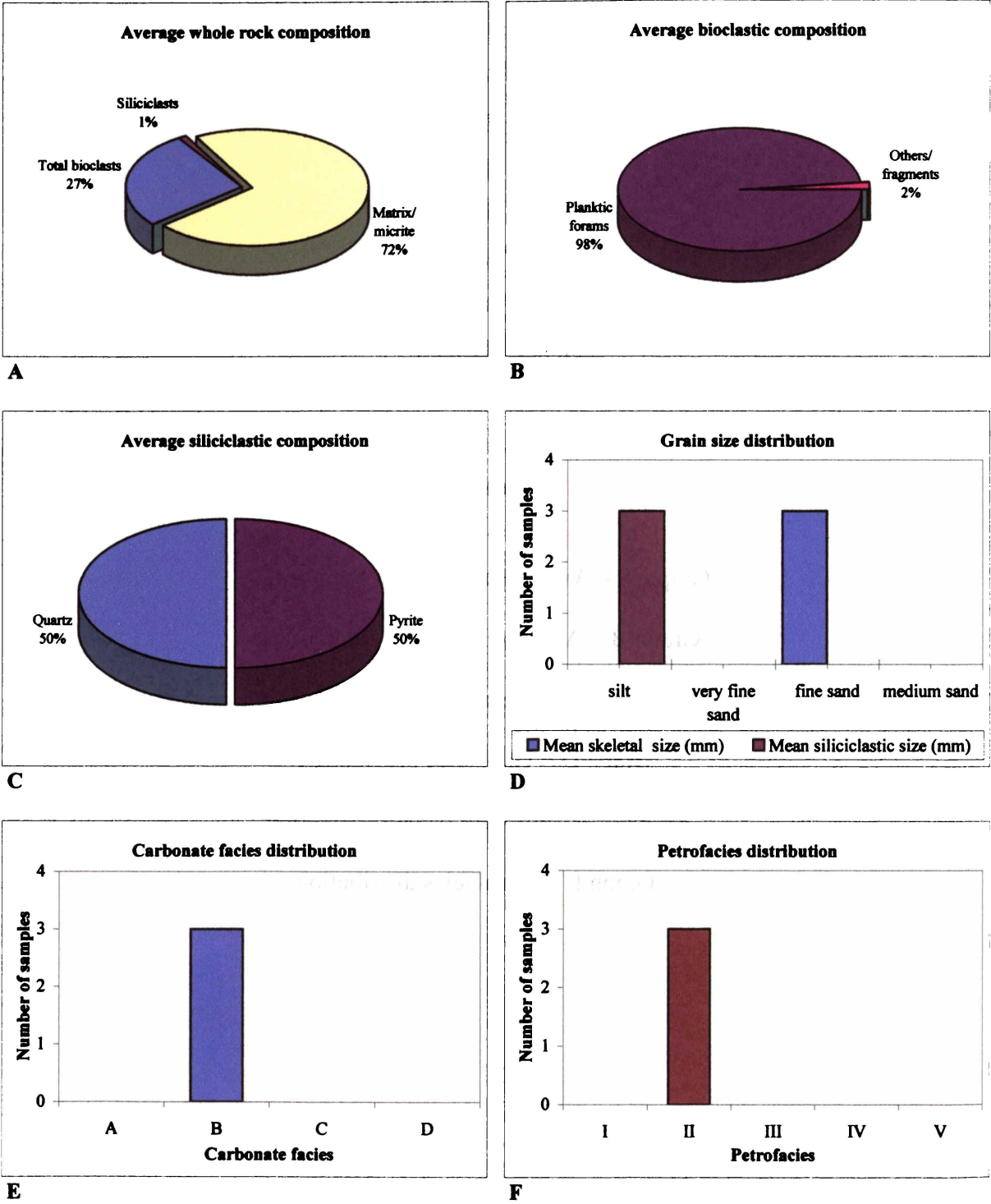
Graph D = Grain size distribution

Graph E = Carbonate facies distribution

Graph F = Petrofacies distribution

Maui-1

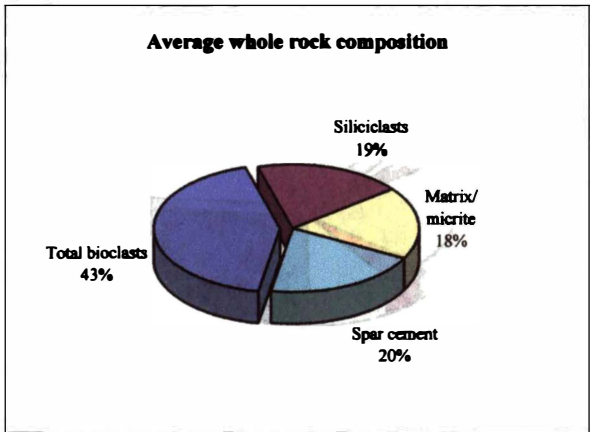
Tikorangi Formation Well Petrographic Summary



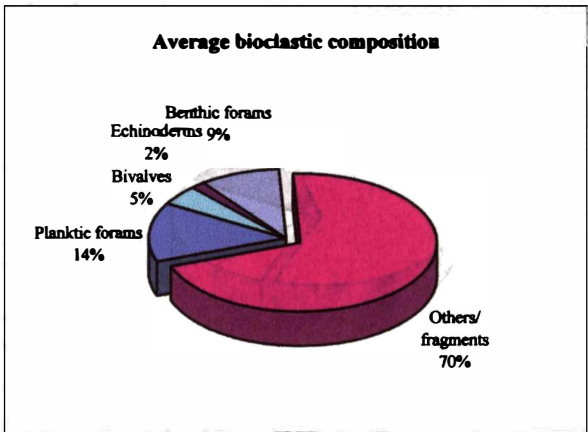
A4.4.1 Note: data displayed above is for grains visible using standard petrography only and does not include data pertaining to the finest micrite/matrix material.

Toko-1

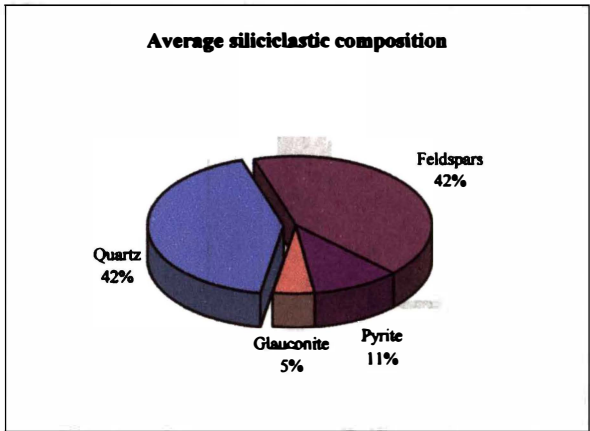
Tikorangi Formation Well Petrographic Summary



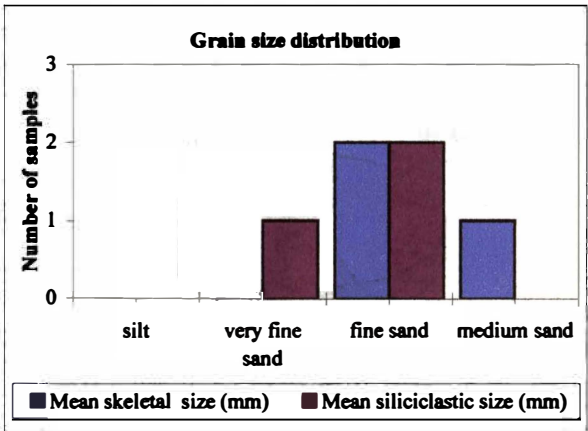
A



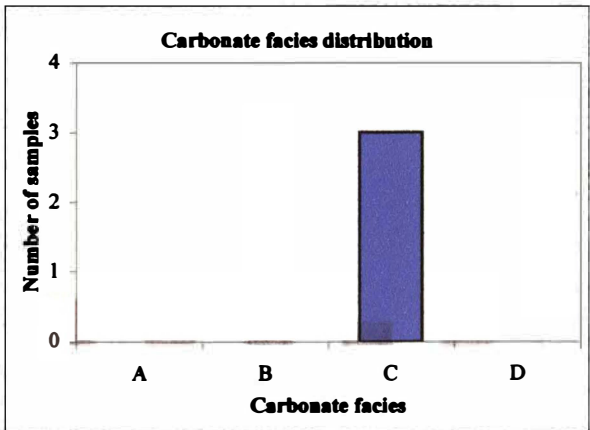
B



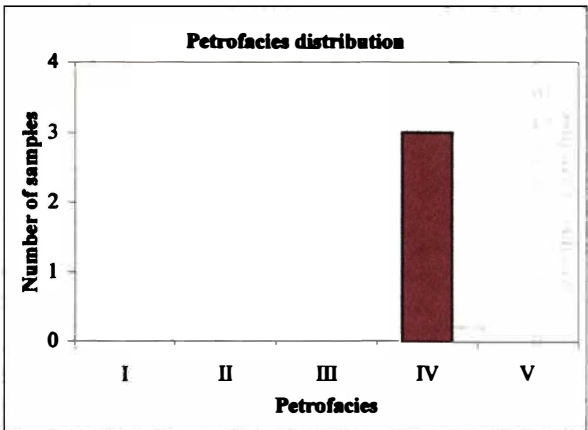
C



D



E

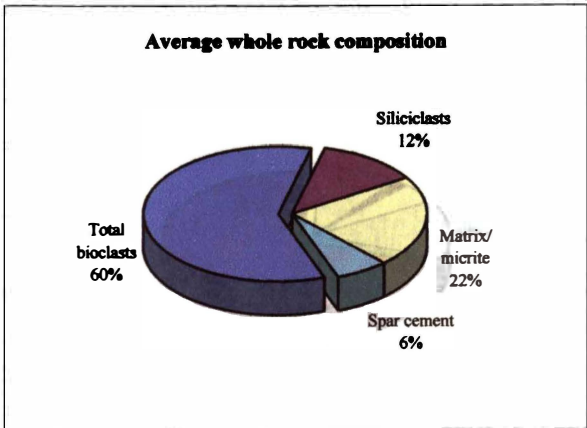


F

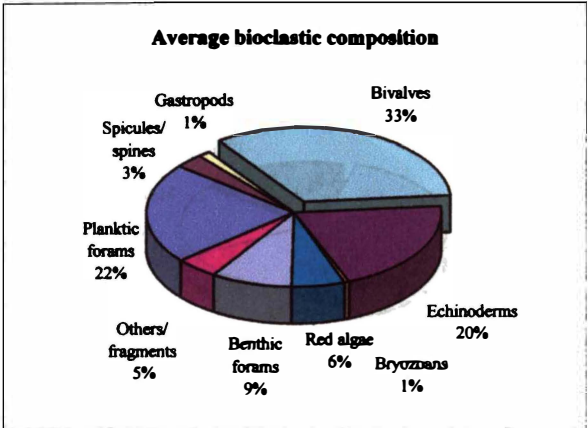
A4.4.2

Ngaere-2

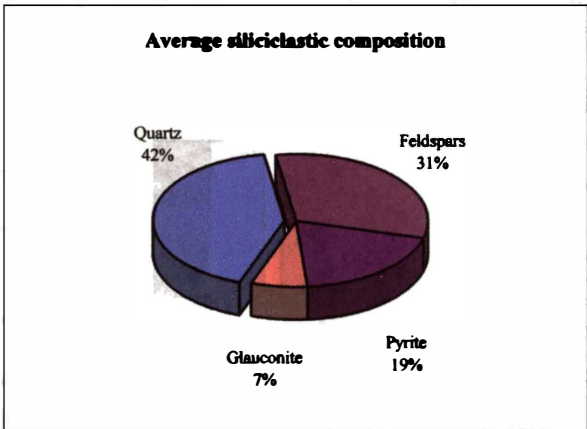
Tikorangi Formation Well Petrographic Summary



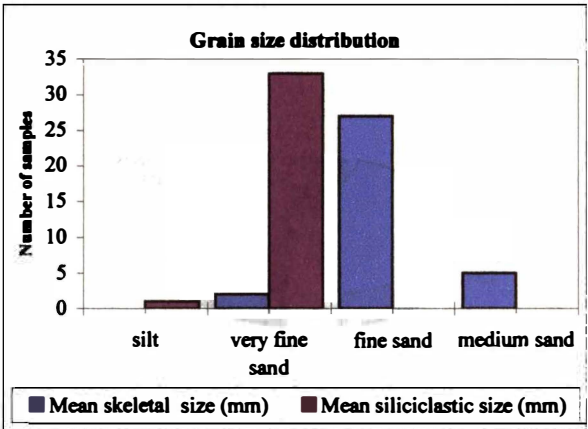
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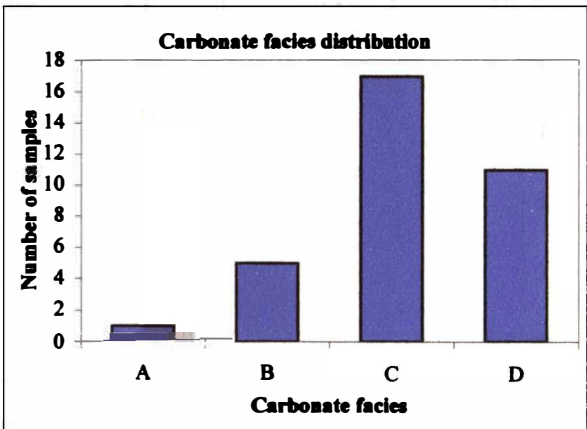
B



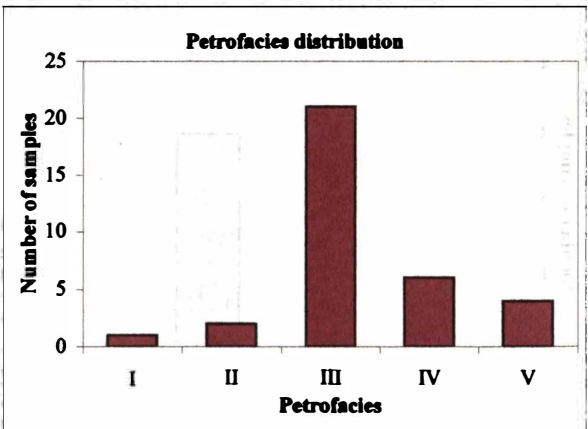
C



D



E

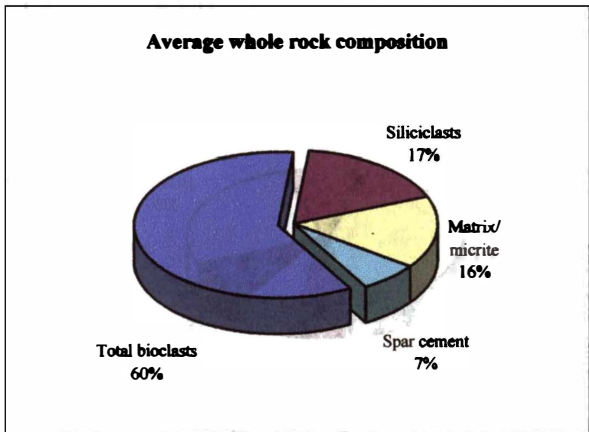


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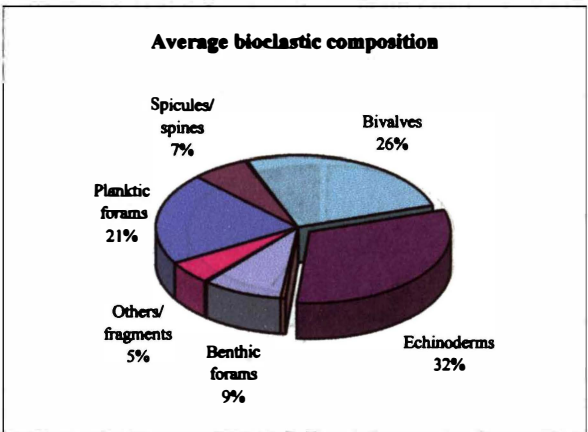
A4.4.3

Waihapa-4

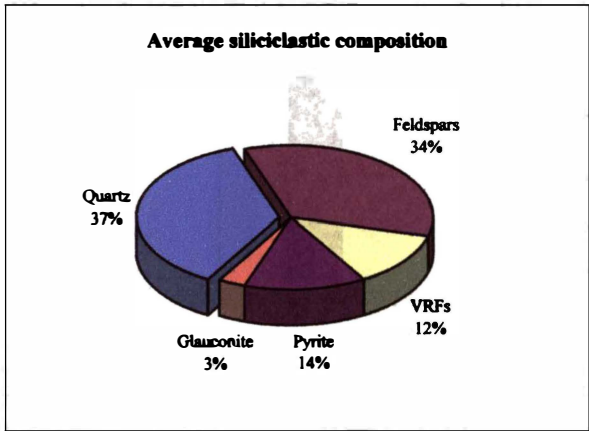
Tikorangi Formation Well Petrographic Summary



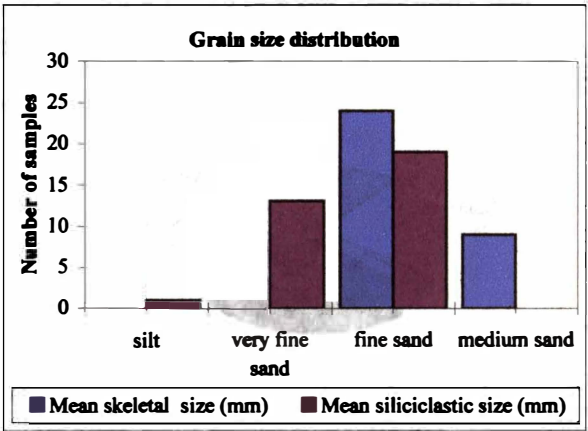
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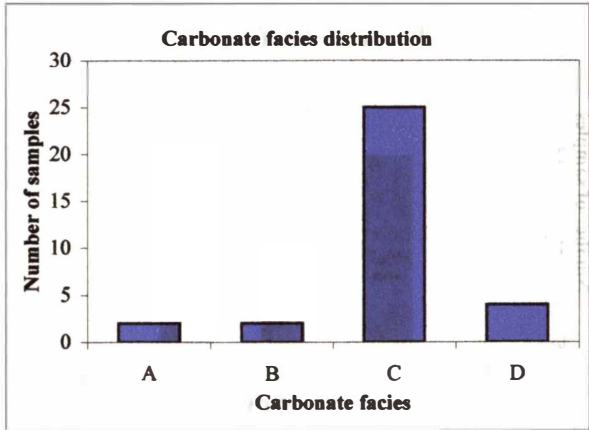
B



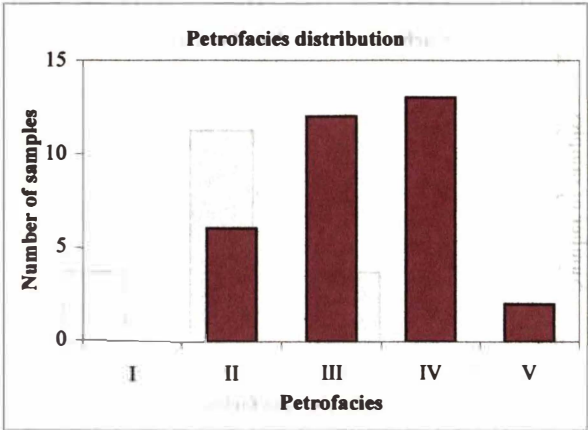
C



D



E

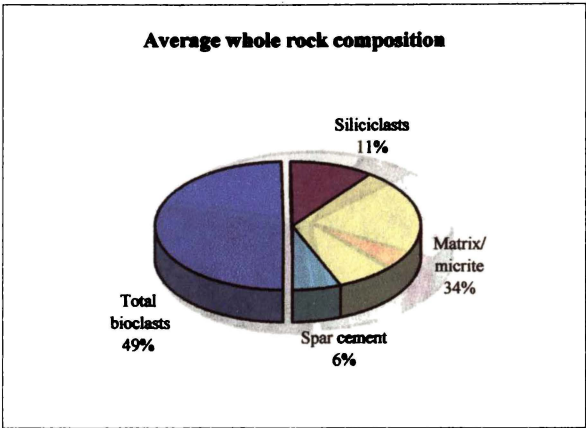


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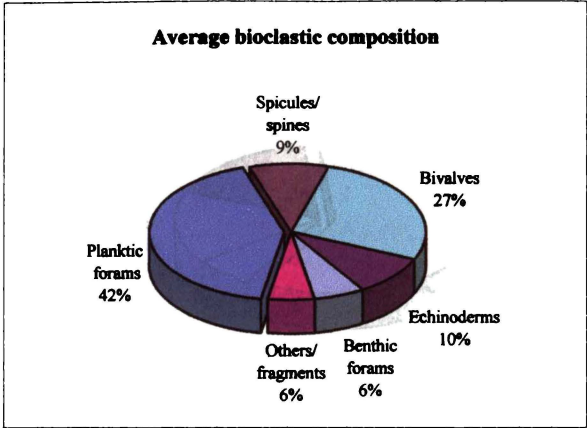
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Waihapa-6

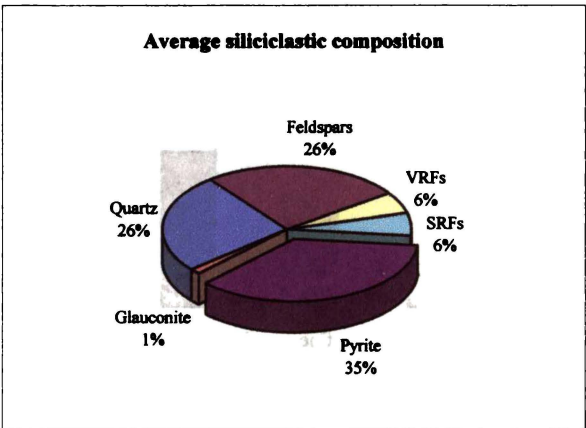
Tikorangi Formation Well Petrographic Summary



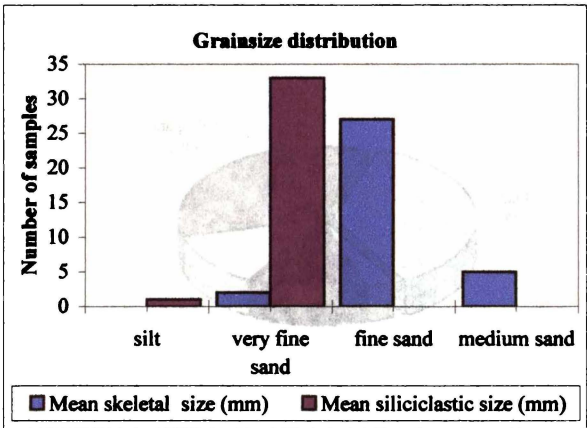
A



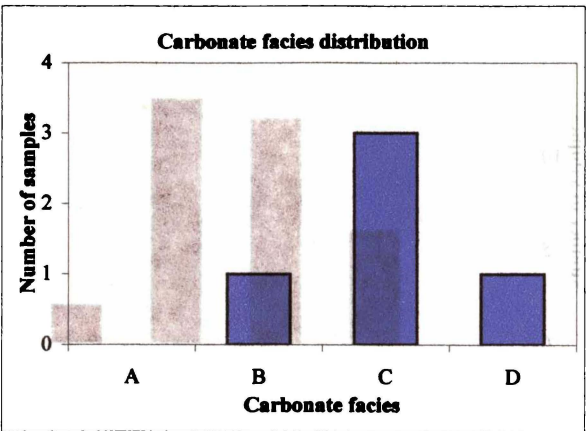
B



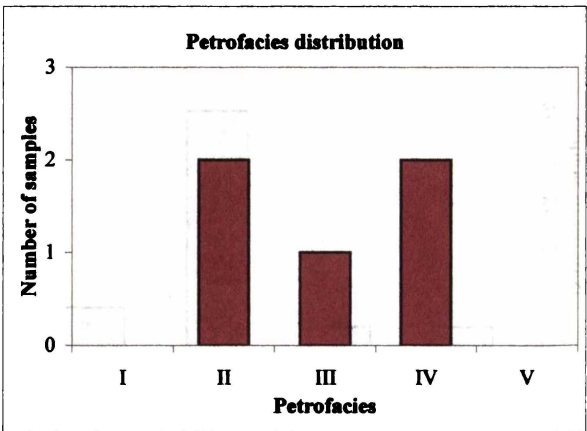
C



D



E

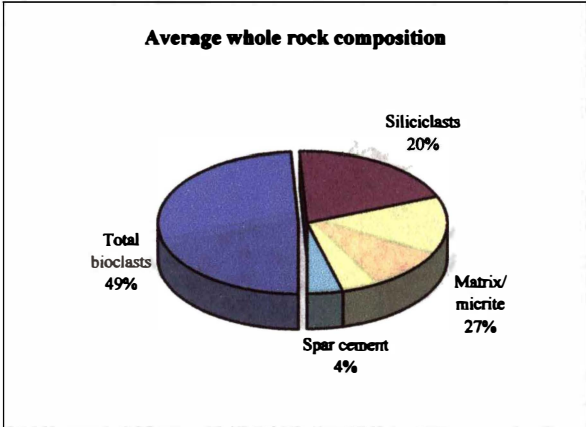


F

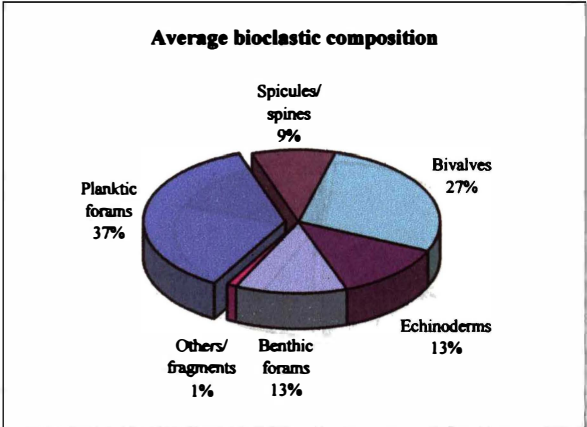
A4.4.5

Waihapa-2

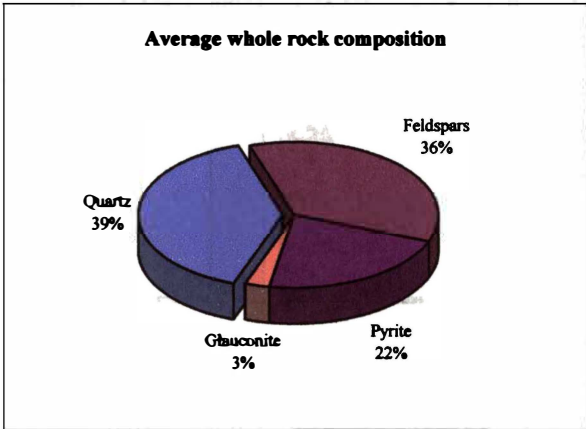
Tikorangi Formation Well Petrographic Summary



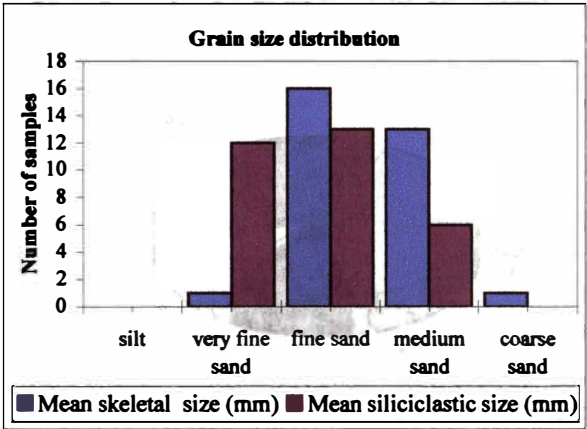
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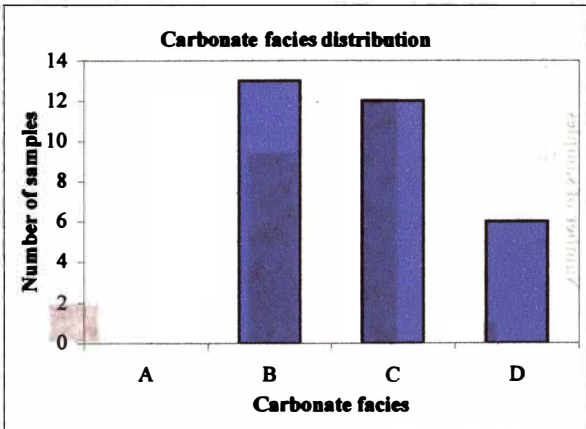
B



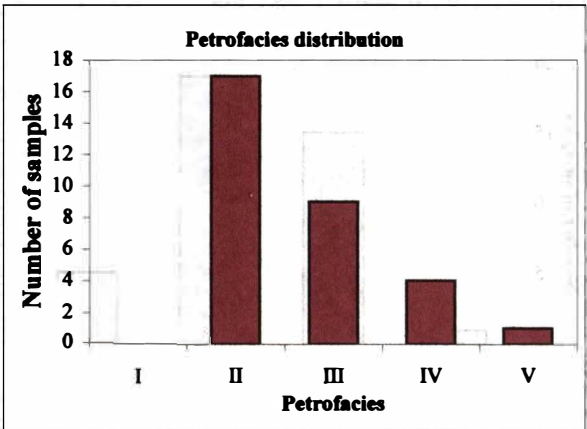
C



D



E

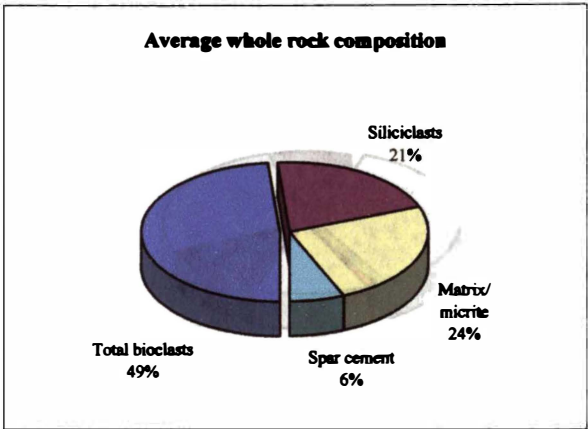


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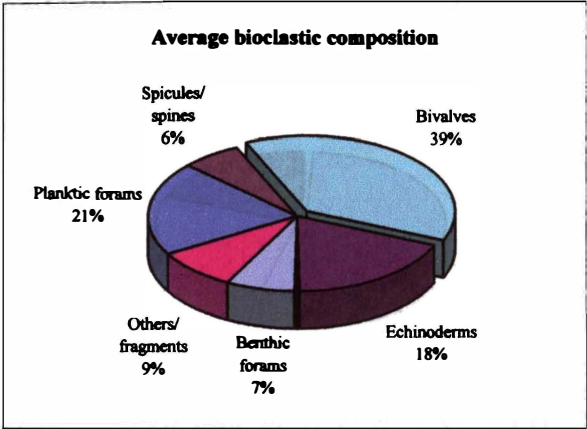
A4.4.6

Waihapa-5

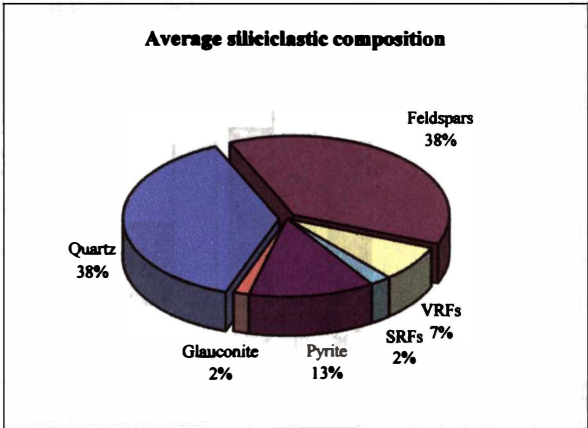
Tikorangi Formation Well Petrographic Summary



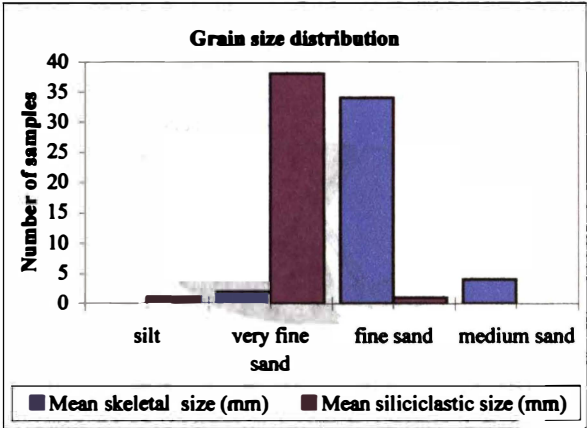
A



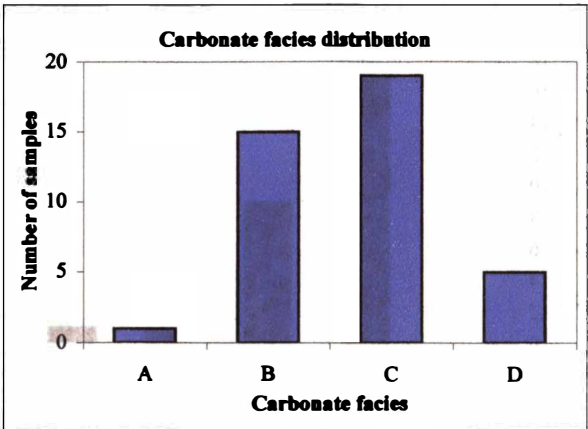
B



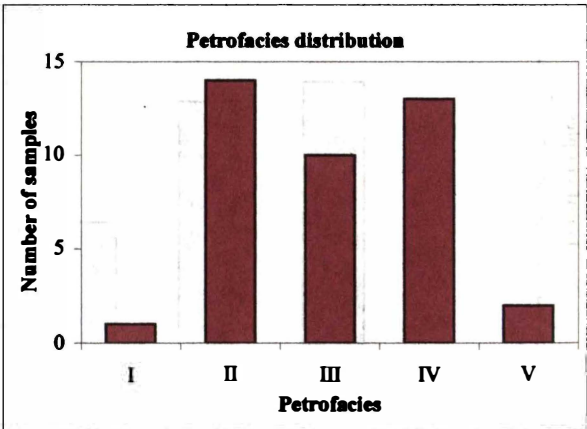
C



D



E

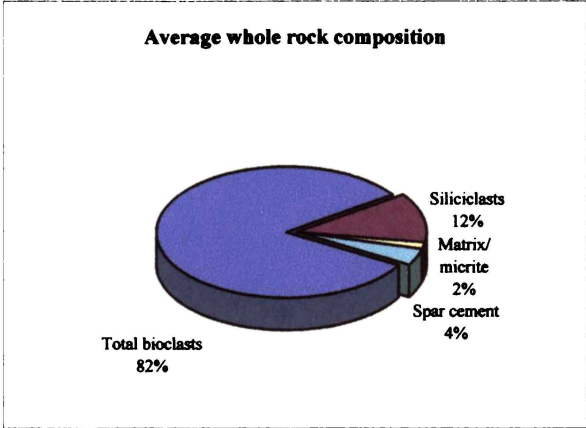


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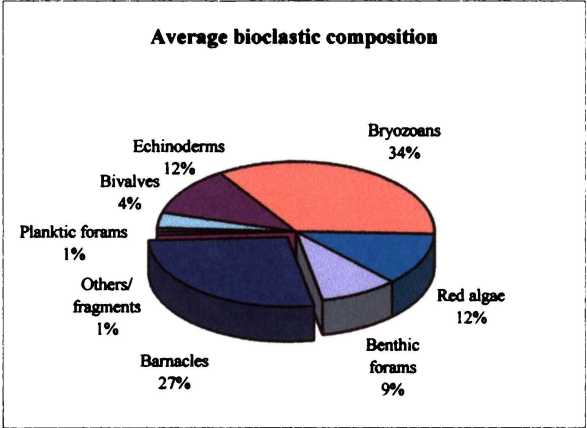
A4.4.7

Hu Rd-1A

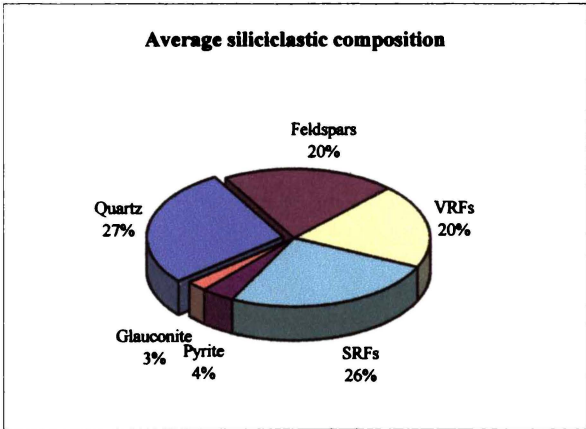
Tikorangi Formation Well Petrographic Summary



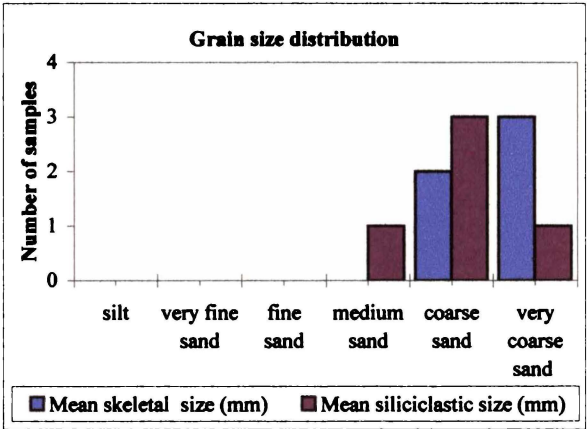
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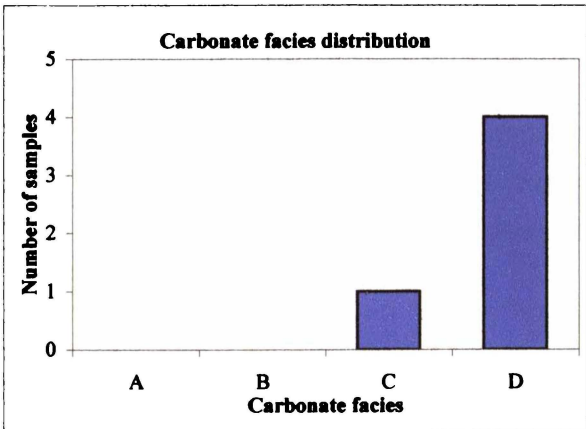
B



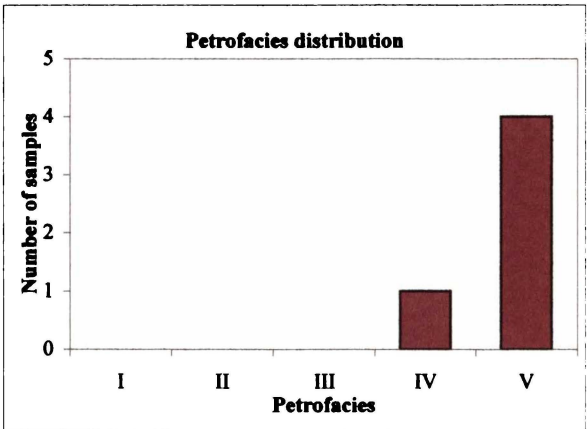
C



D



E



F

A4.4.8

APPENDIX 4.5

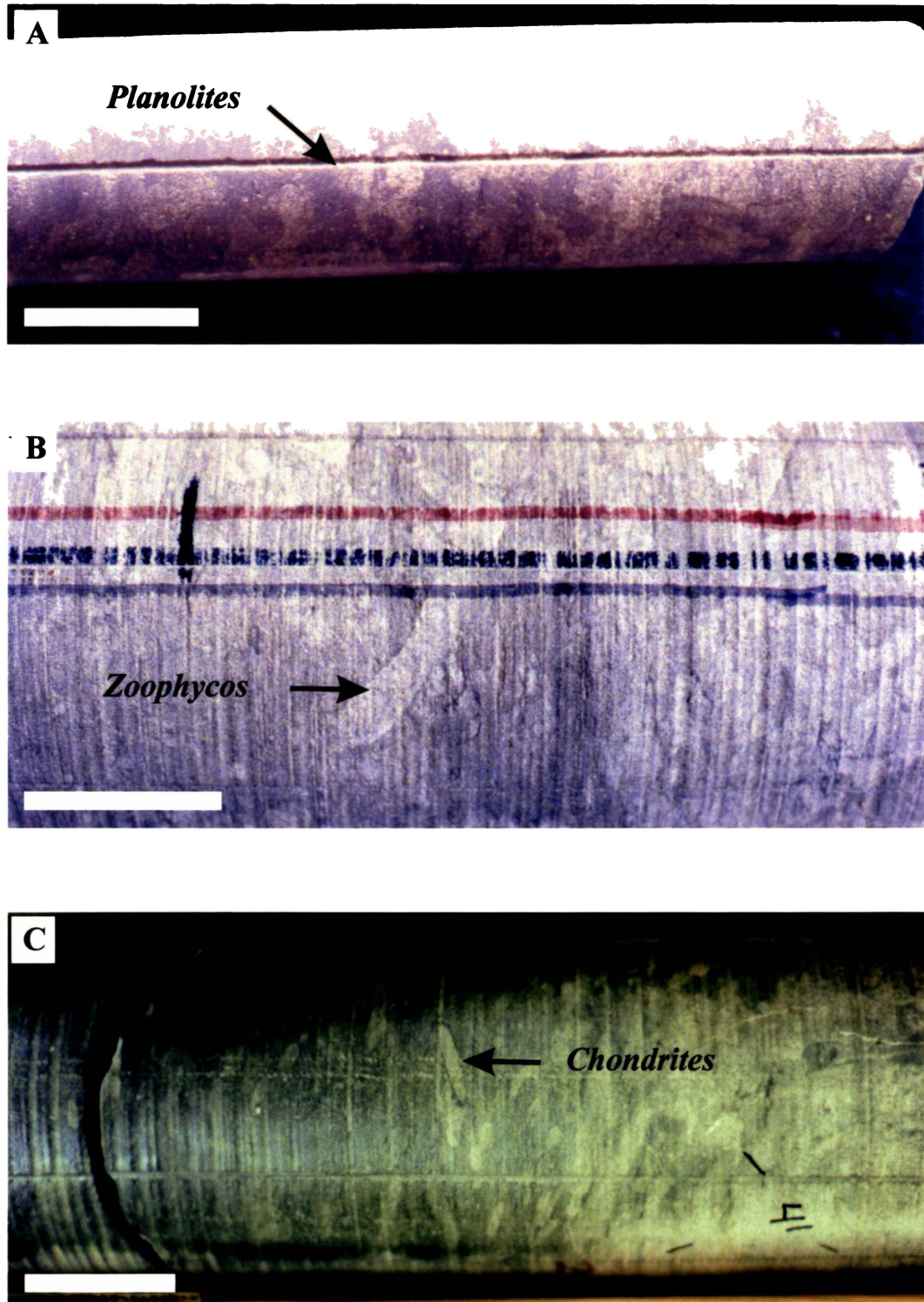
Core photograph of brecciated basement lithoclasts



A4.5 The rare occurrence of brecciated basement lithoclasts in Hu Rd-1A core (2964 mAH) representing the shallow-shelfal megafacies of the Tikorangi Formation, indicates close proximity to subaerially exposed basement, either as an isolated Mesozoic basement paleo-high, or perhaps a fault-controlled block of the Patea-Tongaporutu-Herangi High. Scale shown in metres. Scale bar = 5 cm.

APPENDIX 4.6

Examples of trace fossils in Tikorangi Formation core



A4.6 Representative photographs of the *Planolites*-*Chondrites*-*Zoophycos* assemblage, typical bathyal depth indicators, occurring in Tikorangi Formation core samples. (A) Diffuse blebs and mottles of *Planolites*-like borrows occurring mainly as subcircular, elliptical, or lenticular shapes in cross-section. Waihapa-4, 2846 mAH. (B) Diffuse *Zoophycos* traces consisting of burrowed and back-filled sediment producing characteristic crescentic arcs. Ngaere-2 core, 2926.5 mAH. (C) *Chondrites* appearing as small ovoid blebs. Waihapa-4, 2827 mAH. White scale bar = 5 cm.

Appendix 4.7

Phi values (ϕ)	Particle diameter (mm)	Wentworth grades
-1	2.0	Very coarse sand
0	1.0	
1	0.5	Coarse sand
2	0.25	Medium sand
3	0.125	Fine sand
4	0.0625	Very fine sand
8	0.0039	Silt
		Clay

The grainsize scale used in this study based upon the Wentworth (1922) grade scale, showing correlation with the phi scale.

APPENDIX 5.1

General diagenetic petrographic data sheets for the Tikorangi Formation host rock

PETROGRAPHIC DATA KEY:

Mineral

cal = calcite
dol = dolomite

Fe content

fe = ferroan as detected by thin section staining
non = nonferroan as detected by thin section staining

Crystal habit

eq = equant spar cement (may include coarse neomorphically aggraded micrite particularly infilling planktic foraminifera tests)
meq = micro-equant fine primary precipitated spar cement
ms = microspar (denotes neomorphic aggradation of micrite to microspar)
syn = syntaxial rim spar cement
rhom = dolomite rhombohedra

Crystal size (recorded in mm)/development

Development refers to degree of syntaxial rim cement overgrowth where:

s = some development
m = moderate development
w = well developed

Nature

p = primary precipitate
sec = secondary/replacement origin

Colour/Clarity

dusty = partially dirty/inclusion-rich
clear (c) = clear sparry
/ = denotes mix of
dirty (d) = visibly very dirty/brown discolouration and inclusion-rich

Rel % inter cement = relative proportion of intergranular cement

Rel % intra cement = relative proportion of intragranular cement where:

blank space = feature absent
r = rare <1%
s = some 1-5%
m = many 5-15%
c = common 15-25%
vc = very common 25-50%
a = abundant 50-75%
va = very abundant >75%

CL signature

b = bright luminescence / ***denotes range of values***
- m = moderate luminescence - denotes separation of zones
dull (or d) = dull luminescence
non = non luminescent
z = concentrically zoned

Other features

Neomorphosed skeletons = aragonite to calcite (e.g., bivalves)
Pyrite replacement = replacement of skeletal grains

	Well Core number Box number	Hu 2 1A	Hu 2 3	Hu 2 4	Hu 2 6a	Hu 2 7		NT 1	NT 2		Mau 1	Mau 3
C e m e n t y p e s	Mineral	cal	cal	cal	cal	cal						
	Fe content	non	non	non	non	non						
	Crystal habit	syn	syn	syn	syn	syn						
	Crystal size/developmen	m	w	s-m	s	s-w						
	Nature	p	p	p	p	p						
	Colour/clarity	dusty	dusty	dusty	clear	dusty						
	Rel % inter cemen	s	s	r	s	c						
	Rel % intra cemen	-	-	-	-	-						
	CL signature	m	b/m	b/m	m	m						
	Mineral	cal	cal	cal	cal	cal					cal	cal
	Fe content	fe	fe	fe	fe	fe						
	Crystal habit	eq	eq	eq	eq	eq					eq	eq
	Crystal size	<.13	<.18	<.15	<.05	<.08					<.02	<.02
	Nature	prim	prim	prim	prim	prim					sec	sec
	Colour/clarity	dusty	dusty	dusty	dusty	dusty					dirty	dirty
	Rel % inter cemen	vc	vc	vc	c	m					-	-
	Rel % intra cemen	s	s	m	r	r					vc	vc
	CL signature	m	m	m	m	m					m	m
	Mineral		dol	dol	dol	dol						
	Fe content		fe	fe	fe	fe						
	Crystal habit		rhom	rhom	rhom	rhom						
	Crystal size		0.10	0.10	0.10	0.10						
	Nature		sec	sec	sec	sec						
	Colour/clarity		c/d	c/d	c/d	c/d						
	Rel % inter cemen		s	s	r	r						
	Rel % intra cemen		s	m	r	s						
	CL signature		m/d	m/d	m/d	m/d						
	Micrite cement/matrix %	s	s	m	m	m					va	va
	Rel % inter cemen	m	m	s	m	m					va	va
	Rel % intra cemen	vc	vc	c	vc	vc					s	s
	CL signature	mb	m	m	m	m					d	d
O t h e r	Porosity											
	Porosity type											
	Stylolitic grain contact											
	Condensed seams											
	Geopetal fabrics			s								
	Neomorphosed skeleton			r								s
	Silicification										r	
	Pyrite replacemen											
	Micrite to microspar	a	a	a	a	a					vc	vc
	Feldspar dissolution											
	Limonite staining											
	Skeletal grain boring	s	s	s	r	r						
	Pre-cement skel grain fractur	c	c	m	m	s						
	Post-cement skel grain fractur	s	s	r	-	s						

	Well Core number Box number	K 1	K 2	K 3		Tok 1	Tok 2	Tok 3		W2 1 1	W2 1 5	W2 1 6A
	Mineral									cal		cal
	Fe content									fe		fe
	Crystal habit									meq		meq
	Crystal size/developmen									0.08		0.02
	Nature									prim		prim
	Colour/clarity									clear		clear
	Rel % inter cement									-		c
	Rel % intra cement									m		r
C	CL signature									dull		dull
e	Mineral					cal	cal	cal		cal		
m	Fe content					fe	fe	fe		fe		
e	Crystal habit					ms	ms	ms		ms		
n	Crystal size					0.01	0.01	0.01		0.01		
t	Nature					sec	sec	sec		sec		
	Colour/clarity					dirty	dirty	dirty		dirty		
t	Rel % inter cement					s	s	s		s		
y	Rel % intra cement					vc	vc	vc		vc		
p	CL signature					dull	dull	dull		dull		
e	Mineral									dol	dol	dol
s	Fe content									fe	fe	fe
	Crystal habit									rhom	rhom	rhom
	Crystal size									0.01	0.01	0.01
	Nature									sec	sec	sec
	Colour/clarity									clear	clear	clear
	Rel % inter cement									s	s	s
	Rel % intra cement									-	-	-
	CL signature									z	z	b-n-d
	Micrite cement/matrix %					a	a	a		a	a	a
	Rel % inter cement					a	a	a		a	va	m
	Rel % intra cement					a	a	a		s	s	s
	CL signature					dull	dull	dull		dull	dull	dull
O	Porosity											
t	Porosity type											
h	Stylolitic grain contacts											
e	Condensed seams											
r	Geopetal fabrics											
	Neomorphosed skeletons									s		m
f	Silicification											s
e	Pyrite replacement											s
a	Micrite to microspar					c	c	c		s		c
t	Feldspar dissolution											
u	Limonite staining									m		
r												
e	Skeletal grain boring											
s	Pre-cement skel grain fracture											
	Post-cement skel grain fracture											

	Well	W2		W2	W2	W2	W2	W2	W2	W2	W2	
	Core number	1		2	2	2	2	3	3	3	3	
	Box number	7		3	7b	7c	11	1	2	4	7	
C e m e n t t y p e s	Mineral			cal	cal							
	Fe content			fe	fe							
	Crystal habit			meq	meq							
	Crystal size/development			0.1	0.1							
	Nature			prim	prim							
	Colour/clarity			clear	clear							
	Rel % inter cement			m	s							
	Rel % intra cement			r	c							
	CL signature			dull	non							
	Mineral	cal		cal	cal	cal	cal	cal	cal	cal	cal	
	Fe content	fe		fe	fe	fe	fe	fe	fe	fe	fe	
	Crystal habit	ms		ms	ms	ms	ms	ms	ms	ms	ms	
	Crystal size	0.02		0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03	
	Nature	sec		sec	sec	sec	sec	sec	sec	sec	sec	
	Colour/clarity	dirty		dirty	dirty	dirty	dirty	dirty	dirty	dirty	dirty	
	Rel % inter cement	c		c	c	c	c	c	c	c	c	
	Rel % intra cement	vc		vc	vc	vc	vc	vc	vc	vc	vc	
	CL signature	dull		dull	dull	dull	dull	dull	dull	dull	dull	
	Mineral	dol		dol	dol	dol	dol	dol	dol	dol	dol	
	Fe content	fe		fe	fe	fe	fe	fe	fe	fe	fe	
	Crystal habit	rhom		rhom	rhom	rhom	rhom	rhom	rhom	rhom	rhom	
	Crystal size	0.01		0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	
	Nature	sec		sec	sec	sec	sec	sec	sec	sec	sec	
	Colour/clarity	c		c/d	c/d	c/d	c/d	c/d	c/d	c/d	c/d	
	Rel % inter cement	s		m	m	m	s	r	s	r	r	
	Rel % intra cement	-		-	-	-	-	-	-	-	-	
	CL signature	b-n-d		z	z	z	z	n-m	d-m	m-n-n	n-d	
	Micrite cement/matrix %	c		m	m	m	m	vc	va	va	a	
	Rel % inter cement	c		m	m	m	c	vc	va	va	a	
	Rel % intra cement	s		s	m	m	m	m	s	s	s	
	CL signature	dull		dull	dull	dull	dull	dull	dull	dull	vdull	
O	Porosity											
t	Porosity type											
h	Stylolitic grain contacts	m		s				s	s	s	s	
e	Condensed seams	m				s	s		s	m	s	
r	Geopetal fabrics											
	Neomorphosed skeletons			s								
f	Silicification											
e	Pyrite replacement			r	r		s	r		s	s	
a	Micrite to microspar	c		c	vc		m	s	s		s	
t	Feldspar dissolution											
u	Limonite staining	m				s	s		s	s	s	
r												
e	Skeletal grain boring											
s	Pre-cement skel grain fracture											
	Post-cement skel grain fracture											

Well		W2	W2	W2	W2	W2		W2	W2		W2	
Core number		4	4	4	4	4		5	5		6	
Box number		1	5	6	10A	11C		1	2		2	
C e m e n t t y p e s	Mineral	cal	cal		cal							
	Fe content	fe	fe		fe							
	Crystal habit	meq	meq		meq							
	Crystal size/development	0.05	0.05		0.05							
	Nature	prim	prim		prim							
	Colour/clarity	clear	clear		clear							
	Rel % inter cement	s	-		-							
	Rel % intra cement	s	s		s							
	CL signature	vdull	vdull		vdull							
	Mineral	cal	cal	cal	cal	cal		cal	cal		cal	
	Fe content	fe	fe	fe	fe	fe		fe	fe		fe	
	Crystal habit	ms	ms	ms	ms	ms		ms	ms		ms	
	Crystal size	0.02	0.02	0.02	0.02	0.02		0.02	0.02		0.02	
	Nature	sec	sec	sec	sec	sec		sec	sec		sec	
	Colour/clarity	dirty	dirty	dirty	dirty	dirty		dirty	dirty		dirty	
O t h e r	Rel % inter cement	c	s	vc	c	m		-	s		c	
	Rel % intra cement	c	c	vc	m	c		c	c		c	
	CL signature	vdull	vdull	vdull	vdull	vdull		vdull	vdull		vdull	
	Mineral	dol	dol	dol?	dol						dol	
	Fe content	fe	fe		fe						fe	
	Crystal habit	rhomb	rhomb		rhomb						rhomb	
	Crystal size	0.01	0.01		0.01						0.01	
	Nature	sec	sec		sec						sec	
	Colour/clarity	c/d	c/d		c/d						c/d	
	Rel % inter cement	s	r		s						r	
	Rel % intra cement	-	-		-						-	
	CL signature	dull	vdull		vdull						vdull	
	Micrite cement/matrix %	c	vc	c	c	vc		a	a		c	
	Rel % inter cement	c	vc	c	c	c		a	a		c	
	Rel % intra cement	s	s	s	s	s		c	c		c	
	CL signature	vdull	vdull	vdull	dull	vdull		vdull	vdull		dull	
f e a t u r e s	Porosity											
	Porosity type											
	Stylolitic grain contacts				s	s		s				
	Condensed seams				s	m		s				
	Geopetal fabrics											
	Neomorphosed skeletons	s		r	s							
	Silicification	s		r				s				
	Pyrite replacement				s							
	Micrite to microspar	c	s		m	s		s	s		m	
	Feldspar dissolution											
	Limonite staining	s	s		s	s		s	s		s	
	Skeletal grain boring											
	Pre-cement skel grain fracture											
	Post-cement skel grain fracture											

	Well	W2	W2	W2		W2	W2	W2		W2	W2	W2
	Core number	7	7	7		8	8	8		9	9	9
	Box number	1	2	4		1A	1B	2		1	6B	9
C e m e n t t y p e s	Mineral			cal		cal	cal	cal		cal		cal
	Fe content			fe		fe	fe	fe		fe		fe
	Crystal habit			meq		meq	meq	meq		meq		meq
	Crystal size/development			0.05		0.05	0.05	0.05		0.05		0.03
	Nature			prim		prim	prim	prim		prim		prim
	Colour/clarity			clear		clear	clear	clear		clear		clear
	Rel % inter cement			-		-	-	-		-		-
	Rel % intra cement			r		r	r	r		s		s
	CL signature			vdull		non	non	non		non		non
	Mineral	cal	cal	cal		cal	cal	cal		cal	cal	
	Fe content	fe	fe	fe		fe	fe	fe		fe	fe	
	Crystal habit	ms	ms	ms		ms	ms	ms		ms	ms	
	Crystal size	0.03	0.03	0.02		0.02	0.03	0.03		0.02	0.03	
	Nature	sec	sec	sec		sec	sec	sec		sec	sec	
	Colour/clarity	dirty	dirty	dirty		dirty	dirty	dirty		dirty	dirty	
	Rel % inter cement	m	m	s		s	s	s		s	c	
	Rel % intra cement	c	c	s		s	s	c		s	c	
	CL signature	vdull	dull	vdull		vdull	vdull	vdull		vdull	vdull	
	Mineral	dol	dol	dol								
	Fe content	fe	fe	fe								
	Crystal habit	rhom	rhom	rhom								
	Crystal size	0.01	0.01	0.01								
	Nature	sec	sec	sec								
	Colour/clarity	c/d	c/d	c/d								
	Rel % inter cement	r	s	s-m								
	Rel % intra cement	-	-	-								
	CL signature	zon	zon	vdull								
	Micrite cement/matrix %	vc	c	c		vc	vc	vc		vc	c	vc
	Rel % inter cement	vc	c	c		c	vc	vc		vc	c	vc
	Rel % intra cement	c	c	c		c	s	c		c	s	c
	CL signature	dull	dull	dull		vdull	vdull	vdull		vdull	vdull	vdull
O	Porosity											
t	Porosity type											
h	Stylolitic grain contacts						m					
e	Condensed seams							r				
r	Geopetal fabrics											
	Neomorphosed skeletons						s	r				r
f	Silicification						s	r				r
e	Pyrite replacement											
a	Micrite to microspar	s	m	s		s	s	s		s	c	
t	Feldspar dissolution											
u	Limonite staining	s	s	s		s	s	s		s	s	
r												
e	Skeletal grain boring										s	
s	Pre-cement skel grain fracture											
	Post-cement skel grain fracture											

	Well	W2		W4	W4	W4	W4	W4	W4		W4	W4
	Core number	9		1	1	1	1	1	1		2	2
	Box number	12B		1	4	5	7	8	10		2	4
C e m e n t t y p e s	Mineral			cal	cal	cal	cal		cal		cal	
	Fe content			fe	non	non	non		non		fe	
	Crystal habit			meq	syn	syn	syn		syn		meq	
	Crystal size/development			0.1	mod	mod	poor		poor		0.1	
	Nature			prim	prim	prim	prim		prim		prim	
	Colour/clarity			clear	clear	clear	clear		clear		clear	
	Rel % inter cement			-	s-m	m	s		r		-	
	Rel % intra cement			m	-	-	-		-		s	
	CL signature			non	non	d-n	non		non		d/m	
	Mineral	cal			cal	cal	cal	cal	cal		cal	cal
	Fe content	fe			fe	fe	fe	fe	fe		fe	fe
	Crystal habit	ms			ms	ms	ms	ms	ms		ms	ms
	Crystal size	0.02			0.02	0.03	0.02	0.02	0.02		0.02	0.03
O t h e r f e a t u r e s	Nature	sec			sec	sec	sec	sec	sec		sec	sec
	Colour/clarity	dirty			dirty	dirty	dirty	dirty	dirty		dirty	dirty
	Rel % inter cement	m			-	m	c	s	c		-	c
	Rel % intra cement	m			s	m	c	c	vc		m	m
	CL signature	vdull			dull	vdull	vdull	dull	dull		dull	d/m
	Mineral					dol	dol	dol?				
	Fe content					fe	fe					
	Crystal habit					rhomb	rhomb					
	Crystal size					0.01	0.01					
	Nature					sec	sec					
	Colour/clarity					c/d	c/d					
	Rel % inter cement					r	r					
	Rel % intra cement					-	-					
	CL signature					n-d-n	d-n					
O t h e r f e a t u r e s	Micrite cement/matrix %	c		vc	vc	c	c	vc	c		vc	c
	Rel % inter cement	c		vc	vc	c	c	vc	c		vc	c
	Rel % intra cement	c		m	m	s	s	s	s		s	s
	CL signature	vdull		vdull	dull	dull	dull	dull	dull		vdull	d/m
	Porosity											
	Porosity type											
	Stylolitic grain contacts			s	s	c	c	s	m		m	m
	Condensed seams	s		s			s	s	s		m	m
	Geopetal fabrics											
	Neomorphosed skeletons	r										
	Silicification	r										
	Pyrite replacement											
	Micrite to microspar	m				c	c		c		s	c
	Feldspar dissolution											
O t h e r f e a t u r e s	Limonite staining								s		s	
	Skeletal grain boring											
	Pre-cement skel grain fracture				r							s
	Post-cement skel grain fracture											

	Well Core number Box number	W4	W4	W4	W4	W4		W4	W4	W4	W4	W4
		3	3	3	3	3		4	4	4	4	4
		3	9	13	14	20		1A	1B	2A	2B	5
C e m e n t t y p e s	Mineral	cal	cal		cal	cal			cal		cal	
	Fe content	fe	fe		fe	non			fe		fe	
	Crystal habit	meq	meq		meq	syn			meq		meq	
	Crystal size/development	0.1	0.1		0.1	poor			0.1		0.1	
	Nature	prim	prim		prim	prim			prim		prim	
	Colour/clarity	clear	clear		clear	clear			clear		clear	
	Rel % inter cement	-	-		-	-			-		-	
	Rel % intra cement	s	m		s	r			s		r	
	CL signature	dull	d/m		dull	dull			dull		non	
	Mineral	cal	cal	cal	cal	cal		cal	cal	cal	cal	cal
	Fe content	fe	fe	fe	fe	fe		fe	fe	fe	fe	fe
	Crystal habit	ms	ms	ms	ms	ms		ms	ms	ms	ms	ms
	Crystal size	0.02	0.03	0.2	0.02	0.02		0.03	0.02	0.02	0.02	0.03
	Nature	sec	sec	sec	sec	sec		sec	sec	sec	sec	sec
s	Colour/clarity	dirty	dirty	dirty	dirty	dirty		dirty	dirty	dirty	dirty	dirty
	Rel % inter cement	c	c	-	vc	m		c	s	c	m	s
	Rel % intra cement	m	m	c	c	c		c	c	c	s	s
	CL signature	dull	dull	d-n	dull	dull		dull	d-m	d-m	dull	dull
	Mineral	dol	dol	dol	dol	dol		dol	dol	dol	dol	dol
	Fe content	fe	fe	fe	fe	fe		fe	fe	fe	fe	fe
	Crystal habit	rhom	rhom	rhom	rhom	rhom		rhom	rhom	rhom	rhom	rhom
	Crystal size	0.01	0.01	0.01	0.01	0.01		0.01	0.01	0.01	0.01	0.01
	Nature	sec	sec	sec	sec	sec		sec	sec	sec	sec	sec
	Colour/clarity	clear	clear	clear	clear	clear		clear	clear	clear	clear	clear
	Rel % inter cement	s	s	r	s	r		s	s	s	s-m	s
	Rel % intra cement	-	-	-	-	-		-	-	-	-	-
	CL signature	z	z	z	d-n-d	?non		z	z	z	z	z
	Micrite cement/matrix %	c	c	a	m	c		m	vc	m	vc	v
O t h e r f e a t u r e s	Rel % inter cement	c	c	a	m	c		m	vc	m	vc	vc
	Rel % intra cement	s	s	s	s	s		s	s	s	c	c
	CL signature	dull	dull	dull	dull	dull		dull	d-m	d-m	dull	dull
	Porosity											
	Porosity type											
	Stylolitic grain contacts	m	m		m	s		s				
	Condensed seams	m			m	s		s				
	Geopetal fabrics											
	Neomorphosed skeletons	r								s		
	Silicification											
	Pyrite replacement											
	Micrite to microspar	c	c	s						c	m	s
	Feldspar dissolution											
	Limonite staining							m				
	Skeletal grain boring											
s	Pre-cement skel grain fracture					s						
	Post-cement skel grain fracture											

	Well Core number Box number	W4	W4	W4	W4		W4	W4		W4	W4	W4
		4	4	4	4		5	5		6	6	6
		8	10A	10B	11A		1A	2		3	4	9
C e m e n t t y p e s	Mineral				cal			cal			cal	
	Fe content				non			non			non	
	Crystal habit				syn			syn			syn	
	Crystal size/development				poor			poor			poor	
	Nature				prim			prim			prim	
	Colour/clarity				clear			dusty			clear	
	Rel % inter cement				r			s			s	
	Rel % intra cement				-			-			-	
	CL signature				dull			dull			dull	
	Mineral	cal	cal	cal	cal					cal	cal	cal
	Fe content	fe	fe	fe	fe					fe	fe	fe
	Crystal habit	ms	ms	ms	ms					ms	ms	ms
	Crystal size	0.02	0.02	0.02	0.02					0.02	0.03	0.02
	Nature	sec	sec	sec	sec					sec	sec	sec
O t h e r f e a t u r e s	Colour/clarity	dirty	dirty	dirty	dirty					dirty	dirty	dirty
	Rel % inter cement	-	s	m	s					c	vc	c
	Rel % intra cement	m	m	c	s					c	vc	vc
	CL signature	dull	dull	vdull	dull					vdull	vdull	vdull
	Mineral	dol	dol								cal	
	Fe content	fe	fe								fe	
	Crystal habit	rhom	rhom								meq	
	Crystal size	0.01	0.01								0.03	
	Nature	sec?	sec?								prim	
	Colour/clarity	c/d	c/d								clear	
	Rel % inter cement	s	r								s	
	Rel % intra cement	-	-								-	
	CL signature	z	z								non	
	Micrite cement/matrix %	vc	vc	c	vc		vc	vc		m	m	vc
	Rel % inter cement	vc	c	c	vc		vc	vc		m	m	vc
	Rel % intra cement	c	c	c	c		c	c		r	-	r
	CL signature	dull	dull	vdull	dull		vdull	dull		vdull	vdull	vdull
	Porosity											
	Porosity type											
	Stylolitic grain contacts	s	s	m	m		s	s			c	
	Condensed seams										r	
	Geopetal fabrics											
	Neomorphosed skeletons											
	Silicification											
	Pyrite replacement		s									
	Micrite to microspar									?c	vc	c
	Feldspar dissolution											
	Limonite staining										s	s
	Skeletal grain boring											
	Pre-cement skel grain fracture											
	Post-cement skel grain fracture											

	Well	W4	W4		W4	W4		W4	W5	W5	W5	W5
	Core number	6	6		7	7		8	1	1	1	1
	Box number	13	14		2A	4B		2	2	2	3	4A
C e m e n t t y p e s	Mineral				dol	dol			dol	cal	dol	dol
	Fe content				fe	fe						
	Crystal habit				rhomb	rhomb				syn		
	Crystal size/development				0.01	0.01				poor		
	Nature				sec	sec						
	Colour/clarity				c/d	c/d				dirty	dirty	dirty
	Rel % inter cement				r	r				r	m	m
	Rel % intra cement				-	-				-	-	-
	CL signature				n-d-n	z			z		z	z
	Mineral	cal	cal		cal	cal		cal		cal	cal	cal
	Fe content	fe	fe		fe	fe		fe		fe	fe	fe
	Crystal habit	ms	ms		ms	ms		ms		meq	meq	meq
	Crystal size	0.02	0.02		0.03	0.02		0.02		0.03	0.02	0.02
	Nature	sec	sec		sec	sec		sec		prim	prim	prim
O t h e r f e a t u r e s	Colour/clarity	dirty	dirty		dirty	dirty		dirty		clear	clear	clear
	Rel % inter cement	c	vc		c	m		m		-	-	-
	Rel % intra cement	c	vc		c	vc		vc		s	s	s
	CL signature	vdull	vdull		vdull	vdull		vdull		non	non	non
	Mineral	cal			dol	dol				cal	cal	cal
	Fe content	fe			fe	fe				fe	fe	fe
	Crystal habit	meq			rhomb	rhomb				ms	ms	ms
	Crystal size	0.03			0.01	0.01				0.02	0.02	0.02
	Nature	prim			sec	sec				sec	sec	sec
	Colour/clarity	clear			c/d	c/d				dirty	dirty	dirty
	Rel % inter cement	-			r	r				c	c	m
	Rel % intra cement	r			-	-				vc	vc	vc
	CL signature	non			z	z				vdull	vdull	vdull
	Micrite cement/matrix %	vc	ms		c	vc		vc		c	c	c
	Rel % inter cement	vc	ms		c	vc		vc		c	c	c
	Rel % intra cement	r	s		c	r		s		s	s	s
	CL signature	vdull	vdull		vdull	vdull		vdull		vdull	vdull	vdull
O	Porosity											
t	Porosity type											
h	Stylolitic grain contacts	s-m	c		m	s				m	s	s
e	Condensed seams		s								s	
r	Geopetal fabrics											
	Neomorphosed skeletons	s						s				
f	Silicification	s						s				s
e	Pyrite replacement									s		s
a	Micrite to microspar	c	vc		c	m		c		c		
t	Feldspar dissolution											
u	Limonite staining	s	s		s	m						
r												
e	Skeletal grain boring											
s	Pre-cement skel grain fracture											
	Post-cement skel grain fracture											

	Well	W5	W5	W5		W5	W5	W5	W5	W5		W5
		1	1	1		2	2	2	2	2		3
	Core number	7	8	9		1A	1B	1C	1D	7		3
	Box number											
C e m e n t t y p e s	Mineral	dol	dol	dol		dol	dol	dol	dol			dol
	Fe content	fe	fe	fe		fe	fe	fe	fe			fe
	Crystal habit	rhomb	rhomb	rhomb		rhomb	rhomb	rhomb	rhomb			rhomb
	Crystal size/development	0.01	0.01	0.01		0.01	0.01	0.01	0.01			0.01
	Nature	sec	sec	sec		sec	sec	sec	sec			sec
	Colour/clarity	c/d	c/d	c/d		c/d	c/d	c/d	c/d			dirty
	Rel % inter cement	s	s	s		s	m	s	s			-
	Rel % intra cement	-	-	-		-	-	-	-			s
	CL signature	z	z	z		z	z	z	z			z
	Mineral	cal								cal		cal
	Fe content	fe								fe		fe
	Crystal habit	meq								meq		meq
	Crystal size	0.02								0.02		0.02
	Nature	prim								prim		prim
	Colour/clarity	clear								clear		clear
O t h e r	Rel % inter cement	-								-		-
	Rel % intra cement	s								s		r
	CL signature	n								vdull		vdull
	Mineral	cal	cal	cal		cal	cal	cal	cal	cal		cal
	Fe content	fe	fe	fe		fe	fe	fe	fe	fe		fe
	Crystal habit	ms	ms	ms		ms	ms	ms	ms	ms		ms
	Crystal size	0.02	0.02	0.02		0.02	0.03	0.02	0.02	0.02		0.02
	Nature	sec	sec	sec		sec	sec	sec	sec	sec		sec
	Colour/clarity	c/d	c/d	c/d		c/d	c/d	c/d	c/d	c/d		c/d
	Rel % inter cement	c	c	s		ms	s	s	c	s		s
	Rel % intra cement	vc	vc	vc		vc	vc	vc	vc	vc		vc
	CL signature	vdull	vdull	n		vdull	vdull	vdull	vdull	vdull		vdull
	Micrite cement/matrix %	vc	vc	vc		vc	vc	vc	c	vc		vc
	Rel % inter cement	vc	vc	vc		vc	vc	vc	c	vc		vc
	Rel % intra cement	r	r	r		s	s	s	s	s		r
	CL signature	vdull	vdull	n		vdull	vdull	d	d	vdull		vdull
f e a t u r e s	Porosity											
	Porosity type											
	Stylolitic grain contacts									s		
	Condensed seams									s		
	Geopetal fabrics											
	Neomorphosed skeletons		s	s		s	s			s		s
	Silicification		s	s		s	s					s
	Pyrite replacement											
	Micrite to microspar	c	c	s		m	s	s	c			
	Feldspar dissolution											
	Limonite staining	s										
	Skeletal grain boring											
	Pre-cement skel grain fracture											
	Post-cement skel grain fracture											

	Well	W5	W5	W5	W5	W5	W5		W5	W5	W5	W5
	Core number	3	3	3	3	3	3		4	4	4	4
	Box number	5	9	11	14	15	19		4	6	11	17
C e m e n t t y p e s	Mineral	dol		dol	dol	dol	dol		dol	dol		dol
	Fe content	fe		fe	fe	fe	fe		fe	fe		fe
	Crystal habit	rhom		rhom	rhom	rhom	rhom		rhom	rhom		rhom
	Crystal size/development	0.01		0.01	0.01	0.01	0.01		0.01	0.01		0.01
	Nature	sec		sec	sec	sec	sec		sec	sec		sec
	Colour/clarity	clear		c/d	c/d	dirty	c/d		c/d	c/d		dirty
	Rel % inter cement	-		r	?	s	r		r	m		s
	Rel % intra cement	s		-	-	-	-		-	-		-
	CL signature	z		z	?	z	z		z	z		z
	Mineral	cal	cal	cal	cal	cal	cal		cal	cal	cal	cal
	Fe content	fe	fe	fe	fe	fe	fe		fe	fe	fe	fe
	Crystal habit	ms	ms	ms	ms	ms	ms		ms	ms	ms	ms
	Crystal size	0.02	0.03	0.02	0.02	0.02	0.02		0.03	0.02	0.03	0.02
	Nature	prim	prim	prim	prim	prim	prim		prim	prim	prim	prim
O t h e r	Colour/clarity	c/d	c/d	c/d	c/d	c/d	c/d		c/d	c/d	c/d	c/d
	Rel % inter cement	ms	c	m	m	m	m		m	m	s	r
	Rel % intra cement	vc	vc	vc	vc	vc	vc		vc	vc	vc	vc
	CL signature	dull	vdull	vdull	vdull	vdull	vdull		vdull	vdull	vdull	dull
	Mineral		cal				cal				cal	
	Fe content		fe				fe				fe	
	Crystal habit		meq				meq				meq	
	Crystal size		0.03				0.03				0.03	
	Nature		prim				prim				prim	
	Colour/clarity		clear				clear				clear	
	Rel % inter cement		-				-				-	
	Rel % intra cement		s				r				s	
	CL signature		vdull				vdull				n	
	Micrite cement/matrix %	vc	m	c	c	c	vc		vc	c	vc	vc
f e a t u r e s	Rel % inter cement	vc	m	c	c	c	c		c	c	vc	vc
	Rel % intra cement	r	r	r	r	r	r		r	r	r	r
	CL signature	vdull	vdull	vdull	vdull	vdull	vdull		vdull	vdull	vdull	vdull
	Porosity											
	Porosity type											
	Stylolitic grain contacts	s	c	c	m	s			m	c	m	m
	Condensed seams	s	c	c								
	Geopetal fabrics											
	Neomorphosed skeletons									s	s	
	Silicification									s	s	
	Pyrite replacement											
	Micrite to microspar											
	Feldspar dissolution											
	Limonite staining											
	Skeletal grain boring											
	Pre-cement skel grain fracture											
	Post-cement skel grain fracture											

	Well Core number Box number	W5	W5	W5		W5	W5	W5	W5	W5	W5	W5
		5 19A	5 20	5 21		6 1A	6 1B	6 2	6 3	6 4	6 5	6 7
C e m e n t t y p e s	Mineral	dol	dol	dol		dol	dol	dol	dol	dol	dol	dol
	Fe content	non	non	non		non	non	non	non	non	non	non
	Crystal habit	rhom	rhom	rhom		rhom	rhom	rhom	rhom	rhom	rhom	rhom
	Crystal size/development	0.01	0.01	0.01		0.01	0.01	0.01	0.01	0.01	0.01	0.01
	Nature	sec	sec	sec		sec	sec	sec	sec	sec	sec	sec
	Colour/clarity	c/d	clear	clear		clear	clear	clear	clear	clear	clear	clear
	Rel % inter cement	-	-	-		-	-	-	-	-	-	-
	Rel % intra cement	s	s	s		s	s	c	m	m	vc	c
	CL signature	z	z	z		z	z	z	z	z	z	z
	Mineral	cal	cal	cal		cal	cal	cal	cal	cal		cal
	Fe content	fe	fe	fe		fe	fe	fe	fe	fe		fe
	Crystal habit	ms	ms	ms		ms	ms	ms	ms	ms		ms
	Crystal size	0.02	0.02	0.02		0.03	0.03	0.02	0.02	0.02		0.02
	Nature	sec	sec	sec		sec	sec	sec	sec	sec		sec
O t h e r f e a t u r e s	Colour/clarity	dirty	dirty	dirty		dirty	dirty	dirty	dirty	dirty		dirty
	Rel % inter cement	c	m	c		c	c	c	s	c		s
	Rel % intra cement	vc	vc	vc		vc	vc	vc	vc	vc		vc
	CL signature	dull	dull	dull		dull	dull	dull	dull	dull		dull
	Mineral	cal				cal						cal
	Fe content	fe				fe						fe
	Crystal habit	meq				meq						meq
	Crystal size	0.10				0.10						0.06
	Nature	prim				prim						prim
	Colour/clarity	clear				clear						clear
	Rel % inter cement	-				m						-
	Rel % intra cement	s				-						s
	CL signature	vdull				dull						non
	Micrite cement/matrix %	c	c	m		c	m	m	c	m	m	vc
	Rel % inter cement	c	c	m		c	m	m	c	m	m	vc
	Rel % intra cement	r	r	r		r	r	r	r	r	r	r
	CL signature	dull	dull	dull		dull	dull	dull	dull	dull	dull	dull
	Porosity											
	Porosity type											
	Stylolitic grain contacts	m	c	c		c	c	c	s	c	s	s
	Condensed seams	s		m		s	m	s		m		
	Geopetal fabrics											
	Neomorphosed skeletons		s			s	s					
	Silicification		s									
	Pyrite replacement											
	Micrite to microspar	c	m			c	c	c	s	c		
	Feldspar dissolution											
	Limonite staining	s	s	s		s	s	s				
	Skeletal grain boring											
	Pre-cement skill grain fracture											
	Post-cement skel grain fracture											

	Well Core number Box number	W5	W5	W5	W5	W5	W5	W5		W6	W6	W6
		6 11	6 13	6 19	7 4	7 6	7 9B	7 17		4 2	4 6	4 12
C e m e n t t y p e s	Mineral	dol	dol							dol	dol	dol
	Fe content	non	non							non	non	non
	Crystal habit	rhom	rhom							rhom	rhom	rhom
	Crystal size/development	0.01	0.01							0.01	0.01	0.01
	Nature	sec	sec							sec	sec	sec
	Colour/clarity	c/d	c/d							c/d	c/d	c/d
	Rel % inter cement	-	-							-	-	-
	Rel % intra cement	s	c							c	m	m
	CL signature	?non	z							z	z	z
	Mineral	cal	cal	cal	cal	cal	cal	cal		cal	cal	cal
	Fe content	fe	fe	fe	fe	fe	fe	fe		fe	fe	fe
	Crystal habit	ms	ms	ms	ms	ms	ms	ms		ms	ms	ms
	Crystal size	0.03	0.02	0.02	0.03	0.02	0.02	0.02		0.03	0.02	0.02
	Nature	sec	sec	sec	sec	sec	sec	sec		sec	sec	sec
	Colour/clarity	dirty	dirty	dirty	dirty	dirty	dirty	dirty		dirty	dirty	dirty
O t h e r f e a t u r e s	Rel % inter cement	s	ms	s	-	-	-	-		vc	vc	vc
	Rel % intra cement	vc	vc	vc	vc	vc	vc	vc		vc	vc	vc
	CL signature	dull	dull	vdull	vdull	vdull	vdull	vdull		dull	dull	dull
	Mineral	cal										
	Fe content	fe										
	Crystal habit	meq										
	Crystal size	0.04										
	Nature	prim										
	Colour/clarity	clear										
	Rel % inter cement	-										
	Rel % intra cement	s										
	CL signature	non										
	Micrite cement/matrix %	vc	c	vc	vc	vc	vc	vc		c	m	m
	Rel % inter cement	vc	c	cal	vc	vc	vc	vc		c	m	m
	Rel % intra cement	r	r	r	r	r	r	r		-	-	-
	CL signature	dull	dull	vdull	vdull	vdull	vdull	vdull		dull	dull	dull
	Porosity											
	Porosity type											
	Stylolitic grain contacts	s	c	m	m	m	c	s			m	c
	Condensed seams		c								s	c
	Geopetal fabrics											
	Neomorphosed skeletons	s										
	Silicification	s										
	Pyrite replacement											
	Micrite to microspar	s	m	s	s	s	s	s			c	
	Feldspar dissolution											
	Limonite staining		s		m	m	m	s				
	Skeletal grain boring											
	Pre-cement skel grain fracture											
	Post-cement skel grain fracture											

	Well Core number Box number	W6		W5		W5	W5	W5	W5			
		4 20		4 21		5 4	5 9	5 10	5 17			
C e m e n t t y p e s	Mineral	dol		cal		dol	dol	dol				
	Fe content	non		non		non	non	non				
	Crystal habit	rhom		syn		rhom	rhom	rhom				
	Crystal size/development	0.01		p		0.01	0.01	0.01				
	Nature	sec		prim		sec	sec	sec				
	Colour/clarity	clear		clear		clear	clear	clear				
	Rel % inter cement	m		r		s	s	s				
	Rel % intra cement	-		-		-	-	-				
	CL signature	z		non		z	z	z				
	Mineral	cal		cal		cal	cal	cal	cal			
	Fe content	fe		fe		fe	fe	fe	fe			
	Crystal habit	ms		ms		ms	ms	ms	ms			
	Crystal size	0.03		0.02		0.02	0.02	0.02	0.02			
	Nature	sec		sec		sec	sec	sec	sec			
	Colour/clarity	dirty		dirty		dirty	dirty	dirty	dirty			
	Rel % inter cement	-		m		m	c	m	c			
	Rel % intra cement	vc		c		vc	vc	vc	vc			
	CL signature	dull		dull		dull	dull	dull	dull			
	Mineral			cal								
	Fe content			fe								
	Crystal habit			meq								
	Crystal size			0.08								
	Nature			prim								
	Colour/clarity			clear								
	Rel % inter cement			-								
	Rel % intra cement			s								
	CL signature			non								
	Micrite cement/matrix %	vc		vc		vc	c	c	c			
	Rel % inter cement	vc		vc		vc	s	c	c			
	Rel % intra cement	s		s		s	s	s	s			
	CL signature	dull		dull		dull	dull	dull	dull			
O t h e r f e a t u r e s	Porosity											
	Porosity type											
	Stylolitic grain contacts			m		m	c	s	m			
	Condensed seams						s					
	Geopetal fabrics											
	Neomorphosed skeletons			s				s				
	Silicification											
	Pyrite replacement											
	Micrite to microspar			c								
	Feldspar dissolution											
	Limonite staining											
	Skeletal grain boring											
	Pre-cement skel grain fracture			s					m			
	Post-cement skel grain fracture											

Appendix 5.2

Petrographic data for examples of the Tikorangi Formation dolomite petrotypes

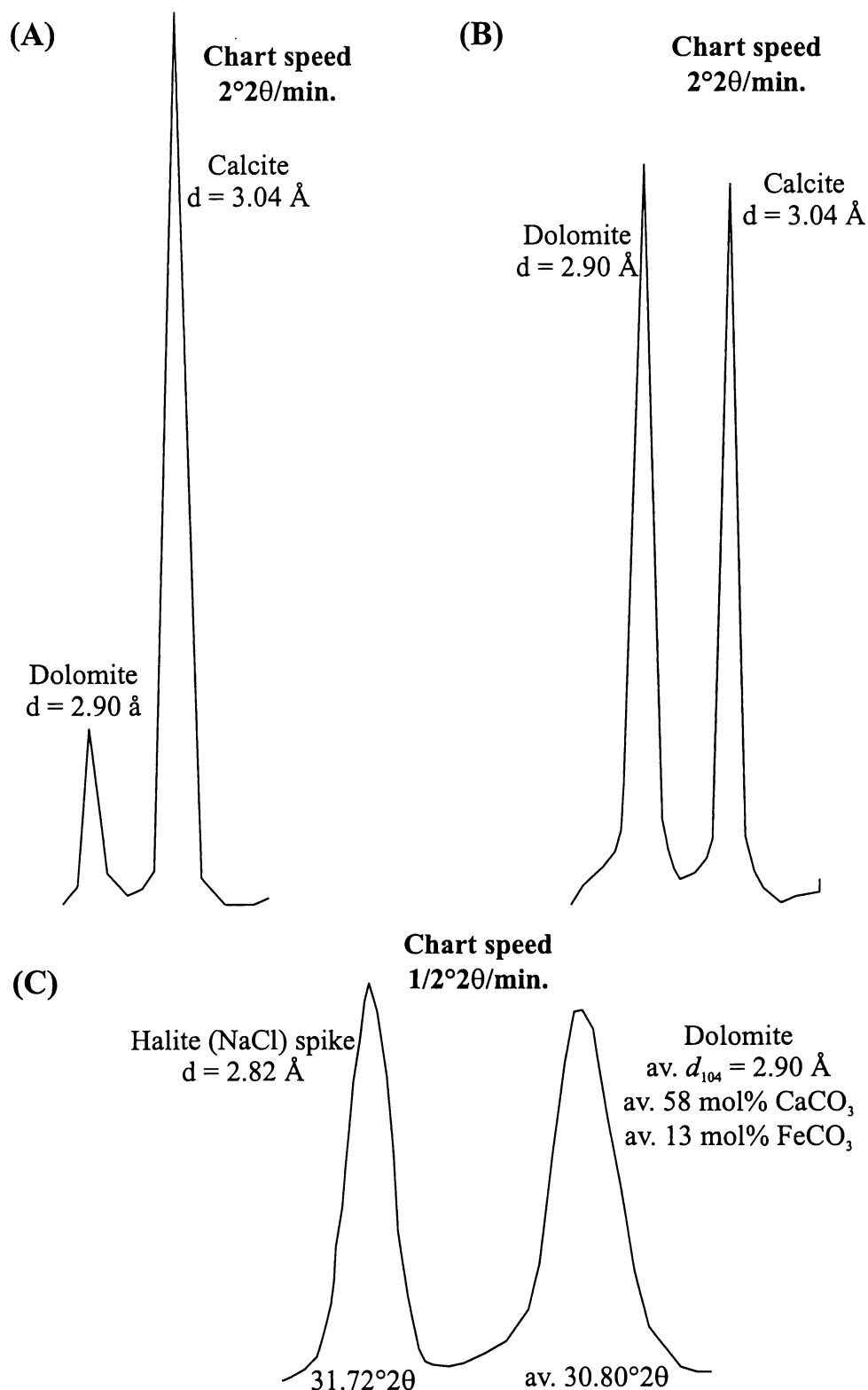
Sample	Depth (m)	Dolomite petrotype	% Intra. dolomite	% Inter. dolomite	Rock classification (Dunham 1962)	Total bioclast %	Siliciclastic grain %	Spar cement %	Micrite/ matrix %
Hu2.1a	2962.00	1a	s	s	Grainstone	85	10	4	1
Hu2.3	2963.50	1a	s	s	Grainstone	82	13	4	1
Hu2.4	2966.50	1a	s	m	Grainstone	87	3	7	3
Hu2.6a	2967.00	1a	r	r	Pw grainstone	66	30	2	2
Hu2.7	2968.50	1a	r	s	Grainstone	90	5	4	1
Mau1	2522.10	-	-	-	Wackestone	25	1	0	74
Mau2	2519.10	-	-	-	Wackestone	25	1	0	74
Mau3	2517.00	-	-	-	Wackestone	30	1	0	69
NG2.4.1	2984.50	2c	s	-	Grainstone	75	5	15	5
NG2.5.3	3003.55	3a	c	-	Pw grainstone	30	7	30	33
NG2.7.13	3073.15	1b	c	-	Packstone	70	5	4	21
W2.2.11	2928.65	2a	s	-	Packstone	65	15	5	15
W2.2.7b	2924.70	3b	m	-	Packstone	75	5	5	15
W2.2.7c	2925.00	3b	m	-	Packstone	76	4	5	15
W2.4.10a	2986.25	3a	s	-	Packstone	50	15	3	32

Sample	Depth (m)	Dolomite petrotype	% Intra. dolomite	% Inter. dolomite	Rock class	Total bioclast %	Siliciclastic grain %	Spar cement %	Micrite/ matrix %
W2.4.5	2981.30	3a	r	-	Wackestone	35	35	5	25
W2.7.4	2998.20	3a	s-m	-	Wackestone	30	25	0	45
W4.4.1a	2883.40	1b	s	-	Packstone	60	20	5	15
W4.4.2a	2884.20	1b	s	-	Pw grainstone	65	5	10	20
W4.7.2b	3005.60	2a	r	-	Packstone	65	20	5	10
W4.7.4c	3007.00	1b	r	-	Pw grainstone	65	20	5	10
W5.1.3	3007.00	3b	m	-	Packstone	70	15	5	10
W5.1.4a	3008.50	1b	m	-	Packstone	70	10	5	15
W5.2.1b	3015.25	1b	m	-	Pw grainstone	75	10	7	8
W5.5.19a	3109.00	3a	-	s	Pw grainstone	60	20	10	10
W5.5.9	3099.00	2a	s	-	Pw grainstone	55	15	15	15
W5.6.1b	3141.00	3b	-	s	Pw grainstone	60	10	15	15
W5.6.2	3141.40	2b	-	c	Pw grainstone	55	10	25	10
W5.6.4	3143.00	3a	-	m	Grainstone	72	10	13	5
W5.6.5	3145.00	2b	-	c	Grainstone	40	10	35	15
W6.4.2	3111.00	2a	-	c	Wackestone	25	12	0	63
W6.4.20	3126.60	2c	-	m	Wackestone	25	25	0	50

r = <1%, s = 1-5%, m = 5-15, c = 15-25, Pw grainstone = poorly washed grainstone, intra. = intragranular, inter. = intergranular.

APPENDIX 5.3

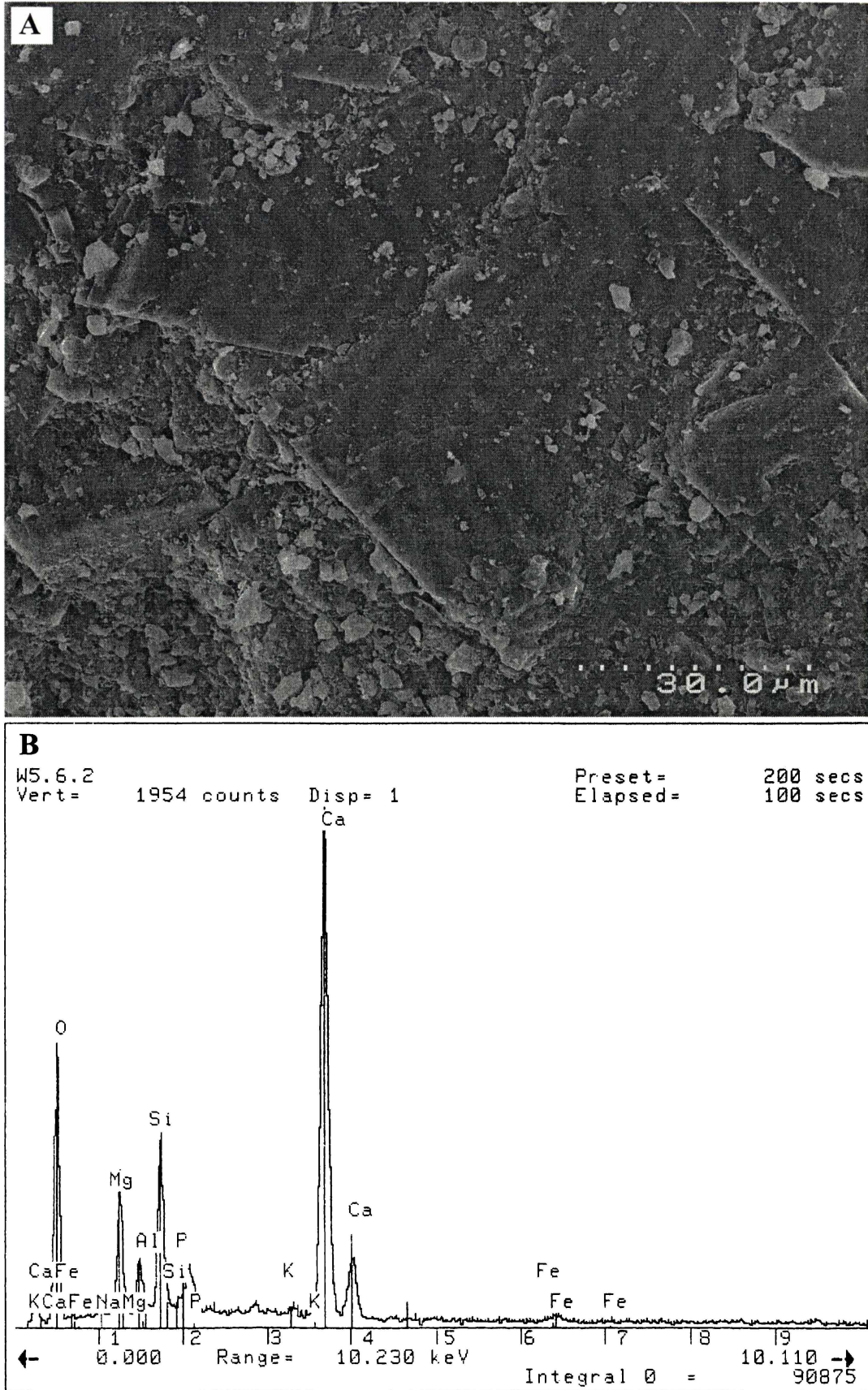
XRD of dolomite in the Tikorangi Formation



Schematic representative XRD traces showing the presence of dolomite and the relative peak heights of dolomite and calcite in bulk powder unoriented mounts of Tikorangi Formation in (A) a typical sample containing a few percent dolomite and in (B) a dolomite-rich sample containing some 50% dolomite. (C) The use of a halite (NaCl) spike and slow scan speed enables the accurate positing of the d_{104} dolomite peak position for determination of Mg and Fe contents.

APPENDIX 5.4

SEM of dolomite rhombohedra



(A) SEM of dolomite rhombohedra in the Tikorangi Formation host rock showing slight curvature of crystal boundaries. (B) SEM EDAX point analysis of a rhomb-shaped crystal is confirmed as dolomite by the presence of Mg and Ca.

APPENDIX 6.1

Bulk Tikorangi Formation trace element data

Sample no.	Petrofacies	Megafacies	Dolomite %	Dolomite % range	Mg ppm	Mg %	Ca ppm	Na ppm	Fe ppm	Sr ppm	Mn ppm	Carbonate %
Hu2.3	Grainstone	Shelfal	2	1-15	5,737	0.57	373,285	963	1,671	776	177	80.0
Hu2.4	Grainstone	Shelfal	8	1-15	13,207	1.32	757,934	1,003	1,110	1,255	490	91.1
Hu2.6A	Pw grainstone	Shelfal	14	1-15	20,146	2.01	338,056	1,696	5,400	828	232	45.0
Hu2.7	Grainstone	Shelfal	0	0	2,060	0.21	364,527	164	2,248	636	191	99.8
Mau1	Wackestone	* see note	*	*	73,736	7.37	472,750	513	23,280	21,689	390	40.6
Mau2	Wackestone	Basinal	0	0	1,771	0.18	369,484	3,014	5,746	2,007	1,501	31.9
Mau4	Wackestone	Basinal	0	0	1,485	0.15	432,775	1,296	5,038	2,009	1,504	36.9
NG2.1.3	Grainstone	Foredeep	1	1-15	4,756	0.48	395,693	2,801	4,450	3,134	97	75.3
NG2.1.5	Packstone	Foredeep	5	1-15	9,453	0.95	280,385	4,669	5,637	14,997	118	43.7
NG2.1.8	Wackestone	Foredeep	6	1-15	11,146	1.11	384,877	22,187	92,308	2,734	387	18.9
NG2.2.3	Packstone	Foredeep	2	1-15	5,242	0.52	381,782	822	3,566	1,907	58	70.1
NG2.2.7	Packstone	Foredeep	2	1-15	6,193	0.62	444,864	2,543	7,059	2,986	189	40.0
NG2.3.1	Packstone	Foredeep	3	1-15	7,085	0.71	189,902	4,155	9,595	2,213	203	47.9
NG2.3.2	Mudstone	Foredeep	11	1-15	16,689	1.67	260,969	13,257	25,094	3,890	408	14.8
NG2.3.8	Wackestone	Foredeep	8	1-15	13,667	1.37	179,071	7,939	14,105	3,780	325	22.2
NG2.4.9	Wackestone	Foredeep	11	1-15	16,983	1.70	292,881	7,085	6,041	3,492	95	29.2
NG2.4.16	Wackestone	Foredeep	5	1-15	8,917	0.89	378,197	3,466	3,373	1,168	68	59.6

Sample no.	Petrofacies	Megafacies	Dolomite %	Dolomite % range	Mg ppm	Mg %	Ca ppm	Na ppm	Fe ppm	Sr ppm	Mn ppm	Carbonate %
NG2.5.3	Pw grainstone	Foredeep	16	>15	22,909	2.29	374,692	907	7,746	2,640	175	64.7
NG2.5.6	Pw grainstone	Foredeep	8	1-15	12,667	1.27	285,152	7,879	5,167	2,533	137	32.8
NG2.6.7	Packstone	Foredeep	8	1-15	12,750	1.27	275,737	2,417	13,473	2,618	224	52.1
NG2.7.2	Packstone	Foredeep	1	1-15	4,775	0.48	267,608	4,457	9,055	3,860	132	50.0
NG2.7.19	Packstone	Foredeep	5	1-15	10,049	1.00	359,342	8,590	6,444	4,325	108	43.1
Tok1	Pw grainstone	Foredeep	5	1-15	9,235	0.92	432,216	2,171	2,500	3,578	262	52.2
Tok2	Pw grainstone	Foredeep	4	1-15	7,610	0.76	301,104	3,954	2,537	2,495	64	61.9
Tok3	Pw grainstone	Foredeep	1	1-15	4,051	0.41	309,606	2,850	1,743	3,326	72	69.1
W2.1.1	Pw grainstone	Foredeep	0	0	3,673	0.37	389,603	1,027	11,400	2,079	217	70.4
W2.2.3	Grainstone	Foredeep	3	1-15	6,535	0.65	386,067	1,218	9,478	2,180	129	81.4
W2.2.11	Packstone	Foredeep	3	1-15	6,965	0.70	245,844	5,585	10,256	2,173	255	60.3
W2.3.7	Packstone	Foredeep	0	0	2,309	0.23	278,017	1,031	11,407	1,940	214	64.9
W2.4.5	Wackestone	Foredeep	4	1-15	8,586	0.86	410,518	2,951	22,968	9,039	358	37.1
W2.4.10A	Wackestone	Foredeep	14	1-15	21,086	2.11	371,246	1,193	10,224	2,473	183	62.4
W2.6.2	Wackestone	Foredeep	7	1-15	12,265	1.23	274,243	2,434	15,523	4,511	220	52.2
W2.7.4	Wackestone	Foredeep	12	1-15	18,314	1.83	254,133	3,663	12,901	2,990	226	61.7
W2.8.2	Wackestone	Foredeep	5	1-15	9,728	0.97	192,438	6,500	12,485	3,581	170	50.0
W2.9.12B	Wackestone	Foredeep	11	1-15	17,557	1.76	378,705	4,285	14,612	2,265	219	53.0
W4.1.5	Grainstone	Foredeep	7	1-15	11,853	1.19	263,176	7,537	8,097	1,157	94	86.5
W4.1.10	Grainstone	Foredeep	0	0	3,457	0.35	288,858	590	7,516	2,080	116	85.7
W4.3.20	Packstone	Foredeep	8	1-15	13,764	1.38	365,546	449	15,546	3,229	168	68.7
W4.4.3	Wackestone	Foredeep	18	>15	26,019	2.60	237,113	9,867	73,981	4,417	1,421	20.3

Sample no.	Petrofacies	Megafacies	Dolomite %	Dolomite % range	Mg ppm	Mg %	Ca ppm	Na ppm	Fe ppm	Sr ppm	Mn ppm	Carbonate %
W4.4.8	Packstone	Foredeep	11	1-15	17,377	1.74	272,984	2,405	18,691	2,071	366	49.4
W4.6.4	Wackestone	Foredeep	17	>15	24,373	2.44	213,526	1,562	14,727	2,956	253	58.4
W4.6.14	Grainstone	Foredeep	20	>15	27,935	2.79	255,698	3,256	15,219	3,128	273	58.1
W4.8.2	Wackestone	Foredeep	6	1-15	10,497	1.05	240,186	7,589	10,840	2,760	233	34.2
W5.1.2	Packstone	Foredeep	8	1-15	13,173	1.32	383,224	5,937	12,721	1,599	212	68.6
W5.1.7	Wackestone	Foredeep	5	1-15	9,205	0.92	394,770	9,456	6,969	3,521	127	47.6
W5.1.9	Mudstone	Foredeep	66	>15	85,526	8.55	131,053	8,717	45,757	3,135	902	30.4
W5.2.1A	Pw grainstone	Foredeep	70	>15	91,114	9.11	191,453	772	41,378	3,323	518	53.5
W5.2.7	Packstone	Foredeep	4	1-15	8,279	0.83	269,542	3,292	16,402	2,680	229	51.6
W5.3.3	Wackestone	Foredeep	8	1-15	13,277	1.33	327,665	9,451	20,657	2,829	326	30.5
W5.3.11	Grainstone	Foredeep	7	1-15	11,910	1.19	372,682	1,960	10,015	2,996	116	66.5
W5.3.15	Wackestone	Foredeep	8	1-15	13,331	1.33	175,041	4,335	13,173	3,389	288	24.8
W5.3.19	Pw grainstone	Foredeep	0	0	3,414	0.34	255,243	293	4,622	3,622	85	61.4
W5.4.4	Packstone	Foredeep	4	1-15	8,225	0.82	368,064	3,372	9,045	355	24	55.7
W5.4.17	Packstone	Foredeep	11	1-15	16,838	1.68	288,035	2,754	5,822	7,565	96	50.4
W5.4.21	Grainstone	Foredeep	6	1-15	10,630	1.06	406,780	6,368	4,501	6,334	110	41.1
W5.5.10	Pw grainstone	Foredeep	2	1-15	5,700	0.57	252,162	5,385	4,786	1,376	112	50.5
W5.5.17	Pw grainstone	Foredeep	0	0	2,983	0.30	224,949	1,451	1,962	4,658	76	73.7
W5.5.21	Wackestone	Foredeep	4	1-15	8,751	0.88	418,897	951	1,971	5,105	61	78.8
W5.6.1A	Pw grainstone	Foredeep	3	1-15	6,866	0.69	381,785	2,060	2,060	2,872	57	77.1
W5.6.7	Pw grainstone	Foredeep	51	>15	67,560	6.76	333,780	7,043	8,444	919	130	52.3
W5.6.13	Wackestone	Foredeep	24	>15	32,645	3.26	326,452	6,913	9,138	4,105	213	41.8
W5.6.19	Wackestone	Foredeep	6	1-15	11,035	1.10	296,690	7,808	6,269	8,080	139	47.9

Sample no.	Petrofacies	Megafacies	Dolomite %	Dolomite % range	Mg ppm	Mg %	Ca ppm	Na ppm	Fe ppm	Sr ppm	Mn ppm	Carbonate %
W5.7.9B	Wackestone	Foredeep	8	1-15	13,022	1.30	268,584	13,294	7,689	1,751	149	37.0
W5.7.17	Wackestone	Foredeep	7	1-15	11,984	1.20	256,825	8,625	7,381	1,586	163	41.3
W6.3.8	Pw grainstone	Foredeep	2	1-15	6,061	0.61	213,675	4,079	14,627	1,592	760	25.6
W6.4.20	Wackestone	Foredeep	7	1-15	12,368	1.24	369,474	10,000	6,416	3,121	151	37.6

Note: Mau1 from the offshore Maui-1 well was not included in trace element calculations for the basinal megafacies due to its high Mg value which is far removed from the other values and is suspect given no other evidence to explain the presence of dolomite. However value was included for completeness in petrofacies (wackestone) TE calculations where the data was deemed to be much less influential if infact erroneous. Pw = poorly washed. For further sample details see Appendix 2.2.

APPENDIX 6.2

Other New Zealand Cenozoic limestone trace element data derived from his study

Sample	No. of samples	Mg (ppm)	Ca (ppm)	Na (ppm)	Fe (ppm)	Sr (ppm)	Mn (ppm)
OrB5	1	3,970	251,735	331	1,112	429	63
OrB2	1	4,382	388,628	615	896	431	62
OtC2	1	6,522	387,790	422	2,438	294	143
Bobs Cove	1	14,346	373,194	354	1,055	3,360	47

APPENDIX 6.3

New Zealand Cenozoic limestone trace element data (compiled from Winfield 1995; Winfield et al. 1996)

ESci. No.	Grid Ref.	Formation	Age	Ca (ppm)	Mg (ppm)	Na (ppm)	Fe (ppm)	Sr (ppm)	Mn (ppm)	Carbonate %
W93419	N02/115505	Waikuku	Miocene	590,821	7,961	3,294	10,308	427	312	48.0
W93420	N02/115505	Waikuku	Miocene	398,191	4,633	375	1,235	203	69	90.6
W93421	N02/120530	Waikuku	Miocene	381,131	6,186	653	2,209	413	161	90.5
W93422	N02/120530	Waikuku	Miocene	373,715	5,643	1,050	3,060	206	428	79.7
W93251	Q08/475733	Whangarei	Miocene	389,033	2,156	787	1,279	469	300	92.3
W93252	Q08/475733	Whangarei	Miocene	407,584	3,457	1,196	1,548	481	744	77.5
W93253	Q08/475733	Whangarei	Miocene	409,327	329	413	64	43	24	98.2
W93254	Q08/475733	Whangarei	Miocene	392,411	3,353	611	1,018	531	253	92.8
W93255	Q07/297004	Whangarei	Miocene	387,201	3,822	662	1,619	416	298	80.3
W93256	Q07/297004	Whangarei	Miocene	348,803	4,130	757	2,393	416	527	68.5
W93257	Q07/297004	Whangarei	Miocene	375,065	3,711	686	2,797	447	311	76.5
W93258		Whangarei	Oligocene	382,461	442	395	600	179	337	92.8
W93259	Q7/356975	Whangarei	Oligocene	384,926	2,628	1,120	2,017	845	44	86.8
W93260	Q07/356975	Whangarei	Oligocene	313,678	7,193	4,524	6,078	685	287	66.3
W93261	Q07/357974	Whangarei	Oligocene	383,828	4,273	2,584	3,454	819	302	78.2
W93262	Q06/268230	Whangarei	Oligocene	365,203	4,083	479	3,919	426	120	97.5
W93263	Q06/268230	Whangarei	Oligocene	387,989	2,910	424	620	327	97	96.9
W93264	P05/995403	Mahurangi	Oligocene	394,432	636	691	3,033	1,790	6,994	60.3
W93265	P05/995403	Mahurangi	Oligocene	375,981	241	379	1,558	2,430	5,002	91.8
W93266	P05/995403	Mahurangi	Oligocene	336,856	1,077	967	6,649	1,697	277	45.4
W93267	O06/459313	Mahurangi	Oligocene	387,012	1,143	3,411	3,362	1,407	231	61.0
W93268	O06/473336	Mahurangi	Oligocene	331,583	1,211	6,182	4,231	1,509	1,035	66.7
W93269	O06/473336	Mahurangi	Oligocene	376,691	1,544	4,495	4,454	1,663	241	48.1
W93270	O06/473336	Mahurangi	Oligocene	364,783	3,703	2,400	4,059	819	531	72.9
W93275	O05/566453	Argill. lst	Paleocene	387,340	1,684	3,807	2,944	418	3,785	45.2
W93276	O05/595616	Mahurangi	Oligocene	388,758	1,038	683	4,611	1,395	382	59.4
W93277		Mahurangi	Oligocene	405,912	265	381	1,671	1,596	2,849	93.4
W93279		Mahurangi	Oligocene	407,452	144	348	888	1,177	2,778	91.8
W93280	Q06/273234	Whangarei	Oligocene	327,937	3,300	441	608	217	108	95.8
W93281	P07/932973	Whangarei	Oligocene	413,341	985	677	3,492	1,360	312	70.2

ESci. No.	Grid Ref.	Formation	Age	Ca (ppm)	Mg (ppm)	Na (ppm)	Fe (ppm)	Sr (ppm)	Mn (ppm)	Carbonate %
W93282	P07/932973	Whangarei	Oligocene	384,698	3,172	525	2,743	464	80	93.3
W93283	P07/932973	Whangarei	Oligocene	344,630	3,836	613	3,149	531	144	87.3
W93284	P07/927972	Whangarei	Oligocene	381,495	3,673	762	6,292	502	149	70.3
W93285	P07/592597	Whangarei	Oligocene	390,346	4,586	600	4,690	719	2,802	95.3
W93286		Whangarei	Oligocene	342,543	548	390	5,323	682	684	89.0
W93287	Q08/108638	Mahurangi	Oligocene	389,384	3,196	1,087	8,078	508	370	51.6
W93288	Q08/203603	Mahurangi	Eocene	432,236	593	671	2,412	1,421	559	71.7
W93289	Q08/203603	Mahurangi	Eocene	397,265	1,604	3,842	3,989	1,190	223	61.4
W93290	Q08/203603	Mahurangi	Eocene	399,958	577	504	4,976	1,402	4,405	96.3
W93291	Q08/262641	Mahurangi	Oligocene	393,871	3,496	578	1,180	383	257	88.1
W93292	Q08/259640	Mahurangi	Oligocene	384,407	3,355	555	956	363	243	92.1
W93293		Mahurangi	Oligocene	404,994	2,014	431	4,658	336	387	95.3
W93294	Q08/259640	Mahurangi	Oligocene	390,800	643	427	7,775	651	868	98.3
W93295	Q08/259640	Mahurangi	Oligocene	409,769	533	624	2,782	1,373	398	73.7
W93371	R12/869570	Papakura	Miocene	363,216	3,008	460	2,938	272	437	86.5
W93372	R12/869570	Papakura	Miocene	379,766	2,460	844	2,844	394	407	65.0
W93373	R12/869570	Papakura	Miocene	376,441	2,374	399	2,996	228	491	88.5
W93296	R17/571006	Tirua	Miocene	348,447	1,364	396	421	183	214	95.3
W93297	R17/571006	Tirua	Miocene	389,464	1,732	410	423	207	209	97.6
W93298	R17/568005	Tirua	Miocene	412,414	2,427	496	1,760	352	86	96.0
W93299	R17/532084	Tirua	Miocene	394,469	3,508	2,329	5,633	587	376	68.7
W93300	S19/178425	Te Kuiti	Oligocene	349,887	1,919	948	5,440	354	1,490	88.6
W93301		Te Kuiti	Oligocene	393,321	1,056	332	3,712	141	1,720	99.5
W93302	S19/282373	Te Kuiti	Oligocene	375,193	3,997	774	2,772	668	119	77.7
W93303	S19/282373	Te Kuiti	Oligocene	409,327	4,582	580	498	699	55	98.2
W93374	S20/186982		Pliocene	375,486	4,172	1,331	2,403	689	243	69.5
W93243	S10/290011	Torehina	Oligocene	420,405	3,557	667	1,648	435	119	95.9
W93244	S10/290011	Torehina	Oligocene	393,532	4,316	476	6,729	367	190	84.1
W93245	T10/317006	Torehina	Oligocene	405,004	2,143	359	7,208	301	98	97.5
W93246	T10/317007	Torehina	Oligocene	416,978	1,866	477	2,431	234	53	93.8
W93247	T10/311007	Torehina	Oligocene	425,510	3,276	430	2,452	345	32	97.1
W93248	T10/311007	Torehina	Oligocene	394,750	958	377	8,299	363	161	99.1
W93249	T10/307010	Torehina	Oligocene	434,921	3,310	609	3,341	392	156	94.3
W93250	S10/289009	Torehina	Oligocene	422,940	4,544	2,655	7,692	706	223	73.1
-	N82/488780	Aotea	Oligocene	365,854	30,149	596	3,489	217	137	59.0

ESci. No.	Grid Ref.	Formation	Age	Ca (ppm)	Mg (ppm)	Na (ppm)	Fe (ppm)	Sr (ppm)	Mn (ppm)	Carbonate %
-	N82/488780	Orahiri	Oligocene	374,601	2,391	588	2,856	171	97	75.2
-	N82/410727	Orahiri	Oligocene	372,124	5,064	535	11,450	144	308	90.8
-	N82/410727	Orahiri	Oligocene	371,147	4,508	415	1,111	117	178	95.3
-	N82/410727	Orahiri	Oligocene	371,772	2,163	515	2,285	154	242	73.9
-	N83/557720	Otorohanga	Miocene	383,676	3,488	524	1,907	174	337	86.0
-	N83/557720	Otorohanga	Miocene	347,950	1,730	357	358	124	195	98.3
-	N83/557720	Otorohanga	Miocene	398,389	3,157	511	430	209	169	91.9
-	N83/557720	Otorohanga	Miocene	404,723	1,918	316	130	113	177	99.1
-	N83/580727	Orahiri	Oligocene	369,884	16,087	530	485	139	233	91.3
-	N83/580727	Otorohanga	Miocene	384,537	2,848	451	284	162	188	98.2
-	N83/580727	Otorohanga	Miocene	395,093	2,495	361	356	156	158	96.2
-	N91/433525	Orahiri	Oligocene	353,671	10,895	779	24,304	354	189	59.6
-	N91/433525	Orahiri	Oligocene	365,907	3,920	603	6,708	322	118	68.9
-	N91/433525	Otorohanga	Miocene	390,976	1,807	313	1,970	107	439	97.9
-	N91/306494	Otorohanga	Miocene	378,812	4,066	534	401	228	12,199	93.5
-	N73/375973	Orahiri	Oligocene	300,889	3,305	515	3,453	361	76	87.8
-	N73/375973	Aotea	Oligocene	386,773	5,133	758	1,934	229	255	83.7
-	N82/486896	Orahiri	Oligocene	391,626	3,021	465	1,406	178	93	96.0
-	N74/642943	Aotea	Oligocene	378,439	6,563	718	5,404	318	126	71.6
-	N73/445084	Aotea	Oligocene	363,386	9,428	852	7,818	251	395	50.9
-	N73/445084	Otorohanga	Oligocene	383,658	3,007	354	220	235	49	96.5
-	N73/445084	Otorohanga	Oligocene	383,706	3,977	485	903	275	51	93.2
-	N73/445084	Aotea	Oligocene	385,717	4,092	517	533	296	69	97.8
-	N73/445084	Aotea	Oligocene	384,317	4,319	529	1,617	368	71	90.3
-	N73/502025	Aotea	Oligocene	386,033	2,439	649	2,334	174	184	57.0
-	N73/502025	Aotea	Oligocene	368,630	3,072	770	4,030	282	161	55.4
-	N74/646034	Aotea	Oligocene	422,103	1,973	419	2,302	100	1,206	91.2
-	N74/646034	Aotea	Oligocene	413,153	1,633	400	2,562	73	512	93.7
-	N74/646034	Orahiri	Oligocene	397,107	4,997	767	6,640	291	631	76.0
-	N83/754727	Waitomo	Oligocene	388,079	2,473	603	6,730	157	753	61.1
-	N82/339861	Orahiri	Oligocene	393,543	3,060	426	1,266	218	71	97.8
-	N82/339861	Orahiri	Oligocene	416,355	3,615	515	2,094	203	103	80.2
-	N82/339861	Whaingaroa	Oligocene	388,854	4,093	697	3,952	332	183	63.5
-	N82/339861	Whaingaroa	Oligocene	389,072	3,402	385	3,412	189	500	94.1
-	N74/642943	Otorohanga	Miocene	421,857	1,884	339	351	99	209	95.5

ESci. No.	Grid Ref.	Formation	Age	Ca (ppm)	Mg (ppm)	Na (ppm)	Fe (ppm)	Sr (ppm)	Mn (ppm)	Carbonate %
-	N74/642943	Otorohanga	Miocene	395,905	3,761	373	490	245	70	95.8
-	N74/642943	Otorohanga	Miocene	409,267	2,756	334	459	222	73	98.0
-	N74/642943	Otorohanga	Miocene	406,836	3,749	460	3,164	363	110	90.6
-	N74/642943	Orahiri	Oligocene	407,784	3,594	516	3,000	208	117	80.7
-	N74/642943	Orahiri	Oligocene	402,444	2,845	605	1,633	237	151	94.9
-	N74/642943	Orahiri	Oligocene	392,135	2,872	538	2,032	168	342	90.6
-	N83/693809	Otorohanga	Miocene	415,291	2,662	384	1,746	168	298	94.0
-	N83/693809	Otorohanga	Miocene	407,166	1,832	325	384	134	92	98.2
-	N83/693809	Otorohanga	Miocene	430,772	2,027	312	311	151	82	98.7
-	N83/781734	Orahiri	Oligocene	441,669	2,231	978	1,483	409	446	89.7
-	N83/781734	Otorohanga	Oligocene	390,212	1,769	491	4,547	205	463	60.5
-	N91/294486	Mahoenui	Miocene	412,160	6,034	482	2,232	285	216	87.8
-	N91/294486	Mahoenui	Miocene	367,839	3,798	511	2,105	378	543	92.1
-	N83/730824	Otorohanga	Miocene	404,029	3,241	453	2,142	377	103	86.4
-	N83/730824	Orahiri	Oligocene	385,384	3,283	574	6,095	270	173	70.1
W93306	Z14/783868		Oligocene	403,449	4,364	543	3,098	103	517	94.0
W93307	Z14/782866		Oligocene	404,359	1,935	530	2,078	79	794	98.1
W93308	Y16/511366		Oligocene	410,859	582	630	1,660	743	970	82.5
W93309	Y16/511366		Oligocene	432,929	573	693	2,158	767	986	75.1
W93310	Y16/511366	Whangai Fm	Oligocene	400,637	2,255	589	5,174	602	1,101	75.4
W93311			Oligocene	407,812	415	4,948	1,710	863	1,133	99.0
W93312	Y17/527095	Patutahi	Miocene	397,667	4,905	6,005	6,257	244	570	75.5
W93313	Y17/527095	Patutahi	Miocene	404,676	5,781	6,719	11,434	217	809	78.0
W93314		Patutahi	Miocene	412,054	1,640	3,875	2,030	145	444	97.6
W93315	Y17/689997	Patutahi	Miocene	400,182	5,245	4,720	4,560	735	217	87.9
W93317	Y17/408806	Ormond	Pliocene	414,390	5,330	991	6,089	763	470	75.1
W93318	Y17/408806	Ormond	Pliocene	436,557	5,848	1,194	5,821	672	216	73.5
W93319	X18/300738	Patutahi	Miocene	408,834	9,173	729	1,495	337	112	88.4
		Patutahi	Miocene	378,647	4,655	3,528	621	379	84	96.7
W93320	X18/300738	Patutahi	Miocene	423,267	6,336	1,711	1,483	368	252	79.0
W93321	X18/300738	Patutahi	Miocene	416,667	6,192	5,921	2,154	599	232	77.6
W93322	Y18/312732	Patutahi	Miocene	419,739	10,437	523	2,984	337	167	88.3
W93323	X18/220682	Patutahi	Miocene	419,390	2,614	818	2,505	405	99	91.9
W93324	X18/100658	Opoiti	Pliocene	389,363	7,253	6,426	9,925	615	214	78.6
W93325		Opoiti	Pliocene	431,493	3,783	1,431	5,389	286	1,053	98.0

ESci. No.	Grid Ref.	Formation	Age	Ca (ppm)	Mg (ppm)	Na (ppm)	Fe (ppm)	Sr (ppm)	Mn (ppm)	Carbonate %
W93326	X18/027541	Whakapunake	Pliocene	397,410	20,442	1,879	5,130	808	159	78.9
W93327	X18/027541	Whakapunake	Pliocene	425,882	5,176	1,058	4,165	769	178	85.2
W93328	X19/147318	Whakapunake	Pliocene	420,532	5,051	1,649	722	1,021	74	97.0
W93329	X19/147318	Whakapunake	Pliocene	436,804	4,757	1,514	1,189	893	97	92.5
W93330	X19/147318	Whakapunake	Pliocene	417,595	4,457	1,490	2,897	873	140	85.3
W93331	V19/405218	Titikura	Pliocene	411,335	6,033	1,230	7,185	755	473	54.8
W93332	V19/405218	Titikura	Pliocene	411,657	6,404	2,039	5,201	937	307	76.6
W93334	V19/391272	Maungaharuru	Pliocene	417,873	7,240	1,363	8,109	734	494	48.4
W93335	V20/447094	Tangoio/Petane	Pliocene	437,443	2,833	1,010	1,371	721	95	88.3
W93336	V20/459080	Waipatiki/Petane	Pleistocene	433,315	2,613	1,481	1,274	898	130	91.9
W93337	V20/448060	Kaiwaka/Petane	Pleistocene	428,929	1,305	3,089	478	731	97	96.0
W93338	V20/489002	Tangoio/Petane	Pleistocene	445,977	1,724	658	1,799	241	204	92.8
W93339	V20/489002	Tangoio/Petane	Pleistocene	481,241	2,375	836	2,849	370	184	63.1
W93340	V20/484002	Tangoio/Petane	Pleistocene	473,588	1,371	866	879	263	141	93.4
W93341	V20/382907	Petane	Pleistocene	436,249	2,811	1,687	1,237	532	255	88.9
W93342	V21/386829	Petane	Pleistocene	430,799	5,344	1,505	1,996	819	185	91.8
W93343	V21/386829	Petane	Pleistocene	436,621	5,815	1,533	941	827	122	94.6
W93344	V21/418820	Park Is/Petane	Pleistocene	426,924	3,636	646	245	581	66	96.3
W93345	V21/472838	Scinde Is.	Pleistocene	430,425	6,079	1,641	1,955	706	179	60.9
W93346	V21/472838	Scinde Is.	Pleistocene	431,818	6,579	1,023	507	584	157	83.7
W93347	V21/448834	Scinde Is.	Pleistocene	430,817	1,824	916	1,123	271	173	71.3
W93348		Te Mata	Pliocene	435,440	1,008	3,155	340	448	26	99.2
W93349	V21/350602	Te Aute	Pliocene	453,470	1,645	895	359	220	86	97.4
W93350	V21/350602	Te Aute	Pliocene	442,243	1,941	1,614	889	400	196	97.9
W93351	V21/350602	Te Aute	Pliocene	416,327	5,408	2,020	321	1,728	47	98.1
W93352	V22/287370	Patangatea	Miocene	437,287	5,546	1,387	2,688	1,021	151	93.8
W93353	V22/445319	Kairakau	Pliocene	432,599	3,605	1,635	578	1,024	112	77.7
W93354	V22/445319	Kairakau	Pliocene	445,500	5,049	1,470	728	566	200	67.4
W93355	V22/445319	Kairakau	Pliocene	439,040	4,842	1,582	807	923	97	93.0
W93356	U23/036218	Te Aute	Pliocene	433,520	3,827	1,390	505	585	86	96.4
W93357	U23/036218	Te Aute	Pliocene	447,013	2,455	992	1,023	476	216	97.8
W93358		Te Aute	Pliocene	434,962	2,480	1,725	428	344	127	96.7
W93359	V22/385588	Te Mata	Pliocene	436,179	2,901	501	1,295	281	64	96.8
W93360	V22/385588	Te Mata	Pliocene	368,974	2,548	1,063	522	482	53	98.2
W93361	V21/298733	Petane	Pleistocene	380,266	1,441	731	459	475	135	90.2

ESci. No.	Grid Ref.	Formation	Age	Ca (ppm)	Mg (ppm)	Na (ppm)	Fe (ppm)	Sr (ppm)	Mn (ppm)	Carbonate %
W93362	V21/295745	Petane	Pleistocene	378,590	3,916	1,538	936	1,019	138	91.9
W93363	V21/236795	Petane	Pleistocene	380,634	2,894	1,617	935	770	149	89.8
W93364	U20/035932	Te Waka	Pliocene	369,288	6,376	1,124	4,862	1,354	399	75.4
W93365	U20/035932	Te Waka	Pliocene	371,727	5,427	921	5,698	905	392	73.8
W93366	U20/894922	TK	Miocene	359,764	5,294	1,565	3,766	990	263	83.1
W93367	U20/894922	TK	Miocene	367,744	6,970	1,130	5,696	1,126	305	83.2
W93368	U21/376865	Ptm	Pliocene	379,467	4,544	1,524	3,205	969	1,326	81.5
W93369	U21/725875	Ptm	Pliocene	374,582	3,846	1,211	5,000	729	642	59.8
W93414	N88/227845	Dome	Eocene	332,895	23,069	640	4,468	346	304	68.5
W93415	N88/243841	Dome	Eocene	392,649	12,559	668	3,503	189	118	75.6
W93416	N88/227845	Dome	Eocene	398,374	711	1,083	389	595	32	99.5
W93379	S27/104855	Haurangi ?	Pliocene	354,367	1,969	1,150	478	588	381	96.5
W93380	S27/105856	Haurangi ?	Pliocene	383,815	1,872	804	347	397	258	96.1
W93381	S28/100979	Clay Creek Lst	Miocene	373,721	4,999	820	1,976	518	219	84.0
W93382	S28/100979	Haurangi Lst	Pliocene	342,491	4,029	1,915	488	1,032	169	89.8
W93383	S28/100979	Bull Creek Lst	Pliocene	356,986	2,966	1,217	758	745	191	91.1
W93384	S28/125568	Kaiwhata Lst	Paleocene	393,018	832	474	2,901	553	1,087	86.5
W93385	S28/125568	Kaiwhata Lst	Paleocene	385,872	918	867	3,688	521	934	64.3
W93386		Vein material	Paleocene	384,229	523	285	2,243	304	915	99.4
W93387	S28/098570	Kaiwhata Lst	Paleocene	413,400	813	1,083	2,224	503	1,383	70.1
W93388	S27/172848	Pukenui	Pleistocene	380,027	2,952	1,082	1,980	676	212	81.3
W93389	S27/172848	Pukenui	Pleistocene	376,511	2,832	1,575	3,541	442	316	57.9
W93390	S27/172848	Pukenui	Pleistocene	378,880	2,762	1,000	983	624	122	90.6
W93391	S27/176867	Pukenui	Pleistocene	431,025	2,053	1,106	1,264	610	129	92.6
W93392	T26/376292	Pukenui	Pleistocene	394,500	2,221	1,215	814	556	319	94.5
W93393	T26/376292	Pukenui	Pleistocene	371,038	3,074	2,112	513	600	277	94.4
W93394	T26/396210	Pukenui	Pleistocene	351,183	3,379	1,144	377	771	130	97.6
W93395	T26/396210	Pukenui	Pleistocene	360,945	1,825	579	302	800	130	98.6
W93396	U26/821288	Castle Pt. Fm	Pleistocene	372,930	5,046	1,875	2,501	438	109	91.2
W93397	U26/763388	Takiritini	Miocene	387,706	5,430	420	1,846	1,220	59	92.1
W93398	T25/390433	Pukenui	Pleistocene	384,774	1,749	803	782	357	189	97.2
W93399	T25/390433	Pukenui	Pleistocene	400,488	1,830	853	742	465	178	98.4
W93400	T24/471746	Kumeroa	Pleistocene	383,370	2,089	1,200	1,086	477	158	95.7
W93401	T24/502928	Kumeroa	Pleistocene	402,796	4,660	1,329	3,506	543	610	90.1
W93402	T25/691610	Pori	Pliocene	376,947	5,447	1,344	1,242	609	126	91.8

ESci. No.	Grid Ref.	Formation	Age	Ca (ppm)	Mg (ppm)	Na (ppm)	Fe (ppm)	Sr (ppm)	Mn (ppm)	Carbonate %
W93403	T25/609689	Pori	Pliocene	390,715	3,466	918	400	915	56	95.2
W93404	T25/685676	Pori	Pliocene	392,950	2,799	800	1,058	913	72	96.4
W93405	U25/829659	Algal	Miocene	395,538	7,888	469	3,674	645	631	88.7
W93406	U25/795683	Argillaceous	Oligocene	394,255	969	394	4,175	659	327	77.6
W93407	U24/759858	Pori	Pliocene	372,573	4,938	875	1,459	303	81	89.0
W93408		Kumeroa	Pleistocene	387,926	3,826	848	405	500	55	94.1
W93409	U24/747832	Pori	Pliocene	381,876	4,298	1,031	1,068	1,170	86	81.5
W93410	U24/734801	Pori	Pliocene	407,280	5,327	1,042	2,242	913	93	90.0
W94641	P30/990192	Amuri	LCret.-Eocene	468,332	1,311	565	1,411	689	2,178	74.8
W94642	P30/990192	Amuri	LCret.-Eocene	384,134	845	1,055	1,410	476	1,181	51.2
W94643	P30/990192	Amuri	LCret.-Eocene	461,024	858	752	817	620	1,024	68.7
W94644	P31/817875	Amuri	LCret.-Eocene	174,177	633	3,584	3,816	17	14	85.7
W94646	O31/666644	Amuri	LCret.-Eocene	494,252	1,400	3,141	2,369	797	234	84.4
W94647	O31/666644	Amuri	LCret.-Eocene	504,372	1,701	5,789	1,852	749	200	90.4
W94648	O31/666644	Contact	LCret.-Eocene	528,416	1,607	5,925	2,585	759	182	91.0
W94649	O31/666644	Spy Glass	Oligocene	454,188	1,285	2,549	1,733	736	192	89.1
W94650	O31/666644	Contact		451,237	1,491	2,732	2,927	711	211	89.3
W94651	O32/350322	Brookdale	Pleistocene	432,092	4,804	5,327	735	2,615	97	77.9
W94652	O32/350322	Brookdale	Pleistocene	443,359	3,501	5,027	1,216	2,360	395	83.9
W94663	O32/350322	Brookdale	Pleistocene	435,311	4,224	2,792	501	2,082	110	83.1
W94664	O32/350322	Brookdale	Pleistocene	446,259	5,269	2,279	680	2,017	110	82.0
W94655	O32/350322	Brookdale	Pleistocene	467,015	4,327	3,080	800	2,336	118	70.8
W94665	L35/314688	Amuri	LCret.-Eocene	458,963	741	939	576	951	783	79.4
W94666	L35/314688	Amuri	LCret.-Eocene	462,821	673	940	698	1,164	146	80.9
W94667	L35/314688	Amuri	LCret.-Eocene	461,206	1,024	975	1,659	1,212	188	62.3
W94686	O33/353166	Amuri	LCret.-Eocene	424,089	1,604	1,080	856	803	78	94.6
W94687	O33/353166	Amuri	LCret.-Eocene	425,537	1,611	1,125	753	909	80	87.5
W94708	M33/870010	Amuri	LCret.-Eocene	435,925	822	1,086	1,921	770	80	84.9
W94708	M33/870010	Amuri	LCret.-Eocene	422,392	781	813	1,636	731	84	84.8
W94710	M33/870010	Amuri	LCret.-Eocene	424,142	783	703	1,725	717	78	84.9
W94711	M33/870010	Amuri	LCret.-Eocene	427,652	737	821	1,631	727	71	82.3
W94712	M33/870010	Amuri	LCret.-Eocene	423,329	629	592	1,231	785	57	89.9
W93375	R22/686568	Kuranui Lst	Pleistocene	386,209	5,636	1,029	4,492	885	365	60.3
W93376	R22/686568	Kuranui Lst	Pleistocene	378,017	5,234	897	2,021	843	173	68.8
W93377	R22/686568	Kuranui Lst	Pleistocene	354,017	4,964	981	4,206	926	233	76.6

ESci. No.	Grid Ref.	Formation	Age	Ca (ppm)	Mg (ppm)	Na (ppm)	Fe (ppm)	Sr (ppm)	Mn (ppm)	Carbonate %
W93378	R22/599482	Nukumaru	Pleistocene	362,996	4,289	1,213	1,348	871	934	65.4
W94625	N26/970182	Takaka	Olig-Mio	451,905	4,305	595	2,383	365	184	90.5
W94626	N26/970182	Takaka	Olig-Mio	464,561	5,292	603	2,280	369	495	89.6
W94627	N26/970182	Takaka	Olig-Mio	446,058	3,643	550	1,476	391	124	92.9
W94628	N26/970182	Takaka	Olig-Mio	460,237	5,309	593	4,831	722	222	82.7
W94629	M25/714451	Takaka	Olig-Mio	450,517	5,020	930	5,460	664	80	75.3
W94630	M25/714451	Takaka	Olig-Mio	472,188	5,587	886	5,036	644	299	65.8
W94631	M25/947398	Takaka	Olig-Mio	452,062	4,525	864	4,824	531	204	71.8
W94632	N26/947398	Takaka	Olig-Mio	468,394	3,368	920	1,006	683	98	83.4
W94633	N26/947398	Takaka	Olig-Mio	450,416	4,123	472	1,025	503	97	91.4
W94634	N25/014425	Takaka	Olig-Mio	463,296	2,106	943	457	337	251	86.2
W94635	N25/014425	Takaka	Olig-Mio	461,240	2,676	540	465	354	147	90.3
W94636	N25/014425	Takaka	Olig-Mio	453,269	4,954	991	881	429	131	87.6
W94637	N26/944358	Takaka	Olig-Mio	459,163	5,986	541	344	320	99	92.9
W94638	N26/944358	Takaka	Olig-Mio	449,932	5,079	430	148	329	127	95.1
W94639	N26/944358	Takaka	Olig-Mio	435,256	5,835	551	311	271	77	94.7
W94640	N26/944358	Takaka	Olig-Mio	450,656	5,600	504	408	313	101	96.0
W94547	S91/47596	Awarua	Olig-Mio	412,212	3,214	542	292	618	119	97.3
W94548	S91/47596	Awarua	Olig-Mio	429,520	2,951	512	391	583	116	96.4
W94549	S91/47596	Awarua	Olig-Mio	417,547	2,797	491	372	702	130	96.5
W94550	S91/47596	Awarua	Olig-Mio	411,307	4,126	546	6,621	602	571	93.9
W94551	S91/47596	Awarua	Olig-Mio	423,536	2,650	1,094	11,537	704	696	77.1
W94552	S91/47596	Awarua	Olig-Mio	402,843	2,079	455	3,637	643	714	96.3
W94553	S91/47596	Awarua	Olig-Mio	375,427	3,178	774	3,520	627	1,136	70.3
W94554	S91/47596	Awarua	Olig-Mio	406,391	4,380	514	766	882	34	95.4
W94555	J33/327094	Potikohua	Olig-Mio	413,509	2,200	413	95	148	121	98.2
W94556	J33/327094	Potikohua	Olig-Mio	465,895	4,726	425	210	156	385	86.3
W94557	J33/327094	Potikohua	Olig-Mio	416,159	2,975	395	148	165	162	98.5
W94558	J33/327094	Potikohua	Olig-Mio	422,998	3,283	459	250	266	237	93.0
W94559	J33/327094	Potikohua	Olig-Mio	423,236	2,968	540	778	294	97	89.7
W94560	J33/327094	Potikohua	Olig-Mio	412,330	4,610	473	131	286	59	97.8
W94561	J33/327094	Potikohua	Olig-Mio	418,016	2,138	489	1,226	226	67	92.0
W94562	J31/634609	Cobden	Olig-Mio	409,747	2,059	776	3,412	1,032	256	77.6
W94563	J31/634609	Cobden	Olig-Mio	474,239	2,454	1,887	4,096	967	251	76.8
W94564	J31/634609	Cobden	Olig-Mio	416,802	3,502	800	6,727	825	191	67.7

ESci. No.	Grid Ref.	Formation	Age	Ca (ppm)	Mg (ppm)	Na (ppm)	Fe (ppm)	Sr (ppm)	Mn (ppm)	Carbonate %
W94565	J31/634609	Cobden	Olig-Mio	381,827	3,404	692	5,194	700	167	78.4
W94566	J31/634609	Cobden	Olig-Mio	420,979	2,799	740	3,217	891	116	78.3
W94567	K30/720967	Welch	Miocene	400,180	5,699	4,255	5,397	719	145	77.7
W94568	K30/720967	Welch	Miocene	412,920	5,492	1,094	8,093	782	192	58.0
W94569	K30/716978	Potikohua	Olig-Mio	449,231	2,820	681	808	303	88	92.4
W94570	K30/716978	Potikohua	Olig-Mio	432,747	2,980	566	769	312	71	96.1
W94571	K30/716978	Potikohua	Olig-Mio	424,091	4,282	1,942	885	388	73	92.2
W94572	K30/716978	Potikohua	Olig-Mio	449,753	2,885	988	781	295	92	95.2
W94573	K30/716978	Potikohua	Olig-Mio	458,356	3,090	658	780	390	203	92.8
W94574	K30/716978	Potikohua	Olig-Mio	433,926	3,053	581	585	326	418	93.4
W94575	K30/716978	Potikohua	Olig-Mio	446,044	2,986	513	873	343	220	95.2
W94576	K30/716978	Potikohua	Olig-Mio	439,995	2,810	1,071	1,331	356	141	85.7
W94577	K30/716978	Potikohua	Olig-Mio	469,388	5,543	936	6,656	386	229	49.5
W94578	K29/833237	Waitakere	Eocene-Olig	451,010	3,469	623	647	331	81	59.9
W94579	K29/833237	Waitakere	Eocene-Olig	440,314	4,156	541	915	320	46	94.1
W94580	K29/833237	Waitakere	Eocene-Olig	426,223	3,716	546	881	298	64	94.3
W94581	K29/833237	Waitakere	Eocene-Olig	430,782	4,766	540	857	290	78	97.0
W94582	K29/826375	Waitakere	Eocene-Olig	434,760	2,190	518	975	206	1,725	96.6
W94583	K29/826375	Waitakere	Eocene-Olig	423,540	1,660	435	866	114	1,839	98.9
W94584	K29/826375	Waitakere	Eocene-Olig	464,966	2,640	594	1,270	181	2,466	91.3
W94585	K29/826375	Waitakere	Eocene-Olig	430,752	2,486	566	878	219	856	98.1
W94586	K29/834386	Waitakere	Eocene-Olig	423,134	3,772	741	1,097	507	509	88.1
W94587	L28/284650	Q Creek	Miocene	435,848	2,741	897	1,981	2,813	86	61.6
W94588	L28/284650	Q Creek	Miocene	431,793	2,686	894	1,290	2,944	71	64.3
W94589	L27/384986	Takaka	Olig-Mio	430,686	3,219	674	4,176	426	440	79.7
W94590	L27/384986	Takaka	Olig-Mio	443,305	1,995	449	950	232	220	92.5
W94591	L27/384986	Takaka	Olig-Mio	439,216	1,281	376	776	158	604	96.9
W94592	L26/344118	Kohaihai	Olig-Mio	442,990	3,574	1,069	1,580	539	1,168	87.1
W94593	L26/344118	Kohaihai	Olig-Mio	424,766	4,165	912	2,297	370	911	88.5
W94594	L26/344118	Kohaihai	Olig-Mio	432,292	4,028	785	1,697	489	161	92.2
W94595	L26/344118	Kohaihai	Olig-Mio	428,974	2,595	666	2,158	375	568	88.7
W94596	L26/344118	Kohaihai	Olig-Mio	424,802	2,263	902	1,730	490	509	89.8
W94597	L26/344118	Kohaihai	Olig-Mio	424,101	4,338	797	691	435	236	94.5
W94600	L28/315788	Q Creek	Miocene	425,619	3,290	620	372	734	70	92.9
W94601	L28/315788	Q Creek	Miocene	434,407	2,788	695	315	1,187	109	79.8

ESci. No.	Grid Ref.	Formation	Age	Ca (ppm)	Mg (ppm)	Na (ppm)	Fe (ppm)	Sr (ppm)	Mn (ppm)	Carbonate %
W94602	L28/315788	Q Creek	Miocene	416,279	3,708	580	1,184	1,073	65	86.0
W94603	L28/315788	Q Creek	Miocene	445,021	5,027	665	1,202	2,172	90	88.7
W94604	L28/221662	Q Creek	Miocene	428,749	4,646	871	765	2,773	52	88.6
W94605	L28/221662	Q Creek	Miocene	423,053	6,127	577	546	2,511	32	94.9
W94606	L28/221662	Q Creek	Miocene	423,974	5,421	656	702	2,570	42	91.3
W94607	L28/221662	Q Creek	Miocene	428,226	3,915	3,542	1,382	2,474	57	70.3
W94609	L29/205294	Cobden	Olig-Mio	475,164	2,785	920	1,537	547	305	48.7
W94610	L29/205294	Cobden	Olig-Mio	449,082	2,384	774	965	503	253	53.9
W94611	L29/205294	Cobden	Olig-Mio	432,687	3,027	680	2,048	915	214	69.1
W94612	L29/205294	Cobden	Olig-Mio	423,168	2,692	664	3,150	869	159	75.8
W94613	L29/297354	Waitakere	Eocene-Olig	447,378	2,278	645	581	423	248	54.9
W94614	L29/297354	Waitakere	Eocene-Olig	420,543	2,350	358	524	377	92	97.1
W94615	L29/297354	Waitakere	Eocene-Olig	418,811	2,913	409	1,031	351	77	95.5
W94616	L29/297354	Waitakere	Eocene-Olig	422,204	3,631	461	1,391	388	88	86.8
W94617	L29/297354	Waitakere	Eocene-Olig	385,437	4,125	485	1,416	401	84	82.4
W94618	L29/297354	Waitakere	Eocene-Olig	423,423	6,645	896	3,351	511	101	56.6
W94619	L29/297354	Waitakere	Eocene-Olig	485,811	4,582	979	4,456	612	139	50.0
W94620	L29/424379	Waitakere	Eocene-Olig	467,448	1,351	489	1,007	271	462	75.2
W94621	L29/424379	Waitakere	Eocene-Olig	462,973	1,471	384	955	250	162	95.9
W94716	J23/466118	Potikohua	Olig-Mio	401,473	4,220	664	894	493	70	82.8
W94622	M28/836602	Huia	Eocene-Olig	456,553	5,176	513	192	584	106	96.8
W94623	M28/836602	Huia	Eocene-Olig	461,915	4,036	459	181	635	95	98.0
W94624	M28/836602	Huia	Eocene-Olig	441,498	4,762	529	515	602	154	93.1
W94656		Flaxdown	Miocene	436,753	4,441	538	1,378	316	300	98.0
W94657	M34/656831	Claremount	Miocene	447,786	4,819	676	1,913	460	184	84.5
W94658	M34/656831	Claremount	Miocene	454,969	2,757	511	2,873	252	263	94.5
W94659	M34/656831	Claremount	Miocene	457,558	1,782	471	750	169	135	95.8
W94660	M34/656831	Claremount	Miocene	417,861	4,144	622	2,059	401	349	87.8
W94661	M34/656831	Claremount	Miocene	435,049	2,146	832	2,602	348	261	89.9
W94662	M34/656831	Claremount	Miocene	442,668	2,798	10,315	5,789	658	235	46.9
W94668	K34/038719	Thomas	Oligocene	442,226	3,227	460	977	200	103	96.6
W94669	K34/038719	Thomas	Oligocene	442,429	3,994	530	380	282	140	94.8
W94670	K34/038719	Thomas	Oligocene	392,707	1,999	500	968	185	949	95.2
W94671	K34/064756	Thomas	Oligocene	392,645	3,792	554	2,267	252	133	92.4
W94672	K34/064756	Thomas	Oligocene	403,253	4,152	577	855	326	82	95.3

ESci. No.	Grid Ref.	Formation	Age	Ca (ppm)	Mg (ppm)	Na (ppm)	Fe (ppm)	Sr (ppm)	Mn (ppm)	Carbonate %
W94673	K34/064756	Thomas	Oligocene	396,573	1,236	1,207	8,043	547	388	65.3
W94674	K34/064756	Thomas	Oligocene	377,565	4,977	683	2,598	287	143	87.8
W94675	K34/064756	Thomas	Oligocene	410,540	2,652	465	2,225	187	414	95.1
W94676	K34/064756	Thomas	Oligocene	387,954	1,587	454	3,744	199	620	96.3
W94677	M34/805924	Mt. Brown	Miocene	402,408	1,432	1,056	613	199	515	54.8
W94680	M34/805924	Mt. Brown	Miocene	418,957	2,349	2,586	1,743	405	1,096	92.5
W94681		Claremount	Miocene	422,493	6,273	708	2,460	627	114	82.9
W94682		North Dean	Miocene	417,160	3,380	555	1,738	251	519	94.5
W94683		North Dean	Miocene	416,494	2,520	582	3,425	322	582	91.6
W94684		Mt. Brown	Miocene	429,521	7,200	805	3,556	690	131	88.8
W94685		Mt. Brown	Miocene	423,928	2,914	570	2,133	328	223	85.8
W94688	N32/124374	Isolated Hill	Olig-Mio	414,023	3,736	515	703	258	292	97.6
W94689	N32/124374	Isolated Hill	Olig-Mio	422,391	3,332	540	728	263	338	95.9
W94690	N32/910420	Hanmer Marb	Oligocene	419,175	3,299	515	801	293	187	96.7
W94691	N32/910420	Hanmer Marb	Oligocene	426,248	2,966	477	619	263	169	97.1
W94692	N32/910420	Hanmer Marb	Oligocene	433,061	1,556	306	318	131	60	97.9
W94693	N32/910420	Hanmer Marb	Oligocene	418,157	2,028	328	1,223	163	268	95.6
W94694	N33/958267	Isolated Hill	Olig-Mio	423,346	3,361	635	2,160	337	69	94.3
W94695	N33/958267	Isolated Hill	Olig-Mio	414,543	2,352	716	1,669	326	66	93.8
W94696	M33/788248	Flaxdown	Miocene	423,212	3,650	1,598	280	1,603	108	97.0
W94697	M33/788248	Flaxdown	Miocene	418,100	3,279	751	938	550	212	95.9
W94698	M33/788248	Flaxdown	Miocene	415,926	3,907	944	568	800	100	97.8
W94699	M33/788248	Flaxdown	Miocene	415,516	4,064	634	522	234	286	96.9
W94700	M33/788248	Flaxdown	Miocene	420,991	2,118	511	436	131	315	94.0
W94701	M34/863983	Glenmark	Miocene	438,290	1,623	1,024	1,410	257	342	62.4
W94702	M34/863983	Glenmark	Miocene	442,845	1,834	1,419	2,089	241	2,225	48.6
W94703	M34/863983	Mt. Brown	Miocene	425,289	2,975	643	755	160	364	80.4
W94704	M34/863983	Mt. Brown	Miocene	422,961	4,561	755	766	206	681	82.9
W94705	M34/863983	Mt. Brown	Miocene	435,720	7,675	887	317	550	299	82.6
W94706	M34/857996	Sandhurst	Miocene	427,018	6,653	986	5,465	496	261	67.2
W94707	M34/857996	Sandhurst	Miocene	449,310	6,814	974	8,284	495	218	70.4
W94713	M33/870010	Weka Pass	Olig-Mio	447,105	1,322	1,535	3,031	684	82	55.9
W94714	M33/870010	Weka Pass	Eocene	412,513	1,168	1,200	2,454	933	79	67.5
W94715	M33/870010	Weka Pass	Eocene	393,978	2,098	2,528	1,917	794	75	78.6
W94373	K36/820285	Otekaike	Olig-Mio	426,079	5,381	942	972	336	130	93.6

ESci. No.	Grid Ref.	Formation	Age	Ca (ppm)	Mg (ppm)	Na (ppm)	Fe (ppm)	Sr (ppm)	Mn (ppm)	Carbonate %
W94374	K36/790247	Otekaike	Olig-Mio	491,998	5,201	768	487	279	93	96.5
W94375	K36/790247	Otekaike	Olig-Mio	469,885	5,576	634	697	210	119	94.9
W94376	K36/790247	Otekaike	Olig-Mio	496,334	4,808	793	388	169	138	94.5
W94377	K36/728246	Otekaike	Olig-Mio	474,783	8,981	1,058	945	323	394	88.4
W94378	K36/728246	Otekaike	Olig-Mio	493,483	4,588	560	313	153	172	95.9
W94379	K36/728246	Otekaike	Olig-Mio	470,782	5,577	827	347	254	392	97.5
W94380	K36/728246	Otekaike	Olig-Mio	524,190	4,558	686	404	169	474	96.4
W94381	K36/728246	Otekaike	Olig-Mio	497,873	6,444	587	427	198	725	96.4
W94382	K36/728246	Otekaike	Olig-Mio	496,217	6,384	685	278	200	517	96.4
W94383	K36/728246	Otekaike	Olig-Mio	791,322	6,095	999	592	152	348	90.6
W94384	K36/728246	Otekaike	Olig-Mio	441,197	4,898	716	818	141	332	84.6
W94385	K36/728246	Otekaike	Olig-Mio	463,661	4,160	824	365	227	334	97.7
W94386	K36/761225	Otekaike	Olig-Mio	512,885	4,559	526	901	85	388	95.9
W94387	K36/761225	Otekaike	Olig-Mio	457,025	3,788	573	1,062	86	425	94.6
W94388	K36/761225	Otekaike	Olig-Mio	439,680	4,873	740	473	156	311	97.5
W94389	K36/761225	Otekaike	Olig-Mio	476,201	3,749	537	854	98	447	94.9
W94390	J38/569572	Otekaike	Olig-Mio	462,978	3,225	1,604	1,083	388	89	84.6
W94391	J38/569572	contact	Oligocene	511,159	3,338	2,087	1,668	1,214	345	50.9
W94392	J38/569572	Amuri	Oligocene	483,144	4,237	1,746	2,210	1,161	254	46.5
W94393	J38/569572	Amuri	Oligocene	488,847	3,723	1,333	1,608	1,195	395	53.4
W94394	J38/483652	Otekaike	Olig-Mio	436,393	5,611	1,623	2,408	519	59	88.1
W94395	J38/483652	Otekaike	Olig-Mio	454,088	5,694	2,121	1,474	572	50	83.4
W94396	J38/513526	U Otekaike	Olig-Mio	457,093	4,128	3,155	912	678	73	73.9
W94397	J39/531397	Otekaike	Olig-Mio	465,602	6,880	9,127	892	713	48	81.4
W94398	J39/531397	Otekaike	Olig-Mio	462,282	6,487	8,314	993	638	48	88.9
W94399	J39/531397	Otekaike	Olig-Mio	469,664	5,638	5,211	1,006	555	56	88.5
W94400	J39/531397	Otekaike	Olig-Mio	466,487	6,412	10,529	652	780	31	48.2
W94401	J39/531397	Otekaike	Olig-Mio	504,799	4,833	925	1,243	448	91	89.2
W94402	J40/507987	Otekaike	Olig-Mio	430,791	4,426	6,235	3,646	460	118	63.7
W94403	J40/507987	Otekaike	Olig-Mio	465,106	4,039	5,393	4,221	400	125	70.1
W94404	J40/507987	Otekaike	Olig-Mio	438,088	4,257	4,742	4,181	429	142	67.0
W94405	J41/499628	Ototara	Olig-Mio	458,215	5,548	2,355	247	159	503	98.6
W94406	J41/499628	Gees Pt.	Oligocene	438,671	9,096	2,986	415	196	3,239	98.7
W94407	J41/499628	Gees Pt.	Oligocene	440,930	10,187	1,192	180	181	657	98.9
W94408	J41/499628	Gees Pt.	Oligocene	448,149	8,611	3,347	971	320	676	92.6

ESci. No.	Grid Ref.	Formation	Age	Ca (ppm)	Mg (ppm)	Na (ppm)	Fe (ppm)	Sr (ppm)	Mn (ppm)	Carbonate %
W94409	J41/499628	Gees Pt.	Oligocene	449,378	9,112	1,822	390	232	453	94.8
W94410	J41/499628	Gees Pt.	Oligocene	420,076	7,200	4,856	1,477	383	620	84.5
W94411	J41/499628	Gees Pt.	Oligocene	434,483	8,265	3,533	1,102	356	515	89.9
W94413	J42/457580	Gees Pt.	Oligocene	424,934	9,452	3,700	1,088	309	466	83.2
W94413	J42/457580	Otekaike	Olig-Mio	447,136	9,174	1,081	132	170	425	98.7
W94414	J42/457580	Otekaike	Olig-Mio	437,287	9,174	2,939	769	293	441	88.1
W94415	J42/457580	Gees Point	Oligocene	429,181	8,738	2,049	228	236	464	96.0
W94416	J42/457580	Gees Point	Oligocene	436,770	7,497	3,088	419	299	389	95.0
W94417	J42/457580	Otekaike	Olig-Mio	443,984	7,804	4,167	885	312	589	84.4
W94418	J42/457580	Gees Point	Oligocene	335,939	4,408	9,944	1,313	617	461	92.1
W94419	J42/452572	Ototara	Olig-Mio	455,602	7,236	1,045	141	236	308	95.6
W94420	J42/452572	Ototara	Olig-Mio	480,033	6,925	787	99	180	270	97.9
W94421	J42/452572	Ototara	Olig-Mio	451,460	6,726	911	158	157	309	97.2
W94422	J42/454579	Ototara	Olig-Mio	440,592	7,289	697	89	178	264	98.6
W94423	J42/454579	Ototara	Olig-Mio	450,313	7,504	873	196	189	221	98.8
W94424	J41/449692	Ototara	Olig-Mio	477,986	3,320	442	285	123	99	99.7
W94425	J41/449692	Ototara	Olig-Mio	464,372	5,080	360	297	99	115	99.6
W94426	J41/449683	Ototara	Olig-Mio	474,256	5,782	689	171	259	484	94.7
W94427	J41/404638	Ototara	Olig-Mio	459,166	8,043	4,716	258	267	119	96.7
W94428	J41/404638	Ototara	Olig-Mio	480,572	7,237	1,112	309	249	137	97.4
W94429	J41/404638	Top Ototara	Olig-Mio	523,731	8,013	1,214	399	430	90	97.3
W94430	J41/404638	Ototara	Olig-Mio	441,422	7,571	1,269	470	397	215	93.4
W94431	J40/307903	B. Otekaike	Olig-Mio	462,500	6,640	6,218	3,422	257	663	74.4
W94432	J40/307903	B. Otekaike	Olig-Mio	446,818	7,163	821	1,798	251	195	87.6
W94433	J40/307903	L. Otekaike	Olig-Mio	411,771	5,314	850	1,783	257	117	91.0
W94434	I40/155966	L. Otekaike	Olig-Mio	393,867	11,580	3,412	1,011	3,273	91	87.5
W94435	I40/155966	L. Otekaike	Olig-Mio	410,955	12,163	8,037	1,217	1,102	77	71.3
W94436	I40/155966	L. Otekaike	Olig-Mio	441,376	8,724	3,709	1,596	705	107	75.5
W94437	I40/155966	M. Otekaike	Olig-Mio	406,396	7,878	7,621	1,362	1,148	104	72.9
W94438	I40/155966	M. Otekaike	Olig-Mio	427,870	8,584	2,160	1,376	1,005	127	83.7
W94439	I40/155966	M. Otekaike	Olig-Mio	402,697	8,961	2,379	1,117	2,614	88	83.9
W94440	J40/460996	Otekaike	Olig-Mio	412,192	5,704	1,341	1,523	489	83	86.7
W94441	J41/511644	Otekaike	Olig-Mio	402,423	14,106	7,242	1,700	216	10,214	83.4
W94442	J41/511644	Otekaike	Olig-Mio	416,013	14,936	7,501	1,341	170	4,082	89.2
W94443	J41/511644	Otekaike	Olig-Mio	457,569	10,030	2,030	225	166	268	96.4

ESci. No.	Grid Ref.	Formation	Age	Ca (ppm)	Mg (ppm)	Na (ppm)	Fe (ppm)	Sr (ppm)	Mn (ppm)	Carbonate %
W94444	J41/499628	Ototara	Olig-Mio	433,563	12,225	4,207	1,404	229	4,245	91.2
W94445	J41/499628	Ototara	Olig-Mio	410,259	12,286	1,782	618	212	1,653	97.6
W94446	J41/499628	Ototara	Olig-Mio	439,089	12,072	3,760	809	217	973	90.9
W94447	J41/499628	Ototara	Olig-Mio	415,177	7,304	3,980	336	129	745	98.4
W94448	J41/499628	Ototara	Olig-Mio	427,938	8,165	3,738	1,123	181	992	97.0
W94449	J41/499628	Ototara	Olig-Mio	423,085	8,767	2,897	916	208	826	97.5
W94450	J41/499628	Ototara	Olig-Mio	408,963	8,277	5,505	553	122	499	96.1
W94451	J41/499628	Gees Point	Oligocene	412,185	10,745	1,837	399	145	268	96.5
W94452	J41/499628	Otekaike	Olig-Mio	423,867	10,038	2,252	353	207	738	94.5
W94453	J41/499628	Ototara	Olig-Mio	286,673	178,243	4,768	2,000	425	1,073	85.0
W94454	J42/457580	Ototara	Olig-Mio	447,487	9,944	5,674	411	313	924	93.1
W94455	J42/457580	Ototara	Olig-Mio	442,895	9,606	4,118	133	196	480	97.4
W94456	J42/457580	Ototara	Olig-Mio	388,258	9,337	8,641	1,508	360	461	66.3
W94457	J42/457580	Ototara	Olig-Mio	426,079	12,410	891	183	147	663	96.9
W94458	J43/367197	Goodwood	Miocene	294,045	179,074	4,069	31,252	651	1,169	72.6
W94459	J43/367197	Goodwood	Miocene	414,255	7,639	7,244	17,352	212	1,183	56.7
W94460	I42/153446	Otekaike	Olig-Mio	442,791	4,642	1,288	1,109	428	340	73.3
W94461	I42/153446	Otekaike	Olig-Mio	416,441	4,761	2,711	514	401	131	74.0
W94462	I42/153446	Otekaike	Olig-Mio	419,429	4,198	1,282	1,185	560	127	87.2
W94463	I42/153446	Otekaike	Olig-Mio	418,562	8,794	1,082	1,477	768	201	92.3
W94717	I42/153446	Otekaike	Olig-Mio	373,309	2,658	723	11,725	643	4,030	82.1
W94464	I44/280885	Dowling Bay	Miocene	431,452	4,159	843	115	3,237	219	89.2
W94465	I44/280885	Dowling Bay	Miocene	421,892	6,211	1,002	1,895	1,092	424	84.7
W94466	I44/280885	Dowling Bay	Miocene	438,371	7,263	580	1,590	846	414	91.8
W94467	I44/280885	Dowling Bay	Miocene	418,501	6,984	616	1,530	837	402	91.8
W94468	I44/267794	Dowling Bay	Miocene	435,660	7,711	806	1,359	550	203	82.3
W94469	I44/267794	Dowling Bay	Miocene	444,231	8,554	763	1,708	763	200	78.1
W94470	I44/267794	Dowling Bay	Miocene	450,974	7,693	494	1,018	637	164	91.3
W94471	I44/267794	Dowling Bay	Miocene	428,426	8,978	562	1,081	713	123	88.5
W94472	I44/267794	Dowling Bay	Miocene	476,819	12,323	545	2,118	720	141	82.6
W94473	I44/127733	Caversham	Miocene	393,380	37,081	23,734	57,749	861	350	65.5
W94474	I44/127733	Caversham	Miocene	398,278	17,646	3,493	200	953	119	95.2
W94475	I44/106725	Caversham	Miocene	433,631	15,354	3,736	4,207	445	429	58.1
W94476	I44/106725	Caversham	Miocene	430,378	6,210	1,291	1,462	277	416	75.1
W94477	H45/777563	B. Otekaike	Olig-Mio	421,440	5,492	626	353	214	36	84.3

ESci. No.	Grid Ref.	Formation	Age	Ca (ppm)	Mg (ppm)	Na (ppm)	Fe (ppm)	Sr (ppm)	Mn (ppm)	Carbonate %
W94478	H45/777563	Otekaike	Olig-Mio	438,631	4,694	475	138	257	29	96.7
W94480	H45/777563	Otekaike	Olig-Mio	438,594	4,970	733	422	215	39	87.3
W94481	H45/777563	T.Otekaike	Olig-Mio	417,235	4,926	720	480	166	34	70.2
W94483	F45/816447	Waimumu	Olig-Mio	412,617	9,066	1,005	1,353	349	904	71.7
W94484	F45/816447	Waimumu	Olig-Mio	427,352	12,327	1,188	2,966	390	576	58.6
W94485	F45/816447	Waimumu	Olig-Mio	395,690	8,359	791	12,832	318	902	84.4
W94486	F45/816447	Waimumu	Olig-Mio	447,289	8,995	458	1,117	230	232	73.0
W94487	F45/816447	Waimumu	Olig-Mio	423,978	7,592	292	143	509	511	96.3
W94488	E46/575336	Forest Hill	Olig-Mio	430,579	5,632	328	995	171	388	89.7
W94489	E46/575336	Forest Hill	Olig-Mio	427,704	3,943	334	2,344	285	598	90.5
W94490	E46/575336	Forest Hill	Olig-Mio	453,223	4,678	363	1,978	274	557	79.7
W94491	E46/575336	Forest Hill	Olig-Mio	426,986	7,733	542	3,564	304	735	56.7
W94492	E46/575336	Forest Hill	Olig-Mio	447,851	5,556	423	2,397	207	838	83.5
W94493	E46/575336	Forest Hill	Olig-Mio	432,432	3,818	345	2,489	426	420	82.5
W94494	E46/575336	Forest Hill	Olig-Mio	439,243	5,833	330	2,132	783	173	94.6
W94495	E46/603336	Forest Hill	Olig-Mio	411,082	12,290	508	1,123	382	927	84.4
W94496	E46/603336	Forest Hill	Olig-Mio	440,936	6,164	560	69	398	641	85.5
W94497	E46/603336	Forest Hill	Olig-Mio	451,316	4,517	337	1,796	320	889	88.1
W94498	E46/603336	Forest Hill	Olig-Mio	422,999	7,161	521	1,769	425	412	83.5
W94499	E46/572274	Forest Hill	Olig-Mio	419,982	7,062	752	748	215	688	90.4
W94500	E46/572274	Forest Hill	Olig-Mio	436,565	5,080	581	1,777	261	1,069	77.5
W94501	E45/557415	Forest Hill	Olig-Mio	465,408	3,979	325	970	287	256	93.2
W94502	E45/557415	Forest Hill	Olig-Mio	472,107	3,997	237	1,992	312	350	96.0
W94503	E44/435774	Castle Down	Olig-Mio	440,503	10,797	515	4,397	1,235	528	83.3
W94504	E44/435774	Castle Down	Olig-Mio	441,654	11,022	881	1,771	1,219	912	78.8
W94505	E44/435774	Castle Down	Olig-Mio	414,787	11,211	693	885	972	418	90.8
W94506	E44/435774	Castle Down	Olig-Mio	442,241	6,391	369	972	341	543	86.2
W94507	E44/435774	Castle Down	Olig-Mio	422,179	6,131	277	885	274	555	92.9
W94508	E44/435774	Forest Hill	Olig-Mio	420,035	8,332	392	4,734	341	598	84.9
W94509	E45/498512	Forest Hill	Olig-Mio	456,433	7,224	511	978	306	510	85.2
W94510	D45/030525	Forest Hill	Olig-Mio	443,700	8,908	739	2,922	675	216	64.2
W94511	D45/030525	Forest Hill	Olig-Mio	429,804	9,713	413	648	386	252	96.2
W94512	D45/030525	Forest Hill	Olig-Mio	444,978	9,800	434	697	249	368	93.8
W94513	D45/030525	Forest Hill	Olig-Mio	436,682	11,640	499	340	274	335	90.9
W94514	D45/030525	Forest Hill	Olig-Mio	446,941	9,548	456	685	340	263	91.2

ESci. No.	Grid Ref.	Formation	Age	Ca (ppm)	Mg (ppm)	Na (ppm)	Fe (ppm)	Sr (ppm)	Mn (ppm)	Carbonate %
W94515	D45/030525	Forest Hill	Olig-Mio	445,427	9,985	655	924	355	320	88.2
W94516	D45/015512	Te Karara	Olig-Mio	430,602	14,648	565	3,131	799	160	78.0
W94517	D45/015512	Te Karara	Olig-Mio	434,227	16,720	745	1,902	923	223	71.2
W94519	D44/934729	Mc Ivor	Miocene	401,704	3,793	1,720	9,982	587	3,149	61.0
W94520	D44/934729	Mc Ivor	Miocene	425,973	3,207	966	9,778	513	2,783	55.0
W94521	D44/934729	Mc Ivor	Miocene	269,958	110,141	1,075	30,353	569	2,200	70.9
W94522	C44	Tunnelburn	Olig-Mio	434,722	884	767	1,249	175	2,506	57.1
W94523	C44	Tunnelburn	Olig-Mio	436,997	1,412	991	595	219	2,438	70.8
W94524	C44	Tunnelburn	Olig-Mio	410,914	2,303	696	924	277	2,164	74.0
W94525	D44/919905	Tunnelburn	Olig-Mio	437,204	3,499	1,184	11,440	471	2,607	52.8
W94526	D44/919905	Tunnelburn	Olig-Mio	470,944	2,431	762	2,377	314	1,437	64.5
W94527	D44/919905	Tunnelburn	Olig-Mio	393,560	1,977	521	967	248	1,765	85.3
W94528	D44/919905	Tunnelburn	Olig-Mio	443,525	2,538	551	1,979	281	700	82.1
W94530	D44/919905	Tunnelburn	Olig-Mio	449,682	2,076	486	1,045	252	1,136	84.8
W94532	D43/926027	Tunnelburn	Olig-Mio	447,356	3,467	1,040	2,725	635	1,182	62.2
W94533	D43/926027	Tunnelburn	Olig-Mio	424,903	3,717	470	3,382	301	830	92.5
W94535	D43/926027	Tunnelburn	Olig-Mio	418,404	3,616	662	3,780	397	578	77.7
W94536	D43/996147	Tunnelburn	Olig-Mio	418,040	3,304	561	1,913	306	369	80.7
W94537	D43/996147	Tunnelburn	Olig-Mio	420,102	3,837	752	1,955	331	395	70.8
W94538	D44/096998	Tunnelburn	Olig-Mio	419,215	5,378	565	4,292	599	192	90.0
W94539	D44/096998	Tunnelburn	Olig-Mio	427,822	8,546	1,041	15,208	606	419	64.8
W94540	D44/096998	Tunnelburn	Olig-Mio	415,225	3,097	577	1,991	449	99	82.1
W94541	E44/688717	Waimea	Olig-Mio	418,586	7,065	935	5,535	642	116	73.3
W94542	E44/688717	Waimea	Olig-Mio	418,748	3,853	707	1,801	404	69	72.8
W94543	E41	Bobs Cove	Olig-Mio	389,343	13,683	494	892	2,209	54	95.4
W94544	E41	Bobs Cove	Olig-Mio	397,637	5,689	550	7,274	845	318	94.0
W94545	E41	Bobs Cove	Olig-Mio	387,868	8,346	965	7,671	2,299	718	94.1

Gaps in some fields in the above data table result from data missing in the original source (i.e., Winefield (1995) and Winefield et al. (1996)). ESci. No. refers to the sample number used by the Department of Earth Sciences, University of Waikato.

Appendix 7.1

Trace element data for calcite first generation and dolomite vein minerals

Sample No.	Well	Depth (mAH)	Mineral type	Mg	Ca	Na	Fe	Sr	Mn
NG2.4.1	Ngaere-2	2984.90	Dolomite	88,437	184,833	403	50,177	11,375	343
W2.9.12	Waihapa-2	3089.30	Dolomite	55,899	179,727	528	61,851	6,138	675
W4.4.1A	Waihapa-4	2883.40	Dolomite	36,840	203,082	273	11,950	2,576	275
W5.2.1B	Waihapa-5	3015.25	Dolomite	11,783	309,558	1,121	62,996	8,223	788
NG2.5.1B	Ngaere-2	3001.95	Calcite	6,332	313,599	2,071	2,947	4,170	54
NG2.6.10A	Ngaere-2	3058.95	Calcite	3,319	351,351	372	5,447	54,166	217
NG2.6.11B	Ngaere-2	3059.50	Calcite	3,386	371,155	198	7,734	2,925	220
NG2.7.3A	Ngaere-2	3064.25	Calcite	2,660	232,074	1,268	4,977	137,972	113
W2.9.6A	Waihapa-2	3083.50	Calcite	10,290	367,193	497	9,598	4,807	159
W2.9.6B	Waihapa-2	3083.75	Calcite	6,277	306,773	85	6,540	5,147	195
W2.9.6C	Waihapa-2	3084.00	Calcite	4,798	330,068	282	9,116	3,513	189
W4.3.3	Waihapa-4	2836.41	Calcite	14,467	345,739	283	12,632	4,812	303
W4.7.1	Waihapa-4	3004.10	Calcite	19,017	257,232	2,152	8,678	4,944	197
W4.7.4B	Waihapa-4	3007.00	Calcite	749	157,095	1,144	2,154	1,096	463
W5.6.1A	Waihapa-5	3140.75	Calcite	4,687	212,265	389	4,054	2,232	119

Note calcite data pertains to calcite phase I only due to lack of calcite phase II sample.

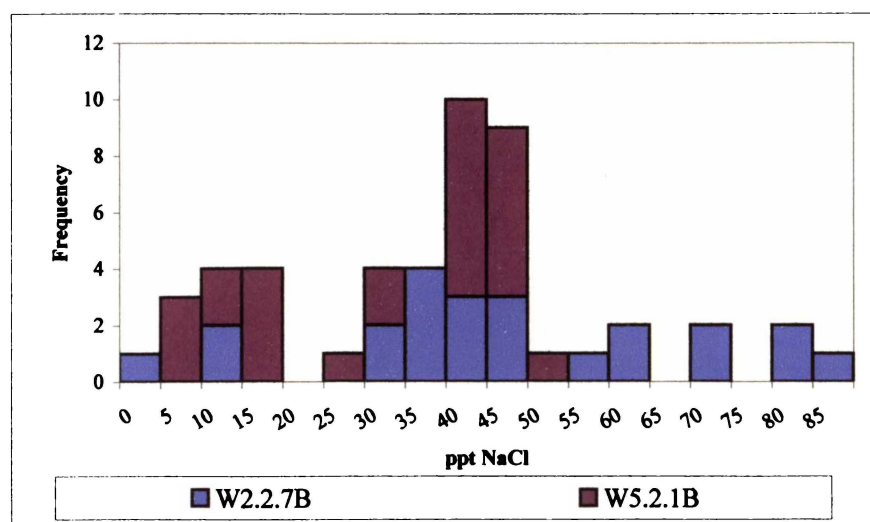
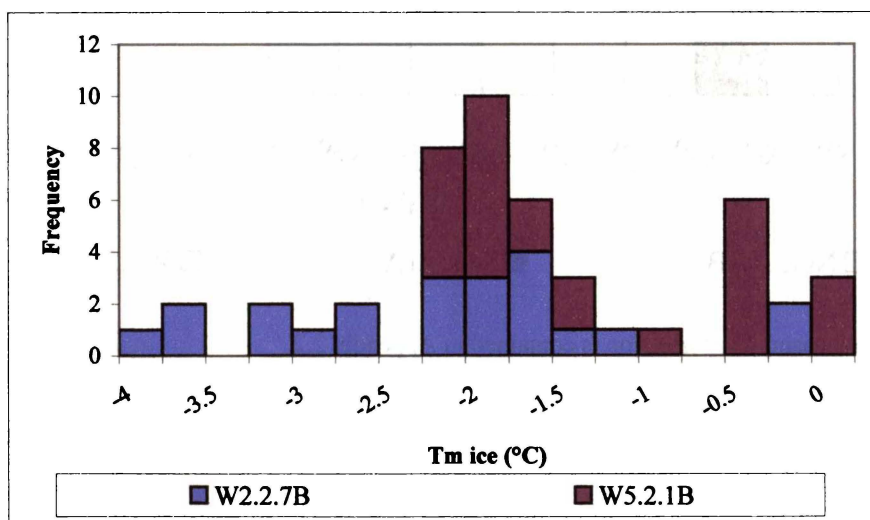
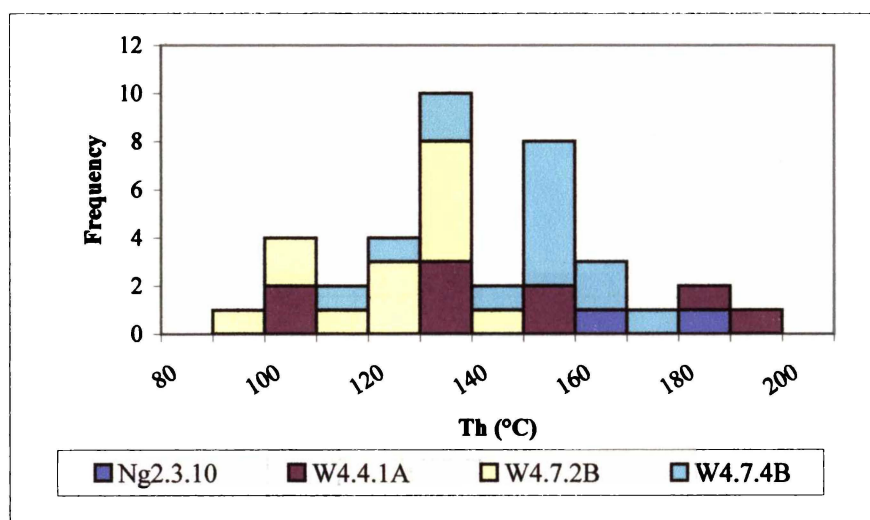
Appendix 7.2

Stable isotope data for carbonate vein minerals and bulk Tikorangi Formation

Sample No.	Well	Depth (mAH)	Host Rock		Calcite phase I		Calcite phase II		Dolomite	
			$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$
NG2.4.1B	Ngaere-2	2984.90							-4.72	-4.31
NG2.4.13A	Ngaere-2	2996.10			-7.74	-1.72				
NG2.6.2B	Ngaere-2	3051.10			-5.79	-2.11	-7.06	-0.45		
NG2.6.10A	Ngaere-2	3058.95			-7.32	-2.01				
W2.2.7B	Waihapa-2	2924.70			-8.72	-6.06	-9.14	-6.32		
W2.4.6	Waihapa-2	2982.18			-8.34	-6.18				
W2.4.10B	Waihapa-2	2986.81			-7.32	-2.98				
W2.9.6B	Waihapa-2	3083.75	-3.49	-0.88			-8.31	-4.17	-6.61	-4.13
W2.9.12	Waihapa-2	3089.30			-7.02	-3.97	-8.07	-4.30	-6.65	-4.18
W4.4.1A	Waihapa-4	2883.40	-1.96	-0.47			-7.96	-5.05	-6.71	-5.70
W4.7.2B	Waihapa-4	3005.60					-8.04	-5.76	-6.50	-5.60
W4.7.4C	Waihapa-4	3007.00			-6.82	-5.71	-8.20	-4.71	-6.51	-5.71
W5.2.1B	Waihapa-5	3015.25					-8.48	-6.18	-5.25	-2.15

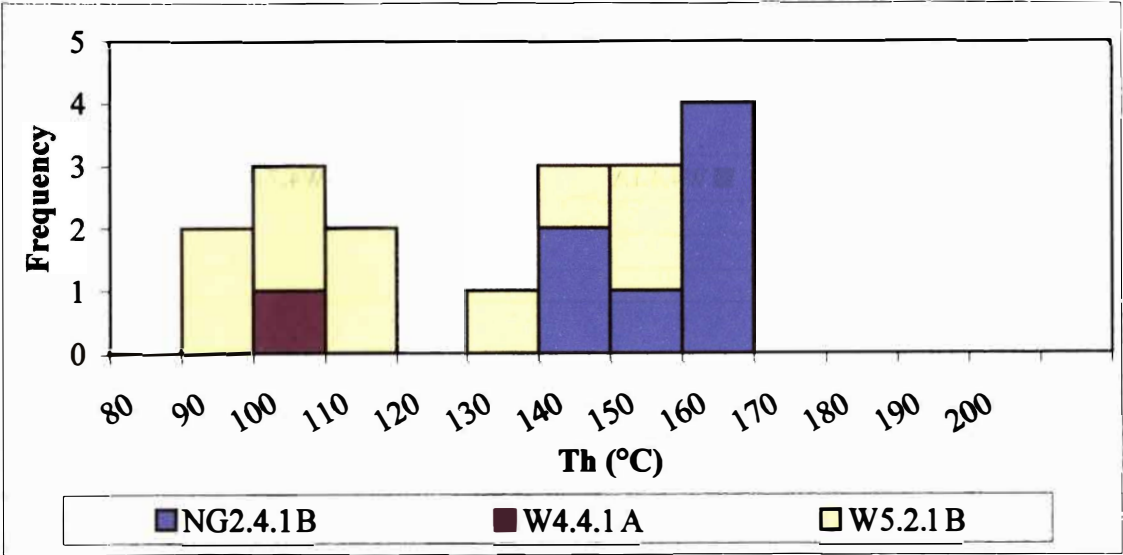
Appendix 7.3

Fluid inclusion geothermometric data for first generation calcite



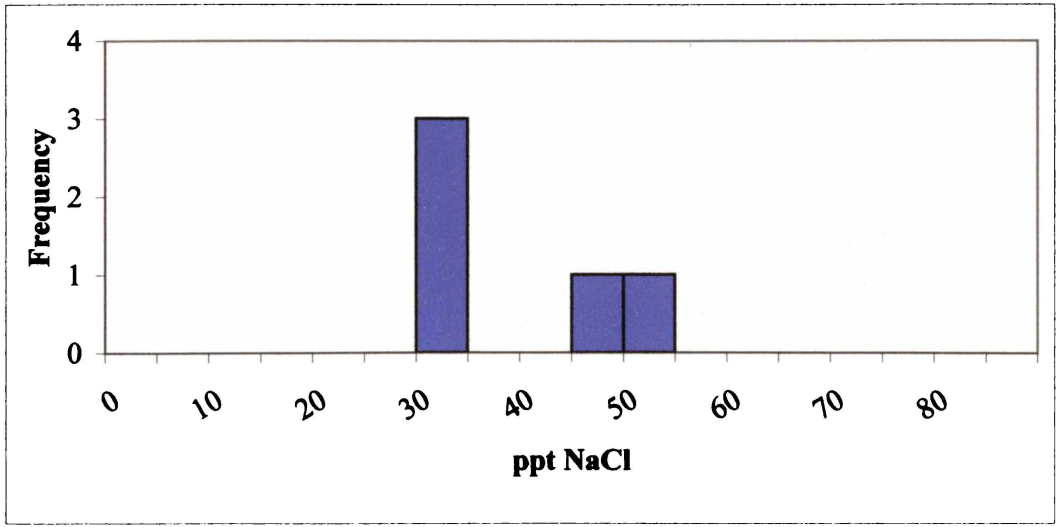
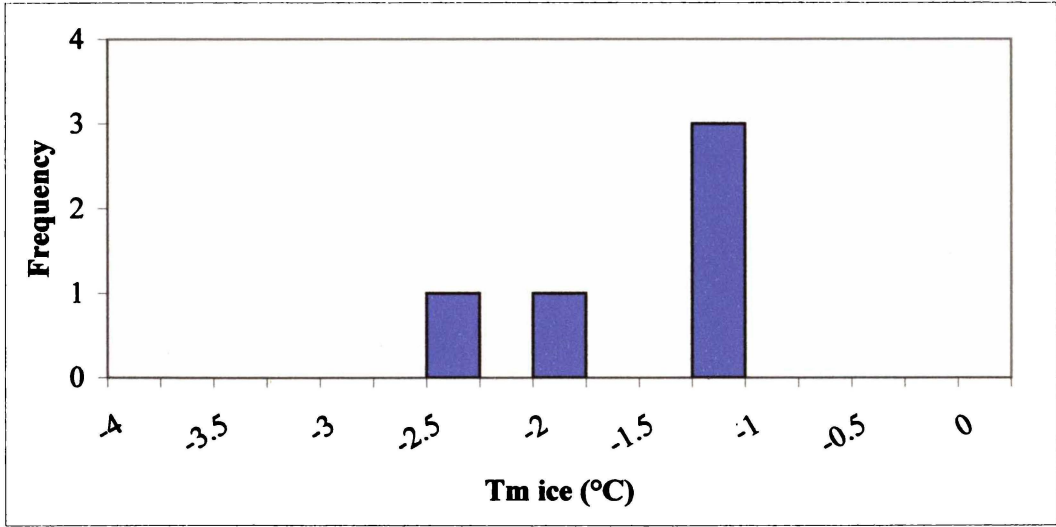
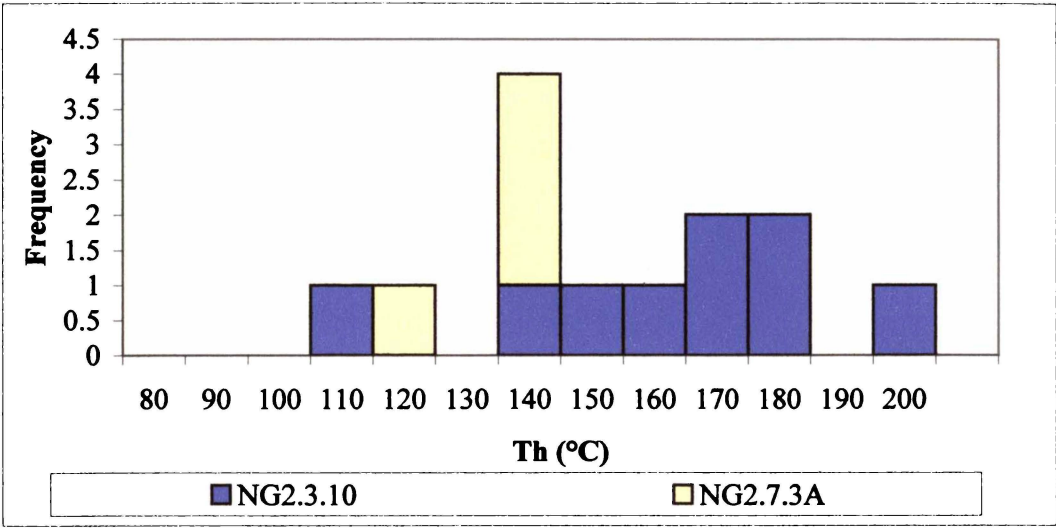
A7.3.1 Note that sample information is contained in Appendix 2.2.

Fluid inclusion geothermometric data for dolomite



A.7.3.2 Note that sample information is contained in Appendix 2.2.

Fluid inclusion geothermometric data for celestite



A.7.3.3 Note that sample information is contained in Appendix 2.2.