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Petrogenesis of diachronous mixed siliciclastic-carbonate megafacies in the cool-water Oligocene Tikorangi Formation, Taranaki Basin, New Zealand

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Abstract The Oligocene (Whaingaroan–Waitakian) Tikorangi Formation is a totally subsurface, lithostratigraphically complex, mixed siliciclastic-limestone-rich sequence forming an important fracture reservoir within Taranaki Basin, New Zealand. Petrographically the formation comprises a spectrum of interbedded rock types ranging from calcareous mudstone to wackestone to packstone to clean sparry grainstone. Skeletal and textural varieties within these rock types have aided in the identification of three environmentally distinctive megafacies for the Tikorangi Formation rocks—shelfal, foredeep, and basinal. Data from these megafacies have been used to detail previous conclusions on the petrogenesis and to further refine depositional paleoenvironmental models for the Tikorangi Formation in the central eastern Taranaki Basin margin.

Shelfal Megafacies 1 rocks (reference well Hu Road-1A) are latest Oligocene (early Waitakian) in age and formed on or proximal to the Patea-Tongaporutu-Herangi basement high. They are characterised by coarse, skeletal-rich, pure sparry grainstone comprising shallow water, high energy taxa (bryozoans, barnacles, red algae) and admixtures of coarse well-rounded lithic sand derived from Mesozoic basement greywacke. This facies type has previously gone unrecorded in the Tikorangi Formation. Megafacies 2 is a latest Oligocene (early Waitakian) foredeep megafacies (formerly named shelfal facies) formed immediately basinward and west of the shelfal basement platform. It accumulated relatively rapidly (>20 cm/ka) from redeposition of shelfal megafacies biota that became intermixed with bathyal taxa to produce a spectrum of typically mudstone through to sparry grainstone. The resulting skeletal mix (bivalve, echinoderm, planktic and benthic foraminiferal, red algal, bryozoan, nannofossil) is unlike that in any of the age-equivalent limestone units in neighbouring onland King Country Basin. Megafacies 3 is an Oligocene (Whaingaroan–Waitakian) offshore basinal megafacies (formerly termed bathyal facies) of planktic foraminiferal-nannofossil-siliciclastic wackestone and mudstone formed away from redepositional influences. The siliciclastic input in this distal basinal setting (sedimentation rates <7 mm/ka) was probably sourced mainly from oceanic currents carrying suspended sediment from South Island provenances exposed at this time.

Tikorangi Formation rocks record the Taranaki Basin's only period of carbonate-dominated sedimentation across a full range of shelfal, foredeep, and basinal settings. Depositional controls on the three contrasting megafacies were fundamentally the interplay of an evolving and complex plate tectonic setting, including development of a carbonate foredeep, changes in relative sea level within an overall transgressive regime, and changing availability, sources, and modes of deposition of both bioclastic and siliciclastic sediments. The mixed siliciclastic-carbonate nature of the formation, and its skeletal assemblages, low-Mg calcite mineralogy, and delayed deep burial diagenetic history, are features consistent with formation in temperate-latitude cool waters.

Keywords petrogenesis; limestone; shelf-to-basin facies; Tikorangi Formation; Oligocene; Taranaki Basin; reservoir; cool-water carbonate

INTRODUCTION

Tikorangi Formation is a temperate or cool-water Oligocene mixed siliciclastic carbonate-rich sequence in Taranaki Basin (Fig. 1A). The formation is an important highly productive fracture-controlled oil reservoir within the onshore Waihapa-Ngaere Field (Fig. 1B) (Hood et al. 2002b).

Taranaki Basin contains a broadly transgressive sedimentary record of Late Cretaceous to early Miocene age overlain by a very thick (up to 9 km) Neogene regressive section still forming today. From mid Oligocene, the basin underwent accelerated subsidence, possibly explained by subduction-induced platform subsidence and at least partly by local movement on the Taranaki Fault (King & Thrasher 1996), which was most pronounced and rapid in the east, resulting in development of a carbonate foredeep within which the bulk of the Tikorangi Formation was deposited (Fig. 2). Paleogeographic reconstructions by King & Thrasher (1996) suggest that a carbonate platform/shelf east of the Taranaki Fault must have been narrow and was probably fault controlled at this time.

A change in plate boundary configuration in the early Miocene saw overthrusting of strata, including the Tikorangi Formation, along the Taranaki Fault and later formation of the Tarata Thrust Zone and associated structures within the Eastern Mobile Belt (Fig. 1B). 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 Road-1A) are located (Fig. 1C). In contrast, western areas of the basin (Western Stable Platform) remained comparatively

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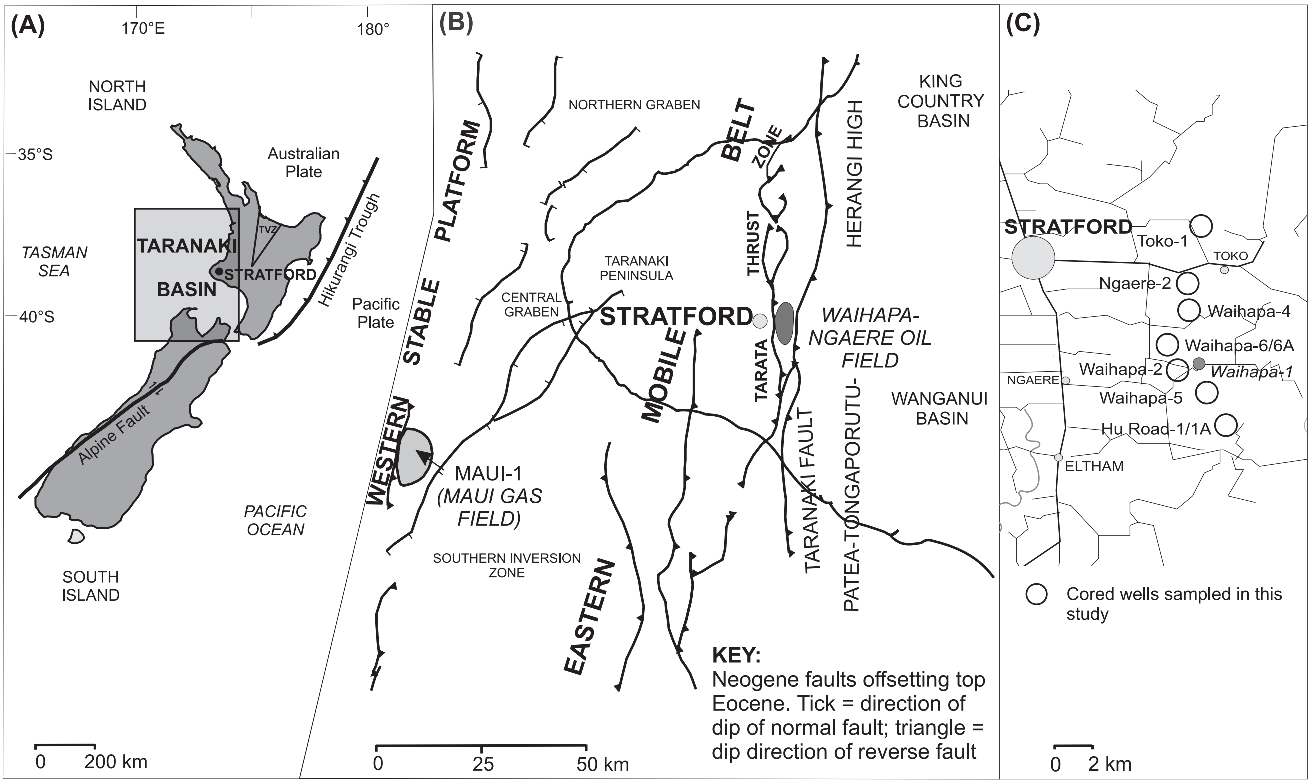


Fig. 1 **A**, Location of Taranaki Basin in New Zealand. TVZ, Taupo Volcanic Zone. **B**, Major structural and tectonic elements within Taranaki Basin, including the Waihapa-Ngaere and Maui hydrocarbon fields. **C**, Location of the seven onshore wells providing core from Tikorangi Formation within the Waihapa-Ngaere Field that form the basis for this study.

tectonically stable (King 1994; King & Thrasher 1996) and provide the setting for accumulation of more basinward facies of Tikorangi Formation, as occurs in the offshore Maui-1 study well (Fig. 1B).

The intention of this paper is to record the compositional and textural character of the Tikorangi Formation rocks using standard petrographic techniques. Following Dunham's (1962) scheme, a range of petrographically based rock types (petrofacies) for the formation has been identified, including mudstone, wackestone, packstone, mixed packstone/grainstone, and sparry grainstone. These rock types provide a framework for defining three major skeletally and texturally defined associations or'"megafacies" within the Tikorangi Formation, which are interpreted to have formed in shelfal, foredeep, and basinal environments (Fig. 2). A reference well for each of the three megafacies is defined, as well as a complete compositional log (devised using correlations between petrographic and geophysical log data) to aid in the

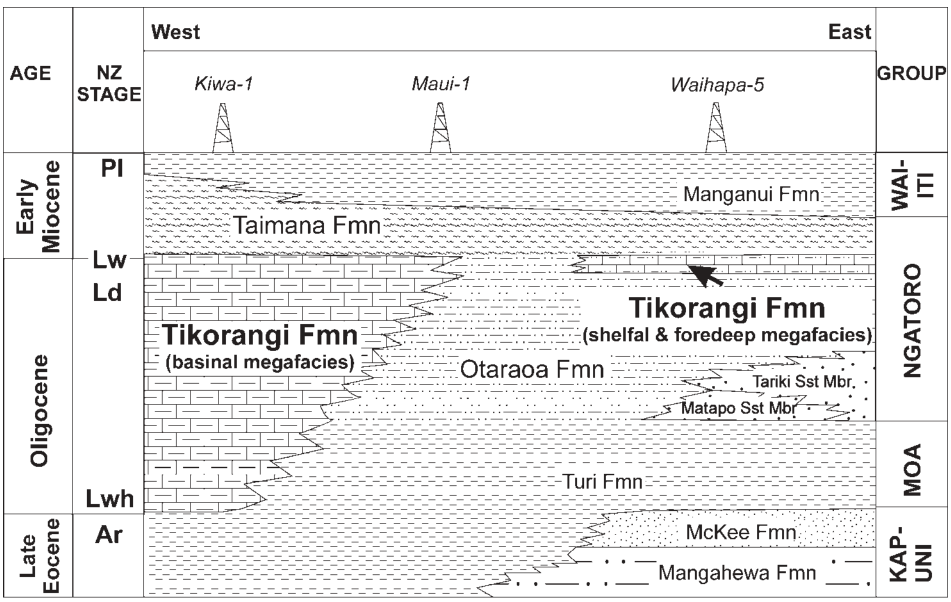


Fig. 2 Schematic lithostratigraphy for Tikorangi Formation in Taranaki Basin showing age comparison of the Oligocene (Lwh–Lw) basinal facies and latest Oligocene (early Lw) shelfal and foredeep facies. The limestone-dominated Tikorangi Formation sits unique amongst otherwise siliciclastic-dominated facies. New Zealand stages are: Ar, Runangan; Lwh, Whaingaroan; Ld, Duntroonian; Lw, Waitakian; Pl, Altonian. Adapted from King & Thrasher (1996).

interpretation and discussion of their respective depositional histories within the wider context of Taranaki Basin geological development.

Previous work

Earlier work has established two broad facies for the Tikorangi Formation. In the central eastern onshore region of Taranaki Basin the formation has been ascribed to a redeposited shelfal (Simpson 1992, Mauri et al. 1999) or platform facies (King & Thrasher 1996), renamed by Hood (2000) the foredeep megafacies. Offshore to the west and north of Taranaki Peninsula lies a bathyal (Simpson 1992; Mauri et al. 1999) or basinal facies (King & Thrasher 1996), renamed the basinal megafacies by Hood (2000). These end-member megafacies are diachronous. The foredeep megafacies has been assigned to the early part of the New Zealand Waitakian Stage (Morgans 1985). Historically, this stage has fluctuated from being entirely within, to partly within, to wholly younger than, the Oligocene (Nelson et al. 2001). Here we adopt the most recent strontium isotope age estimates made by Nelson et al. (2001) for the base and top of the Waitakian Stage at c. 25.5 and 22.2 Ma, respectively. On this basis, the early Waitakian (c. 25.5–23.8 Ma) sits within the latest Oligocene, whose boundary with the Miocene was set at 23.8 Ma by Berggren et al. (1995). The more distal basinal megafacies has been dated by Scott (1985) as ranging from Whaingaroan to Waitakian (early Oligocene to earliest Miocene), but with most of the Tikorangi Formation suggested to be also of early Waitakian age (latest Oligocene).

METHODS

A representative suite of 236 samples of Tikorangi Formation was collected from cores held in the Ministry of Commerce Core Library, Gracefield, Lower Hutt. Information relating to drill core numbers, subsurface depths, percent recovery, and other core statistics, including a sample catalogue of core samples used in this study, petrographic data, geophysical log data, and total carbonate percentage values are publicly available in Hood (2000) are available on CD on request.

Geophysical log data, including sonic, gamma-ray (GR), and a suite of resistivity logs (LLS—Laterolog shallow, LLD—Laterolog deep (ohms m^2/m)), were provided for the eight study wells by Petrocorp Exploration Ltd. The suite of geophysical logs typically provides measurements at 0.125 mAH (metres along hole) intervals throughout Tikorangi Formation.

Powders of 65 selected samples of Tikorangi Formation 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 et al. (1996), which involved digestion of 1 g of powdered sample in 1*M* HCl to obtain carbonate percentage values.

X-ray diffraction (XRD) of un-oriented powder mounts was used to determine the amount of Mg substitution in calcite (Tucker 1988). Mounts were slow scanned at 0.25°2θ/min, with the addition of an analytical grade NaCl (halite) spike for accurate peak position determination. 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).

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°2θ/min over the range of 3–15°2θ. The poor quality of clay mineral peaks necessitated digestion of new powder samples in 1:4 acetic acid for 2 h, 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 h, and after heating to 500°C for 1 h (Hume & Nelson 1982).

Correlation of laboratory-derived petrographic data with both sonic and GR geophysical log data was conducted using a transformed regression model on linear trend lines within Microsoft Excel 2000.

MINERALOGY

X-ray diffraction shows that bulk samples of Tikorangi Formation include low-Mg calcite (LMC, <4 mol% $MgCO_3$) as the sole calcium carbonate phase, with various admixtures of siliciclastic quartz, feldspar, and phyllosilicate (mica/clay) minerals. Some samples include late diagenetic replacement dolomite rhombs (Hood et al. 2002a). Judging from the temperate-latitude, cool-water origin of the deposits (Hood et al. 2001), it is likely that the primary skeletal assemblages were dominated by LMC and IMC (intermediate-Mg calcite, 4–12 mol% $MgCO_3$), with some HMC (high-Mg calcite, >12 mol% $MgCO_3$) and aragonite (e.g., Nelson et al. 1988). The mineralogically metastable carbonate minerals have been dissolved or altered to LMC during diagenesis (Hood & Nelson 1996). For example, thin-shelled former aragonitic infaunal bivalves, and rare gastropods, within the muddier sediments have been neomorphically transformed to LMC spar. Also, originally HMC (echinoderms, calcareous red algae) and IMC (bryozoans, benthic foraminifera) skeletons have undergone neomorphic stabilisation to LMC via incongruent dissolution (e.g., Hood & Nelson 1996). Primary LMC skeletons (e.g., epifaunal bivalves, planktic foraminifera, coccoliths, barnacles, and some bryozoans) have remained unaltered.

PETROGRAPHY

Sampling for this petrographic study was fundamentally controlled by the stratigraphic position of available drill core material. Five main rock types characterise the formation. Using the classification scheme of Dunham (1962) for calcareous rocks, these are mudstone, wackestone, packstone, mixed packstone/grainstone, and sparry grainstone (Fig. 3; Table 1). Petrographic information for the rock types is outlined below and summarised in Fig. 4.

Mudstone (Fig. 5A, 7)

Defined by <10% identifiable (coarse silt- and sand-sized) bioclasts and having mud-supported fabrics, mudstones are dominated by dark, very fine grained (clay to fine silt) matrix/micrite which accounts for c. 50% of the average whole rock composition (Fig. 6A). Texturally these rocks are lutites. Skeletons are dominated by planktic foraminifera (Fig. 6B) and, in their fine fraction, by conspicuous calcareous nannofossils (coccoliths). Other bioclasts include rare

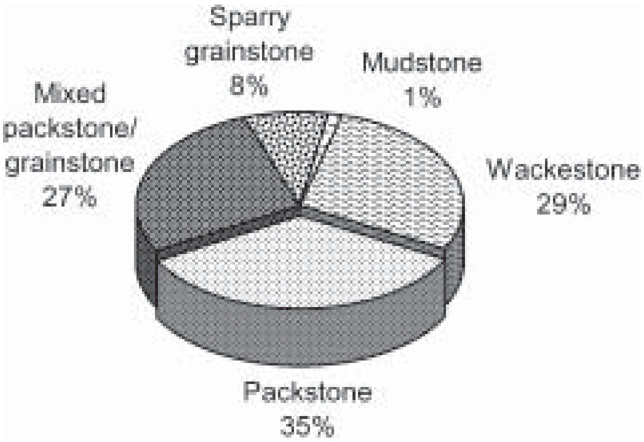


Fig. 3 Abundance of rock types amongst analysed samples of Tikorangi Formation.

fragments of echinoderms, spicules and spines, benthic foraminifera, and bivalves. Skeletal grain size is typically silt to very fine sand grade (Fig. 6D). Siliciclasts are dominated by subangular quartz and feldspar of mainly silt to rarely fine sand size (Fig. 6C). Pyrite is common as both test infills and scattered grains, while glauconite is rare. Spar cement infills planktic foraminiferal tests.

Carbonate content ranges from 15 to 30%, and averages 22% (Fig. 6E). This suggests that a large proportion of the matrix is clay- to silt-sized siliciclastic material and not carbonate mud or micrite. X-ray diffraction analysis detected only modest amounts of clay minerals, but high quartz and feldspar contents.

Wackestone (Fig. 5A,B, 7)

Wackestone is defined as containing >10% bioclasts and in having a mud/matrix-supported fabric. Matrix averages c. 40% (Fig. 6A). Among identifiable components, bioclasts dominate over siliciclasts and on average account for one-third of the whole rock composition. Bioclasts are variously dominated by planktic foraminifera (av. 34%), bivalves (av. 26%), echinoderm particles, benthic foraminifera, and sponge spicules (Fig. 6B). 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. Skeletal grains are highly abraded and fragmented, and typically fine sand sized (av. 0.18 mm) (Fig. 6D).

Observable siliciclasts account for about one-quarter of these rocks and typically comprise very fine sand-sized (range silt to medium sand), usually subangular grains of quartz and feldspar (Fig. 6C,D). Pyrite is an important authigenic mineral appearing as scattered clusters and chamber infills. Glauconite, rock fragments, and intergranular

Table 1 Summary characteristics of the five rock types identified within Tikorangi Formation.

Rock classification (After Dunham 1962)	Rock name	Bioclast content (av. %)	Fabric	Occurrence (sampled)	Carbonate content	Skeletal types
Mudstone	Calcareous lutite	<10	Mud/matrix supported	Rare	15–30 (av. 22)	Planktic foraminifera, nannofossils
Wackestone	Calcareous very sandy lutite	30	Mud/matrix supported	Common	30–50 (av. 38)	Planktic foraminifera, bivalves, benthic foraminifera, echinoderms
Packstone	Fine muddy calcarenite	65	Grain supported	Very common	29–86 (av. 53)	Bivalves, planktic foraminifera, echinoderms (benthic foraminifera, spicules/spines, red algae)
Mixed packstone/ grainstone	Impure fine muddy calcarenite to sparry medium calcarenite	60	Grain supported	Common	60–70 (av. 61)	Bivalves, planktic foraminifera, echinoderms, benthic foraminifera (red algae, spicules/spines, bryozoans, barnacles)
Sparry grainstone	Fine to very coarse pure sparry calcarenite	80	Grain supported	Some	75–99 (av. 85)	Echinoderms, bivalves, bryozoans, barnacles (benthic foraminifera, red algae)

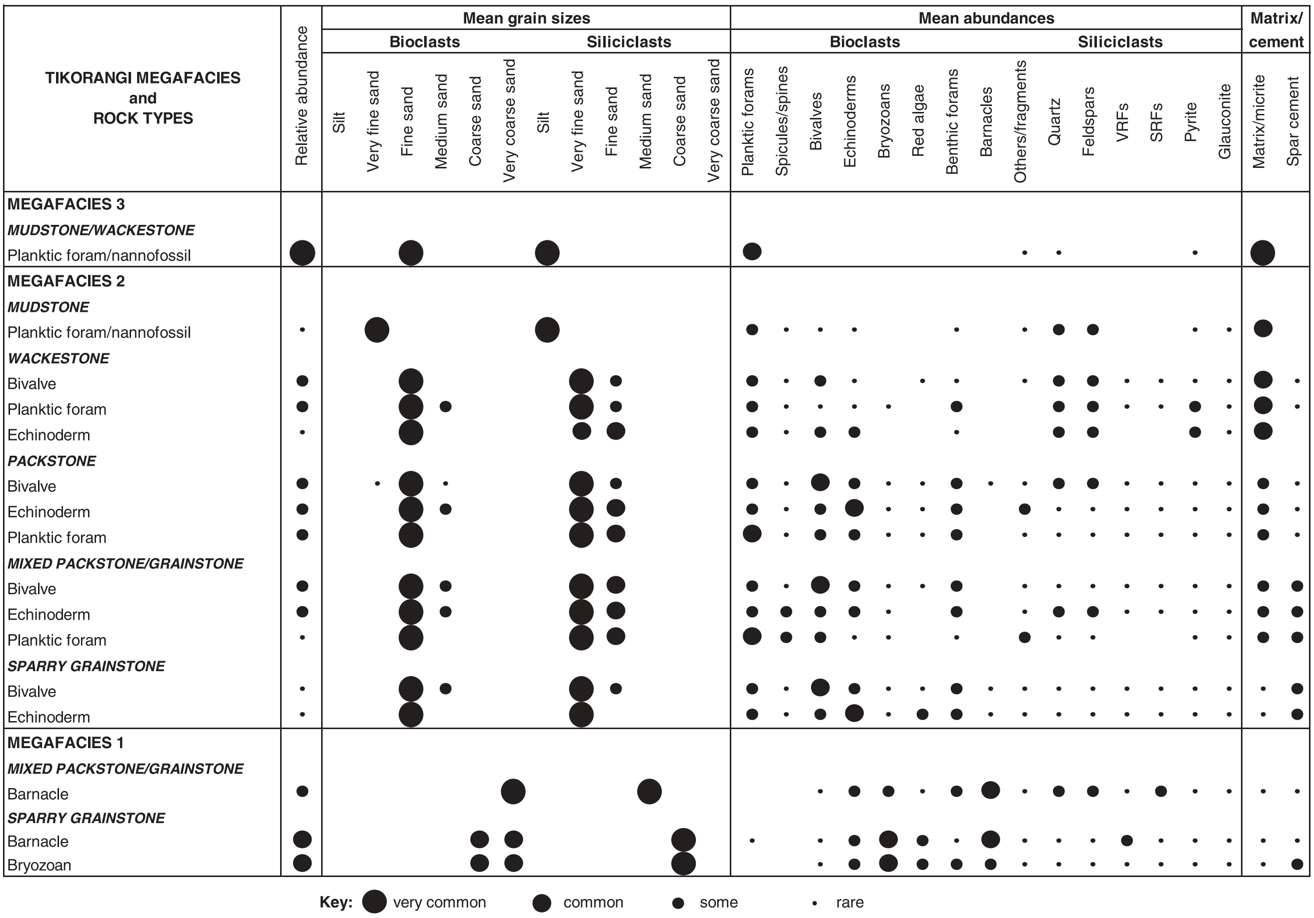


Fig. 4 Summary petrographic information for Tikorangi Formation.

spar cement are rare. Carbonate contents range from 30 to 50%, and average 38% (Fig. 6E).

Packstone (Fig. 5B,C, 7)

Packstone, defined by >5% mud matrix in a grain-supported fabric, is the most commonly occurring rock type in the Tikorangi Formation (Fig. 3). Bioclasts average 65% of the whole rock composition (Fig. 6A) and are dominantly fragmental and fine sand sized (av. 0.2 mm) (Fig. 6D). Many skeletal grains are abraded and are moderately well sorted. The packstone units are variously dominated by bivalve (av. 32%; Fig. 6B), planktic foraminifera (av. 26%), or echinoderm fragments (av. 20%). Other bioclasts include fragments of benthic foraminifera, locally common spicules and spines, and rare calcareous red algae.

Matrix/micrite is the second most abundant component (av. 18%) in the packstone units. Siliciclasts are relatively few and are generally angular to subangular and well sorted. They are dominated by very fine sand sized quartz and feldspar (Fig. 6C,D). Glauconite is present in minor quantities, as are volcanic rock fragments. Spar cement contents increase in relation to the other matrix-rich rock types, but still only average 4%. Carbonate values across all packstone samples vary from 29 to 86%, and average 53% (Fig. 6E).

Mixed packstone/grainstone (Fig. 5D, 7)

Mixed packstone/grainstone units are defined here as having subequal quantities of mud matrix and spar cement, analogous to biomicsparite of Folk (1962). Rocks are skeletal-rich limestone that average 60% bioclasts (Fig. 6A), variously dominated by one or other of bivalve fragments (av. 31%), planktic foraminifera (av. 22%), echinoderm fragments (av. 21%), and occasionally barnacle debris (Fig. 5D, 6B). Benthic foraminifera, calcareous red algae, and spicules and spines form minor components, as do bryozoan fragments. Skeletal material is commonly fine to medium sand sized (av. 0.24 mm), rarely coarser (Fig. 6D). Skeletons are abraded and are mainly moderately sorted.

Matrix/micrite is substantially reduced (av. 14%) in comparison to previously described rock types, 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. 6C,D). Other components include rare volcanic and sedimentary rock fragments, and some pyrite and glauconite. Carbonate values are mainly in the 60–70% range (Fig. 6E).

Sparry grainstone (Fig. 5E,F, 7)

Defined as having <5% mud matrix, these grain-supported, spar-cemented grainstone beds are notably bioclast rich (av. 78%) (Fig. 5E, 7A). Bioclasts are considerably coarser grained (av. 0.5 mm) than in other rock types, especially in Hu Road-1A, and typically of medium to coarse sand size (Fig. 5F, 6D). Grainstone beds are variously dominated by one or other of echinoderm (av. 25%) and bivalve (av. 22%)

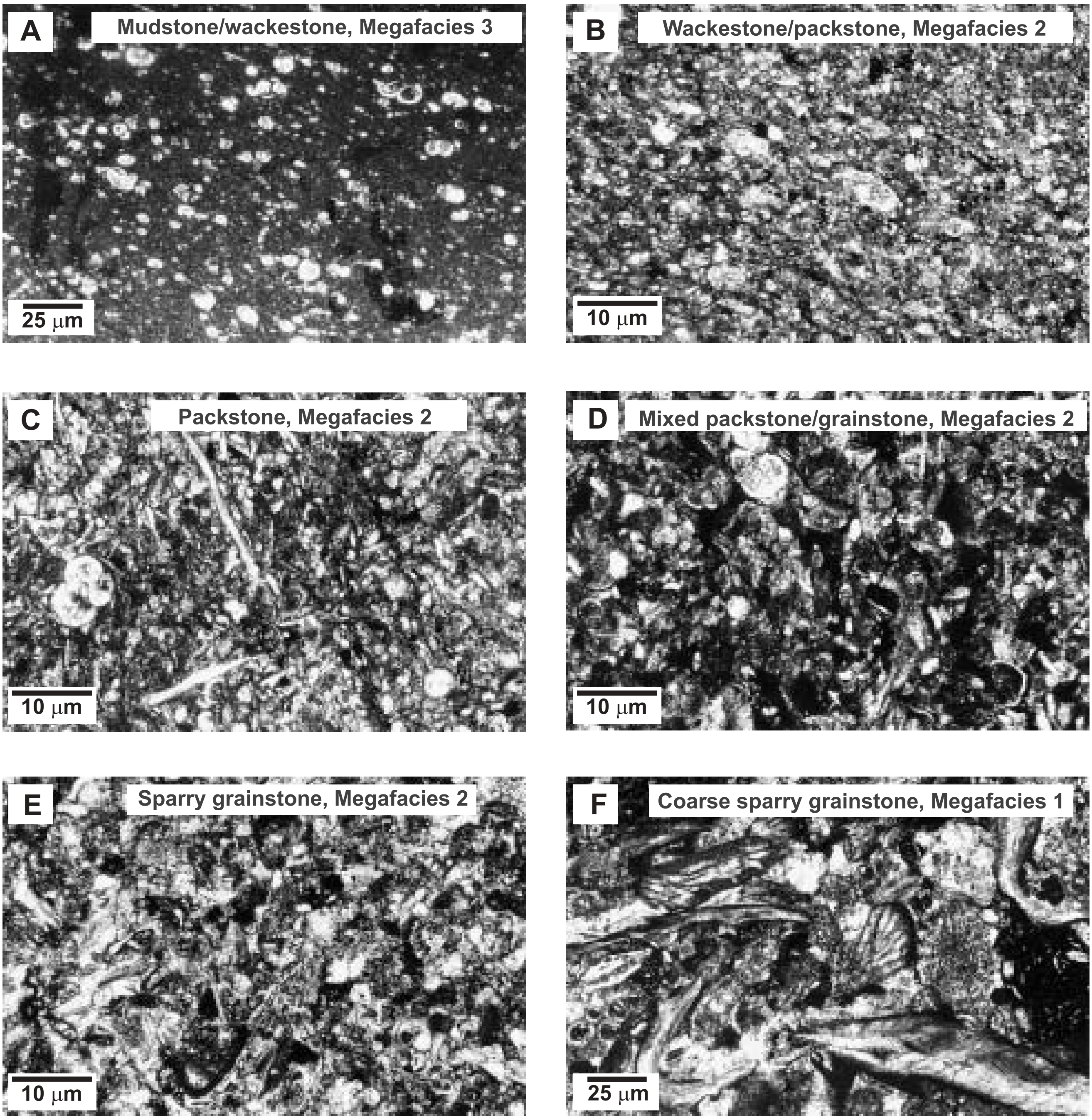


Fig. 5 **A–F** Photomicrographs of representative samples from the five rock types and three megafacies in the Tikorangi Formation (see Fig. 4). **A**, Foraminiferal/coccolith assemblage in a wackestone, offshore basinal Megafacies 3, Maui-1 well (W00523). **B**, Planktic foraminiferal-rich wackestone, onshore foredeep Megafacies 2 (W00733). **C**, Bivalve-rich/echinoderm/planktic foraminiferal packstone, onshore foredeep Megafacies 2 (W00681). **D**, Bivalve/echinoderm/planktic foraminiferal assemblage in a mixed packstone/grainstone, onshore foredeep Megafacies 2. This sample includes conspicuous amounts of calcareous red algae, supportive of redeposition from shelfal areas (W00528). **E**, Echinoderm-rich/bivalve/benthic/planktic foraminiferal sparry grainstone, onshore foredeep Megafacies 2 (W00661). **F**, Bryozoan/barnacle/calcareous red algal/benthic foraminiferal assemblage in a sparry grainstone, onshore shallow shelfal Megafacies 1 (W00501).

fragments (Fig. 6B), and less commonly by bryozoan or barnacle debris. Benthic foraminifera and calcareous red algal grains, previously unimportant in any other rock type, together form c. 40% of the bioclastic composition. Planktic foraminifera average only 10%. Skeletal grains are generally moderately well sorted and moderately abraded.

Spar cement is the second most important component of the whole rock composition (av. 11%) and reaches as high as 20% in some rocks. In contrast to other rock types, matrix/micrite is rare (av. 3%), while siliciclastics are similarly the lowest of all rock types at only 8%. Subangular to subrounded, well sorted, dominantly very fine to coarse sand

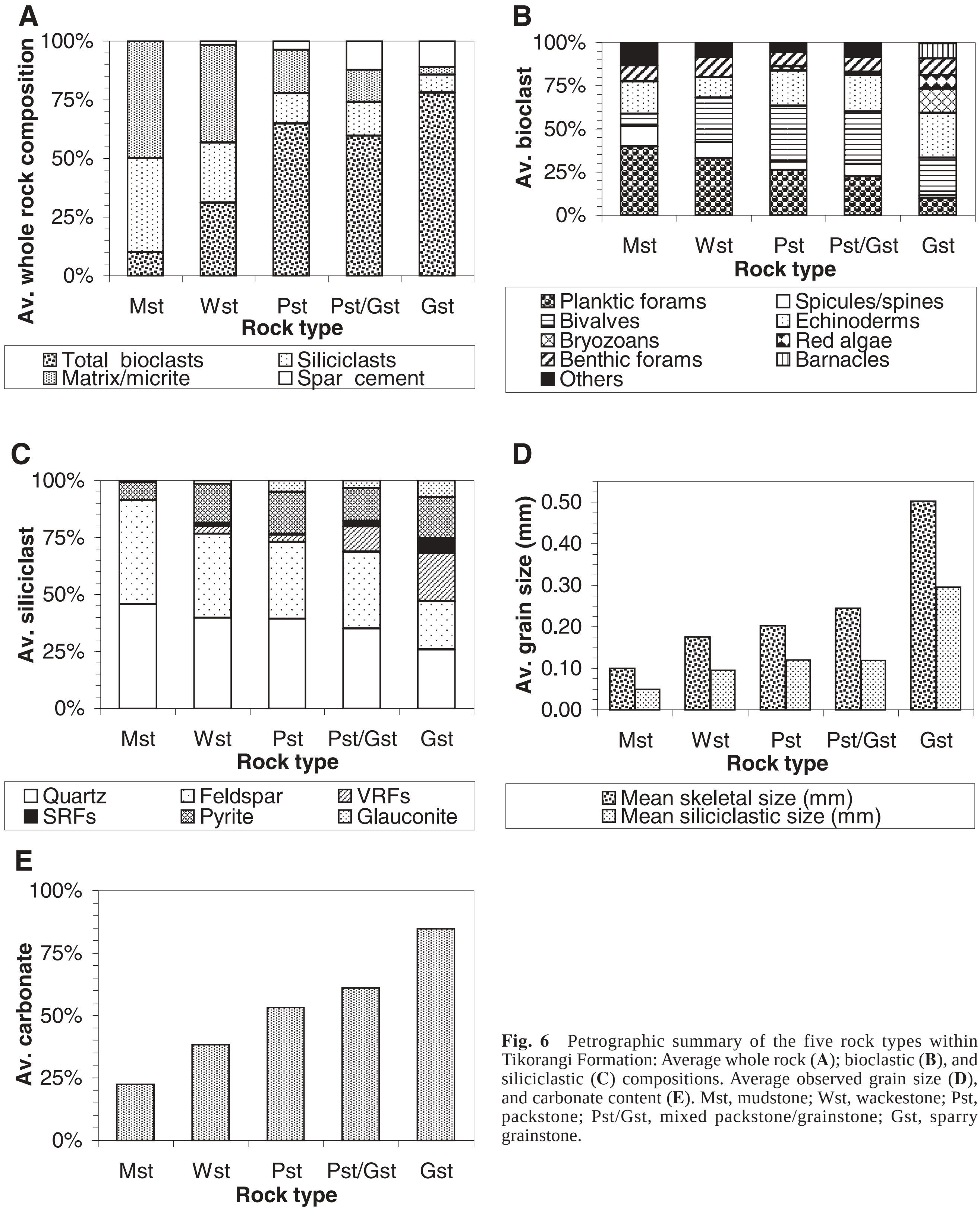


Fig. 6 Petrographic summary of the five rock types within Tikorangi Formation: Average whole rock (**A**); bioclastic (**B**), and siliciclastic (**C**) compositions. Average observed grain size (**D**), and carbonate content (**E**). Mst, mudstone; Wst, wackestone; Pst, packstone; Pst/Gst, mixed packstone/grainstone; Gst, sparry grainstone.

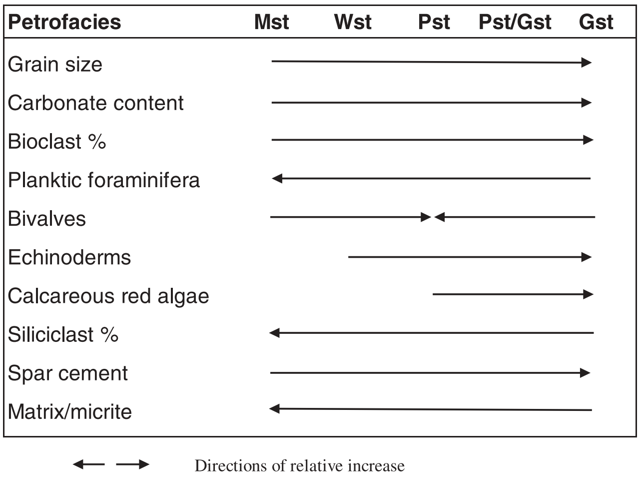


Fig. 7 Summary of petrographic trends amongst Tikorangi Formation rock types. Mst, mudstone; Wst, wackestone; Pst, packstone; Pst/Gst, mixed packstone/grainstone; Gst, sparry grainstone.

sized quartz and feldspar grains dominate the siliciclastics, along with common volcanic rock fragments (Fig. 6C) reworked out of basement greywackes. Pyrite, sedimentary rock fragments, and glauconite are rare. Carbonate contents range >75–99% (Fig. 6E).

Component trends amongst rock types

The following are some of the general trends existing for the componentry amongst the five rock types (Fig. 6), summarised in Fig. 7.

(1) The average whole rock composition is one of increasing bioclastic and spar cement content with corresponding decreasing matrix/micrite and siliciclastic content from mudstone to sparry grainstone.
(2) Planktic foraminifera and spicule and spine content decrease from mudstone to sparry grainstone beds.
(3) Bivalve fragments increase in abundance from mudstone to packstone, but decline in mixed packstone/grainstone and sparry grainstone beds.
(4) Echinoderms overall tend to be slightly more common in packstone through sparry grainstone beds, while calcareous red algae first appear rarely in packstone and increase to become locally significant components in sparry grainstone beds.
(5) The content of quartz and feldspar decreases from mudstone to sparry grainstone beds at the expense of increasing amounts of rock fragments and pyrite in particular, and also glauconite.
(6) From mudstone to mixed packstone/grainstone there is a gradual increase in mean skeletal grain size from very fine to fine sand grade, which then suddenly increases to medium/coarse sand size in sparry grainstone beds.
(7) A similar increasing trend occurs in mean siliciclastic grain size, but mainly in the silt to very fine sand from mudstone to mixed packstone/grainstone beds, increasing to medium sand in sparry grainstone beds.

Rock type distribution in wells

The overall distribution of rock types amongst the study wells emphasises the complex and varied textural and compositional make-up of the Tikorangi Formation (Fig. 8). Mudstone is scarce and sampled only in Ngaere-2 and Waihapa-5. Wackestone is much more widespread, occurring in Ngaere-2 and in all Waihapa wells (Waihapa-2, -4, -5, -6), and it is the dominant rock type in offshore Maui-1. Packstone is similarly widespread, dominating in Ngaere-2 and occurring in all Waihapa wells. Mixed packstone/grainstone is the sole rock type sampled in Toko-1, is common in Waihapa-4, -5, and -6, and is present also in the other onshore wells. Sparry grainstone dominates Hu Road-1A units, and has limited occurrence in Ngaere-2, Waihapa-2, -4, and -5.

A general trend of increasing dominance of packstone through sparry grainstone occurs from the southern to northern Waihapa wells (Fig. 8). Hu Road-1A, unlike the Waihapa and Ngaere-2 wells, is very much a pure limestone section, dominated by sparry grainstone, with a few mixed packstone/

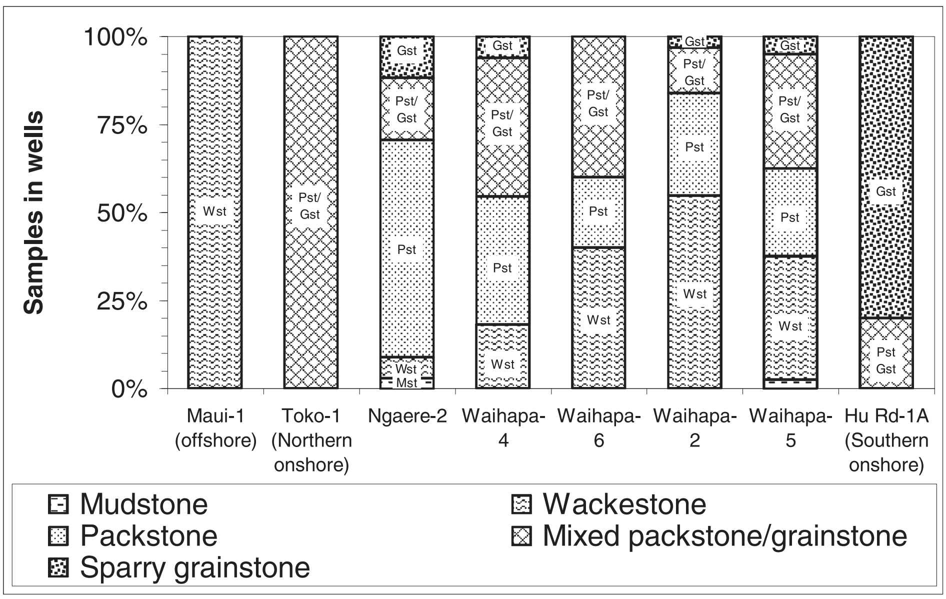


Fig. 8 Relative abundance of the five Tikorangi Formation rock types within the eight study wells. Mst, mudstone; Wst, wackestone; Pst, packstone; Pst/Gst, mixed packstone/grainstone; Gst, sparry grainstone.

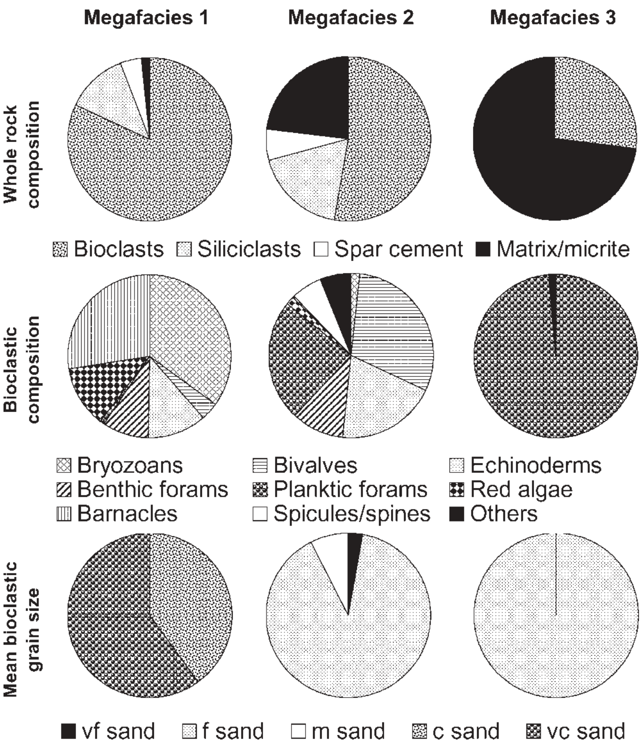


Fig. 9 Summary whole rock and bioclastic compositional and textural petrographic data for Megafacies 1, Megafacies 2, and Megafacies 3 of the Tikorangi Formation. vf, very fine; f, fine; m, medium; c, coarse; vc, very coarse.

grainstone units. Maui-1 is unique and from the limited sample database comprises solely wackestone lithology.

SKELETAL MEGAFACIES

From a review of the five rock types, an evident feature is the occurrence of three main groups of rocks that are distinctive on the collective basis of their skeletal assemblages, siliciclastic sediment plus matrix content, and grain size (Fig. 9). We show that these three groups, or "megafacies", are spatially more or less unique to particular wells, and consequently they are likely to relate to different paleoenvironmental settings (see Discussion). Here, we first describe the petrographic characteristics of the megafacies.

Megafacies 1: bryozoans/barnacles/calcareous red algae/benthic foraminifera

This megafacies is characterised by pure limestone with unique textural and compositional properties (Fig. 9). Texturally they are coarse grained, from medium to very coarse sand sized (Fig. 5F). Compositionally they are bioclast dominated, with a prevalence of spar cement over rare matrix/micrite. Skeletal components include shallow-water biota atypical of any other rocks sampled within Tikorangi Formation. These biota include co-dominant bryozoans and barnacles with major contributions from calcareous red algae and large benthic foraminifera (*Amphistegina*) (Fig. 5F). Siliciclastic laminae show a predominance of rock fragments, both sedimentary and volcanic, compared to quartz and feldspar in other megafacies. Their high carbonate values (up to 99%) result in a dominance of sparry grainstone, with rare mixed packstone/grainstone. This megafacies is limited in occurrence to core sampled from the southernmost well in this study, at Hu Road-1A.

Megafacies 2: bivalves/echinoderms/planktic foraminifera

The second megafacies identified within Tikorangi Formation typifies the other onshore wells in this study, namely, Toko-1, Ngaere-2, and Waihapa-2, -4, -5, and -6. This megafacies comprises a spectrum of siliciclastic-carbonate mixtures having highly variable textures and compositions (Fig. 5B–E). However, three main skeletal types persist throughout, namely, bivalves, planktic foraminifera, and echinoderms, typically in that order of decreasing abundance (Fig. 9). The rocks are mainly fine sand-sized skeletal sandstone to limestone with variable quantities of very fine sand-sized siliciclastics.

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 rock type distribution within Megafacies 2, 28% of rocks are wackestone with only 1% mudstone (Fig. 5A,B). Packstone comprises 37% of the rocks (Fig. 5C), while 28% are mixed packstone/grainstone (Fig. 5D). Some 6% are sparry grainstone (Fig. 5E).

Megafacies 3: planktic foraminifera/nannofossils (coccoliths)

Offshore Maui-1 well provides the third example of a unique Tikorangi Formation megafacies. It is characterised by mudstone or wackestone having a high matrix/micrite content, and less than one-third of the average whole rock composition comprises recognisable sand/silt-sized bioclasts (Fig. 5A, 9). These are typically fine sand-sized planktic foraminifera, while in the mud fraction SEM analysis (Hood 2000) reveals common calcareous nannofossils (coccoliths). Observable siliciclastics are rare and of silt size. Carbonate values range from c. 30 to 40%. X-ray diffraction analysis suggests the majority of the matrix/micrite comprises silt- and clay-sized siliciclastic material, but apparently only limited clay minerals. Intergranular spar cement is not evident.

Up-core petrographic trends

Using correlations between petrographic and geophysical log data we have been able to construct complete compositional logs for the entire Tikorangi Formation for individual wells in this study, despite a paucity of core sample in most wells (Fig. 10). Despite the often variable petrographic make-up of the formation, our aim of this interpretative petrography is to discern general trends to assist with broad 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 compositional logs are shown and discussed for the three identified megafacies. Hu Road-1A is used as a reference for Megafacies 1; Waihapa-5 as a reference for the other onland Waihapa/Ngaere-2 and Toko-1 wells representing Megafacies 2; and Maui-1 is the reference for Megafacies 3 (Fig. 10).

Megafacies 1 (Hu Road-1A)

The barnacle/bryozoan/calcareous red algal/benthic foraminiferal megafacies shows a general up-core increase

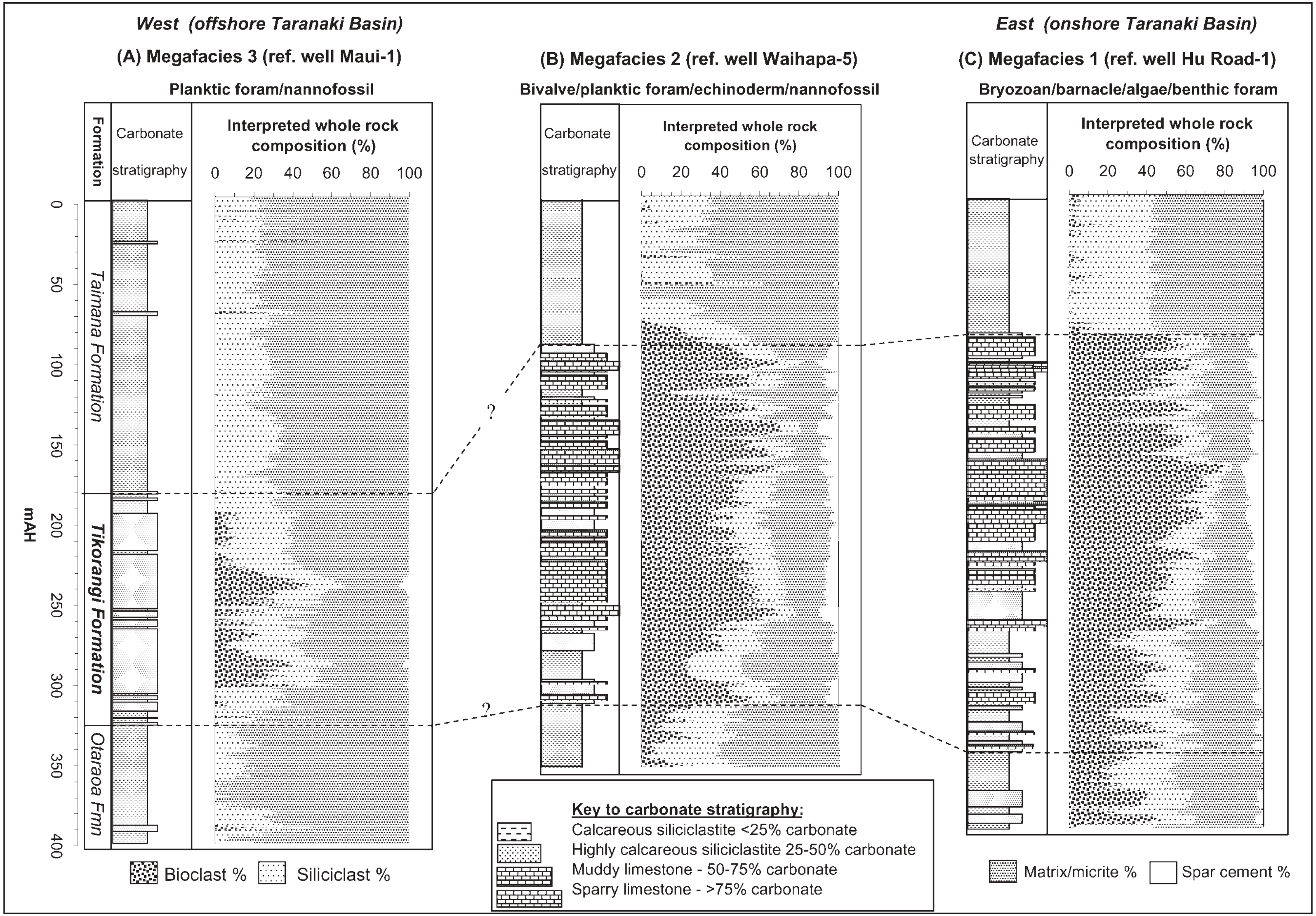


Fig. 10 Summary lithostratigraphy and interpreted whole rock compositions for the three Tikorangi Formation megafacies. Whole rock compositions have been derived for the Tikorangi Formation by integrating gamma-ray (GR) and sonic (Dt) logs with bioclastic, siliciclastic, micrite/matrix, and spar cement contents obtained from sample petrography (Hood 2000). These correlations have been tentatively extended into the underlying and overlying Otaraoa and Taimana Formations, respectively, for comparative purposes only. The absence of Dt data from 3100 to 3138 mAH in Waihapa-5, Megafacies 2, has necessitated the use of GR correlations to infill and complete the interpreted composition over the entire Tikorangi Formation interval.

in bioclastic content reaching a maximum of c. 85% some two-thirds up-section (Fig. 10C). 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 <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 basal sections to reach nearly 15% in upper sections. Across the upper boundary of Tikorangi Formation there is a dramatic drop in the bioclastic content into the siliciclastic-rich Taimana Formation.

Megafacies 2 (Waihapa-5)

The base of the bivalve/echinoderm/planktic foraminiferal megafacies is marked by a sharp increase in bioclastic material moving out of the Otaraoa Formation (Fig. 10B). Bioclasts reach a maximum of c. 70% in the upper part of the formation before a sharp reduction upon entering the overlying Taimana Formation. For siliciclasts, the up-core trend drops from 30% in lower sections to 10% or less in the upper formation, with matrix content showing a similar trend, declining from 50% in lower sections to 10% in upper sections (Fig. 10). Spar cement is present throughout most of the formation, but generally forms <10% of the whole rock composition.

Additional petrographic logs in Hood (2000) show that planktic foraminifera decrease in abundance from the underlying Otaraoa Formation into Tikorangi Formation, and then show an overall increase up-core, reaching a maximum in upper sections where bioclastic contents are low. The more siliciclastic/matrix-rich beds are enriched in planktic foraminifera. Echinoderms generally follow a reverse trend to planktic foraminifera, decreasing up-core and being more abundant in bioclastic-rich upper beds. 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 up-core and being more prevalent in siliciclastic matrix-rich units. Interpreted siliciclastic compositions for Waihapa-5 show no major variation up-core, although a decrease in quartz and feldspar content and an increase in pyrite occurs on entering the basal Tikorangi Formation. Pyrite appears to be more prevalent in the bioclastic-rich units.

Megafacies 3 (Maui-1)

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

DISCUSSION

The Taranaki Basin underwent accelerated subsidence from 30 to 22 Ma (late Oligocene to early Miocene), particularly in the eastern areas adjacent to Taranaki Fault (King & Thrasher 1996). Subsidence in the Oligocene was related ultimately to early development of the Australia-Pacific plate boundary and basin formation (carbonate foredeep), into which the majority of the latest Oligocene Tikorangi Formation was deposited at bathyal (outer shelf to slope) depths (Fig. 11). The inferred across-basin relationships of the three megafacies forming the Tikorangi Formation at this time are summarised in Fig. 12. Petrographic trends amongst these megafacies are summarised in Fig. 13.

Megafacies 1

Megafacies 1 rocks are interpreted to represent moderate to high energy shelfal sediments formed either in shoal nearshore locations or atop basement pedestals rising up into shallow depths. The presence of barnacles, calcareous red algae, and large *Amphistegina*, coupled with the coarse sand-sized textures, are supportive of such shallow depositional conditions (Hayton et al. 1995). Hu Road-1A taxa are consistent with oxygenated waters and bottom-water circulation expected at agitated inner-shelf depth settings (New Zealand 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 megafacies originating in shallow water 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 environment and a proximal basement source. The rare occurrence of brecciated basement rocks in Hu Road-1A core (Hood 2000) indicates close proximity to subaerially exposed basement, such as about isolated paleohighs (Fig. 14).

A supply of proximal basement rock fragments, rare in the other megafacies, decreases up-core as the bioclastic content increases. This suggests that while carbonate production sites kept pace with long-term relative sea-level rise, the major supply of siliciclastics progressively declined as basement source(s) became increasingly submerged by marine transgression, which was reaching its peak during Tikorangi Formation deposition. From well log characteristics, Hood et al. (2003, this issue) inferred that the time of maximum onlap and clastic starvation in the upper part of the Tikorangi Formation corresponds to highstand conditions. Timing is constrained by the c. 22.5–23 Ma age ascribed to the Tikorangi seismic reflector (King & Thrasher 1996).

Shelf-derived megafacies rocks are typically coarse sparry and mixed packstone/grainstone dominated by barnacle and bryozoan fragments. The limestone beds are compositionally similar to many age-equivalent deposits in the Te Kuiti Group in neighbouring King Country Basin (Nelson 1978a; Nelson et al. 1994), and more generally elsewhere in New Zealand at this time (Nelson 1978b; Hayton et al. 1995). King & Thrasher (1996) placed the Hu Road-1/1A well in a contemporary outer shelf or slope environment, different from the rather shallower carbonate shelf platform setting invoked here.

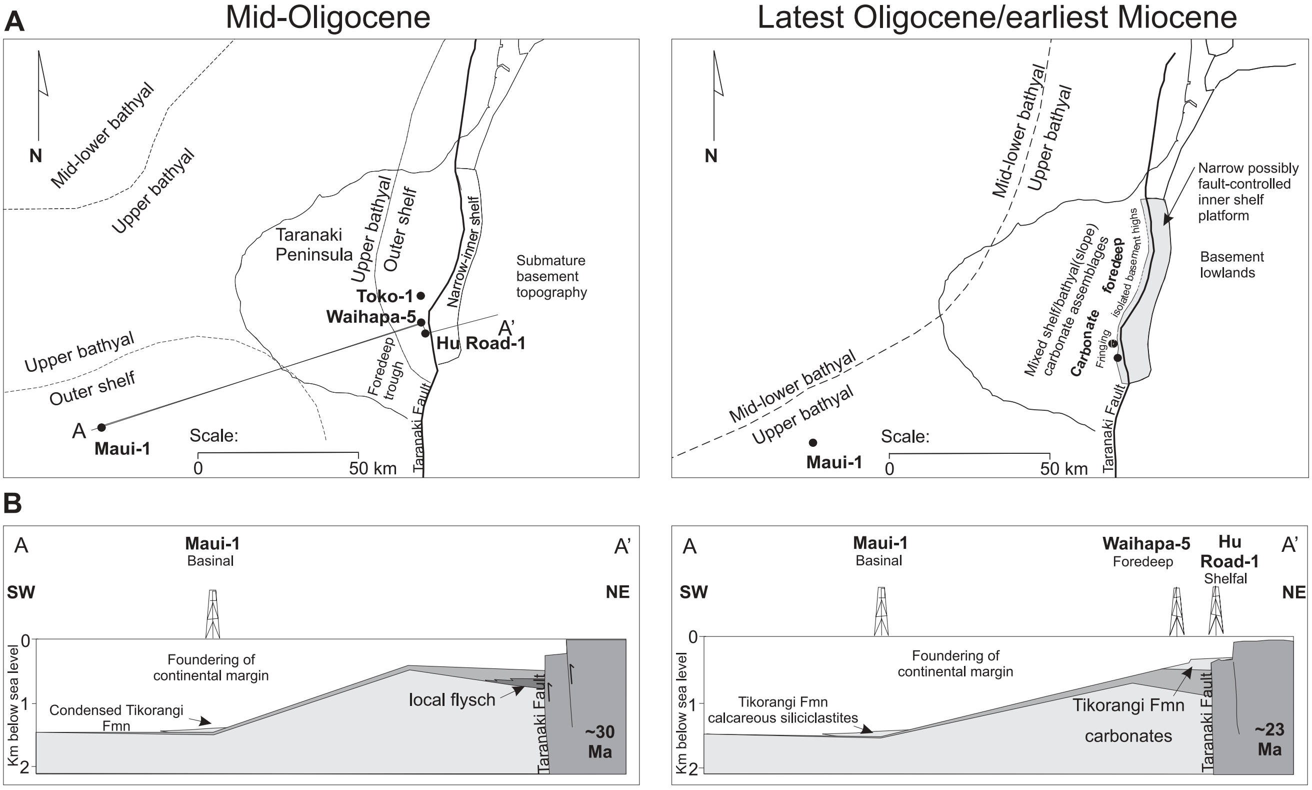


Fig. 11 **A**, Paleogeographic changes for the central eastern Taranaki Basin margin from the mid Oligocene to latest Oligocene/earliest Miocene during deposition of the Tikorangi Formation basinal (Maui-1), foredeep (Waihapa-5), and shelfal megafacies (Hu Road-1). Hu Road-1 is shown in a pre-allochthonous/thrusting position. **B**, Cross-sections (see A for location) showing changes in basin structure due to subsidence and progressive deformation of the Oligocene/Eocene boundary (base of shaded interval). Developed from conceptual reconstructions suggested by Simpson (1992), Palmer (1985), King & Thrasher (1996, fig. 5.5), and Mauri et al. (1999). Selected study wells are shown in their current position although units encountered in these wells are allochthonous in nature and have been thrust eastwards from their original positions.

Megafacies 2

By mid Oligocene, the eastern margin of Taranaki Basin had developed into a carbonate foredeep (Fig. 11) with bathyal water depths (King & Thrasher 1996). Despite these bathyal depths, this study has shown the predominance in Megafacies 2 of fine fragmental shallow-water skeletal debris intermixed with pelagic biota that is evidence for basinward redeposition from shallow shelfal areas, or topographic highs, presumed to be the sites where the skeletal debris formed Megafacies 1 (Fig. 14). Detailed microfaunal studies in Waihapa-1 (Fig. 1C) show skeletons characteristic of inner to mid-shelf conditions, further evidence of shelfal material redeposition into the foredeep (Young & Carter 1989).

Increased water depths associated with foredeep development (Fig. 11B) are reflected in increased numbers of planktic foraminifera up-core. This may be interpreted as a shift towards a 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.

Individual wells in the mixed shelfal/basinal foredeep megafacies emphasise the commonly site specific nature of the Tikorangi Formation. 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, and are dominated overall by shelfal skeletons indicative of preferentially receiving thicker or more frequent shallower water inputs. Ngaere-2 shows a decrease in coralline red algal debris up-core, suggestive of drowning of shallower shelfal areas or a change in source area.

Rock textures in the foredeep megafacies reference well (Waihapa-5) are initially dominantly wackestone, by mid section are packstone, and in the carbonate-rich upper sections are typically mixed packstone/grainstone (Fig. 12). This is suggestive of dwindling siliciclastic source areas as sea level transgressed, while carbonate production increasingly flourished under reduced siliciclastic input.

Subsequent reworking of sediment by often intense bioturbation is probably responsible for destruction of any clear sedimentological evidence for redeposition in the Tikorangi cores, a matter noted by Naish (1991) having described Toko-1 core samples. Despite this, the occasional indication of a *Planolites-Chondrites-Zoophycos* trace fossil assemblage in foredeep cores is consistent with deposition at bathyal depths (e.g., Ekdale et al. 1984; Nelson 1985).

With mobility of the Patea-Tongaporutu-Herangi High (e.g., Nelson et al. 1994; King & Thrasher 1996) and potentially uplift of South Island basement, an increase in siliciclastic supply resulted in a gradual decrease in bioclastic material in the upper part of Tikorangi Formation at Waihapa-5, and a much more rapid cut-off of bioclastic input in the shelfal Hu Road-1/1A locality. This suggests there remained reworking of sediment, formed in drowned

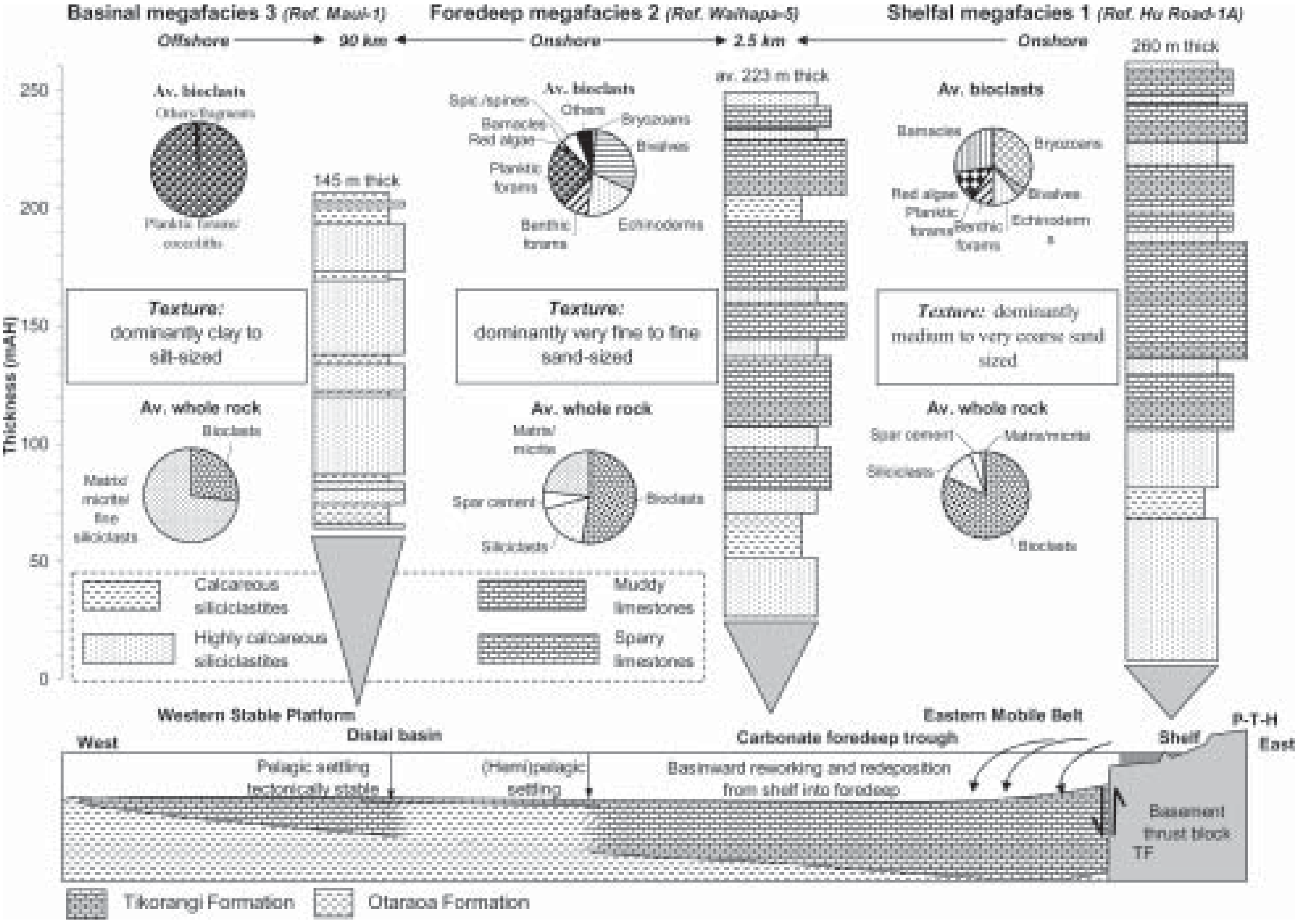
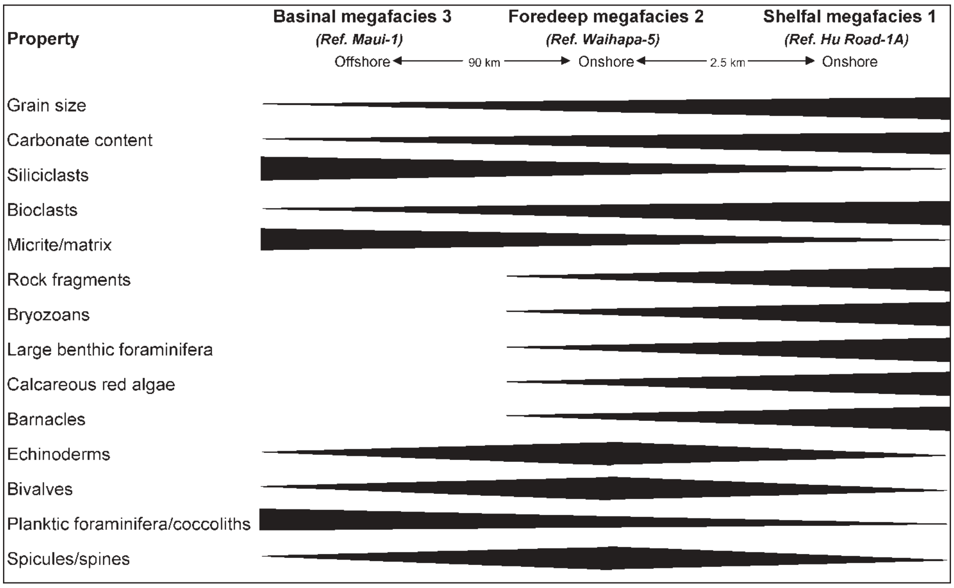


Fig. 12 Simplified stratigraphy showing the thickness, carbonate facies, and compositional and textural differences between shelfal, foredeep, and basinal megafacies of the Tikorangi Formation in relation to their generalised depositional settings. TF, Taranaki Fault; P-T-H, Patea-Tongaporutu-Herangi basement high.

Fig. 13 Summary textural and compositional changes between the three Tikorangi Formation megafacies within a shelf-to-basin perspective. An increase or decrease in value/content is denoted by changing thickness of the bars.



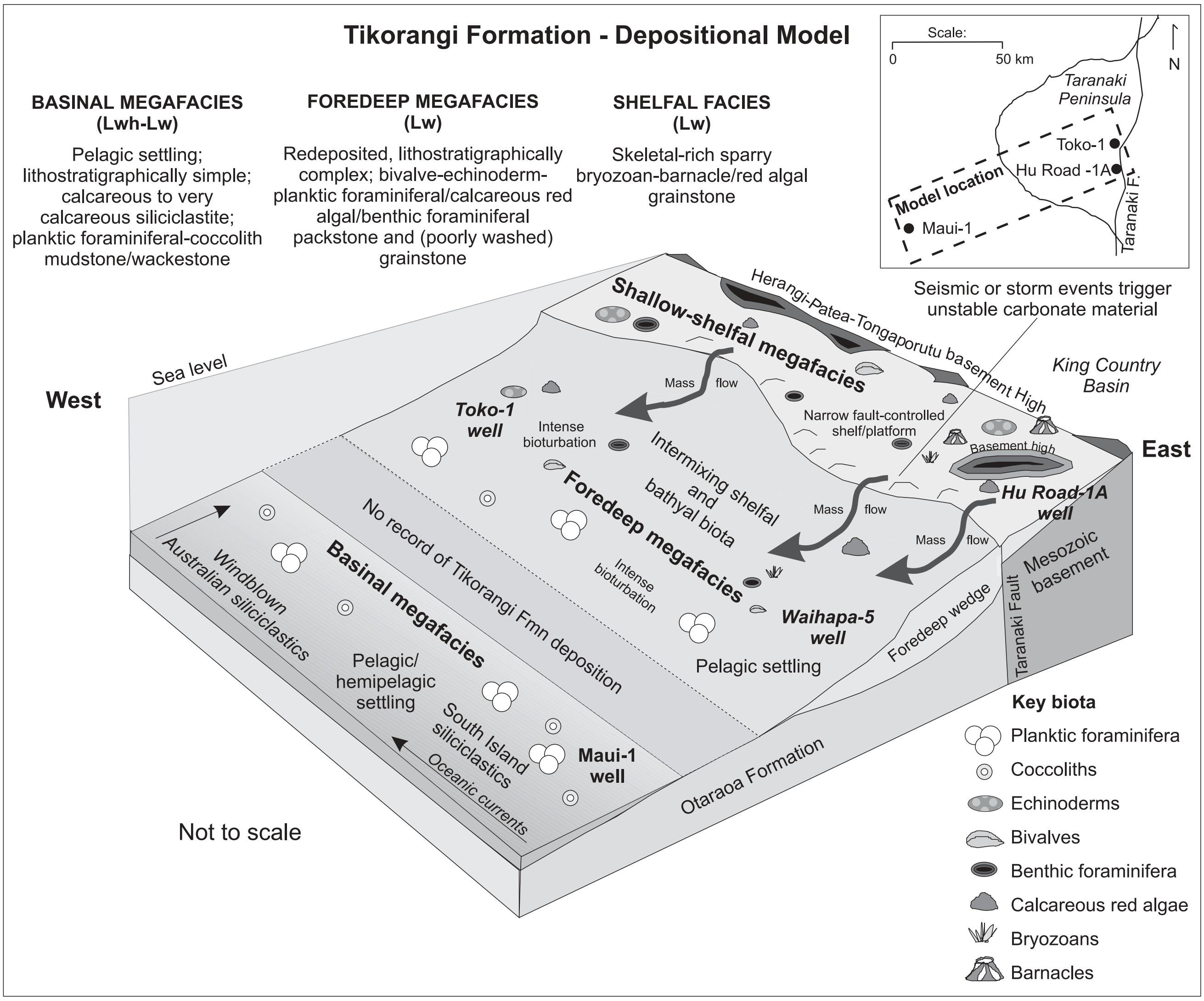


Fig. 14 Tikorangi Formation depositional model for the central eastern margin of Taranaki Basin to Taranaki Peninsula region showing the location and major characteristics of the three identified megafacies during latest Oligocene (early Lw) time. Lwh = Whaingaroan; Lw = Waitakian. Region of no Tikorangi carbonate deposition is based on information contained in Palmer (1985), Simpson (1992), King & Thrasher (1996), and Mauri et al. (1999).

carbonate factories, into deeper water while little or no new production was occurring on the shelf at Hu Road-1/1A. Eventually, siliciclastic input overwhelmed carbonate production, when deposition of Taimana Formation replaced the carbonate-rich Tikorangi Formation.

Megafacies 3

The more basinal pelagic setting of Maui-1 (Fig. 11–14) allowed accumulation of foraminiferal nannofossil wackestone, 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 ongoing 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 both eastern Taranaki and South Island provenances, the latter via a forerunner of the modern Westland Current (Hume & Nelson 1986; Hudson 1996).

Depositional models and sedimentation rates

The development of a depositional model for the Tikorangi Formation is centred on elucidating the origins of the latest Oligocene redeposited mixed bathyal/shelfal foredeep megafacies which dominates the Tikorangi Formation onshore. Key questions to address are: by what mechanism(s) was shelfal material displaced basinward into the Taranaki foredeep; what was the trigger(s) for that mechanism(s); and what was the timing of these transportation events? We reiterate that although there is clear evidence for displacement and redeposition of shelfal skeletons basinward (particularly fragmented and abraded calcareous red algae and large benthic foraminifera (*Amphistegina*) fragments intermixed with bathyal flora and fauna), a lack of good age-control data throughout the formation, and a masking of any clear physical evidence of mass-depositional events due to high levels of bioturbation, forces any model to be rather general in nature. Consequently, we draw upon the wider carbonate literature for potential model analogues.

Mullins & Neumann (1979) and Mullins (1983) have developed several carbonate depositional models from the modern tropical carbonate setting of the Bahama Platform, of which the escarpment model (eastern side of the Little Bahama Bank) has some applicability to the ancient cool-water Tikorangi Formation foredeep depositional setting. In the Bahaman case, 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 grain flows, and turbidite mechanisms. Tucker & Wright (1990) considered this to be an appropriate model for an ancient fault-controlled platform, which in the Tikorangi case would be Taranaki Fault (Fig. 14).

In such settings as the Bahaman case, highstand shedding is responsible for mass transport of shoal-water carbonate sediment into deeper water (e.g., Driscoll et al. 1991; Emery & Myers 1996; Westphal et al. 1999). Carbonate resedimentation occurring during highstand stages is well documented for such tropical carbonate settings (photozoan sediments) where over-production in shallow photic water results in overloading and steepening of the slope, and then instability leads to failure and generation of sediment gravity flows (Tucker & Wright 1990). In the cool-water shelf setting (heterozoan sediments), carbonate factories are commonly deeper (generally aphotic), and during regressive sea-level periods redepositional events would be perhaps most important.

The potential of highstand shedding as a mechanism for supplying shelfal material basinward in the cool-water Taranaki foredeep setting is possible given the broad scale transgressive event (King & Thrasher 1996) which was reaching its culmination (highstand) during and following Tikorangi deposition (Hood et al. 2003). The occurrence and importance of carbonate mass redeposition events in the cool-water setting, whether solely or truly highstand or not, is certainly worthy of specific mention alone. Bernecker et al. (1997) document for the Oligocene–Miocene Seaspray Group, Gippsland Basin, southeastern Australia, that sediments are fine-grained siliciclastic-rich calc-turbidites and bioclastic wackestone and packstone, deposited on the slope. The exact nature of the turbidite flows in southeastern Australia is difficult to assess, their overall fine-grained character suggesting the carbonate materials were transported in low- to medium-concentration turbidity currents. Similarly, in the Tikorangi Formation, we cannot be any more specific in relation to statements exemplified in these Australian studies. Highstand sea-level conditions as a trigger for mass depositional events in the cool-water setting is documented by Holdgate & Gallagher (1997) in carbonates of the Australian Gippsland Basin. Here, fine-grained carbonate-rich rocks, similar to the Tikorangi Formation, comprising bioclastic wackestone and packstone, 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 via turbidite flows from shallower shelfal areas to upper and mid-slope depths.

Given the above Australian examples, it is difficult to not be open to the likelihood of mass redepositional events occurring with increased frequency as sea level neared its transgressive peak, resulting in more regular highstand influxes or pulses of coarser carbonate material when the shelfal carbonate factories reached peak production. This may explain the thicker, better developed limestone units in the upper Tikorangi Formation.

Superimposed on this background transgressive episode is what we consider to be a much more locally important tectonically controlled subsidence and foredeep development, which is much more likely to have had a far greater influence on local sea-level change during this time, initiated by movement on the Taranaki Fault as a result of movement at the Australia/Pacific plate boundary. This movement responsible for the creation of a high-energy, narrow Taranaki Fault-controlled platform (our source for shelfal sediments from shoal nearshore locations or atop basement pedestals—Megafacies 1) (Fig. 14), and the development of the foredeep and rapidly increasing water depths to the west of the Taranaki Fault, was most likely to have involved periodic seismic events/activity during this time. The apparent cyclical yet episodic sedimentation patterns seen in geophysical and compositional logs, with more limestone-rich redeposited units separated by more shale-like units representing background sedimentation, imply localised tectonic and/or storm triggering of pulses of shallow water input downslope (e.g., Foreman et al. 1991). Any small-scale sea-level changes within the broad transgressive sequence were probably of secondary importance in controlling the timing of shedding of material basinward.

The redeposited carbonate, whether possibly triggered by seismic or storm events alone, became interbedded and intermixed with background pelagic facies more typical of the basinal setting, accumulating as laterally extensive aprons. Progradation would have been controlled by rate of basinal sedimentation, rate of foredeep subsidence, platform width, and foredeep depth. Initial deepening-upward sequences show foredeep subsidence outpaced sedimentation. Shallowing-upward sequences developed in the upper part of Tikorangi Formation (Hood et al. 2003) when sedimentation exceeded subsidence/sea-level rise, so that the foredeep was gradually filled with Tikorangi carbonate 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 earliest 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.

Depositional rates have been calculated for Tikorangi Formation foredeep facies using a maximum true stratigraphic thickness of c. 240 m in the vicinity of the Waihapa-2 and -4 wells. Given the restricted latest Oligocene (early Waitakian, 25.5–23.8 Ma) age of Tikorangi Formation foredeep megafacies (King & Thrasher 1996), deposition may have occurred over a 1–2 m.y. interval, giving sedimentation rates in the order of 120–240 m/m.y. The higher rate is similar to that of c. 220 m/m.y. for fine-grained siliciclastic-rich turbidites reported by Bernecker et al. (1997) for Tertiary deep-water mixed shelf-slope temperate carbonate of the Seaspray Group in the Gippsland Basin, southeastern Australia, and provides supportive evidence for a mass-emplacement origin for much of the foredeep megafacies. In comparison, hemipelagic muds in the Gippsland case accumulated at rates of <10–80 m/m.y. (Bernecker et al. 1997), values more consistent with calculated rates for Tikorangi Formation at Maui-1 well of only 7 m/m.y.

Table 2 Major properties of the three Tikorangi Formation megafacies identified within onshore and offshore Taranaki Basin.

Megafacies	Depositional setting	Skeletal assemblage	Age	Reference well	Basin location	Depositional mechanisms	Rock types	Texture	Environmental parameters	Hydrocarbons
1 Shelfal carbonate	Shallow-inner shelfal – proximal basement	Bryozoan, barnacle, calcareous red algae, benthic foraminifera	Latest Oligocene–earliest Miocene (Waitakian)	Hu Road-1A	Onshore, Tarata Thrust Zone, Eastern Mobile Belt	Redeposited	Sparry grainstone> mixed packstone/grainstone	Medium to coarse sand	Photic, shallow, moderate to high energy, topographic highs, rocky substrate	Non-producing
2 Mixed carbonate-siliciclastite Shelfal/bathyal biota	Foredeep	Bivalve, echinoderm, Planktic foraminifera	Latest Oligocene–earliest Miocene (Waitakian)	Waihapa-5	Onshore, Tarata Thrust Zone, Eastern Mobile Belt	Redeposited shelfal component intermixed with background bathyal biota	Packstone> wackestone/mixed packstone/grainstone>> sparry grainstone>> mudstone	Very fine to fine sand	High energy mass flows into low energy pelagic bathyal foredeep	Producing
3 Bathyal calcareous siliciclastite	Basinal	Planktic foraminifera, nannofossil (coccolith)	Oligocene–early Miocene (Whaingaroan–Otaian)	Maui-1	Offshore, Western Stable Platform	Pelagic settling	Wackestone> mudstone	Clay to very fine sand	Deep-water, low energy	Non-producing

CONCLUDING REMARKS

A need for a more comprehensive and detailed stratigraphic and sedimentological evaluation of the Oligocene (Whaingaroan–Waitakian) Tikorangi Formation reservoir rock has been the impetus for this study. From a petrographic viewpoint, the Tikorangi Formation comprises a spectrum of compositionally and texturally variable interbedded rock types ranging from calcareous mudstone to wackestone to packstone to clean sparry grainstone. Skeletal varieties within these rock types have aided in identification of three texturally and compositionally distinctive megafacies for the Tikorangi Formation, namely shelfal, foredeep, and basinal megafacies (Table 2). Petrographic trends amongst these megafacies are summarised in Fig. 13, and a depositional model depicting the megafacies within their depositional setting is presented in Fig. 14.

The latest Oligocene (early Waitakian) shallow shelfal Megafacies 1 (reference well Hu Road-1A) has not previously been described in the Tikorangi literature. These carbonates formed in shoal nearshore locations or atop basement pedestals rising up into shallow depths, and they are characterised by coarse, skeletal-rich, pure sparry grainstone comprising shallow-water high-energy taxa and admixtures of coarse well-rounded siliciclastic sand derived from Mesozoic basement greywacke. These rocks have aided in refining and understanding the paleogeography at the eastern margin of Taranaki Basin in the vicinity of Taranaki Peninsula during this time (Fig. 11).

Megafacies 2 (reference well Waihapa-5) comprises latest Oligocene (early Waitakian) mixed siliciclastic-carbonate deposits formed immediately basinward and west of the shelfal basement platform from redeposition of shelfal megafacies biota that became intermixed with bathyal taxa to produce a spectrum of mudstone through to sparry grainstone. Key indicators of the redepositional history include the high sedimentation rates (>20 cm/ka), the skeletal mix of photic zone dwellers such as calcareous red algae and large benthic foraminifera with slope biota, and the highly fragmental and abraded nature of the shelfal skeletons. The resulting skeletal associations are unlike those in any of the age-equivalent limestone units in neighbouring onland King Country Basin. Planktic foraminifera generally increase in abundance up-core, while siliciclastic material decreases in content as facies belts migrated landward with ongoing basinwide marine transgression. High levels of bioturbation of sediment enhanced skeletal mixing and destroyed any original depositional bedding structures; occurrence of a *Planolites-Chondrites-Zoophycos* assemblage is supportive of bathyal depositional depths. Uplift of eastern basement siliciclastic source areas during the latest Oligocene to early Miocene brought an abrupt halt to carbonate production by drowning shallower water carbonate factory sites and diluting pelagic test fallout.

Petrographic variability over short vertical intervals within the foredeep megafacies 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, active foredeep, and tectonically quiescent distal basinal settings; (2) deposition during a number of relative sea-level changes within an overall transgressive or submergence regime (Hood et al. 2003); (3) the proximity to, and availability of, different siliciclastic sources, including from the east (Patea-Tongaporutu-Herangi High), south (South Island), and possibly 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.

Megafacies 3 (reference well Maui-1) is an Oligocene (Whaingaroan–Waitakian) offshore basinal megafacies comprising moderately calcareous siliciclastic-rich rocks which contain planktic foraminifera and coccoliths formed away from redepositional influences. Although previous studies (e.g., King & Thrasher 1996) have emphasised the siliciclastic sediment-starved setting of Maui wells, the siliciclastic-rich nature and mainly low carbonate content (<40%) 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. These same currents may have been responsible for erosion of the Tikorangi Formation in a region directly west of onshore Taranaki Peninsula where the Tikorangi Formation is absent (Fig. 14).

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REFERENCES

Berggren, W. A.; Kent, D. V.; Swisher, C. C.; Aubry, M. P. 1995: A revised Cenozoic geochronology and chronostratigraphy. *In*: Berggren, W. A.; Kent, D. V.; Aubry, M. P.; Hardenbol, J. *ed*. Geochronology, time-scales and global stratigraphic correlation. *SEPM Special Publication 54*: 129–212.

Bernecker, T.; Partridge, A. D.; Webb, J. A. 1997: Mid–Late Tertiary deep-water temperate carbonate deposition, offshore Gippsland Basin, southeastern Australia. *In*: James, N. P.; Clarke, J. A. D. *ed*. Cool-water carbonates. *SEPM Special Publication 56*: 205–220.

Driscoll, N. W.; Weisiel, J. K.; Karner, G. D. 1991: Stratigraphic response of a platform to relative sea level changes: Broken Ridge, southeast Indian Ocean. *American Association of Petroleum Geologists Bulletin 65*: 808–831.

Dunham, R. J. 1962: Classification of carbonate rocks according to depositional texture. *In*: Ham, E. D. *ed*. Classification of carbonate rocks—a symposium. *American Association of Petroleum Geologists Memoir 1*: 62–84.

Ekdale, A. A.; Bromley, R. G.; Pemberton, S. G. 1984: Ichnology: the use of trace fossils in sedimentology and stratigraphy. *SEPM Short Course No. 15*. 317 p.

Emery, D.; Myers, K. 1996: Sequence stratigraphy. Cambridge, Blackwell Science Publishing. 297 p.

Folk, R. D. 1962: Spectral subdivision of limestone types. *In*: Ham, E. D. *ed*. Classification of carbonate rocks—a symposium. *American Association of Petroleum Geologists Memoir 1*: 62–84.

Foreman, J. L.; Walker, K. R.; Weber, L. J.; Driese, S. G.; Dreier, R. B. 1991: Slope and basinal carbonate deposition in the Nolichucky shale (Upper Cambrian), east Tennessee: effect of carbonate suppression by siliciclastic deposition on basin-margin morphology. *In*: Lomando, A. J.; Harris, P. M. *ed*. Mixed carbonate-siliciclastic sequences. *SEPM Core Workshop Notes 15*: 511–540.

Goldsmith, J. R.; Graf, D. L.; Heard, H. C. 1961: Subsolidus phase relations in the system $CaCO_3$–$MgCO_3$. *Journal of Geology 69*: 45–74.

Hayton, S.; Nelson, C. S.; Hood, S. D. 1995: A skeletal assemblage classification system for non-tropical carbonate deposits based on New Zealand Cenozoic limestones. *Sedimentary Geology 100*: 123–141.

Holdgate, G.; Gallagher, S. 1997: Microfossil paleoenvironments and sequence stratigraphy of Tertiary cool-water carbonates, onshore Gippsland Basin, southeastern Australia. *In*: James, N. P.; Clarke, J. A. D. *ed*. Cool-water carbonates. *SEPM Special Publication 56*: 205–220.

Hood, S. D. 2000: Subsurface stratigraphy and petrology of a cool-water carbonate fracture reservoir—the mid-Tertiary Tikorangi Formation, Taranaki Basin, New Zealand. Unpublished PhD thesis, lodged in the Library, University of Waikato, Hamilton, New Zealand.

Hood, S. D.; Nelson, C. S. 1996: Cementation scenarios for New Zealand Cenozoic nontropical limestones. *New Zealand Journal of Geology and Geophysics 39*: 109–122.

Hood, S. D.; Nelson, C. S.; Kamp, P. J. J. 2001: Diagenetic evolution of the Tikorangi Formation, Waihapa-Ngaere Field, Taranaki Basin: a cool-water carbonate fracture reservoir. *In*: 2001 Geological Society of New Zealand Annual Conference, Hamilton. *Geological Society of New Zealand Miscellaneous Publication 110A*: 69.

Hood, S. D.; Nelson, C. S.; Kamp, P. J. J. 2002a: Dolomitisation in an Oligocene carbonate reservoir, Taranaki Basin, New Zealand. *In*: 2002 Geological Society of New Zealand Annual Conference, Whangarei. *Geological Society of New Zealand Miscellaneous Publication 112A*: 29.

Hood, S. D.; Nelson, C. S.; Kamp, P. J. J. 2002b: Petrogenesis of the Tikorangi Formation Fracture Reservoir, Waihapa-Ngaere Field, Taranaki Basin. *In*: 2002 New Zealand Petroleum Conference Proceedings. Wellington, Ministry of Economic Development. Pp. 206–220.

Hood, S. D.; Nelson, C. S.; Kamp, P. J. J. 2003: Lithostratigraphy and depositional episodes of the Oligocene carbonate-rich Tikorangi Formation, Taranaki Basin, New Zealand. *New Zealand Journal of Geology and Geophysics 46*: 363–386 (this issue).

Hudson, D. S. 1996: Provenance of Miocene to Recent sands and sandstones of the Taranaki-Wanganui region, New Zealand. Unpublished MSc thesis, lodged in the Library, University of Waikato, Hamilton, New Zealand.

Hume, T. R.; Nelson, C. S. 1982: X-ray diffraction analytical procedures and some mineralogical characteristics for South Auckland region sediments and sedimentary rocks, with special reference to their clay fraction. *Department of Earth Sciences Occasional Report 10*. Hamilton, University of Waikato.

Hume, T. R.; Nelson, C. S. 1986: Distribution and origin of clay minerals in surficial shelf sediments, western North Island, New Zealand. *Marine Geology 69*: 289–308.

King, P. R. 1994: The habitat of oil and gas in Taranaki Basin. *In*: 1994 New Zealand Petroleum Conference Proceedings. Wellington, Ministry of Commerce. Pp. 180–203.

King, P. R.; Thrasher, G. P. 1996: Cretaceous–Cenozoic geology and petroleum systems of the Taranaki Basin, New Zealand. *Institute of Geological & Nuclear Sciences Monograph 13*. 6 enclosures, 243 p. Lower Hutt, Institute of Geological & Nuclear Sciences.

Mauri, S.; Brewster, A.; de Bock, F. 1999: PEP38455 Technical Report—March 1999. Fletcher Challenge Energy. Unpublished open-file petroleum report PR 2281. Wellington, Ministry of Economic Development.

Morgans, H. E. G. 1985: Biostratigraphy of Waihapa-1 onshore exploration well, Taranaki. *New Zealand Geological Survey Report PAL 102*. Lower Hutt, Department of Scientific and Industrial Research.

Mullins, H. T. 1983: Modern carbonate slopes and basins of the Bahamas. *In*: Cook, H. E.; Hine, A. C.; Mullins, H. T. *ed*. Platform margin and deepwater carbonates. *SEPM Short Course Notes 12*: 4.1–4.138.

Mullins, H. T.; Neumann, A. C. 1979: Deep carbonate bank margin structure and sedimentation in the northern Bahamas. *In*: Doyle, L. J.; Pilkey, O. H. *ed*. Geology of continental slopes. *SEPM Special Publication 27*: 165–192.

Naish, T. R. 1991: Petrography of the Tikorangi Limestone Toko-1 3099.2–3101.4 m. Contract report 1991/12. Wellington, Department of Scientific and Industrial Research.

Nelson, C. S. 1978a: Stratigraphy and paleontology of the Oligocene Te Kuiti Group, Waitomo County, South Auckland, New Zealand. *New Zealand Journal of Geology and Geophysics 21*: 553–594.

Nelson, C. S. 1978b: Temperate shelf carbonate sediments in the Cenozoic of New Zealand. *Sedimentology 25*: 737–771.

Nelson, C. S. 1985: Bioturbation in middle bathyal, Cenozoic nannofossil oozes and chalks, southwest Pacific. *Initial Reports of the Deep Sea Drilling Project 90*: 1189–1200.

Nelson, C. S.; Keane, S. L.; Head, P. S. 1988: Non-tropical carbonate deposits on the modern New Zealand shelf. *Sedimentary Geology 60*: 71–94.

Nelson, C. S.; Kamp, P. J. J.; Young, H. R. 1994: Sedimentology and petrography of mass-emplaced limestone (Orahiri Limestone) on a late Oligocene shelf, western North Island, and tectonic implications for eastern margin development of the Taranaki Basin. *New Zealand Journal of Geology and Geophysics 37*: 269–285.

Nelson, C. S.; Lee, D.; Maxwell, P.; Maas, R.; Kamp, P. J. J.; Cooke, S. 2001: Strontium isotope dating of the New Zealand Oligocene: some preliminary results. *Geological Society of New Zealand Miscellaneous Publication 110A*: 111.

New Zealand Oil & Gas Ltd 1992: Hu Road 1 & Hu Road-1A well completion report. Unpublished open-file petroleum report PR1825. Wellington, Ministry of Commerce.

Palmer, J. A. 1985: Pre-Miocene lithostratigraphy of Taranaki Basin, New Zealand. *New Zealand Journal of Geology and Geophysics 28*: 197–216.

Passlow, V. 1997: Slope sedimentation and shelf to basin sediment transfer: a cool-water carbonate example from the Otway Margin, southeastern Australia. *In*: James, N. P.; Clarke, J. A. D. *ed*. Cool-water carbonates. *SEPM Special Publication 56*: 107–126.

Rao, C. P. 1996: Modern carbonates—tropical temperate polar. Introduction to sedimentology and geochemistry. Tasmania, Howrah.

Robinson, P. 1980: Determination of calcium, magnesium, manganese, strontium, sodium and iron in the carbonate fraction of limestones and dolomites. *Chemical Geology 28*: 135–146.

Scott, G. H: 1985: Biostratigraphic revision of Maui-2 offshore well south Taranaki Basin. *New Zealand Geological Survey Report PAL 111*. Lower Hutt, Department of Scientific and Industrial Research.

Simpson, J. 1992: Taranaki Basin review. Technical evaluation of the Tikorangi Limestone. New Plymouth, Petrocorp Exploration Ltd.

Stein, R.; Robert, C. 1986: Siliciclastic sediments at sites 588, 590, and 591: Neogene and Paleogene evolution in the southwest Pacific and Australian climate. *Initial Reports of the Deep Sea Drilling Project 90*: 1437–1458.

Tucker, M. 1988: Techniques in sedimentology. Oxford, Blackwell Scientific Publications.

Tucker, M. E.; Wright, V. P. 1990: Carbonate sedimentology. Oxford, Blackwell Scientific Publications. 482 p.

Westphal, H.; Reijmer, J. J. G.; Head, M. J. 1999: Sedimentary input and diagenesis on a carbonate slope (Bahamas): response to morphologic evolution of the carbonate platform and sea-level fluctuations. *In*: Harris, P. M.; Saller, A. H.; Simo, J. A. T. *ed*. Advances in carbonate sequence stratigraphy: application to reservoirs, outcrops, and models. *SEPM Special Publication 63*: 247–275.

Winefield, P. R.; Nelson, C. S.; Hodder, P. W. 1996: Discriminating temperate carbonates and their diagenetic environments using bulk elemental geochemistry: a reconnaissance study based on New Zealand Cenozoic limestones. *Carbonates and Evaporites 11*: 19–31.

Young, J.; Carter, M. 1989: Waihapa-5 well completion report. Petroleum Corporation of New Zealand (Exploration) Ltd. Unpublished open-file petroleum report PR1851. Wellington, Ministry of Commerce.