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Pliocene Te Aute limestones, New Zealand: expanding concepts for cool-water shelf carbonates

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Abstract Acceptance of a spectrum of warm- through cold-water shallow-marine carbonate facies has become of fundamental importance for correctly interpreting the origin and significance of all ancient platform limestones. Among other attributes, properties that have become a hallmark for characterising many Cenozoic non-tropical occurrences include: (1) the presence of common bryozoan and epifaunal bivalve skeletons; (2) a calcite-dominated mineralogy; (3) relatively thin deposits exhibiting low rates of sediment accumulation; (4) an overall destructive early diagenetic regime; and (5) that major porosity destruction and lithification occur mainly in response to chemical compaction of calcitic skeletons during moderate to deep burial. The Pliocene Te Aute limestones are non-tropical skeletal carbonates formed at paleolatitudes near 40–42°S under the influence of commonly strong tidal flows along the margins of an actively deforming and differentially uplifting forearc basin seaway, immediately inboard of the convergent Pacific-Australian plate boundary off eastern North Island, New Zealand. This dynamic depositional and tectonic setting strongly influenced both the style and subsequent diagenetic evolution of the limestones. Some of the Te Aute limestones exhibit the above kinds of "normal" non-tropical characteristics, but others do not. For example, many are barnacle and/or bivalve dominated, and several include attributes that at least superficially resemble properties of certain tropical carbonates. In this regard, a number of the limestones are infaunal bivalve rich and dominated by an aragonite over a calcite primary mineralogy, with consequently relatively high diagenetic potential. Individual limestone units are also often rather thick (e.g., up to 50–300 m), with accumulation rates from 0.2 to 0.5 m/ka, and locally as high as 1 m/ka. Moreover, there can be a remarkable array of diagenetic features in the limestones, involving grain alteration and/or cementation to widely varying extents within any, or some combination of, the marine phreatic, burial, and meteoric diagenetic environments, including locally widespread development of meteoric cement sourced from aragonite dissolution. The message is that non-tropical shelf carbonates include a more diverse array of geological settings, of skeletal and mineralogical facies, and of diagenetic features than current sedimentary models mainly advocate. While several attributes positively distinguish tropical from non-tropical limestones, continued detailed documentation of the wide spectrum of shallow-marine carbonate deposits formed outside tropical regions remains an important challenge in carbonate sedimentology.

Keywords limestone; diagenesis; aragonite; non-tropical; tectonics; Pliocene; New Zealand

INTRODUCTION

More than 30 years ago Chave (1967) questioned the validity of an exclusively warm-water origin for shallow-marine carbonates by noting several occurrences of modern skeletal deposits accumulating on shelves outside tropical regions. However, his observation received little attention from mainstream carbonate researchers of the day who were pre-occupied with recording and understanding the processes and products of carbonate sedimentation and diagenesis in warm shallow seas (e.g., Bathurst 1975). Over the next decade or so, through the 1970s, a handful of geologists began to document significant areas of carbonate sediments forming on modern cool-water shelves in the North Atlantic (e.g., Lees & Buller 1972; Lees 1975; Scoffin et al. 1980), about New Zealand (e.g., Summerhayes 1969; Carter 1975; Nelson et al. 1982), and off southern Australia (e.g., Wass et al. 1970; Marshall & Davies 1978). Moreover, the facies characteristics of these modern cool-water deposits closely matched known occurrences of nearby onland Tertiary limestones (e.g., Nelson 1978), which provided the critical step for advocating a non-tropical shelf carbonate paradigm. The 1980s and 90s saw a steady expansion of examples, descriptions, and databases for cool-water carbonates, both modern and ancient, as exemplified by the two synthesis volumes edited by Nelson (1988a) and James & Clarke (1997). Along the way there has naturally been an attempt to establish the key lithological features that characterise non-tropical carbonates, and particularly those that might serve to help distinguish tropical and non-tropical limestones in the rock record. One such comparative scheme, the parameters for which effectively form the basis for the development of end-member facies models for warm- and cool-water carbonates, is summarised in Table 1. Of course, valid sedimentary models are an

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Table 1 Some contrasting environmental, compositional, and diagenetic features of typical end-member tropical and non-tropical shelf carbonate facies (after Nelson 1988b and James 1997).

Tropical shelf carbonates	Non-tropical shelf carbonates
Warm water (>20°C) Saturated to supersaturated	Cool water (<20°C) Saturated to undersaturated
Rimmed and unrimmed shelf High to low energy	Unrimmed shelf High energy
Hermatypic coral reefs (from 30°N to 30°S)	No hermatypic reefs (beyond 30°N and S)
Non-skeletal grains (ooids, aggregates)	No non-skeletal grains
Bioclastic sediments: coral-calcareous green algal-molluscan-benthic foram	Bioclastic sediments: bryozoan-echinoderm-bivalve molluscan-benthic/planktic foram
Photozoan grain association	Heterozoan grain association
Sand and mud textures dominate, or *in situ* framework	Gravel and sand textures dominate
Constructive marine diagenesis	Destructive marine diagenesis
Aragonite and high-Mg calcite mineralogy	Low- and intermediate-Mg calcite mineralogy
Typically high (>10 cm/ka) accumulation rates	Typically low (<10 cm/ka) accumulation rates

ultimate end-point, and it is essential that their appropriateness be continually assessed and revised, and that any significant deviations from the norm be fully appreciated.

This paper integrates some previous work with new geochemical data on the sedimentology and diagenesis of widely distributed non-tropical Pliocene carbonates known as the Te Aute limestones in eastern North Island of New Zealand (Fig. 1). In doing so it cautions against the indiscriminate application of some of the attributes shown in Table 1 as being definitive hallmarks of non-tropical carbonates, and concludes that a more diverse array of geological settings, of skeletal and mineralogical facies, and of diagenetic features exist for cool-water shelf carbonate deposits than are currently advocated.

GEOLOGICAL SETTING

The East Coast Basin of New Zealand (Fig. 1) includes very thick (up to 6 km or more) Neogene sections dominated by marine mudstone, sandstone, and flysch (Field et al. 1997). Depositional environments range from deep to shallow water in trench, accretionary slope, forearc, and transform basin settings that developed along the eastern North Island in response to evolution of the Australia-Pacific convergent plate boundary through New Zealand since the early Miocene, c. 25 Ma (Fig. 1A) (Kamp 1986; Lewis & Pettinga 1993). The Te Aute limestones of this study form a volumetrically small (<10%), but regionally persistent and conspicuous component within the inboard and shallower facies of the mainly Pliocene deposits in this terrigenous-dominated succession (Fig. 2). Their outcrop pattern (Fig. 1B) is suggestive of deposition about the margins of an evolving forearc basin, and in smaller transform basins to the south (Kamp et al. 1988).

Progressive shallowing and narrowing of the forearc basin following the Miocene was associated with uplift along its eastern margin, involving inversion of small slope basins by imbricate thrusting on the inboard edge of the subduction complex (Lewis & Pettinga 1993). By the early Pliocene, differential elevation of the margins of the forearc basin progressively formed a long (up to 300 km; paleolatitude c. 40–42°S), narrow (30–60 km), northeast–southwest-trending seaway, named the Ruataniwha strait by Beu (1995), extending from the vicinity of modern Cook Strait to north of Gisborne (Fig. 1B). The active tectonism at times diversified parts of this seaway to include more protected areas of large marine embayments, particularly by late Pliocene time (Beu 1995), but in the main the strait was dominated by tidal current flows involving temperate to subantarctic surface-water masses (Nelson et al. 2000). In this otherwise siliciclastic-dominated setting, skeletal carbonate factories developed in two main settings: (1) most commonly atop and about actively growing and deforming antiforms or submarine highs, wherever strong tidal flows promoted active by-passing of fine terrigenous sediment into deeper water (Fig. 3) (Kamp et al. 1988); but (2) also across broad shallow embayments or basins experiencing much less direct tidal current influence and consequently often increased amounts of fine terrigenous sediment admixtures (Beu 1995). A schematic cross-section across the strike of the central portion of the forearc basin in Fig. 1C shows some of the limestones and emphasises their basin-margin position, their lateral gradation into, and interbedding with, siliciclastic deposits, and the progressive displacement of successively younger limestones having lesser dips and often lower elevations towards the basin axis, features collectively consistent with ongoing synsedimentary deformation associated with differential uplift of the basin margins.

The development of localised carbonate factories that are separated in time and space upon upthrust ridges within an active forearc setting has formed discrete ribbon- and lens-like cool-water limestone bodies, extending uninterruptedly for typically only a few to a few tens of kilometres. This laterally restrictive geometry of most of the individual Te Aute limestone units contrasts markedly with the very extensive (several 100s–1000s of km^2) sheet-like or tabular bodies of skeletal deposits characterising many unrimmed non-tropical carbonate shelves and ramps in general (Table 1), as exemplified by several southern Australian and New Zealand modern and Tertiary passive-margin occurrences (e.g., Wass et al. 1970; Nelson 1978; Nelson et al. 1988b; James & von der Borch 1991; Boreen & James 1995). However, some of the youngest Te Aute units deposited within large shallow-marine embayments do exhibit thin sheet-like geometries, but over relatively limited areas of up to a few 100 km^2 (Haywick et al. 1992).

STRATIGRAPHY AND LITHOLOGY

The Pliocene limestones of the East Coast Basin have a long and complex history of stratigraphic nomenclature, recently reviewed by Beu (1995). Based on a detailed study of the pectinid biostratigraphy of the limestones, Beu (1995, p. 73)

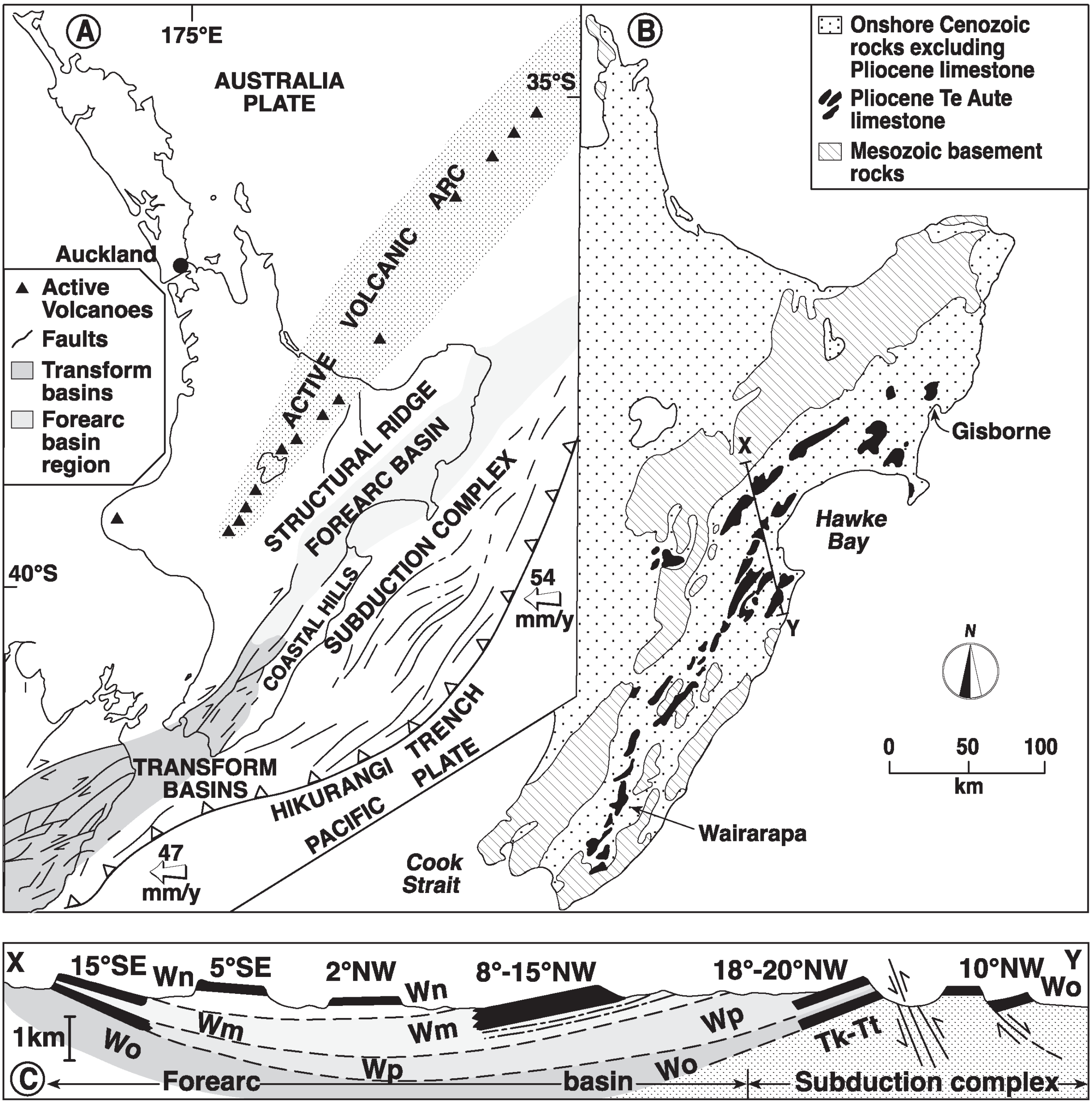

Fig. 1 A, Tectonic setting of the North Island of New Zealand. **B**, The general distribution of Pliocene limestone in East Coast Basin, North Island. **C**, Schematic section across the forearc basin along line X–Y in (B) showing the progressive displacement of younger limestone units towards the basin axis, the confinement of limestone to the basin paleo-margins, and progressive decrease in dip of successively younger limestone units (adapted from Kamp et al. 1988). New Zealand stage symbols in (C) are defined in Fig. 2.

showed, contrary to much earlier work which tended to lump otherwise separate limestone occurrences into a single widespread formation, that the "Te Aute limestone is a recurrent lithofacies, repeatedly and intermittently deposited over much or all of eastern North Island at several discrete times during the Pliocene...". Consequently, he proposed abandonment of the formal lithostratigraphic name Te Aute, except in a general, all-embracing lithofacies context (as we use in this study), and went on to subdivide the Neogene limestones of eastern North Island into 6 groups, 45 formations, and 12 members on the basis of a combination of their age, geographic location, and lithology. For this synthesis we adopt Beu's (1995) age classification of the limestones and assign samples to one of three time intervals within the Pliocene, including for completeness some late Miocene carbonate units which were forerunners to the Te Aute occurrences proper (Table 2). A simplified time-space diagram (Fig. 2) illustrates the complex stratigraphic distribution of some of the major Te Aute limestone units from north to south in central eastern North Island.

Despite their wide spatial distribution and age differences, the majority of the Te Aute limestones have broadly similar lithological characteristics, being coarse skeletal calcarenites, skeletal calcirudites, and shell coquinas with variable amounts

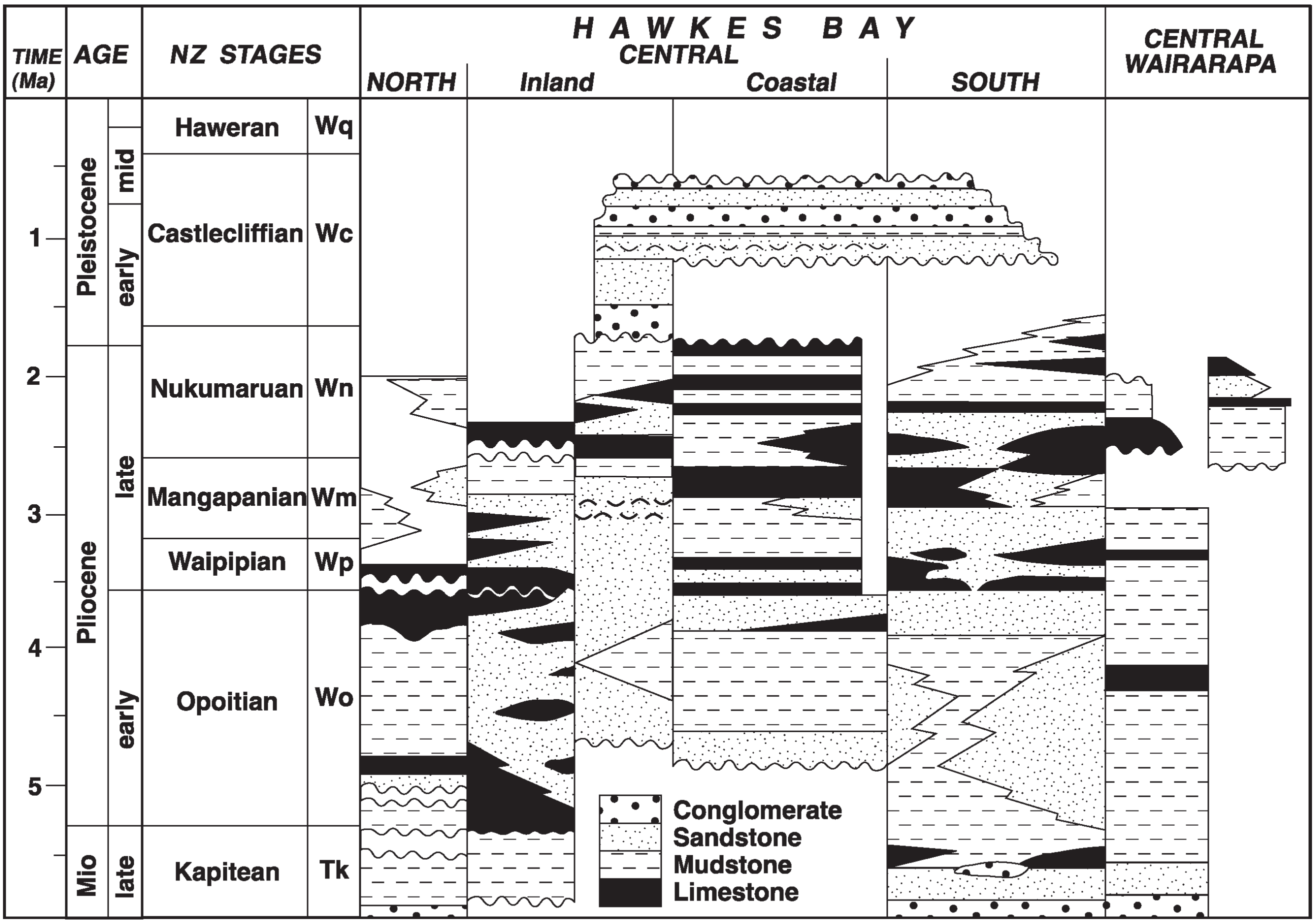

Fig. 2 Time-space diagram showing the complex distribution of some of the main Pliocene Te Aute limestone occurrences (in black) from north to south in central eastern North Island. Note the local New Zealand stage names and symbols (adapted from Field et al. 1997).

of terrigenous material (Fig. 4C). They occur interbedded on different scales with siliciclastic mudstone or sandstone, often in a cyclic fashion (e.g., Haywick et al. 1992; Haywick 2000). Their colour is cream to yellow or yellow-brown. The limestones are locally massive, but are most commonly horizontally bedded and cross-bedded on a wide range of scales (Fig. 4A,B), including giant tabular sets 10–40 m thick, analogous to sand ridges (see Kamp et al. 1988, fig. 9–13). Together with the common occurrence of bi-directional foreset orientations (Fig. 4B), the spectrum of cross-bedded structures is testimony to a strong influence of tidal current flows on sedimentation in the forearc seaway (Fig. 3). Some of the limestones are well cemented, dense, and hard, but the majority are only moderately to weakly cemented and tend to be rather soft, friable, and highly porous (Fig. 4C). Commonly, preferential cementation of beds relatively impoverished in terrigenous sediment leads to conspicuous differential erosion of exposures, emphasising sedimentary structures (Fig. 4A,B). A special feature of several of the younger limestones in particular is the development of prominent secondary mouldic porosity from the variable dissolution of locally abundant, formerly aragonitic bivalve shells (Fig. 4D).

SEDIMENTATION RATES

Despite the laterally discontinuous nature of most of the Te Aute limestone bodies, many of them are relatively thick. Maximum thickness information recorded by Beu (1995) for about 40 different limestone units shows that about half of them reach 10–50 m thick, a further 30% attain 50–90 m thickness, and the remainder are 100–300 m thick. In one case, Beu (1995) suggested the thickness of the Whakapunake Limestone was as much as 460 m, possibly representing the aggregate thickness across a series of clinoforms, but our own calculations indicate a vertical thickness nearer 150 m is more likely for the Whakapunake sheet.

Knowing the age of the different limestone units to stage level (Table 2), and their stratigraphic position and thickness in relation to associated bounding formations within that stage (Fig. 2) (Field et al. 1997), it is possible to convert the rock thicknesses into approximate accumulation rates. Calculated values (pers. data) are most commonly in the range 0.2–0.5 m/ka, sometimes less, but occasionally also as high as 1 m/ka. These rates are similar to values of c. 0.1–0.5 m/ka recorded by Haywick (2000) for the Nukumaruan limestone sheets in central Hawke's Bay. In Fig. 5 we place the Te Aute limestones on a diagram adapted from James (1997) which summarises estimates of production and accumulation rates for warm-water tropical carbonates and cool-water temperate carbonates of different ages from various shelf/platform depositional settings. The plot emphasises that the rates of accumulation for non-tropical carbonates are mainly considerably lower than for tropical carbonates, suggested to be a function of both slower production rates and proneness to diagenetic modification

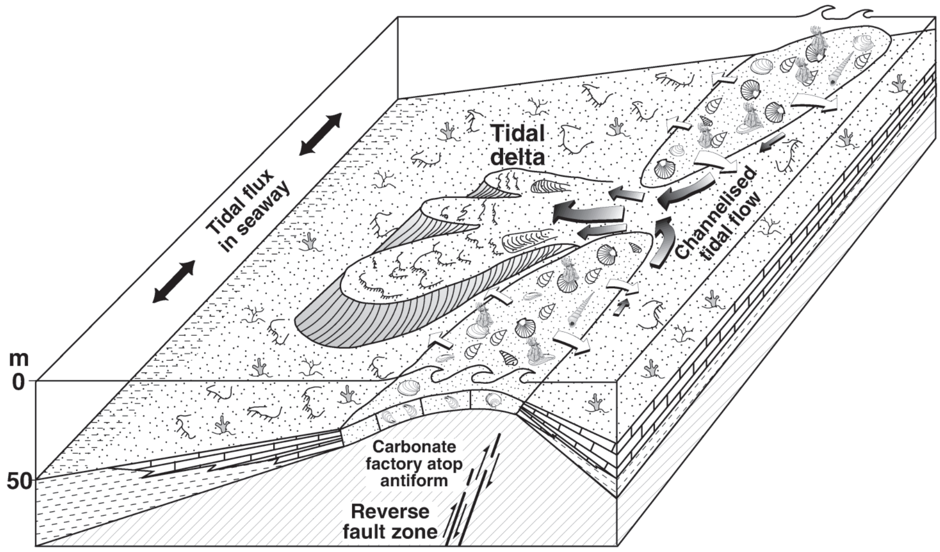

Fig. 3 Conceptual depositional model for the giant cross-bedded facies as carbonate deltas and sand bars fronting saddles that transect actively growing and deforming, northeast-trending, submarine antiformal ridges, a favoured carbonate factory for many of the Te Aute limestone occurrences. Double-headed arrows show tidal flux directions in forearc basin seaway, while single-headed arrows indicate tidal flows across depressions between subtidal banks and downslope current reworking from bank tops.

and degradation of the skeletal carbonates at or near the seafloor in cool marine waters (e.g., Alexandersson 1979; Smith 1988; Young & Nelson 1988; Smith & Nelson 1994). In the case of many occurrences of non-tropical Australasian shelf limestones of Tertiary age, the average rates of sedimentation are only a few centimetres per thousand years (Fig. 5), comparable to deep-sea carbonate ooze rates. In contrast, the rates associated with the Te Aute shelf carbonates are consistently higher than for the other cool-water occurrences, overlapping with values more typical of tropical carbonate platforms (Fig. 5). The explanation likely relates to prolific rates of skeletal production in shoal areas of the strongly tidal-influenced Pliocene forearc seaway (Fig. 3), to depositional focusing of the carbonates about the flanks of the growing antiforms (Fig. 3), and to an often enhanced preservation potential of the deposits during diagenesis (see later).

LABORATORY METHODS

From the field collections made by Hood (1993) in his reconnaissance study of North Island Cenozoic limestones, 76 samples were selected as representative of the Te Aute limestone units (Appendix 1). The distribution of these samples across the four defined age intervals for the Te Aute limestones reflects roughly the occurrence abundance of the limestones in the field, late Pliocene limestones being the most abundant and late Miocene ones the least common (Table 2; see Fig. 7A). Standard and stained thin sections of these samples were examined using plane polarised (PPL) and cathodoluminescence (CL) light sources, and the petrographic information recorded on data sheets (Hood 1993) and summarised here in Fig. 6.

The bulk-rock geochemistry of the same samples selected for petrography was analysed by Winefield (1995) in a wider

Table 2 Age groupings of the Te Aute limestone units adopted in this study (based on Beu 1995 and Field et al. 1997), showing some of the formations represented and the numbers of samples analysed.

Age[1]	New Zealand stage(s) and abbreviation	Formations represented	Total samples
Late Pliocene (basal Pleistocene) [1.6–2.6 Ma]	Nukumaruan (Wn)	Matapiro/Puketautahi, Tangoio, Waipatiki, Kaiwaka, Park Island, Scinde Island, Pakipaki, Pukenui, Bull Creek, Castlepoint, Kumeroa	34
"Middle" Pliocene [2.6–3.6 Ma]	Mangapanian (Wm) Waipipian (Wp)	Te Onepu, Te Waka Awapapa, Titiokura, Tahaenui, Rongomai	16
Early Pliocene [3.6–5.3 Ma]	Opoitian (Wo)	Kairakau, Ormond, Maungaharuru, Whakapunake, Waiouru, Haurangi, Opoiti	15
Late Miocene [5.3–10.5 Ma]	Kapitean (Tk) Tongaporutuan (Tt)	Owhaoko, Clay Creek Patutahi	11

[1]Some recent unpublished data (McIntyre 2002) suggest the Wm/Wn boundary may be c. 2.3 Ma, and the Wp/Wm boundary c. 2.8 Ma.

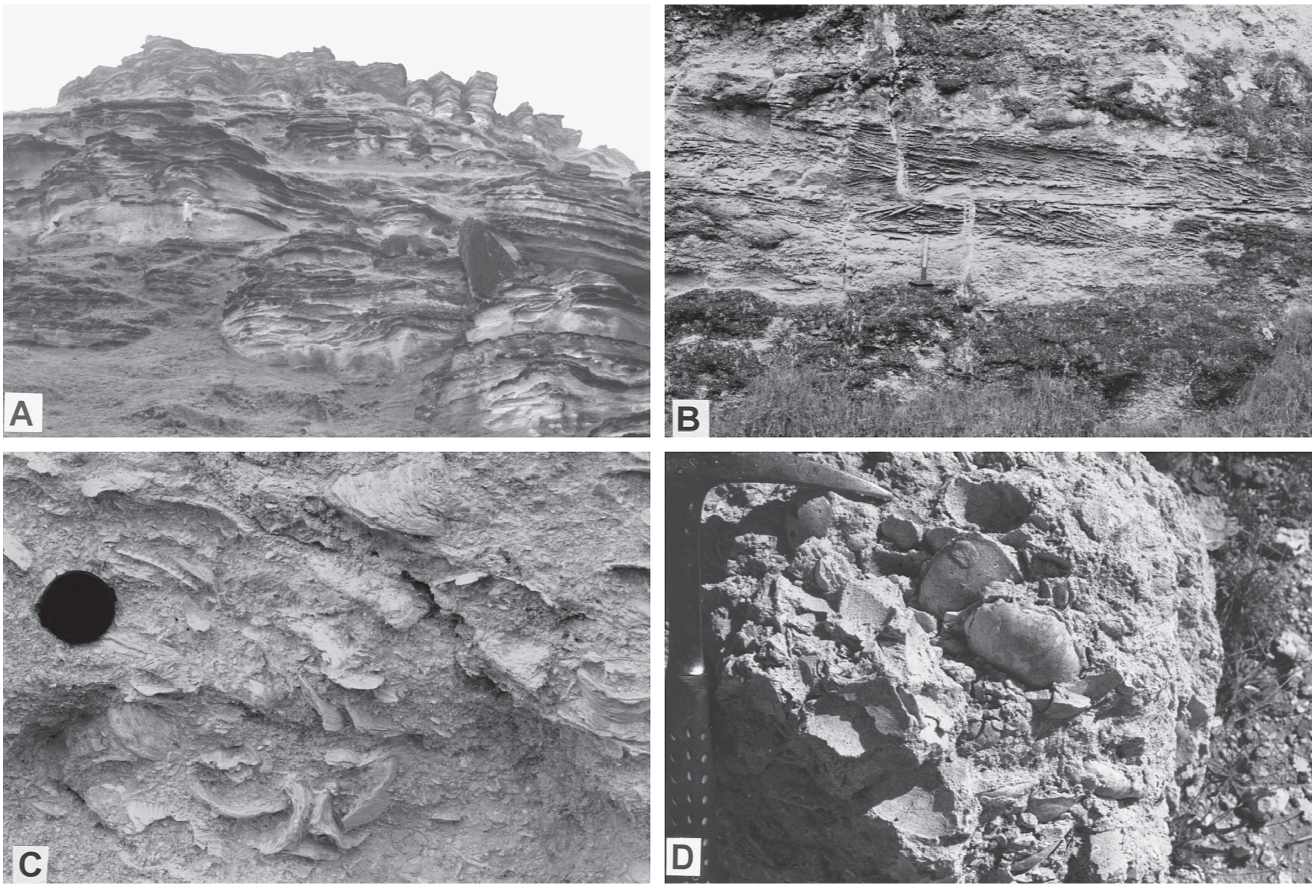

Fig. 4A–D Some field features of Te Aute limestones. **A**, Differentially cemented outcrop of early Pliocene Maungaharuru Formation comprising alternations of sandy limestone and calcareous sandstone beds, often in large-scale cross-stratified sets, Pohokura Road (NZMS 260 map grid reference V19/386262). **B**, Prominent herringbone cross-stratification and differential cementation in the late Pliocene Matapiro Limestone, Ohiti Road (V21/300733). **C**, Close up of coarse shellbed rich in pecten and oyster valves in a roadside exposure of the "middle" Pliocene Awapapa Limestone, Te Mata Peak Road (V22/452598). **D**, Boulder of late Pliocene Tangoio Limestone rich in large infaunal aragonitic bivalve shells that have been variably dissolved leaving casts and biomoulds, Tangoio Quarry (V20/490004).

study of New Zealand Cenozoic limestones. Rock chips were powdered using a ring mill with a tungsten carbide head. Approximately 1 g of powdered sample was dissolved in 1*M* HCl and, following appropriate dilution, the solutions were analysed for Ca, Mg, Na, Fe, Sr, and Mn by atomic absorption spectroscopy following the procedures of Robinson (1980). Precision was ±1% for Ca and Mg, and ±5 ppm for Sr, Na, Mn, and Fe. For stable isotope analysis, c. 50 mg of the whole-rock powder was reacted with 100% orthophosphoric acid for 30 min at c. 70°C. The CO_2 extracted from each sample was analysed for $\delta^{18}O$ and $\delta^{13}C$ on a Micromass 602D mass spectrometer. Precision of the data is ±0.1‰ for both $\delta^{18}O$ and $\delta^{13}C$, and these values are reported relative to the PDB standard. Elemental and stable isotope data are reported in Appendix 1.

GENERAL PETROGRAPHY

A variety of general petrographic information for the four age groups of Te Aute limestone (Table 2) is summarised schematically in Fig. 6. Samples are typically coarse-grained calcarenites and calcirudites that classify petrographically as poorly to moderately sorted skeletal rudstones and grainstones, with less common skeletal packstones. Hood (1993) reported an average whole-rock composition for Te Aute limestones as bioclasts c. 70% (range 30–93%), terrigenous grains c. 10% (range 1–45%), cement/matrix c. 15% (range 2–55%), and unoccluded porosity c. 5% (range 1–25%), values that do not change substantially amongst the averages for the different age groups (Fig. 7B).

Skeletal associations

The Te Aute limestones are compositionally distinctive because they are mainly dominated by barnacle plates and bivalve shells and fragments, with locally common bryozoan fragments, some echinoderms and benthic foraminifera, and rare calcareous red algae (Fig. 7C). A barnacle-rich skeletal makeup is unusual amongst cool-water limestones in general, which are most typically dominated by bryozoan, echinoderm, molluscan, and foraminiferal remains (Fig. 8A)—the bryomol and echinofor skeletal assemblages of Hayton et al. (1995). In contrast, using the Hayton et al. (1995) classification scheme, the majority of the Te Aute limestones are barnamol (barnacle ± mollusc) or bimol (bivalve mollusc) carbonates (Fig. 7D, 8A), with relatively few bryomol occurrences that are most evident in the older limestones (e.g., Caron 2002). Kamp et al. (1988) inferred that the prolific barnacle contribution may reflect maintenance of very high nutrient levels associated with strong tidal flows over the antiform ridges in the Pliocene seaway, the hard

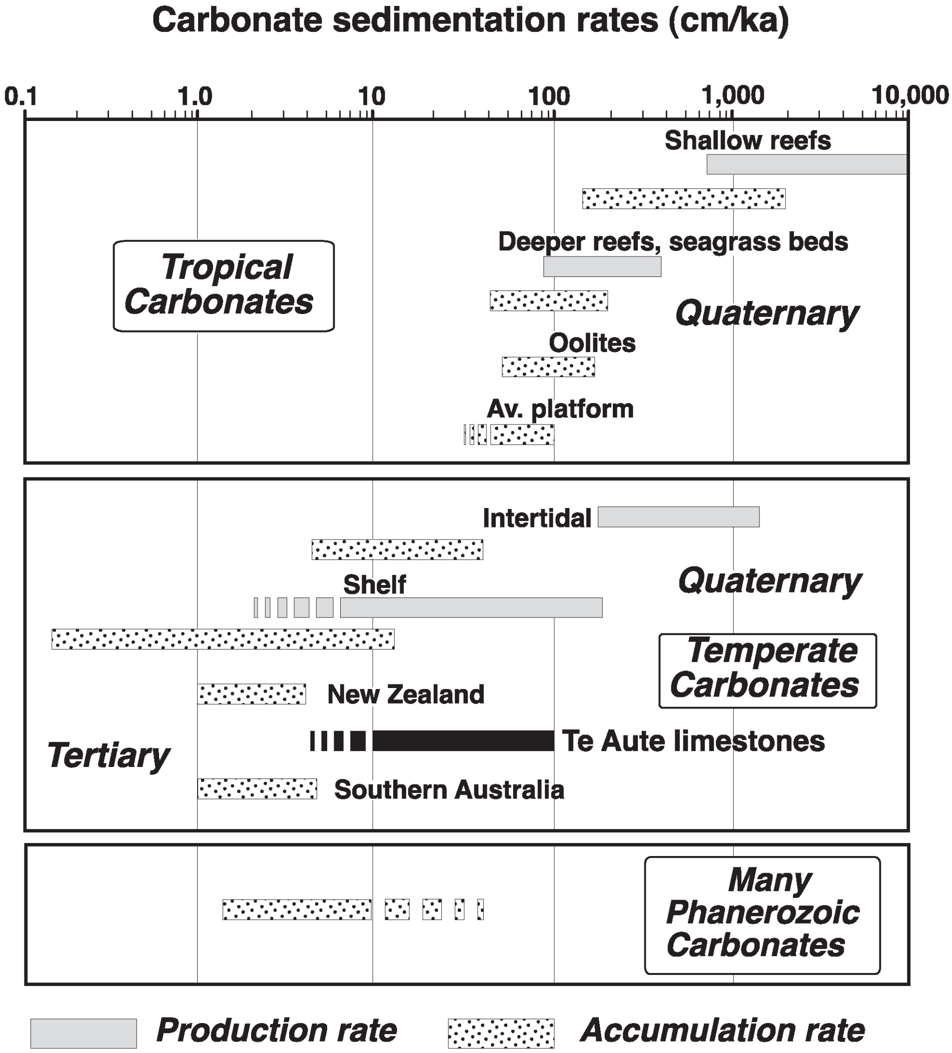

Fig. 5 Estimates of production and accumulation rates for warm-water and cool-water carbonates of different ages from various shelf depositional settings, including typical non-tropical occurrences from the mid Tertiary in New Zealand and southern Australia (adapted from Smith 1988 and James 1997), in comparison to rates estimated for the Pliocene Te Aute limestones on the basis of their thickness and age (Table 2).

substrate for barnacle attachment being provided by the shells of large epifaunal bivalves such as pectens and oysters.

Primary mineralogy

Cool-water carbonates are typically predominantly calcitic deposits (Nelson 1988b; Rao 1996), the mineralogy of the primary skeletal sediments comprising mainly low-Mg (<4 mol% $MgCO_3$) and intermediate-Mg (4–12 mol% $MgCO_3$) calcite varieties, and some high-Mg (>12 mol% $MgCO_3$) calcite (Fig. 8B) (Bone & James 1993; Hood & Nelson 1996; Smith et al. 1998). In the barnacle and bivalve rich Te Aute carbonates, the barnacles are exclusively low-Mg calcite whereas the bivalves are either low-Mg calcite if epifaunal (e.g., pectens and oysters) or aragonite if infaunal. The original content of aragonitic molluscs in most of the Te Aute limestones appears to have been limited, but in some units there is a significant contribution from infaunal bivalves to the extent that, in several late Pliocene examples in particular (Table 2), aragonite shells, both preserved and as moulds, are the dominant skeletal constituent (Fig. 4D). This spectrum of predominantly low-Mg calcite to predominantly aragonite primary mineralogies in the different Te Aute limestones contrasts with the mixed low-, intermediate-, and high-Mg calcite mineralogy most frequently reported for cool-water carbonate deposits in general (Table 1; Fig. 8B).

DIAGENESIS

Cements

The degree of lithification of Te Aute limestones is highly variable, both areally and temporally, and strongly differential cementation is conspicuous in many outcrops (Fig. 4A,B) (Hood & Nelson 1996). In places, outcrop surfaces are case hardened by calcite precipitated from modern percolating meteoric water. Interparticle pore volumes (cement + voids) range from c. 10 to 50%, largely depending upon the degree of burial-related mechanical and chemical compaction experienced by the different limestone units.

The younger Pliocene limestones are typically open-textured rocks with large (25–50%) interparticle pore spaces that are partially, rarely fully, filled with calcite spar cement. Microbioclastic micrite matrix is uncommon. Cement fabrics can be complex and include the following varieties:

(a) common, but variably developed and locally substrate (especially bivalve) specific, isopachous fringes of dull luminescent, non-ferroan, scalenohedral to fibrous calcite spar (Fig. 9B,C);
(b) poorly to well-developed syntaxial rim calcite spar about scattered echinoderm particles;
(c) local dull luminescent, equant, ferroan calcite spar;

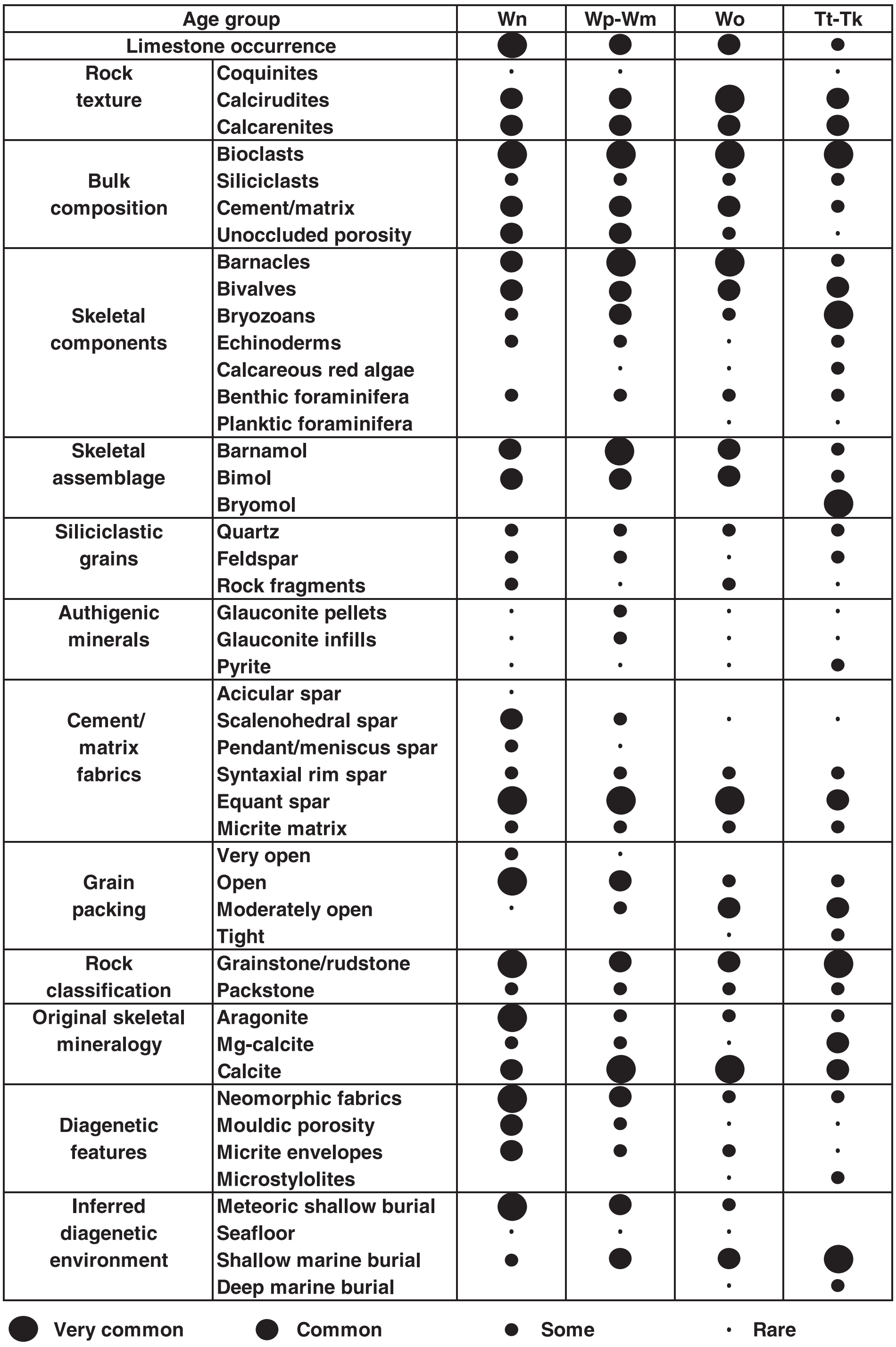

Fig. 6 Summary data sheet based on information in Hood (1993) showing the relative importance/abundance of various petrographic properties for the four age groups of Te Aute limestone (see Table 2). The raw petrographic data are available on request, and are partly summarised in Fig. 7.

(d) volumetrically important, dull ± bright banded luminescent, equant, non-ferroan calcite spar (Fig. 9B,C);
(e) rare examples of meniscus calcite cement (Fig. 9D).

In some of the older Pliocene limestones, and throughout the late Miocene deposits, interparticle pore volumes become progressively reduced to only 10–25% or less, and there is increased development of skeletal grain fracturing and pressure-dissolved grain fabrics in the rocks (Fig. 9A). Cements include rare fringes of bladed to dog-toothed spar [like (a) above], some syntaxial rim spar [like (b) above], and common pore-occluding, dominantly ferroan, locally drusy, equant spar with characteristically dull luminescence [like (c) above].

Aragonite alteration

Some of the Te Aute limestones, particularly amongst the late Pliocene examples, include a significant primary aragonite content contributed mainly from their infaunal bivalve component (Fig. 4D, 8B). What is remarkable about the aragonite shells and grains is the wide spectrum of alteration/preservation processes that have affected these components,

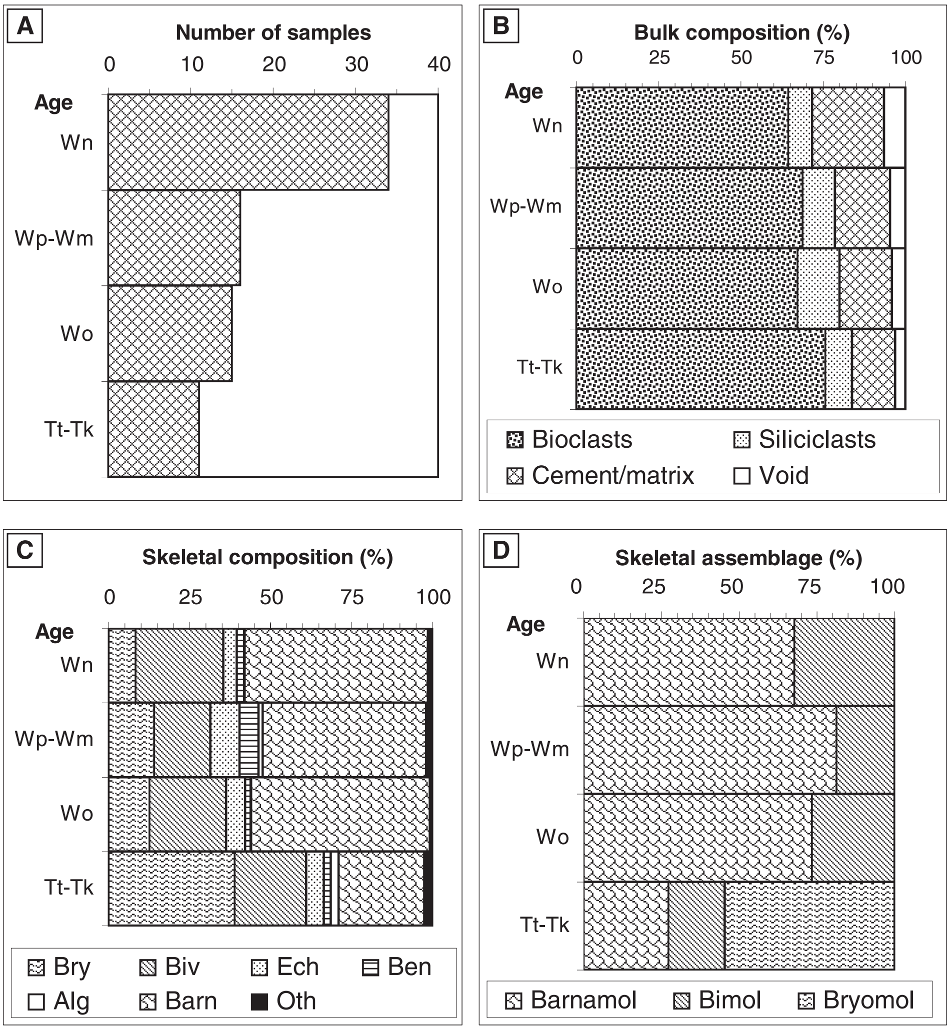

Fig. 7A–D Petrographic histograms for the four age groups of Te Aute limestones (see Table 2) in relation to (**A**) their sample abundance in our database (Appendix 1), (**B**) their average bulk rock composition, (**C**) their average skeletal composition, and (**D**) their contributing skeletal assemblages (following scheme of Hayton et al. 1995). Primary data are from Hood (1993). In (C) Bry, bryozoans; Biv, bivalves; Ech, echinoderms; Ben, benthic foraminifera; Alg, red algae; Barn, barnacles; Oth, other bioclasts.

which have been both selective and differential at scales ranging from outcrop to hand-specimen to thin-section. For example, in a single thin-section it is possible to find preserved aragonite skeletons sitting alongside others that are partly or fully stabilised by any of thin-film transformation, dissolution-reprecipitation, or complete dissolution and empty mould formation (Haywick 1990; Hood 1993). More specifically, originally aragonite components can be evident from any of the following:

- actual preservation of fresh aragonite shells (Fig. 9B)
- preservation of chalky aragonite shell remains
- empty dissolution moulds of former aragonite grains (Fig. 4D)
- equant non-ferroan (rarely ferroan) calcite spar-filled, or partly filled, dissolution moulds of former aragonite grains outlined by micrite envelopes
- neomorphic calcite spar after aragonite in which a degree of retention of the original shell microstructure is evident (Fig. 9D).

This diversity of alteration types amongst the aragonite components suggests that grain microstructural effects, including shell thickness and robustness, shell porosity, shell crystallite fabric and size, and the nature and distribution of organic shell matrices, probably exert a significant influence on the diagenetic behaviour and stability of aragonite in addition to simply mineralogical thermodynamic considerations (e.g., Walter & Morse 1985).

Cementation scenarios

During shallowest burial in the marine phreatic zone, sporadic and small amounts of non-ferroan, fibrous to scalenohedral, isopachous spar fringes of type (a) were selectively precipitated about grains. This spar was possibly sourced from the onset of some aragonite dissolution, and assisted preservation of open interparticle textures. In rare cases, detrital micrite filtered into pore spaces from the seafloor. Continued burial to depths of perhaps 10s to >100 m saw the initiation of mild chemical compaction, especially evident in the older Pliocene and late Miocene limestones, which preferentially sourced non-ferroan, locally complexly zoned, syntaxial rim cements of type (b) about the scattered echinoderm grains (Hood & Nelson 1996).

Subsequent cements in the late Pliocene limestones, and to a varying but generally small degree in some of the older Pliocene limestones, have a predominantly meteoric origin [type (d)]. Differential uplift and tilting of these limestones subjected them to highly variable contact with recharging

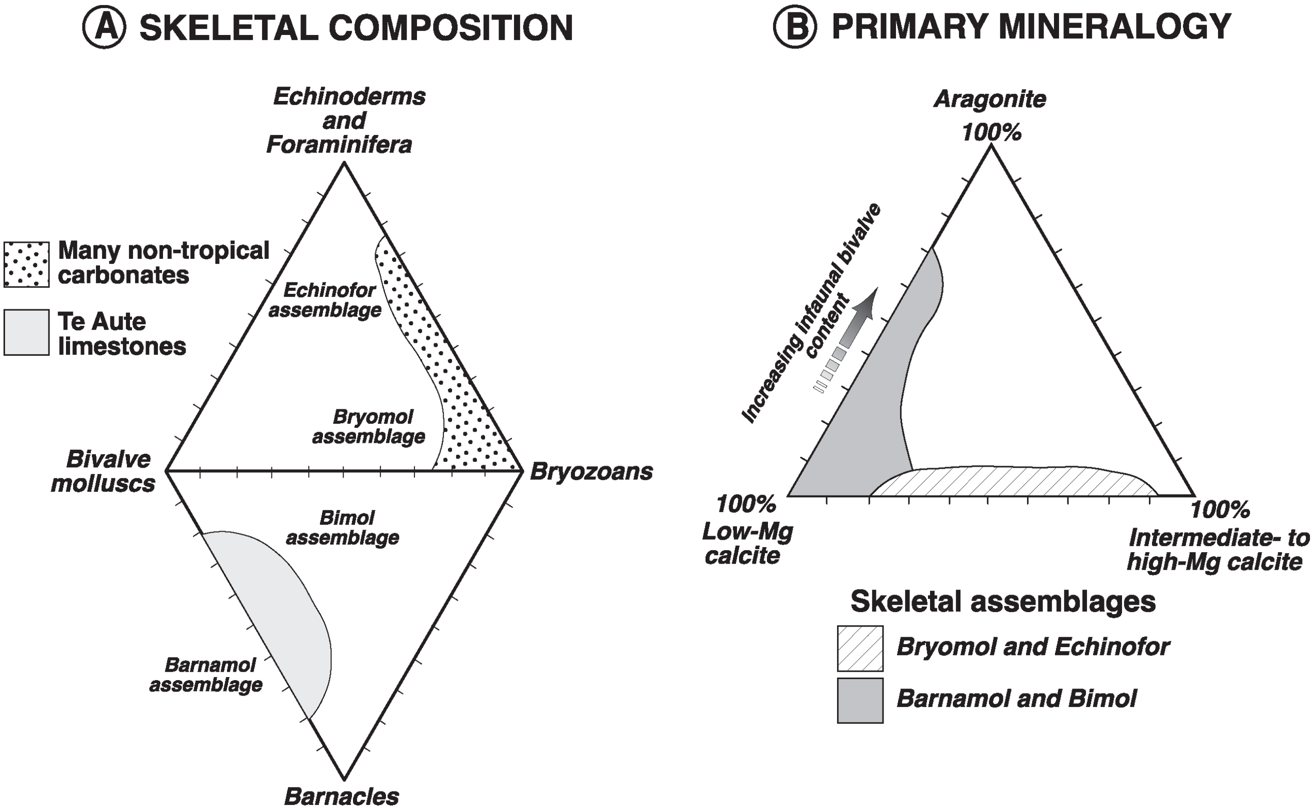

Fig. 8 Triangular diagrams summarising (**A**) the typical skeletal composition (dominant components only) and (**B**) primary mineralogy fields for Te Aute limestones in comparison to fields most commonly reported for cool-water carbonates in general.

meteoric fluids from the basin margins, beginning while the limestones were in the shallow-burial marine realm, but undoubtedly continuing once they were further uplifted and eventually subaerially exposed. The precipitated syntaxial rim and (micro)equant spar cement was sourced from both widespread dissolution and neomorphic alteration of aragonite skeletons, leaving often considerable secondary biomouldic porosity in many of the late Pliocene limestones. By contrast, in the majority of the early Pliocene and late Miocene limestones, the later formed syntaxial and equant spar cements are typically ferroan with dull luminescence [types (b) and (c)]. These were sourced from the increased influence of pressure-dissolution of skeletal grains of any composition during burial to depths of several 100 m to 1 km or more (Fig. 6, 9A) (Hood & Nelson 1996).

Diagenetic potential

Cool-water carbonate sediments are typically regarded as having a low diagenetic potential because of their predominantly calcitic primary mineralogy. This holds true for many of the Te Aute barnamol limestones, in which very patchy lithification by cements of types (a) and (b) was locally possible during shallow burial, and progressively more intensive lithification involving cement type (c) could occur only with increasing burial from pressure-dissolution of calcitic skeletons. In contrast, the aragonite-bearing barnamol and bimol Te Aute carbonates intrinsically had much higher diagenetic potential, with the prospect of locally intensive lithification by cement type (d) sourced from the selective alteration of particular aragonite skeletons, and without the necessity for deeper burial-related pressure-dissolution processes. In this sense the aragonite-bearing cool-water Te Aute carbonates can potentially mimic the diagenetic behaviour of their aragonite-dominant tropical counterparts.

In many non-tropical carbonates, including the extensive tracts of mid-Tertiary occurrences in New Zealand, there is evidence that aragonite skeletons in the initial sediments were often completely dissolved during very early diagenesis, on or close to the cool-water seafloor, without meteoric influence (Beu et al. 1972; Nelson 1978; Alexandersson 1979; Nelson et al. 1988a,b; Nelson & James 2000). Why then has aragonite survived into the subsurface in several of the cool-water Te Aute carbonate occurrences? We suspect that the very high sedimentation rates, up to two orders of magnitude greater than in other Australasian Tertiary examples (Fig. 5), played an important role, the rapid initial burial of shells deterring wholesale early dissolution of metastable aragonite from the primary sediments. Moreover, both the high accumulation rates and the high energy, coarse shelly nature of deposits probably favoured reduced levels of sediment bioturbation which would have tended to protect shells from dissolution by allowing buildup of alkalinity within surficial pore waters (Aller 1982).

GEOCHEMICAL DISCRIMINATION OF DIAGENETIC SETTINGS

Variations in the trace element and stable isotope composition of carbonates have been used extensively in the published literature to provide an indication of the extent and identity of diagenetic processes that have affected ancient limestones. For

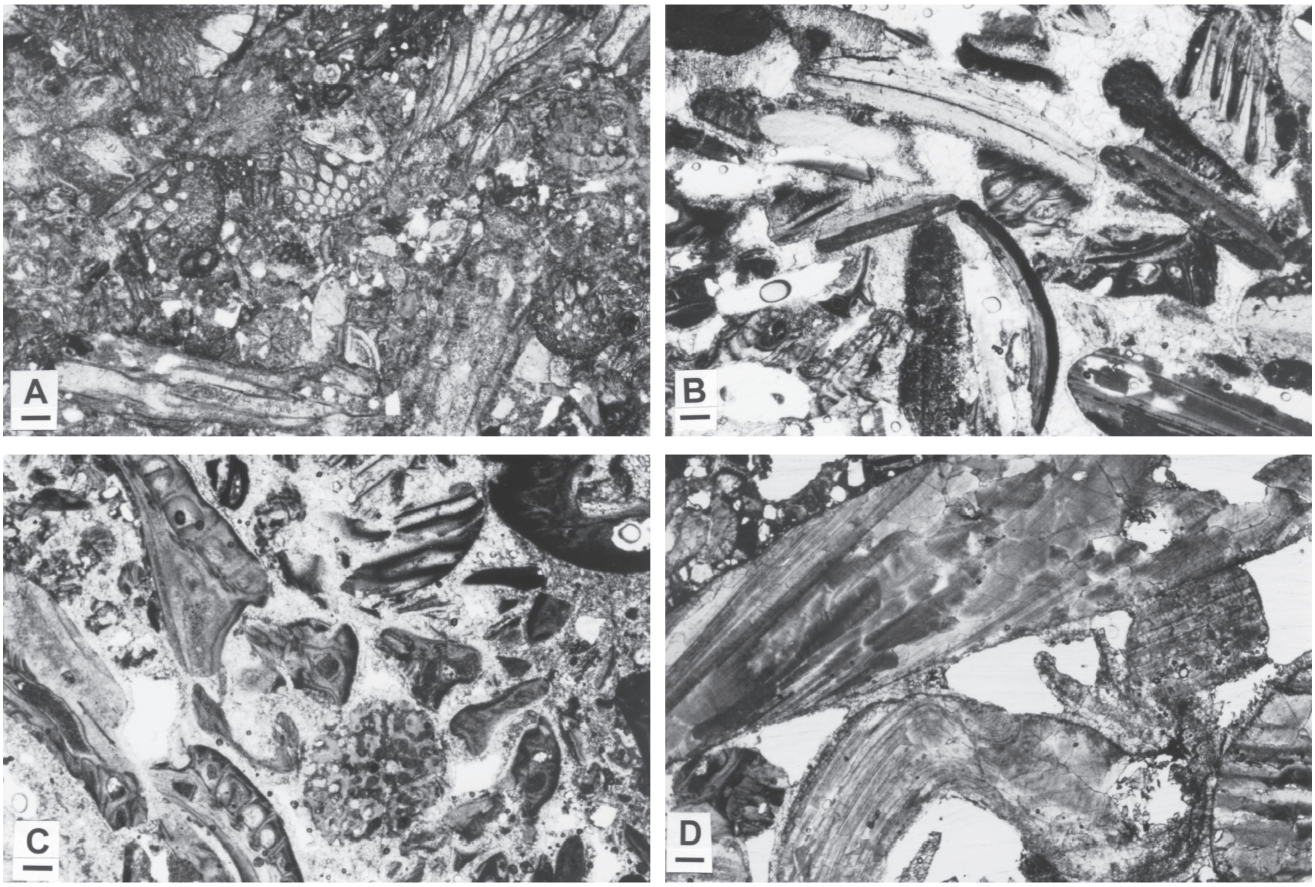

Fig. 9A–D Some petrographic features of Te Aute limestones. **A**, Thin-section of late Miocene Patutahi Limestone showing tight pressure-dissolved fabric in a bryomol carbonate, Rock Products Quarry. Cements are both non-ferroan and ferroan equant calcite spar. PPL, stained, sample SH10 (Appendix 1). **B**, Thin-section of late Pliocene Pakipaki Limestone in which cement fabrics include rare acicular and common scalenohedral isopachous rinds of non-ferroan calcite spar, and common drusy (micro)equant spar. Skeletons include mainly bivalves, some preserving their aragonite and others partially to fully dissolved, and barnacles. PPL, unstained, sample SH39. **C**, Thin-section of barnamol carbonate in late Pliocene Pukenui Limestone, Weraiti Quarry. Skeletal grainstone cemented by non-ferroan dog-tooth to bladed isopachous spar and equant spar, with some micrite. PPL, stained, sample SH83. **D**, Thin-section of bimol carbonate in late Pliocene Matapiro Limestone, Ohiti Road, showing large former aragonitic bivalves which have been neomorphosed to calcite with retention of much of their original internal microarchitecture. The sparse cements are thin rinds of non-ferroan bladed isopachous spar and meniscus spar. PPL, stained, sample SH49. Bar scale in all photomicrographs is 0.25 mm.

example, a strong meteoric influence is suggested by negative values for both $\delta^{18}O$ and $\delta^{13}C$ (Lohmann 1988; Rao 1990; Nelson & Smith 1996), and by a significant negative correlation between Sr and Mn content (e.g., Brand & Veizer 1980; Veizer 1983; Rao 1990). Changes in the chemical composition of carbonates orginate in the pore waters associated with the marine, meteoric, and/or burial (connate) diagenetic realms, each of which has characteristic geochemical attributes (e.g., Veizer 1983; James & Choquette 1990; Tucker & Wright 1990). Ideally the trace chemistry and stable isotope composition ought to be determined for individual components drilled from the limestones, especially the cements, a matter being addressed elsewhere (e.g., Caron 2002). The analyses presented here are from the acid-soluble fraction of bulk rock samples, which nevertheless can provide useful insights into the diagenetic processes that have affected ancient carbonates (e.g., Robinson 1980; Scudeler Baccelle & Marrusso 1983; Rao 1991; Adabi & Rao 1991; Winefield et al. 1996).

Elemental composition

Histograms of the elemental composition of the carbonate fraction of the bulk Te Aute limestones analysed in this study are shown in Fig. 10. Average values of all samples in Appendix 1 are: Ca 405 000 ppm; Mg 4400 ppm; Na 1500 ppm; Fe 2300 ppm; Sr 680 ppm; and Mn 220 ppm. In accordance with their cool-water heritage, the Mg and Sr values are much lower than is typical for tropical carbonates, while the Na, Fe, and Mn contents are higher (cf. Winefield et al. 1996). Compared to the average results reported by Winefield et al. (1996) for New Zealand Cenozoic temperate limestones as a whole, the above values are slightly lower for Ca, Mg, Fe, and Mn, and higher for Na and Sr. However, they mostly fall within the one standard deviation range of the New Zealand-wide values, and the small differences probably reflect the overwhelming dominance of barnacle and bivalve skeletons in the Te Aute limestones compared to other New Zealand Tertiary limestone occurrences (Hayton et al. 1995).

A number of published studies (e.g., Brand & Veizer 1980; Scudeler Baccelle & Marrusso 1983; Veizer 1983; Al-Aasm & Veizer 1986; Brand & Morrison 1987; Rao 1990, 1991; Adabi & Rao 1991; Rao & Jayawardane 1994) have identified direct or inverse relationships between pairs of elements in carbonate rocks that are inferred to be associated with alteration in either meteoric, marine, or burial diagenetic

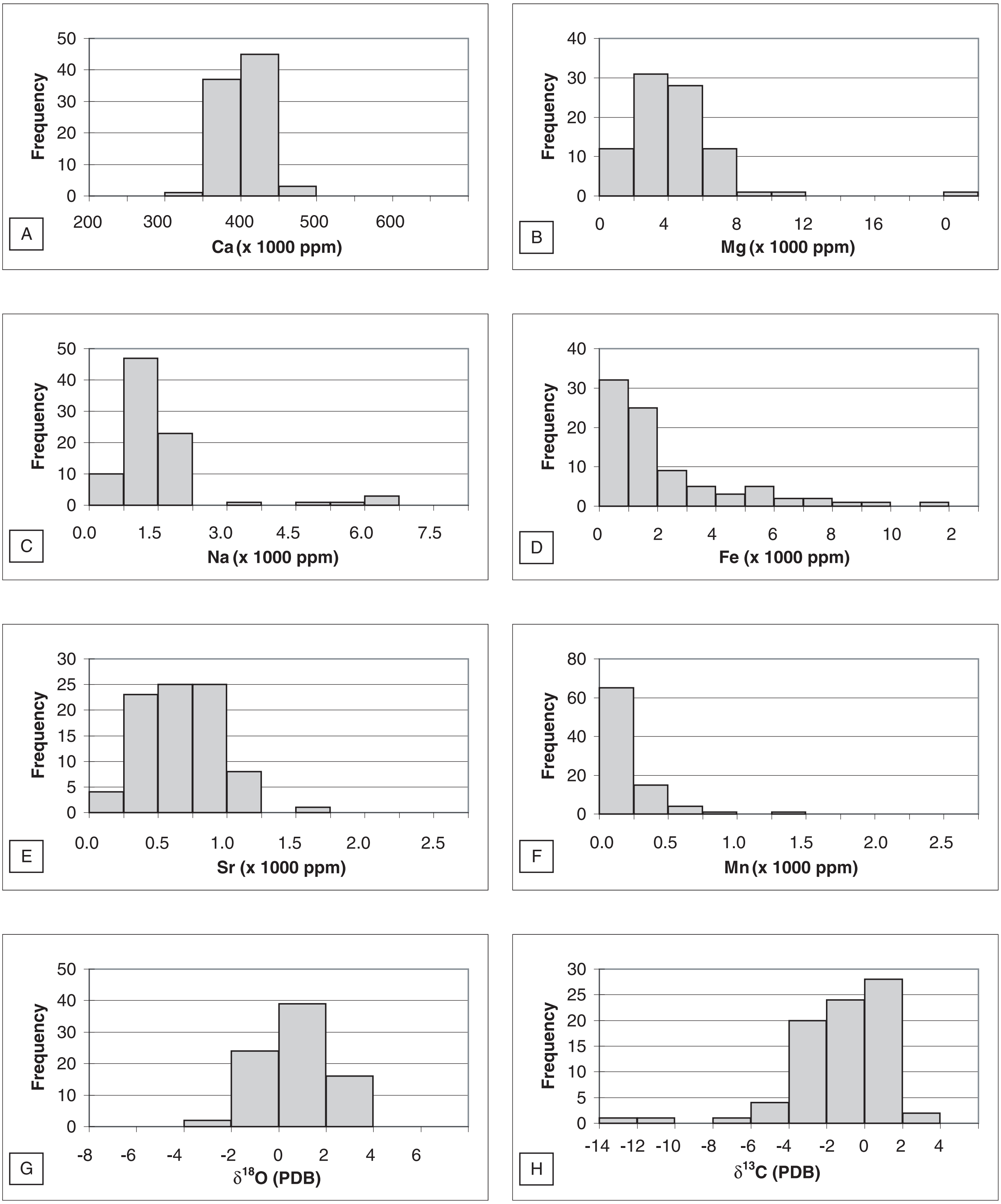

Fig. 10A–H Geochemical histograms showing the range of elemental concentrations and stable oxygen and carbon isotope compositions for the carbonate fraction of bulk Te Aute limestones. Data given in Appendix 1.

environments. These relationships are displayed here as matrices (Fig. 11A), the construction and interpretation of which have been explained by Winefield et al. (1996). The degree of agreement of an "unknown" matrix with each of the "master" matrices is represented as a pie diagram which may be used to infer the possible relative influences of the different diagenetic regimes on the samples constituting the "unknown" matrix.

A comparison of the summary elemental matrices and their diagenetic implications for the various age groups of Te Aute

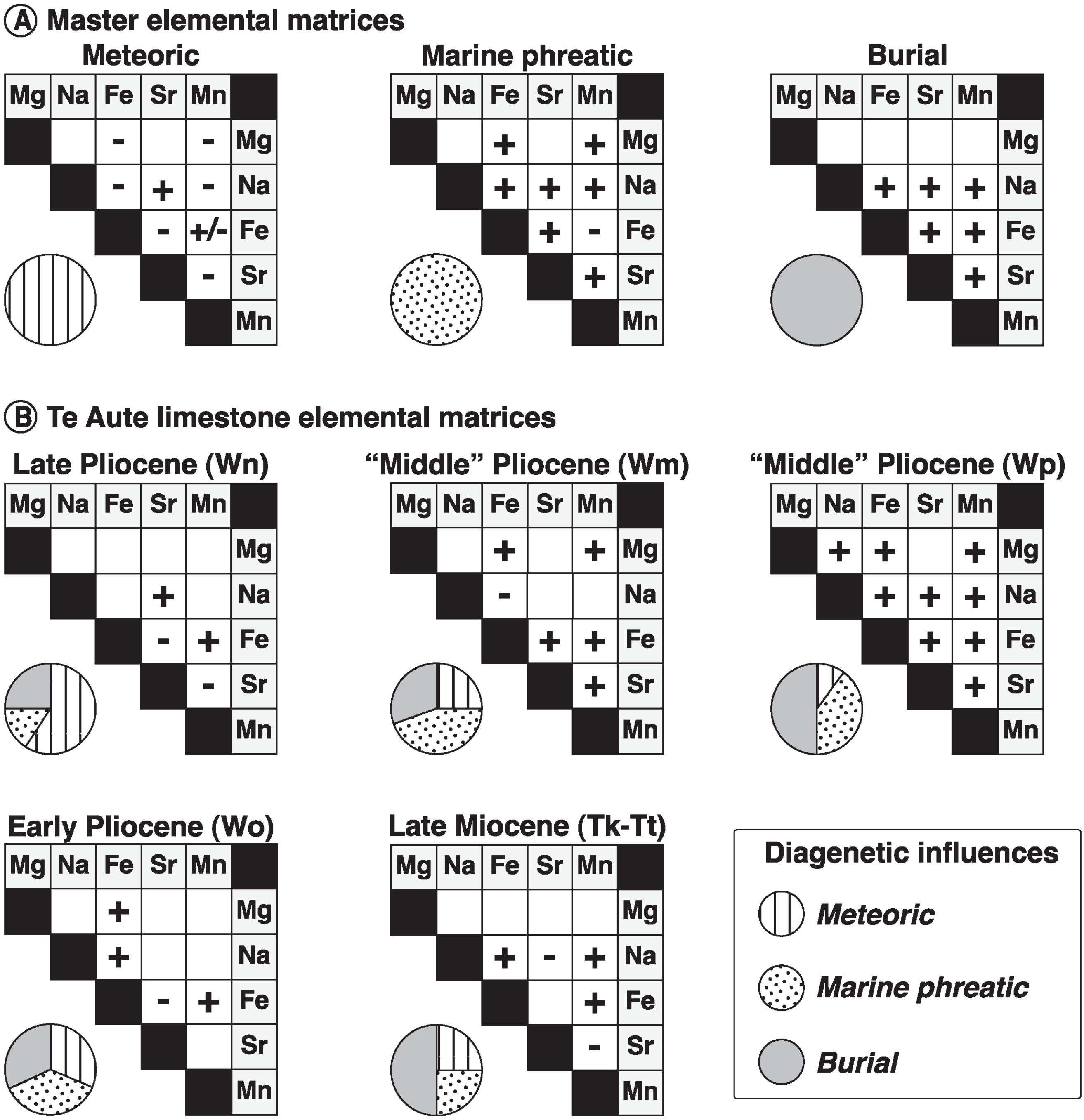

Fig. 11 **A**, Summary elemental matrices for idealised meteoric, marine phreatic, and deeper burial diagenetic trends, developed by Winefield et al. (1996). Positive and negative symbols indicate the sign of the slope of linear regression lines drawn through element-element plots. Schematic pie diagrams are used to quantitatively show the relative influence of each regime on a particular matrix. Each diagenetic regime has a number of element-element trends which can be used collectively to infer the dominant processes which have affected each matrix. The pie diagrams illustrate the influence of each diagenetic process on the overall matrix rather than individual element-element trends. **B**, Summary elemental matrices and linear regression trends (+ or –) for element pairs in bulk samples of Te Aute limestones (from Appendix 1) according to age. For example, the summary elemental matrix for the "middle" Pliocene (Wp) limestones has two out of eight regressions in agreement with those for meteoric diagenesis (see A), or an overall face value of 25% agreement. Similarly, seven out of eight (87.5%) agree with the marine phreatic master plot, and six out of six (100%) agree with the burial diagram, giving an overall ratio of burial > marine phreatic >> meteoric (47:41:12) as displayed in the schematic pie diagram for the Wp limestones.

limestones demonstrates some important trends and differences (Fig. 11B). The late Pliocene limestones exhibit a predominant meteoric influence, the "middle" to early Pliocene ones more of a mixed marine phreatic-burial signature, and some of these and the older limestones a predominantly burial diagenetic evolution. These patterns are broadly consistent with the diagenetic environments inferred from petrography (Fig. 6), as well as the diagenetic scenarios reported for the Te Aute limestones by Hood & Nelson (1996). Possible intraformational variability was investigated

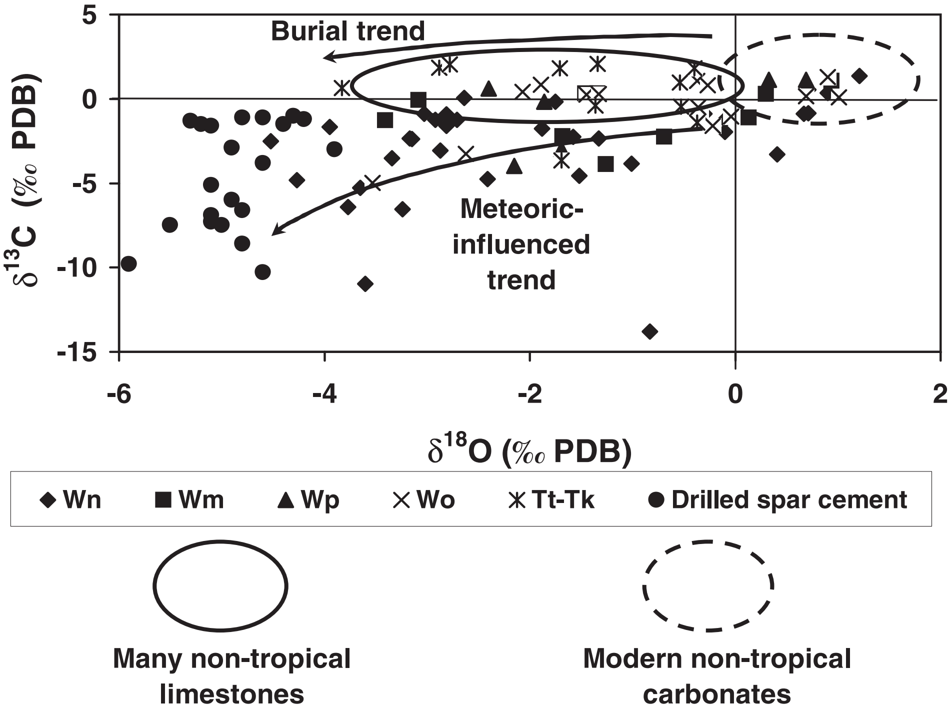

Fig. 12 Cross-plot of $\delta^{18}O$ and $\delta^{13}C$ values for bulk Te Aute limestones (Appendix 1) discriminated on the basis of age (New Zealand stage symbols defined in Table 2). Drilled cement data are from Haywick's (1990) study of late Pliocene Te Aute limestones in central Hawke's Bay (Fig. 1B), while the typical fields for modern and ancient non-tropical carbonates are from Nelson & Smith (1996). The diagenetic evolution of the Te Aute limestones has involved a highly variable mix of marine phreatic, burial, and meteoric processes, which is supported by the elemental results (Fig. 11B).

by Winefield (1995) and Winefield et al. (1996) by discriminating, where possible, each limestone formation on the basis of its skeletal assemblage, as defined by Hayton et al. (1995). This showed that while there was broad agreement of the above diagenetic trends irrespective of the various skeletal assemblages, those having a significant infaunal bivalve component, and therefore an initial aragonite mineralogy, displayed some variability, possibly reflecting the wide range of aragonite grain alteration pathways alluded to previously.

Oxygen and carbon isotopes

The oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotope analyses for the bulk Te Aute limestones range widely from small positive to moderately negative values, the overall average results being near –1.5‰ for both stable isotopes (Fig. 10, 12). Published $\delta^{18}O$ and $\delta^{13}C$ isotope data from other studies of New Zealand Cenozoic carbonates (Nelson & Smith 1996) show that the influence of meteoric diagenesis can dramatically lower $\delta^{13}C$ values, with a less well defined decrease in $\delta^{18}O$ values. By comparison, burial diagenesis significantly decreases $\delta^{18}O$ values, with relatively little change in $\delta^{13}C$ composition. The spread of data in Fig. 12 emphasises the wide range of diagenetic settings influencing the different Te Aute samples, including marine, shallow to moderate burial, and meteoric realms. Examples from all limestone age groups, but particularly the early Pliocene and late Miocene categories, follow the marine to marine phreatic/shallow burial to moderate subsurface burial trend involving increasingly negative $\delta^{18}O$ values with little change in $\delta^{13}C$ composition. The diagenetic influence of meteoric pore waters is indicated by the distinctive trend towards increasingly lower values for both $\delta^{18}O$ and $\delta^{13}C$, and is especially evident in the late Pliocene limestones. The strong meteoric influence in many of the younger limestones is emphasised by including in Fig. 12 the isotope results of Haywick (1990) for calcite spar cements isolated by drilling from the Tangoio and Waipatiki limestones (Table 2).

CONTROLS OF DIAGENETIC PATHWAYS

Despite their young age, restricted age range, similar temperate-latitude depositional setting, and similar coarse skeletal-dominated facies, the petrographic and geochemical data for the Te Aute limestones demonstrate they have been influenced by variable and contrasting diagenetic histories. Some (especially the late Miocene to early Pliocene formations) show a predominantly moderately deep (up to 1–2 km) burial diagenetic overprint, others (especially the "middle" Pliocene formations) a strong marine phreatic to shallow burial diagenetic signature, and still others (especially the late Pliocene formations) a significant meteoric overprint (Fig. 11). While this generalised relationship between dominant diagenetic environment and limestone age could be viewed as an anticipated one, there are nevertheless several exceptions to the trend so that, for example, some older limestones do exhibit evidence of meteoric alteration (e.g., Fig. 11). Moreover, amongst limestones of similar age, and even within the same formation, the degree of diagenetic alteration and cementation can range widely, both vertically and laterally, and differential cementation is commonplace (e.g., Fig. 4). Thus, the nature and overall impact of the different diagenetic environments and processes have been highly variable in both time and space, and at the local scale must be complex (e.g., Caron 2002).

The complexity of the diagenetic scenarios for the different Te Aute limestones reflects an equally complex interplay of tectonic processes and sea-level fluctuations affecting the Pliocene forearc basin, as well the variable content of metastable aragonite in the deposits. Active subsidence of the forearc provided accommodation for up to 2–3 km of Pliocene sediments, but the subsidence was strongly differential and involved locally significant zones of temporary and/or more long-lived uplift, especially about the margins of the seaway. Away from uplift areas, diagenesis was driven essentially by mechanical and ultimately chemical compaction (pressure-dissolution) processes as burial progressed under the influence of marine phreatic and marine-modified connate pore fluids. Aragonite-poor carbonates were much less susceptible to diagenetic alteration than aragonite-rich facies. Differential uplift and tilting of the limestones in the vicinity of the basin margins (Kamp & Nelson 1988) in places enabled incursions of reactive meteoric fluids to penetrate deeply into the porous skeletal carbonate aquifers while remaining predominantly in the shallow-burial environment (Haywick 1990). The degree of exposure to meteoric input was also influenced by Pliocene glacio-eustatic sea-level oscillations, which during falling stages served to reinforce the effects of local tectonic uplift. Meteoric diagenesis has played a minimal role in the alteration and lithification of the mainly calcitic facies of Te Aute limestones, because of their low diagenetic reactivity, and their degree of cementation and porosity remains primarily a function of depth of burial history and burial residence times. In contrast, the diagenesis of the aragonite-bearing and aragonite-rich Te Aute carbonates was profoundly influenced by contact with meteoric waters. Selective dissolution of aragonite provided a shallow source of low-Mg calcite cement and produced a range of partially to strongly lithified limestone bodies.

RESERVOIR POTENTIAL

The occurrence in eastern North Island of diverse subsurface structures (Field et al. 1997), numerous oil seeps (Francis 1995), and recent substantial gas strikes (Davies et al. 2000) highlights the hydrocarbon prospectivity of the East Coast Basin of New Zealand (Cole et al. 1992). Given the relatively few potential reservoir facies in an otherwise fine-grained siliciclastic-dominated Cenozoic record, the Te Aute limestones are an attractive target to drill (Harmsen 1990). Visual estimates of macroporosity in our suite of limestone thin sections are typically near 10%, but range from 1 to 25% (Fig. 7B). Actual laboratory measurements of porosity on c. 170 samples by de Caen & Darley (1968, 1969), summarised by Beu (1995), give typically higher values than this: late Pliocene limestones, av. 22% (range 9–47%); "middle" Pliocene limestones, av. 21% (range 10–37%); and early Pliocene limestones, av. 15% (range 6–22%). The overall decrease of porosity with increasing age reflects the generally greater degree of compaction and cementation in the older limestones (Fig. 6). However, the very wide range of porosities irrespective of limestone age emphasises the highly variable and differential nature of the diagenetic modifications that have affected these carbonates exhibiting a spectrum of burial histories and calcite-aragonite mixtures (see above). The few permeability measurements available for the Te Aute limestones range from practically zero to as high as 44 000 Md, with most samples ranging from c. 3 to 50 Md (de Caen & Darley 1968, 1969).

Pliocene strata reach thicknesses of up to 1000–3000 m in different parts of the East Coast Basin (Field et al. 1997). Te Aute limestones have been intersected in some wells drilled (e.g., Davies et al. 2000), but not in others where they have been anticipated (e.g., Harmsen 1990). The distribution of the limestones in the subsurface is poorly known at present, but is likely to be complex considering both the laterally discontinuous nature of units and the structural intricacies associated with the tectonically active forearc basin setting (Fig. 1A). Nevertheless, we anticipate that these young Te Aute limestones will prove to include examples of hydrocarbon reservoirs in non-tropical carbonates, a situation now beginning to be reported as carbonate reservoirs are re-evaluated in terms of a warm-water versus cool-water origin (e.g., Martindale & Boreen 1997).

CONCLUSIONS

The temperate Pliocene Te Aute limestones in eastern North Island, New Zealand, exhibit several features compatible with developing models for non-tropical shelf carbonate facies (e.g., Table 1), but other features that are different and may closely mimic tropical occurrences, including the following.

1. Limestone formation occurred mainly on and about linear submarine antiformal ridges or banks bounding a major forearc basin within a tectonically very active convergent continental margin setting, not upon an unrimmed (passive margin) shelf or ramp. The geometry of most limestones is consequently rather more ribbon- or lens-like, and laterally discontinuous, than it is sheet-like and continuous.
2. The limestones are locally thick (up to 100 m or more), indicating high production and accumulation rates from 10 to 100 cm/ka, values more typical of many shallow-marine tropical carbonate settings.
3. Skeletons are frequently dominated by barnacles and epifaunal and infaunal bivalves, forming barnamol and bimol skeletal carbonate deposits, rather than bryomol and echinofor skeletal associations most typical of cool-water carbonate occurrences.
4. The primary mineralogy of the carbonates was dominated by low-Mg calcite ± aragonite, not simply low- to intermediate- or high-Mg calcite, and those deposits with significant amounts of aragonite had the potential for subsequent increased diagenetic reactivity.
5. Despite cool-water conditions, metastable carbonate minerals like aragonite were not necessarily lost to dissolution during early seafloor diagenesis, possibly because of high sedimentation rates and short seabed residence times. Consequently, aragonite can be preserved into the burial realm, and the subsequent processes of aragonite alteration were diverse and selective.
6. The degree of lithification and the variety of cement types reflect an interplay of aragonite content and burial history. For aragonite-poor carbonates, cementation was mainly dependent on pressure-dissolution accompanying shallow to moderately deep burial. For aragonite-rich deposits, meteoric flushing in the subsurface and following uplift was an important source of equant calcite cement, irrespective of burial depth.

The message is that non-tropical shelf carbonates include a far more diverse array of geological settings, of skeletal and mineralogical facies, and of diagenetic features than current sedimentary models advocate. Moreover, they potentially can form excellent hydrocarbon reservoirs. While several attributes positively distinguish tropical from non-tropical limestones, continued detailed documentation and understanding of the wide spectrum of shallow-marine carbonate deposits formed outside tropical regions remains an important challenge in carbonate sedimentology.

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Appendix 1

Geochemical data for bulk Te Aute limestone samples. Grid references are based on NZMS 260 Topomap Series. Formations are described by Beu (1995). New Zealand stage symbols are defined in Table 2. Skeletal assemblages (after Hayton et al. 1995) are: Ba, barnamol; Bi, bimol; Br, bryomol. $\delta^{18}O$ and $\delta^{13}C$ are per mille values relative to the PDB standard.

Field No.	Grid Ref.	Formation	N.Z. Stage	Assem.	%CO3	Ca(ppm)	Mg(ppm)	Na(ppm)	Fe(ppm)	Sr(ppm)	Mn(ppm)	$\delta^{18}O$	$\delta^{13}C$
SH27	V20/489002	Tangoio	Wn	Ba	63.12	481241	2375	836	2849	370	184	-3.65	-5.28
SH28	V20/484002	Tangoio	Wn	Ba	93.40	473588	1371	866	879	263	141	-4.52	-2.52
SH30	V21/386829	Tangoio	Wn	Ba	91.75	430799	5344	1505	1996	819	185	0.90	0.36
SH31	V21/386829	Tangoio	Wn	Ba	94.56	436621	5815	1533	941	827	122	0.71	0.56
SH32	V21/418820	Park Island	Wn	Ba	96.27	426924	3636	646	245	581	66	0.67	-0.87
SH33	V21/472838	Scinde Island	Wn	Ba	60.89	430425	6079	1641	1955	706	179	0.71	-0.86
SH34	V21/472838	Scinde Island	Wn	Ba	83.65	431818	6579	1023	507	584	157	0.41	-3.30
SH35	V21/448834	Scinde Island	Wn	Ba	71.27	430817	1824	916	1123	271	173	-3.24	-6.54
SH37	V21/350602	Pakipaki	Wn	Ba	97.36	453470	1645	895	359	220	86	-3.60	-10.96
SH38	V21/350602	Pakipaki	Wn	Ba	97.90	442243	1941	1614	889	400	196	-3.34	-3.51
SH39	V21/350602	Pakipaki	Wn	Ba	98.13	416327	5408	2020	321	1728	47	-0.83	-13.79
SH75	S27/172848	Pukenui	Wn	Ba	81.33	380027	2952	1082	1980	676	212	-2.81	-0.91
SH78	S27/172848	Pukenui	Wn	Ba	90.62	378880	2762	1000	983	624	122	-2.81	-1.60
SH81	T26/376292	Pukenui	Wn	Ba	94.38	371038	3074	2112	513	600	277	-1.75	-0.18
SH82	T26/396210	Pukenui	Wn	Ba	97.62	351183	3379	1144	377	771	130	-1.58	-2.25
SH87	T25/390433	Pukenui	Wn	Ba	97.18	384774	1749	803	782	357	189	-3.17	-2.35
SH88	T25/390433	Pukenui	Wn	Ba	98.40	400488	1830	853	742	465	178	-3.15	-2.37
SH71	S28/100979	Bull Creek	Wn	Ba	91.06	356986	2966	1217	758	745	191	-1.01	-3.86
SH84	U26/821288	Castlepoint	Wn	Ba	91.15	372930	5046	1875	2501	438	109	1.21	1.37
SH89	T24/471746	Kumeroa	Wn	Ba	95.72	383370	2089	1200	1086	477	158	-1.52	-4.56
SH90	T24/502928	Kumeroa	Wn	Ba	90.09	402796	4660	1329	3506	543	610	-0.30	-0.90
SH97	U24/784832	Kumeroa	Wn	Ba	94.06	387926	3826	848	405	500	55	-0.10	-1.97
SH83	T26/396210	Pukenui	Wn	Ba	98.59	360945	1825	579	302	800	130	-3.77	-6.42
SH23	V20/447094	Tangoio	Wn	Bi	88.27	437443	2833	1010	1371	721	95	-2.64	0.05
SH24	V20/459080	Waipatiki	Wn	Bi	91.86	433315	2613	1481	1274	898	130	-3.03	-0.90
SH25	V20/448060	Kaiwaka	Wn	Bi	95.96	428929	1305	3089	478	731	97	-0.10	-1.24
SH26	V20/489002	Tangoio	Wn	Bi	92.84	445977	1724	658	1799	241	204	-4.27	-4.83
SH29	V20/382907	Tangoio	Wn	Bi	88.90	436249	2811	1687	1237	532	255	-2.71	-1.23
SH49	V21/298733	Matapiro	Wn	Bi	90.16	380266	1441	731	459	475	135	-3.95	-1.68
SH50	V21/295745	Matapiro	Wn	Bi	91.93	378590	3916	1538	936	1019	138	-1.88	-1.77
SH51	V21/236795	Matapiro	Wn	Bi	89.81	380634	2894	1617	935	770	149	-1.33	-2.36
SH76	S27/172848	Pukenui	Wn	Bi	57.91	376511	2832	1575	3541	442	316	-2.87	-3.08
SH79	S27/176867	Pukenui	Wn	Bi	92.56	431025	2053	1106	1264	610	129	-2.92	-1.25
SH80	T26/376292	Pukenui	Wn	Bi	94.46	394500	2221	1215	814	556	319	-2.41	-4.75
SH52	U20/035932	Te Waka	Wm	Bi	75.42	369288	6376	1124	4862	1354	399	-1.34	0.32
SH53	U20/035932	Te Waka	Wm	Bi	73.76	371727	5427	921	5698	905	392	-3.08	-0.06
SH44	U23/036218	Te Onepu	Wm	Ba	96.42	433520	3827	1390	505	585	86	-1.68	-2.23
SH45	U23/036218	Te Onepu	Wm	Ba	97.84	447013	2455	992	1023	476	216	-3.41	-1.27
SH91	T25/691610	Te Onepu	Wm	Ba	91.76	376947	5447	1344	1242	609	126	0.94	1.05
SH92	T25/609689	Te Onepu	Wm	Ba	95.22	390715	3466	918	400	915	56	-0.69	-2.26
SH93	T25/685676	Rongomai	Wm	Ba	96.39	392950	2799	800	1058	913	72	-1.26	-3.89
SH96	U24/759858	Te Onepu	Wm	Ba	89.04	372573	4938	875	1459	303	81	0.30	0.27
SH98	U24/747832	Te Onepu	Wm	Ba	81.49	381876	4298	1031	1068	1170	86	0.13	-1.11
SH99	U24/734801	Te Onepu	Wm	Ba	90.04	407280	5327	1042	2242	913	93	-1.46	0.33
SH17	X19/147318	Tahaenui	Wp	Ba	92.51	436804	4757	1514	1189	893	97	0.69	1.13
SH19	V19/405218	Titiokura	Wp	Ba	54.80	411335	6033	1230	7185	755	473	-1.86	-0.17
SH20	V19/405218	Titiokura	Wp	Ba	76.58	411657	6404	2039	5201	937	307	-2.40	0.62
SH47	V22/385588	Awapapa	Wp	Ba	96.81	436179	2901	501	1295	281	64	-2.15	-3.99
SH48	V22/385588	Awapapa	Wp	Ba	98.18	368974	2548	1063	522	482	53	-1.69	-2.99
SH18	X19/147318	Tahaenui	Wp	Bi	85.30	417595	4457	1490	2897	873	140	0.33	1.13
SH22	V19/391272	Kairakau	Wo	Ba	48.39	417873	7240	1363	8109	734	494	-1.45	0.25
SH41	V22/445319	Kairakau	Wo	Ba	77.65	432599	3605	1635	578	1024	112	-0.34	-0.88
SH42	V22/445319	Kairakau	Wo	Ba	67.35	445500	5049	1470	728	566	200	-0.04	-1.05
SH43	V22/445319	Kairakau	Wo	Ba	92.95	439040	4842	1582	807	923	97	-0.22	-1.60
SH14	X18/027541	Whakapunake	Wo	Ba	78.93	397410	20442	1879	5130	808	159	0.69	0.15
SH6A	Y17/408806	Ormond	Wo	Ba	75.05	414390	5330	991	6089	763	470	-0.36	-0.51
SH6B	Y17/408806	Ormond	Wo	Ba	73.53	436557	5848	1194	5821	672	216	-0.37	1.07
SH67	S27/104855	Haurangi	Wo	Ba	96.52	354367	1969	1150	478	588	381	-2.62	-3.27
SH57	U21/725875	Waiouru	Wo	Ba	59.80	374582	3846	1211	5000	729	642	-2.07	0.40
SH68	S27/105856	Haurangi	Wo	Ba	96.07	383815	1872	804	347	397	258	-3.53	-4.97
SH70	S28/100979	Haurangi	Wo	Ba	89.77	342491	4029	1915	488	1032	169	1.01	0.09
SH12	X18/100658	Kairakau	Wo	Bi	78.64	389363	7253	6426	9925	615	214	-1.89	0.84
SH15	X18/027541	Whakapunake	Wo	Bi	85.15	425882	5176	1058	4165	769	178	-0.27	0.81
SH56	U21/376865	Waiouru	Wo	Bi	81.50	379467	4544	1524	3205	969	1326	-1.33	0.29
SH16	X19/147318	Whakapunake	Wo	Bi	97.00	420532	5051	1649	722	1021	74	0.90	1.29
SH1	Y17/527095	Patutahi	Tt	Br	75.46	397667	4905	6005	6257	244	570	-2.88	1.86
SH2	Y17/527095	Patutahi	Tt	Br	77.99	404676	5781	6719	11434	217	809	-2.78	2.05
SH4	Y17/689997	Patutahi	Tt	Br	87.88	400182	5245	4720	4560	735	217	-3.83	0.65
SH7	X18/300738	Patutahi	Tt	Br	88.42	408834	9173	729	1495	337	112	-0.40	1.81
SH8	X18/300738	Patutahi	Tt	Br	78.99	423267	6336	1711	1483	368	252	-1.69	-3.66
SH10	Y18/312732	Patutahi	Tt	Br	88.25	419739	10437	523	2984	337	167	-0.54	0.98
SH9	X18/300738	Patutahi	Tt	Bi	77.59	416667	6192	5921	2154	599	232	-0.53	-0.46
SH11	X18/220682	Patutahi	Tt	Bi	91.87	419390	2614	818	2505	405	99	-1.71	1.80
SH54	U20/894922	Owhaoko	Tk	Ba	83.13	359764	5294	1565	3766	990	263	-1.36	-0.40
SH55	U20/894922	Owhaoko	Tk	Ba	83.22	367744	6970	1130	5696	1126	305	-1.34	2.06
SH69	S28/100979	Clay Creek	Tk	Ba	83.97	373721	4999	820	1976	518	219	-0.37	-1.40