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A review of Wanganui Basin, New Zealand: global reference section for shallow marine, Plio–Pleistocene (2.5–0 Ma) cyclostratigraphy

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Abstract

Wanganui Basin, New Zealand, contains one of the most complete late Neogene marine stratigraphic records in the world. The ca. 2 km thick basin-fill for the last ca. 2.5 Ma comprises 47 superposed cyclothems which correspond to successive 5th (100 ka) and 6th (41 ka) order glacio-eustatic, sea-level fluctuations on the palaeo-New Zealand shelf since oxygen isotope stage 100. Stages 100 to 5 are represented by marine cyclothems, whereas stages 17 to 3 are represented by a suite of coeval and younger uplifted marine terrace sequences. Additionally, a predominantly glacial loess stratigraphy exists for isotope stages 12–2. The presence of interbedded tephras and an established paleomagnetic stratigraphy allows the development of an integrated cyclostratigraphy for Wanganui Basin which correlates closely with the global oxygen isotope scale. In all except two cases (cycles 12 and 36), individual unconformity-bound cyclothems (sequences) represent a single glacial/interglacial couplet of Milankovitch frequency. Lithologic and faunal variation within the cyclothems corresponds closely to that predicted by the sequence stratigraphic model. Each cyclothem generally contains a transgressive systems tract, a mid-cycle condensed shellbed, a highstand systems tract, and often a regressive systems tract. Six common cyclothem motifs are inferred to represent deposition in shelf locations between the highstand and lowstand shorelines, viz. the Hawera, Maxwell, Turakina, Seafield, Castlecliff, and Rangitikei motifs. A seventh type, the Nukumaru motif, includes coquina limestone and represents deposition in shoreface and very shallow water marine environments.

Keywords: Wanganui Basin; cyclostratigraphy

1. Introduction

In the Plio–Pleistocene Wanganui Basin, New Zealand (Fig. 1), sedimentation broadly matched subsidence until basin eversion occurred by smooth and rapid uplift in the late Quaternary. As a result, the basin contains one of the most complete and undeformed shallow marine Plio–Pleistocene records in the world. Because Wanganui Basin sediments are geologically young, they contain sedimentary facies and fossil faunas which are closely similar to well-described counterparts around the modern New Zealand coast and shelf. Accordingly, and as first shown by Fleming (1953), the environments of deposition for Wanganui sedimentary units and rhythms can be established with great accuracy.

The Wanganui basin fill comprises 47 uncon-

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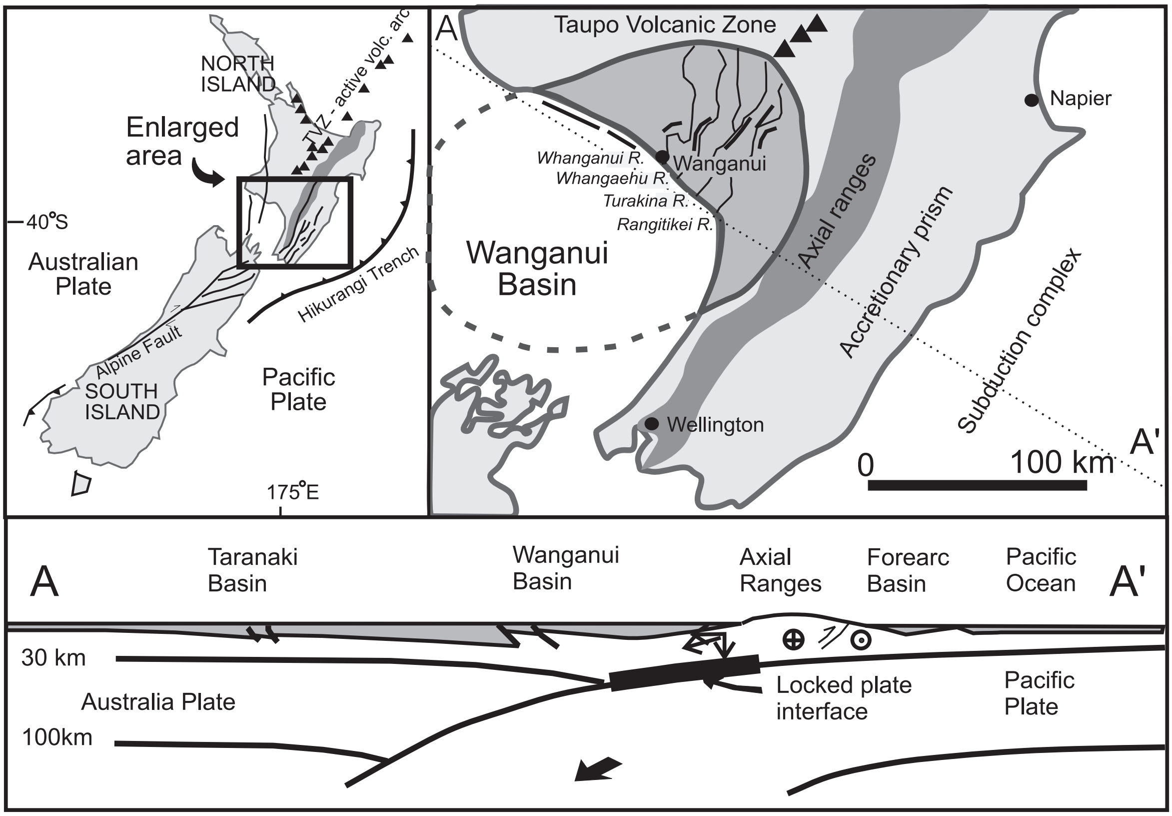


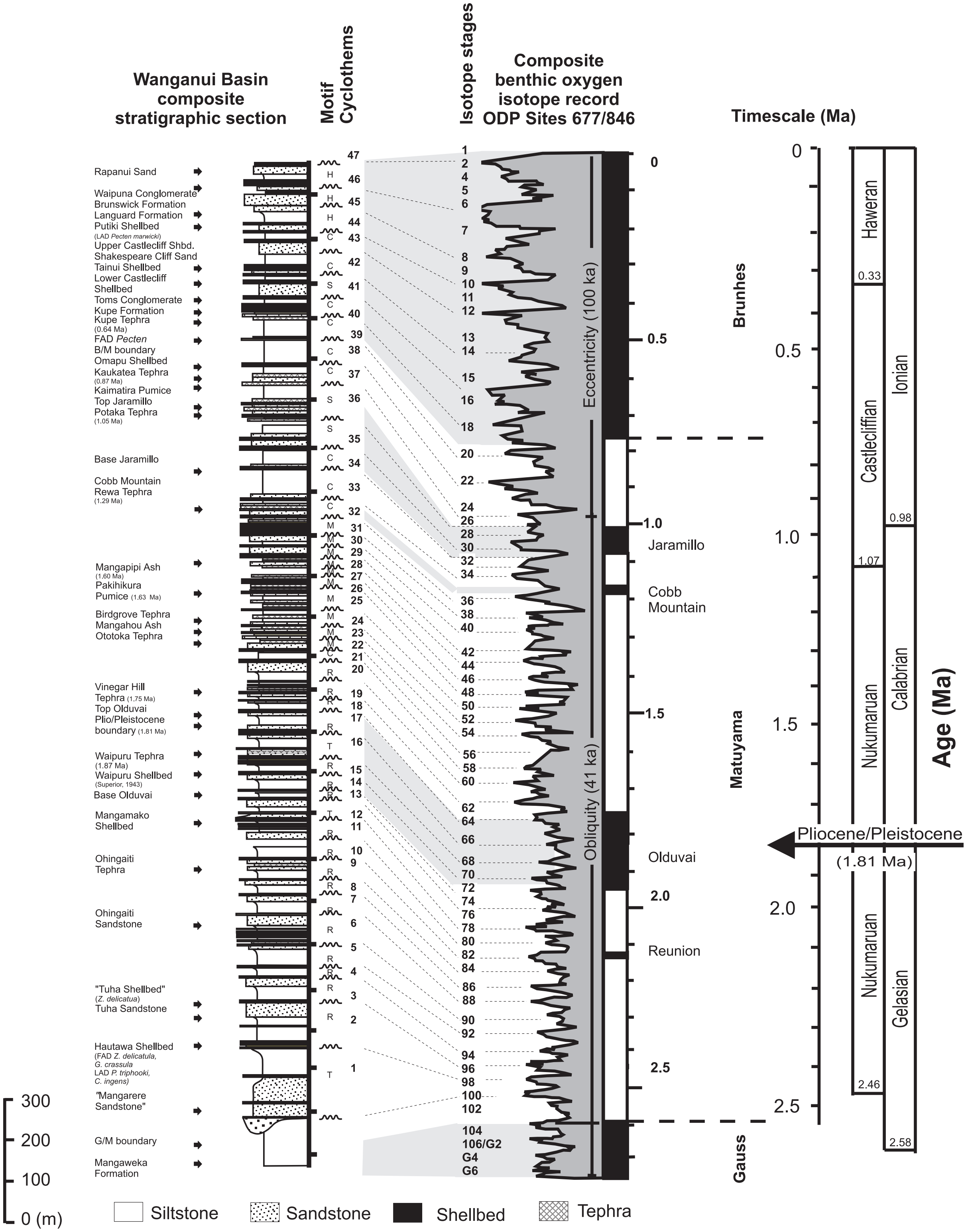
Fig. 1. Locality map and geologic setting of Wanganui Basin. Regional tectonic interpretation after Stern and Davey (1989), and Stern et al. (1992, 1993).

formity-bound, Milankovitch-scale, sedimentary cycles which were deposited during the glacio-eustatic sea-level cycles equivalent to oxygen isotope stages 100–4 (Fig. 2). Oxygen isotope stages 100 to 9 are represented by marine cyclothems, whereas stages 17 to 3 are represented by a suite of coeval and younger uplifted marine terrace sequences. This paper summarises the earlier work, much of it of recent origin, which led to the establishment of detailed sequence stratigraphic (Saul et al., 1998) and cyclostratigraphic (Naish et al., 1998) interpretations of the Wanganui Basin, and to its prominence as a global reference section (e.g. Pillans et al., 1991). We provide background information for the several other papers in this volume which deal with Wanganui Basin stratigraphy, and also summarise the established literature on the basin. Valuable earlier reviews of the stratigraphy have been contributed by Fleming (1953), Anderton (1981), Beu and Edwards (1984), Beu et al. (1986), and Pillans (1992).

1.1. Basin setting

The Wanganui Basin is a 200 × 200 km, ovoid sedimentary basin in western North Island, New Zealand (Anderton, 1981), situated in a back-arc position with respect to the modern Pacific–Australia plate boundary zone (Fig. 1). Plio–Pleistocene subsidence and basin formation has been attributed to lithospheric loading in combination with compres-

Fig. 2. Composite stratigraphy for Wanganui Basin, showing the 47 cyclothems which occur, and their correlation to the orbitally tuned isotope scale. Isotope record after Shackleton et al. (1990, 1995b).



Wanganui Basin composite stratigraphic section
Motif
Cyclothems
Isotope stages
Composite benthic oxygen isotope record ODP Sites 677/846
Timescale (Ma)
Rapanui Sand
Waipuna Conglomerate
Brunswick Formation
Languard Formation
Putiki Shellbed
(LAD Pecten marwicki)
Upper Castlecliff Shbd.
Shakespeare Cliff Sand
Tainui Shellbed
Lower Castlecliff Shellbed
Toms Conglomerate
Kupe Formation
Kupe Tephra (0.64 Ma)
FAD Pecten
B/M boundary
Omapu Shellbed
Kaukatea Tephra (0.87 Ma)
Kaimatira Pumice
Top Jaramillo
Potaka Tephra (1.05 Ma)
Base Jaramillo
Cobb Mountain
Rewa Tephra (1.29 Ma)
Mangapipi Ash (1.60 Ma)
Pakihikura Pumice (1.63 Ma)
Birdgrove Tephra
Mangahou Ash
Ototoka Tephra
Vinegar Hill Tephra (1.75 Ma)
Top Olduvai
Plio/Pleistocene boundary (1.81 Ma)
Waipuru Tephra (1.87 Ma)
Waipuru Shellbed (Superior, 1943)
Base Olduvai
Mangamako Shellbed
Ohingaiti Tephra
Ohingaiti Sandstone
"Tuha Shellbed" (Z. delicatua)
Tuha Sandstone
Hautawa Shellbed (FAD Z. delicatula, G. crassula LAD P. triphooki, C. ingens)
"Mangarere Sandstone"
G/M boundary
Mangaweka Formation
300
200
100
0 (m)
Eccentricity (100 ka)
Obliquity (41 ka)
Brunhes
Matuyama
Gauss
Jaramillo
Cobb Mountain
Olduvai
Reunion
0
0.5
1.0
1.5
2.0
2.5
Haweran
Castlecliffian
Nukumaruan
Nukumaruan
Ionian
Calabrian
Gelasian
0.33
1.07
0.98
2.46
2.58
Pliocene/Pleistocene (1.81 Ma)
Age (Ma)
104
106/G2
G4
G6
Siltstone
Sandstone
Shellbed
Tephra

sional downwarping driven by coupling of the overriding and subducting plates (Stern and Davey, 1989; Stern et al., 1992, 1993; Wilson and McGuire, 1995). Sedimentation evidently kept pace with subsidence throughout much of the basin history, resulting in the deposition of several kilometres of predominantly shelf and shallow water sediment. The eastern margin of the basin has undergone gentle uplift along the plate boundary, resulting in excellent onland exposures through 47 superposed Plio–Pleistocene cyclothems (Fig. 2) which represent oxygen isotope stages 3 through to 100 (Pillans, 1983; Abbott and Carter, 1994; Journeaux et al., 1996; Naish and Kamp, 1997a; Saul et al., 1998). Each 41 ka ($\delta^{18}O$ stages 100–18) and 100 ka ($\delta^{18}O$ stages 17–2) glacial/interglacial stage couplet is represented by an individual depositional sequence comprising transgressive (TST), highstand (HST) and, in many cyclothems, regressive systems tracts (RST). The cyclostratigraphy is a composite record of five well-exposed sections; the coastal cliffs to the northwest of Wanganui city, and the cliffs within four north–south oriented river valleys, from east to west the Whanganui, Whangaehu, Turakina and Rangitikei Rivers (Figs. 1 and 3A). These sections are located roughly across depositional strike, and represent a basinal cross-section from the western basin flank to the basin axis. Correlations between sections are underpinned by a high-resolution chronology based on the new magnetostratigraphic and tephrochronologic data summarised by Naish et al. (1996, 1997a,b). Biostratigraphic datums and geochemical fingerprinting of tephras, together with the determination of paleomagnetic transitions, allow individual cyclothems to be traced over 100 km across the basin.

In general, major sedimentary facies represented within the Wanganui Basin were deposited in coastal plain, shoreface and shelf marine environments during the late rise, highstand and early falling part of each glacio-eustatic cycle. The onland Wanganui stratigraphic record was therefore deposited mainly during odd numbered (interglacial) isotope stages (Beu and Edwards, 1984). Glacial stages are represented onland only by the surfaces of marine planation and bioerosion which occur at the base of each cyclothem, and which mark modified sequence boundaries. Lowstand systems tracts are, however, well developed in the offshore part of the Wanganui Basin, where the modern shelf-edge is underlain by a thick sequence of seawards-prograding clinoforms of Plio–Pleistocene age (termed the ‘giant foresets’ formation; Beggs, 1990; Carter et al., 1991; Nodder, 1995).

2. Wanganui Basin stratigraphy

2.1. Biostratigraphy and local stages

The well-preserved fossil faunas from the Wanganui Basin attracted the attention of palaeontologists as early as the middle of the 19th century (e.g. Mantell, 1850; Hutton, 1873). In a series of historic works, New Zealand’s pioneer geologists pieced together the stratigraphy of the sediments which enclosed the fossils, noting particularly the presence of shellbeds, fossiliferous blue ‘clays’, and beds rich in volcanic ash, all of which were useful in mapping and correlation (Von Hochstetter, 1864; Buchanan, 1870; Hutton, 1886; Park, 1887, 1905). Because most interest centred on the fossil faunas, which differed from those of similar age overseas, a series of biostratigraphic stages was set up by Thomson (1917) and Finlay and Marwick (1940, 1947) as an aid to correlation. Thus the Waitotaran (substages Waipipian and Marahauan), Nukumaruan (substages Hautawan and Marahauan) and Castlecliffian (substages Putikian and Okehuan) stages had their type localities designated in the Wanganui region (Fig. 2), but were subsequently recognized throughout the New Zealand Plio–Pleistocene. More recently, a Pouakai Oppelzone (Carter, 1974) or a Haweran stage (Beu et al., 1986) have been suggested for sediments younger than ca. 0.35 Ma, and revised stage definitions have been suggested based either on biostratigraphic (Boreham, 1963; Beu, 1969, 1995; Beu et al., 1981) or magnetostratigraphic and tephrochronologic grounds (Carter and Naish, 1998).

2.2. Lithostratigraphy

During the late 19th and early 20th century, many particular beds in the Wanganui Basin were referred to by local geographic names. Overall, the younger parts of the stratigraphy were often included in the Wanganui Beds, Series, Formation or System,

the choice of classification varying with the author. However, the establishment of a modern lithostratigraphic framework for Wanganui sediments did not occur until the completion of field investigations by officers of the New Zealand Geological Survey (Fleming, 1947, 1953; Te Punga, 1952). Fleming's lithostratigraphy, supported by detailed biostratigraphy, provided a full description of the sediments of the coastal section of the Wanganui Basin, a map of the extension of the sediments inland, and an integrated lithostratigraphic framework that forms the basis for all subsequent studies. Naish and Kamp (1995) have provided a detailed stratigraphic description of the important Plio–Pleistocene succession exposed in the Rangitikei River valley.

Abbott and Carter (1998) presented a detailed stratigraphic column for the key mid-Pleistocene section along the Castlecliff coast, making minor adjustments to the nomenclature of Fleming (1953) to systematise better the relationship between lithostratigraphy and cyclostratigraphy.

2.3. Recognition of the Plio–Pleistocene boundary

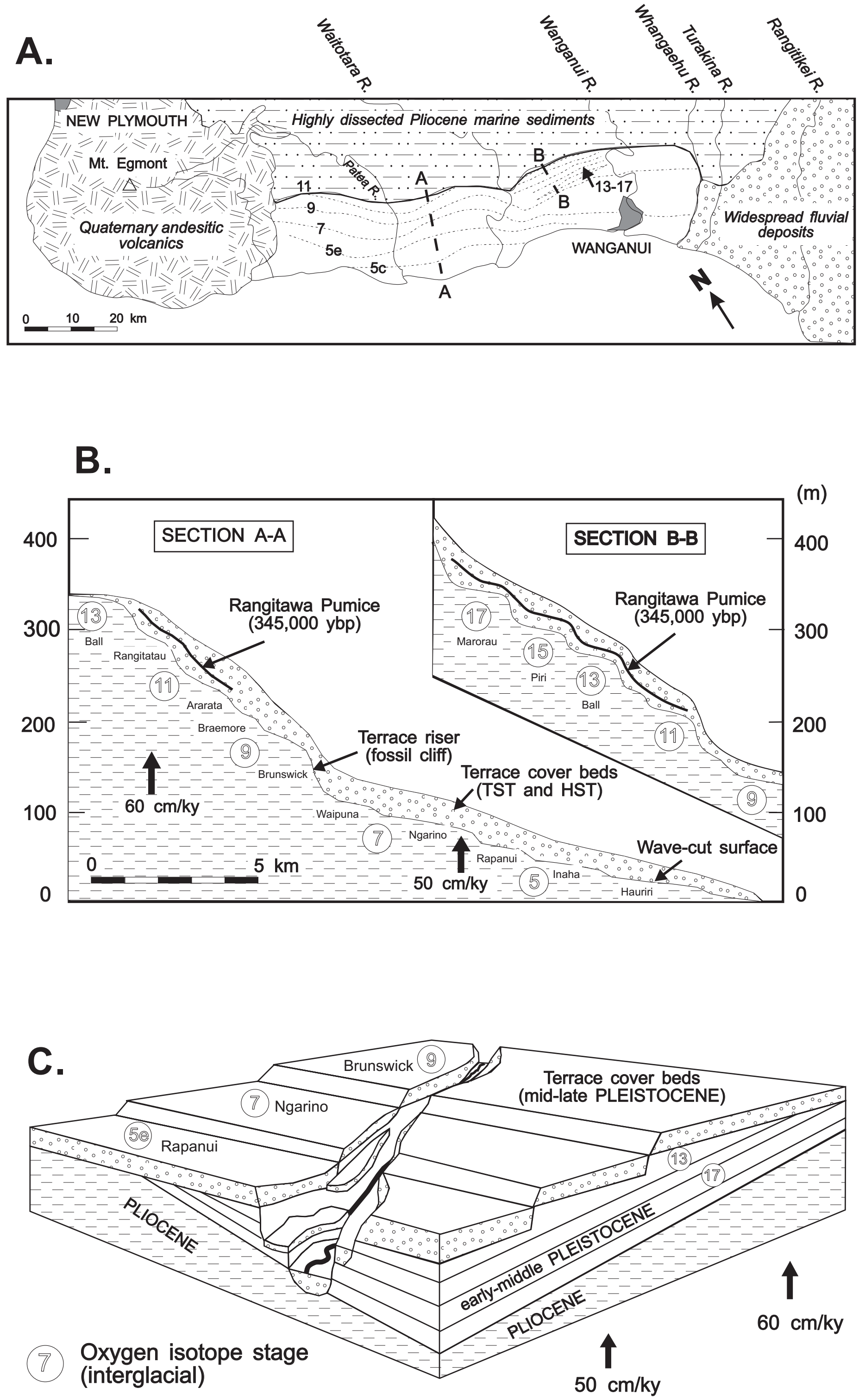
Much interest was evinced in the 1960s and 1970s in locating the precise position of the Plio–Pleistocene boundary (PPB) in New Zealand rocks (Fleming, 1953; Kennett et al., 1971; Jenkins, 1971; Te Punga, 1981). The first occurrence of the cold-water scallop *Zygochlamys delicatula*, which defined the base of the Nukumaruan Stage in the Wanganui Basin, was perhaps the favoured bioevent used to mark the boundary in New Zealand (Fleming, 1944; Fleming, 1953; Boreham, 1963; Beu, 1969, 1995; Beu et al., 1981; Edwards, 1987, 1997). However, efforts to locate the boundary accurately in New Zealand at that time were destined to fail, for two reasons. First, because of the complete ambiguity which existed regarding the definition of the boundary in its type area in southern Italy (see summary in Berggren and Van Couvering, 1979) at the same time as oceanographers were adopting a pragmatic (and different) boundary in their studies of deepsea cores. And second, because of the endemic nature of the biostratigraphic elements being used for correlation both within the Mediterranean type region and in the southwest Pacific.

The first ambiguity was removed by the achievement of international agreement on a new stratotype for the PPB, at the base of marine claystones overlying sapropel bed e at Vrica, southern Italy (Aguirre and Pasini, 1985). This placed the definition of the international boundary in firm, physical context, at a stratigraphic level a little below the top of the Olduvai magnetic subchron, with an estimated age of 1.81 Ma (Hilgen, 1991). The second ambiguity to recognition of the boundary in New Zealand was removed by the development of multiple means of correlation, including magnetostratigraphy, tephrochronology and cyclostratigraphy. This allowed Naish et al. (1996) to estimate that the PPB in New Zealand falls at the base of the highstand systems tract siltstone of Rangitikei River sequence 17 (Fig. 2), corresponding to the top of interglacial oxygen isotope stage 65 and lying within the top of the Olduvai chron.

2.4. Incorporation of the late Quaternary terrace record

A record of interglacial isotope stages 17–3 (0.68–0.04 Ma) which in part overlaps with the marine cyclothems is represented by a flight of 13 marine terraces which extend up to 20 km inland and up to 400 m above present sea-level along the Wanganui coast (Fig. 3). These terraces developed in response to smooth, regional uplift rates of 0.3–0.6 m/ky (Pillans, 1986). Terrace treads comprise a lower section of shallow marine and fluviomarine sediment of late transgressive and highstand-regressive origin, overlain by an upper section of loess-soil couplets. On any particular terrace, one such loess-soil couplet occurs for each glacial–interglacial cycle which occurred after the deposition of the interglacial marine strata at its base (Pillans, 1988; Pillans and Wright, 1990). Matching the terrace record with the oxygen isotope scale has been achieved by Pillans (1983, 1990) and Pillans et al. (1988, 1993, 1996), who used radiocarbon, amino acid racemisation and tephrochronology for dating.

Terrace sediments often include non-marine, carbonaceous facies, and tephra, which contain an excellent palynological, climatic and chronostratigraphic record. Thus the climatic history of the younger part of the succession (stage 9 and younger) has been well described in a number of papers (Bussell, 1986, 1988, 1990, 1992, 1993; Alloway et al., 1992; Bussell and Pillans, 1992; Pillans et al., 1993).


A.
Waitotara R.
Wanganui R.
Whangaehu R.
Turakina R.
Rangitikei R.
NEW PLYMOUTH
Highly dissected Pliocene marine sediments
Mt. Egmont
Quaternary andesitic volcanics
Patea R.
11
9
7
5e
5c
A
A
B
B
13-17
WANGANUI
Widespread fluvial deposits
N
0 10 20 km
B.
SECTION A-A
SECTION B-B
(m)
400
300
200
100
0
Rangitawa Pumice (345,000 ybp)
Ball
Rangitatau
Ararata
Braemore
Brunswick
Waipuna
Ngarino
Rapanui
Inaha
Hauriri
Marorau
Piri
Terrace riser (fossil cliff)
Terrace cover beds (TST and HST)
Wave-cut surface
60 cm/ky
50 cm/ky
0 5 km
C.
Brunswick
Ngarino
Rapanui
Terrace cover beds (mid-late PLEISTOCENE)
PLIOCENE
early-middle PLEISTOCENE
60 cm/ky
50 cm/ky
Oxygen isotope stage (interglacial)

3. Cyclothems and glacio-eustasy: the oxygen isotope stages

Based on his knowledge of the cyclic variations which occurred in the sediments and fossil faunas, Fleming (1953) was already well aware that Wanganui Basin sediments accumulated under the influence of a changing sea-level. He was also the first writer to use the term ‘cyclothem’ in description of the sedimentary rhythms of the Wanganui coastal section, illustrating the cyclicity by depicting a changing relative sea-level curve as a result of the interaction of tectonic subsidence and eustasy (Fig. 4). At the time at which Fleming was writing, however, conventional wisdom dictated that the Pleistocene only contained four major glacial cycles, with the result that his demonstration that at least 16 climatic cycles had occurred lay fallow until much later. In a parallel classic paper, Emiliani (1955) showed from oxygen isotope evidence from Caribbean deepsea cores that at least 8 major climatic cycles had occurred in the last 650 000 years. The climatic implications of this contribution too remained largely unrecognized until the early 1970s.

The use of oxygen isotope data as a tool for the recognition of climatic cyclicity, and for refined correlation, stemmed from the analysis of core V28-238 from a depth >4000 m in the western Pacific by Shackleton and Opdyke (1973). These authors confirmed Emiliani’s earlier observations, and showed that the climatic cyclicity extended back to about 1 million years. They also showed that closely similar isotope signals were preserved in both the planktic and benthic foraminiferal record, thus indicating (a) that the cyclicity is primarily due to a changing ratio of ^{18}O:^{16}O between glacials and interglacials; and (b) that the oxygen isotope curve is an accurate indicator of ice-volume, and therefore represents a proxy eustatic sea-level curve.

With the confirmation of Emiliani’s work by Shackleton and Opdyke (1973), the worldwide research community finally came to accept the reality of multiple Plio–Pleistocene glaciations. In New Zealand, Fleming (1976) quickly realised that the glacio-eustatic cyclicity reflected by the oxygen isotope curve was the forcing function which had controlled the development of the Wanganui Basin cyclothems, and attempted a first, generalised correlation between the two. This insight was consolidated by Beu and Edwards (1984) and Pillans (1992) who provided more detailed and accurate correlations of the Wanganui sedimentary cycles with the international oxygen isotope scale. By the early 1990s, therefore, the Castlecliff coastal section was firmly established as an outstanding example of the interplay between eustasy, tectonics and sedimentation, and as a southern hemisphere reference section for Plio–Pleistocene stratigraphy.

Correlations of parts of the Wanganui Basin succession with modern deep sea oxygen isotope records have been made by Beu and Edwards (1984), Kamp and Turner (1990), Abbott and Carter (1994), Pillans et al. (1994), Naish et al. (1996), and Naish (1998), and a complete basin cyclostratigraphy for the last 3.6 Ma has been compiled by Carter et al. (1996, 1998) and Saul et al. (1998). The calibration of this cyclostratigraphy with the radiometric and palaeomagnetic ages discussed above allows the mid-Pliocene to Pleistocene Wanganui basin cyclothem succession to be correlated directly with the oxygen isotope timescale. This permits age estimates to be made for stratigraphic horizons and events not used in establishing the correlations, such as cyclothem boundaries or biostratigraphic stage boundaries (Fig. 2). In general, each cyclothem corresponds to an odd numbered isotope stage (interglacial), and its erosional basal sequence boundary marks a hiatus equivalent to the immediately preceding even numbered stage (glacial). With the exception of cyclothems 12 and 36 (which apparently represent double couplets, i.e. embrace four successive isotope stages), each cyclothem and its bounding surfaces correspond in this fashion to a glacial/interglacial couplet.

Fig. 3. The coastal terraces of the Wanganui region, and their correlation with the oxygen isotope stages. (A) Map of terrace distribution. (B) cross-sections *A* and *B*, showing distribution of the Rangitawa Pumice within the terrace treads. (C) Sketch of relationship between the dipping marine Plio–Pleistocene strata, and the flat lying terrace cover (after Fleming, 1953; and Pillans, 1983, 1990).

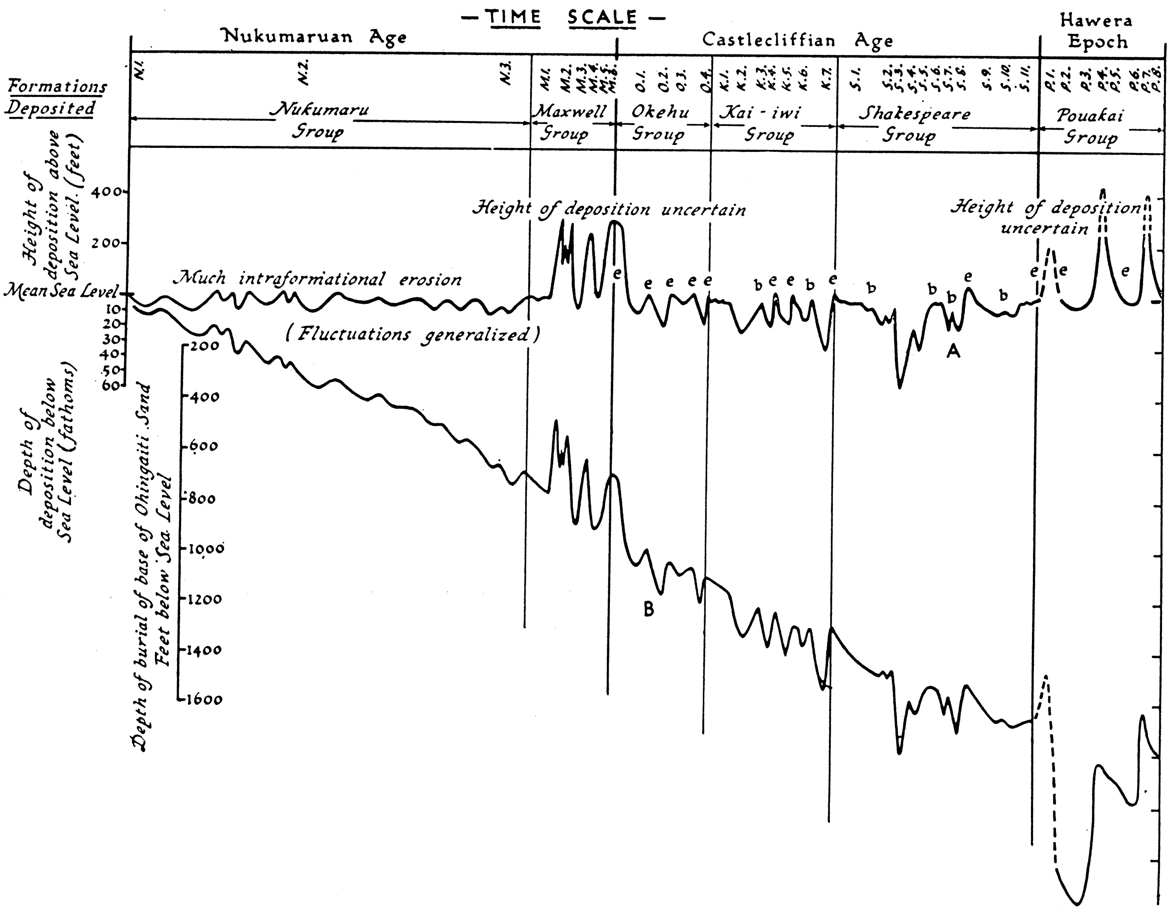


Fig. 4. Subsidence and sea-level curves inferred for Wanganui Basin by Fleming, 1953 (his fig. 62). The original caption reads, in part: "Pattern of geosynclinal sinking on west side of Wanganui Basin. Curve A is controlled by diastrophic and eustatic movements and by variation in the supply of sediment. The second curve, B, represents the erratic sinking and progressive burial of a point at the base of the Ohingaiti Sand (= near base of Nukumaru Group). Underlying beds were eroded at points marked 'e', and sediment by-passed at points marked 'a'."

4. Other modern chronostratigraphic studies

The study of Wanganui Basin stratigraphy had its genesis in the richly fossiliferous nature of the shallow marine cyclothemic sediments. However, species endemism has always precluded accurate international correlation using these faunal criteria alone. The establishment of the oceanic oxygen isotope scale in the 1970s was the first of three modern means of chronostratigraphic correlation which today allow New Zealand Plio–Pleistocene strata to be correlated accurately worldwide. The two other important methods of correlation are magnetostratigraphy and tephrochronology.

4.1. Magnetostratigraphy

The blue-grey (mostly highstand) siltstones which occur cyclically throughout the Wanganui succession yield excellent palaeomagnetic signatures. Early studies of the Rangitikei section (Seward et al., 1986) have been supplemented by more recent work across the basin (Turner and Kamp, 1990; Pillans et al., 1994; Naish et al., 1996). Key paleomagnetic tie-points which have been identified, and are used for calibrating the section to the isotope record, include the Gauss/Matuyama boundary (2.58 Ma), the Olduvai Subchron (1.94–1.76 Ma), the Cobb Mountain Subchron (1.19 Ma), the Jaramillo Subchron

(1.07–0.99 Ma), and the Matuyama/Brunhes boundary (0.78 Ma).

4.2. Tephrochronology

Wanganui Basin is situated in a back-arc location, and nearby to the andesitic volcanoes of central North Island (Fig. 1). Subduction along the Hikurangi margin during the Plio–Pleistocene resulted in the episodic eruption of voluminous silicic ashes, many of which have been recognized within the Wanganui Basin succession. Most ashes possess a characteristic geochemical signature which allows them to be fingerprinted for correlation purposes (Froggatt, 1983; Froggatt and Lowe, 1990; Shane and Froggatt, 1991). Fission track, isothermal fission track and argon–argon dates are available for many ashes (Seward, 1974, 1976, 1979; Boellstorff and Te Punga, 1977; Kyle and Seward, 1984; Kohn et al., 1992; Alloway et al., 1993; Pillans et al., 1994; Shane, 1990, 1991, 1994; Shane et al., 1995, 1996a,b; Naish et al., 1996), and these numeric age estimates contribute greatly towards the chronologic framework which now exists for Wanganui Basin sediments (Naish et al., 1996, 1998).

5. The sequence stratigraphic model

The sequence stratigraphic model predicts the response of sedimentation to sea-level change (e.g. Payton, 1977; Vail et al., 1991), and has become a dominant paradigm for the interpretation of cyclical sedimentary successions. Though initially developed by the EXXON oil company, and applied at the exploration seismic scale with a resolution of tens of meters, from the mid-1980s sequence stratigraphy has been increasingly applied to higher resolution outcrop studies. The concept of cyclically recurring sedimentary motifs is of course not new, and stems from the classic work of Weller (1930, 1958) and Wanless and Weller (1932) on unconformity-bound sedimentary cycles within the Permo–Carboniferous of North America. Following their observations, Elias (1937) inferred that the cyclical modulation of facies/environments in Pennsylvanian cyclothems was caused by a fluctuating base level. In remarkable anticipation of the modern stratigraphic concepts, Fleming (1953) and Vella (1963) in New Zealand, and Ueda (1973) and others in Japan, recognised that unconformity-bound Pleistocene cyclothems also represent alternating periods of sedimentation during advancing seas and erosion during low sea-levels. Early correlations between Pleistocene onland, unconformity-bound, shallow water sedimentary cycles and the oceanic isotope proxy sea-level curve were made by Kamp (1978) in New Zealand, Clifton et al. (1988) in California, and Tokuhashi and Kondo (1989) in Japan.

Surprisingly, however, it was not until the late 1980s that the sequence stratigraphic model began to be tested against New Zealand Plio–Pleistocene successions (Abbott et al., 1989; Carter et al., 1991; Abbott and Carter, 1994; Naish and Kamp, 1997b). Abbott and Carter (1994, 1998) described ten superposed cyclothems from the coastal Castlecliff section of Wanganui Basin, and correlated them with interglacial parts of oxygen isotope stages 31–11 (0.95–0.35 Ma). The dominant style of sedimentary cycle recognised by Abbott and Carter (1994) (Castlecliff motif of Saul et al., 1998) comprises a lower interval of shallow marine sands and transported shellbeds (transgressive systems tract), an in-situ or near-situ mid-cycle condensed unit (shellbed), and an upper interval of shelf siltstone (highstand systems tract). Subsequently, Naish and Kamp (1995, 1997a) described twenty superposed cyclothems from the late Pliocene–early Pleistocene succession which occurs in Rangitikei River. The motif these authors describe (Rangitikei motif of Saul et al., 1998) comprises a lower fossiliferous unit (combined transgressive systems tract/mid-cycle condensed unit), followed by a middle aggradational interval of siltstone (highstand systems tract) which grades up into a progradational shoreline facies assemblage (regressive systems tract). Most recently, Carter et al. (1997) and Saul et al. (1998) have summarised the complete fill of the Wanganui Basin, recognizing seven major sedimentary motifs (Fig. 5) which occur as variations of the 47 vertically stacked cyclothems.

Depending upon the particular cyclothem motif, some combination of the following sedimentary elements occurs in ascending stratigraphic order within each Wanganui Basin marine cyclothem (Fig. 6). The listed systems tracts and surfaces are all observable

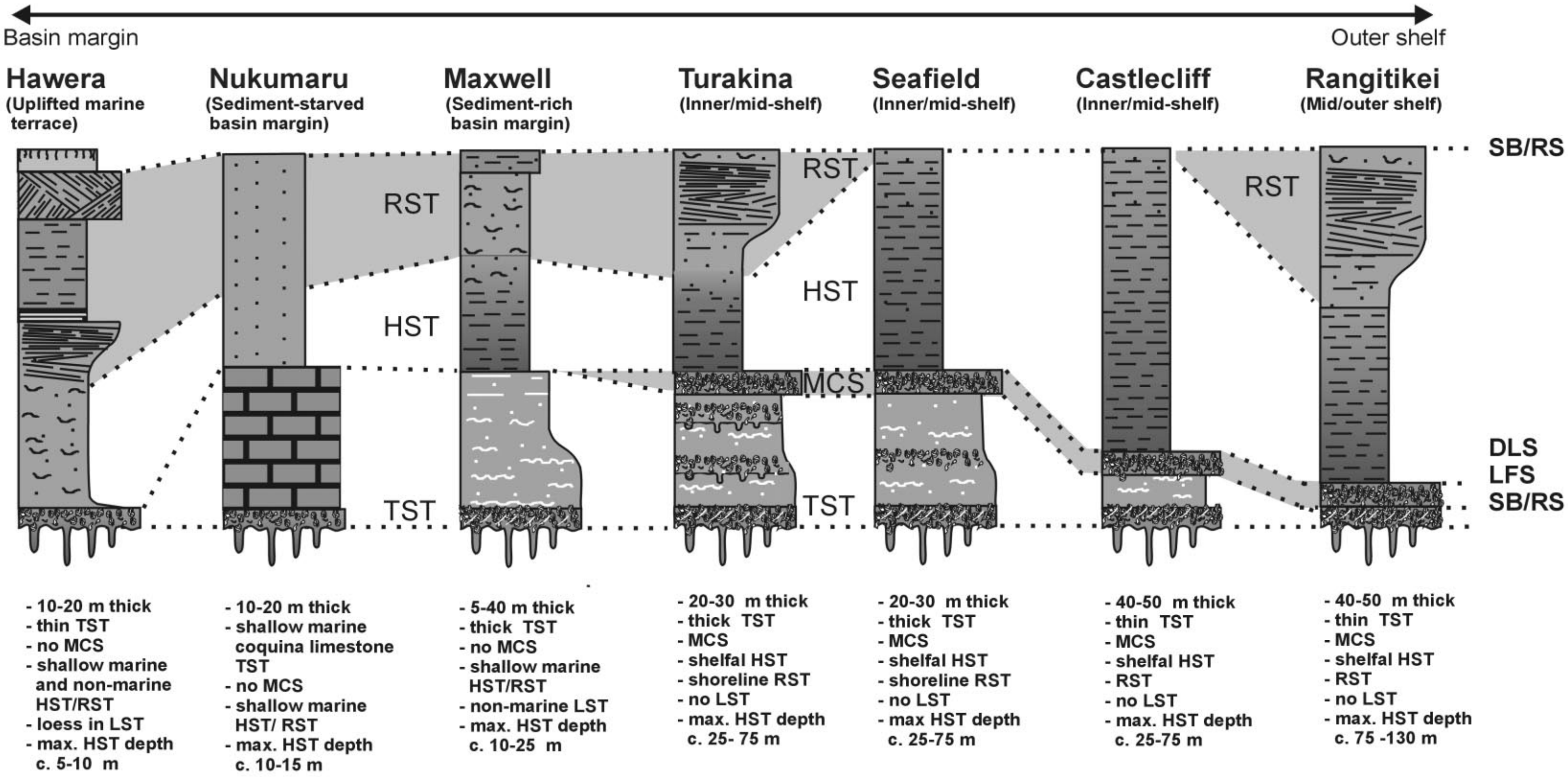


Fig. 5. The seven major cyclothem (sequence) motifs recognised within Wanganui Basin (after Saul et al., 1998).

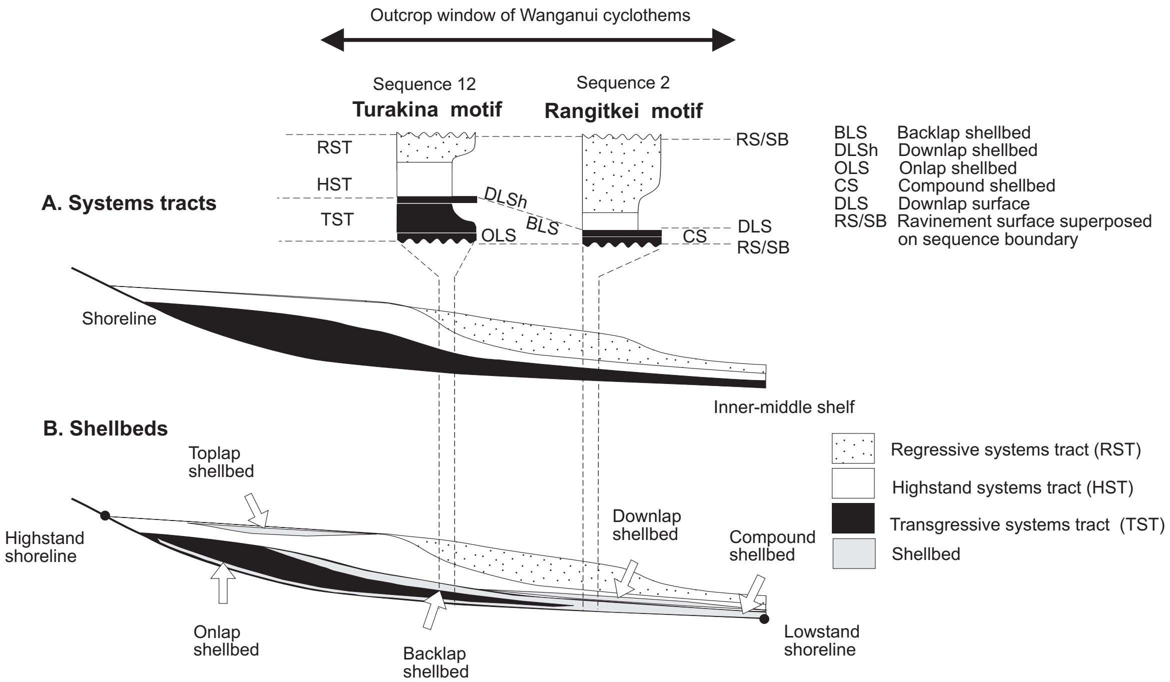


Fig. 6. Reconstructed architecture of a Wanganui Basin sequence at the eastern (highstand) margin of the basin, showing the inferred palaeo-shelf locations of two types of cyclothem (sequence) motif.

in the field, although individual elements may of course be truncated, or superposed one upon another, along one of the key surfaces.

(1) A basal sequence boundary corresponding to an unconformity, on which is superposed the ravinement surface (RS) cut by the transgressing post-glacial shoreline; rarely, and only near the basin margins, a soil may be preserved at the sequence boundary (Abbott, 1992).

(2) Either, (a) a transgressive systems tract which comprises a shallow water reworked shellbed (Castlecliff motif), sometimes overlain by shoreline-inner shelf sandstone or heterolithic sediment (Seafield motif), or (b) a thin transgressive systems tract (<2 m), corresponding mainly to a transgressive shell lag which passes up insensibly to a condensed (mid-cycle) shellbed (Rangitikei motif).

(3) A local flooding surface (LFS), across which rapid deepening occurs, usually located at the base of a mid-cycle condensed shellbed (MCS) up to 2 m thick, and containing an offshore shelf fauna (Abbott, 1997b).

(4) A downlap surface (DLS).

(5) A highstand systems tract (10–20 m) comprising an aggradational interval of shelf siltstone.

(6) For the Turakina and Rangitikei motifs, a regressive systems tract (10–60 m) which commences with a gradational inner shelf to shoreface facies transition, and passes up into strongly progradational shoreline facies.

Wanganui Basin cyclothems generally possess boundaries with identifiable signs of subaerial exposure during glacial lowstands (soil, lignite, loess, karsting), and/or signs of marine ravinement produced during post-glacial shoreline transgressions (sharp eroded surface, transgressive shell lag, pholad borings, *Ophiomorpha* burrows). It is inferred thereby that such cyclothems were deposited on the shelf, landwards of the glacial lowstand shoreline. Four Rangitikei motif sequences in the Rangitikei River section (cyclothems 5, 6, 13 and 14 of Naish and Kamp, 1997a) do not exhibit clear evidence of subaerial or transgressive shoreface erosion at their bounding surfaces. The relative lowstand part of such cycles may represent deposition just seaward of the lowstand glacial shoreline (i.e. encompass some

lowstand systems tract), as for similar cyclothems described by Haywick et al. (1991, 1992, 1998) in the eastern North Island New Zealand forearc basin.

Interpretation of the depositional paleoenvironments for each Wanganui cyclothem motif is based upon detailed sedimentary facies and faunal analysis (Abbott and Carter, 1994; Naish and Kamp, 1995, 1997a,b; Abbott, 1997a,b, 1998; Abbott and Carter, 1997; Journeaux et al., 1996, 1998; Kamp and McIntyre, 1998; Kamp et al., 1998; Kondo et al., 1998). Distinctive shellbeds and their associated stratal discontinuities delineate the stratigraphic geometry of the sequences, and allow systems tracts to be differentiated. Paleobathymetric analysis of the cyclothems, based on foraminifera and mollusca, confirms that cyclical changes in water depth occurred with an amplitude of ca. 50–100 m (Journeaux et al., 1996; Abbott, 1997a; Abbott and Carter, 1997; Naish and Kamp, 1997b). The inferred water depth changes are consistent with a glacio-eustatic origin for the cyclothems. Within the chronologic framework discussed above, this confirms that cyclothem frequency corresponds with that of Milankovitch orbital rhythms, and allows the precise correlation of cyclothems and oceanic oxygen isotope stratigraphy (cf. Fig. 2).

6. Conclusions

A combination of cyclostratigraphic, biostratigraphic, magnetostratigraphic and tephrochronologic data has allowed an integrated chronologic and sequence stratigraphic framework to be established for the Wanganui Basin (Naish et al., 1996, 1997a,b, 1998), and for the local New Zealand Plio–Pleistocene stages to be redefined (Carter and Naish, 1998). The chronostratigraphy enables individual cyclothems to be correlated with astronomically-tuned, high resolution, Plio–Pleistocene δ^{18}O records [e.g. Atlantic, ODP Site 659, Tiedemann et al. (1994); Pacific Ocean, ODP Site 677, Shackleton et al. (1990); and ODP Site 846, Shackleton et al. (1995a)], using the astrochronologic time scale of Lourens et al. (1996). Such correlation allows the frequency of the sedimentary cyclicity to be determined, and age estimates to be made for stratigraphic horizons and events at Milankovitch and sub-Milankovitch resolution. It is thereby apparent that the 47 sedimentary cycles which comprise the Wanganui Basin record accumulated mainly during the interglacial parts of isotope stages 100–5, and that in all but two cases each cyclothem and its bounding surfaces correspond to individual 41 or 100 ka glacial/interglacial stage couplets (Fig. 2).

The availability of a high-resolution chronostratigraphic template for Wanganui Basin also greatly aids the practice of sequence stratigraphy, by (a) allowing the correlation of individual sequences between sections; and (b) allowing the timing of facies deposition and systems tract formation to be evaluated with respect to precise phases of glacio-eustatic sea-level change. The seven cyclothem (sequence) motifs recognised from Wanganui Basin correspond well with this understanding, and with the sequence stratigraphic model.

Wanganui Basin has become one of the best understood young sedimentary basins in the world because gentle uplift has raised its eastern edge above sea-level, where it can be directly inspected, and because the location of the basin near a volcanic arc results in good tephrochronologic age control. The application of current and new stratigraphic methodologies to the sediments of the Wanganui Basin will undoubtedly contribute further to our understanding of late Cenozoic climatic change, cyclostratigraphy and sequence stratigraphy, as exemplified by several of the papers in this Special Issue.

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