Journal of the Royal Society of New Zealand

ISSN: 0303-6758 (Print) 1175-8899 (Online) Journal homepage: http://www.tandfonline.com/loi/tnzr20

Sequence stratigraphy of the Nukumaruan Stratotype (Pliocene-Pleistocene, c. 2.08–1.63 Ma), Wanganui Basin, New Zealand

S. T. Abbott , T. R. Naish , R. M. Carter & B. J. Pillans

Journal of the Royal Society of New Zealand
Volume 35, Numbers 1 & 2, March/June, 2005, pp 123–150

Sequence stratigraphy of the Nukumaruan Stratotype (Pliocene-Pleistocene, c. 2.08–1.63 Ma), Wanganui Basin, New Zealand

S. T. Abbott[1]*, T. R. Naish[2], R. M. Carter[3], and B. J. Pillans[4]

Abstract Late Pliocene to Early Pleistocene (c. 2.08—1.63 Ma) strata exposed in coastal cliffs along Nukumaru and Ototoka beaches near Wanganui, between the top of the Nukumaru Limestone and the base of the Butlers Shell Conglomerate, comprise 11 depositional sequences of a total thickness of c. 86 m. The sequences consist predominantly of silicilclastic shoreline facies. Non-marine facies (including palaeosols), and a variety of shallow-marine shellbed facies, are also represented. Patterns in facies composition and sequence architecture reveal three sequence motifs (*Maxwell*, *Nukumaru*, and *Birdgrove*) that represent progressively increasing maximum palaeowater depths within a broadly basin-margin palaeogeographic setting. The sequence motif changes systematically up section and records a lower order tectonic influence on accommodation that has modulated the stacking patterns of individual sequences. Correlation of the sequences with oxygen isotope stages 77–57 is achieved using the basin-wide Ototoka tephra, and indicates that the sequences accumulated in response to obliquity driven (41 k.y. duration) glacio-eustatic sea-level oscillations. Correlation of the Nukumaru coast sequences with other sections along basin strike, and the global oxygen isotope record indicates that (i) 500 k.y. ($\delta^{18}O$ stages MIS 56–34) is missing at the unconformity between the Nukumaruan and overlying Castlecliffian stratotypes on the Wanganui coast, and (ii) the Pliocene-Pleistocene boundary lies within sequence NC7 at the base of the Lower Maxwell Formation.

Keywords cyclothem; sequence; motif; systems tract; tephra; cyclostratigraphy; obliquity; glacio-eustasy; sea level; Pliocene; Pleistocene; Nukumaruan; Wanganui Basin; New Zealand

INTRODUCTION

Fleming (1947, 1953, p. 303) recognised that as many as 40 oscillations of "Pleistocene" sea level were recorded in the shallow-marine strata of the Wanganui Basin, North Island, New Zealand (Fig. 1), and attributed the cyclicity to "spasmodic diastrophic movements". Later, at about the same time as the orbital theory of glacio-eustasy was becoming widely accepted (Shackleton & Opdyke 1973; Hays et al. 1976), Fleming (1975) suggested that a glacio-eustatic origin should be considered for the Wanganui cycles.

[1]School of Earth Sciences, University of Tasmania, Private Bag 79, Hobart, TAS 7001, Australia.
[2]Institute of Geological and Nuclear Sciences, P.O. Box 30 368, Lower Hutt, New Zealand.
[3]Marine Geophysical Laboratory, James Cook University, Townsville, QLD 4811, Australia.
[4]Research School of Earth Sciences, Australian National University, Canberra, ACT 2000, Australia.
*Present address: School of Environmental Science and Management, Southern Cross University, P.O. Box 157, East Lismore, NSW 2480, Australia. Email: sabbott@scu.edu.au.

R04015 Received 23 August 2004; accepted 13 May 2005; Online publication date 27 July 2005

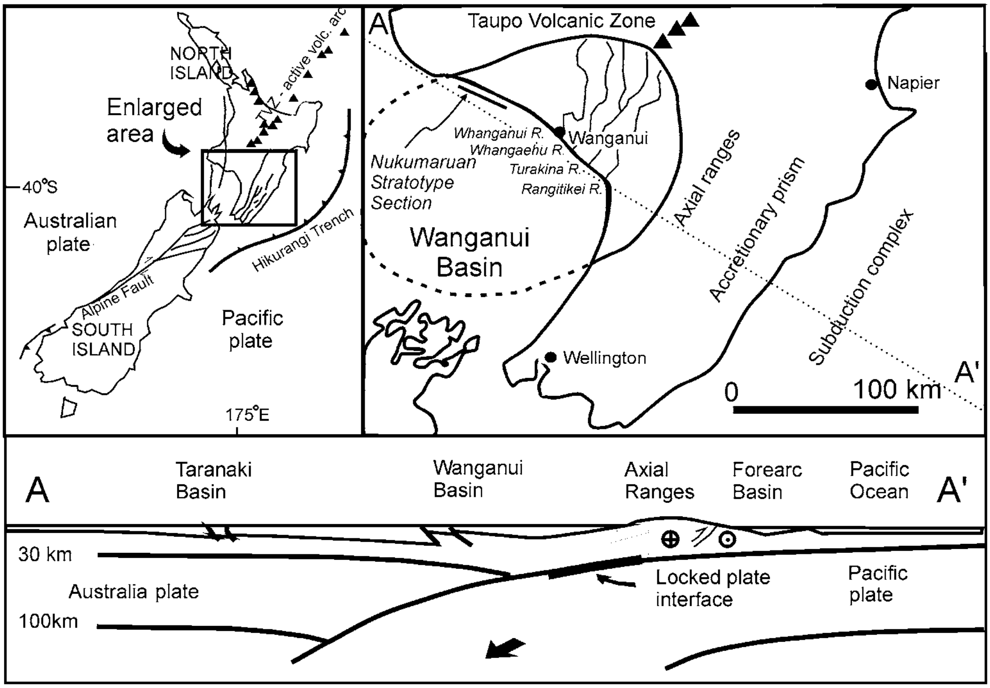


Fig. 1 Plate tectonic setting of the Wanganui Basin in western North Island, showing the location of the Nukumaruan stratotype section.

In a study of the Castlecliffian and younger strata at Cape Kidnappers, Kamp (1978) made the first correlation between the oxygen isotope scale and a New Zealand cyclic sedimentary succession. Subsequent studies established correlations between the oxygen isotope curve and Nukumaruan and Castlecliffian cyclothems in Hawke's Bay, Wairarapa, and Wanganui basins (Beu & Edwards 1984), and a flight of uplifted marine terraces from the Wanganui hinterland that overlap in age with the Wanganui Basin cycles (Pillans 1983, 1990).

Abbott & Carter (1994) and Naish & Kamp (1997) undertook detailed stratigraphic and sedimentological studies of Wanganui Basin cycles exposed in the Castlecliffian stratotype near Wanganui and the Rangitikei Valley, respectively, and described their development in terms of the evolving concepts of sequence stratigraphy. Based on this work, Naish et al. (1998) and Saul et al. (1999) synthesised a Wanganui Basin cyclostratigraphy for the past 3.6 Ma. Carter & Naish (1998) and Carter et al. (1999) have underscored the global significance of the Wanganui Basin as a late Neogene cyclostratigraphic reference section.

In this paper we detail the sequence stratigraphy of the upper part of the Nukumaruan Stage (c. 2.08–1.63 Ma) stratotype exposed in coastal cliffs north-west of Wanganui city (Fig. 1). We apply sedimentary facies analysis within a sequence stratigraphic context following the approach of Abbott & Carter (1994), Naish & Kamp (1997), and McIntyre & Kamp (1998). The sedimentary facies represent coastal plain, shoreface, and shallow shelf environments. The succession of facies has been resolved into 11 depositional sequences (*sensu* Vail et al. 1991).

The cyclostratigraphy presented here underpins part of the basin-wide synthesis of glacio-eustatic sea-level changes in Wanganui Basin since 3.6 Ma (e.g., Naish et al. 1998). This cyclostratigraphic framework permits identification of the Pliocene-Pleistocene boundary

(1.81 Ma, $\delta^{18}O$ Stage 65, sapropel "e" at the Vrica type section; Aguirre & Pasini 1985) in the Nukumaruan stratotoype.

Geological setting

Wanganui Basin is a 200 × 200 km, ovoid sedimentary basin in western North Island, New Zealand, situated in a behind-arc position with respect to the modern Pacific-Australia plate boundary (Fig. 1). Although Pliocene-Pleistocene subsidence and sedimentation have been concentrated in Wanganui Basin, Pliocene-Pleistocene sediments extend across the modern continental shelf west of the North Island. Wanganui Basin subsidence is attributed by Stern & Davey (1989) to the presence of a subjacent, locked, subducting plate interface, combined with foreland basin thrust loading.

Sedimentation kept pace with subsidence throughout much of the basin history, resulting in a 5 km thick succession of predominantly shelf and marginal marine sediment. The eastern margin of the basin has undergone gentle upwarping along the plate boundary, resulting in excellent onland exposures. Fifty-eight Pliocene-Pleistocene sequences, representing oxygen isotope stages 5 through to MG 6 (Abbott & Carter 1994; Journeaux et al. 1996; Naish & Kamp 1997; Naish et al. 1998; Saul et al. 1999) have been recognised. An overlapping and partly younger record of interglacial isotope stages 17–3 (0.68–0.04 Ma) is represented by a flight of 13 marine terraces that extend up to 20 km inland and up to 400 m above present sea level along the Wanganui coast (Pillans 1983, 1990).

The Nukumaruan stratotype

The fossiliferous sands at Nukumaru beach (= Rotella beds of Park 1887) were shown to contain similar faunas to those of the Matapiro and Petane beds in Hawke's Bay by Marshall (1919), who proposed that the North Island-wide biostratigraphic term "Nukumaru Series" be applied to these strata. The correlation between Nukumaru beach and Hawke's Bay strata was confirmed by Marwick (1924), who renamed the unit "Nukumaruan Stage". While the stage was originally based on the Nukumaru Brown Sand, a formation of the Nukumaru Group, sediments occurring within the stratigraphic interval from the base of the Hautawa Shellbed to the base of the Butlers Shell Conglomerate (upper Okiwa, Nukumaru, and Maxwell Groups) were classed as Nukumaruan by Fleming (1953).

The incoming of the subantarctic bivalve *Zygochlamys delicatula* at the level of Hautawa Shellbed in Wanganui Basin, and other basins of southern and eastern North Island (Fleming 1944; Beu et al. 1977; Orpin et al. 1998), represents the earliest macrofaunal evidence of climatic cooling in New Zealand Pliocene-Pleistocene marine sequences. Accordingly, for many years the Pliocene-Pleistocene boundary in New Zealand was placed at the base of the Nukumaruan Stage.

Beu et al. (1987) estimated an age of 2.4 Ma for the base of the Nukumaruan Stage in Wanganui Basin, which was considered coeval with the first major Northern Hemisphere cooling reported by Shackleton (1985). Naish et al. (1996) correlated Nukumaruan strata in the Rangitikei River valley with the astronomically-tuned oxygen isotope timescale. These authors demonstrated that the base of the Hautawa Shellbed was best correlated with the top of $\delta^{18}O$ Stage 98 (2.46 Ma). This position was three sequences above the location of the Gauss/Matuyama polarity transition ($\delta^{18}O$ Stage 104, 2.58 Ma), and one sequence above the $\delta^{18}O$ Stage 100 unconformity (2.50 Ma) considered to mark one of the first major Northern Hemisphere ice ages. Naish et al. (1998) observed that further work may reveal cold water taxa from $\delta^{18}O$ Stage 100 in New Zealand, but also commented that the occurrence of such taxa may have been precluded by regional environmental factors such as palaeoceanography or sedimentation rate.

Establishment of the top of the Nukumaruan Stage has been more problematic. It is currently placed at the base of the Butlers Shell Conglomerate which rests on an unconformity representing a time break of c. 500 ka ($\delta^{18}O$ Stages MIS 56–34; Naish et al. 2005 this issue). This raises the question as to whether sequences that were deposited during $\delta^{18}O$ Stages 56–34 (basin cyclothems 22–30) that occur in the Turakina River and Rangitikei River sections (e.g., Naish et al. 1998; Saul et al. 1999) and drillcore (Naish et al. 2005 this issue) should be included in the Nukumaruan or Castlecliffian Stages.

The incomplete succession across the Nukumaruan/Castlecliffian Stage boundary was commented on by Pillans (1991), who recommended repositioning the boundary near the top of the Upper Maxwell Formation, an interval of marginal marine to non-marine facies that contains numerous rhyolitic tephras that could be used in any formal redefinition. New biostratigraphic (Beu 2001) and tephrostratigraphic (Alloway et al. 2004; Pillans et al. 2005 this issue) data indicate that one of the tephras in this interval, the Ototoka tephra, is a basin-wide marker separating the last appearance of Nukumaruan taxa from the first appearance of Castlecliffian taxa. Cooper (2004) designates the base of the Ototoka tephra at Ototoka Beach as the new section stratotype and point for the base of the Castlecliffian Stage. However, Carter (in press) rejects the recommendation to lower the base-Castlecliffian boundary, and follows Carter & Naish (1998) in equating it with the base of the Jaramillo subchron (1.07 Ma), close to its historic position at the base of the Butlers Shell Conglomerate.

The Ototoka tephra (Alloway et al. 2004; Pillans et al. 2005 this issue) is the only basin-wide rhyolitic tephra that has been identified in the Nukumaru stratotype. It occurs as a reworked vitric ash in sandy shoreline facies of sequence NC11 (= basin sequence 21) just below the unconformity at the base of the Butlers Shell Conglomerate. This tephra provides a key tie-point for correlation of the Nukumaruan coastal sequences into the composite cyclostratigraphy which has been erected for Wanganui Basin based largely on the Castlecliff, Rangitikei, and Turakina sections (Naish et al. 1998; Saul et al. 1999). The older Vinegar Hill, Waipuru, and Ohinagiti Tephras, that occur respectively within sequences 19, 16, and 9 in the Rangitikei section further east (Naish et al. 1996) have not been recognised at the coast. Rangitikei sequences 23, 25, 26, and 30, which enclose the Mangahou Ash, Pakihikura Pumice, Mangapipi Ash, and Rewa Pumice, respectively, are not present at the coast section because they occur within the 500 ka time gap represented by the unconformity at the base of the Butlers Shell Conglomerate.

Study section

The Nukumaruan stratigraphy described herein is exposed in coastal cliffs to the north-west of Wanganui city. Access to the section is via the walking track from the cliff-top car park at Ototoka Stream (Fig. 2A). The Nukumaruan strata are exposed in the lower part of the cliffs, and dip gently towards the SSE (Fig. 2B). The upper part of the cliffs comprise flat-lying late Pleistocene terrace cover (MIS 5e Rapanui Terrace) that unconformably overlies Nukumaruan strata. The cliffs are vegetated and fresh exposure is created sporadically by mass wasting. Consequently, the amount, location, and quality of exposure vary over time. Cliffs comprising the upper Tewkesbury Formation and the Lower Maxwell Formation are set back from the beach and are always densely vegetated such that documentation of this part of the section is indicative only.

The lithostratigraphic units studied (Fig. 2B,C), referred to herein as the Nukumaru section, comprise the upper part of the Nukumaru Group (Nukumaru Brown Sand and Tewkesbury Formation) and the overlying Maxwell Group (Lower Maxwell Formation, Pukekiwi Shell Sand, Middle Maxwell Formation, Mangahou Siltstone, and Upper Maxwell Formation). We describe the Nukumaru section up to the historical base of the Castlecliffian Stage, at the

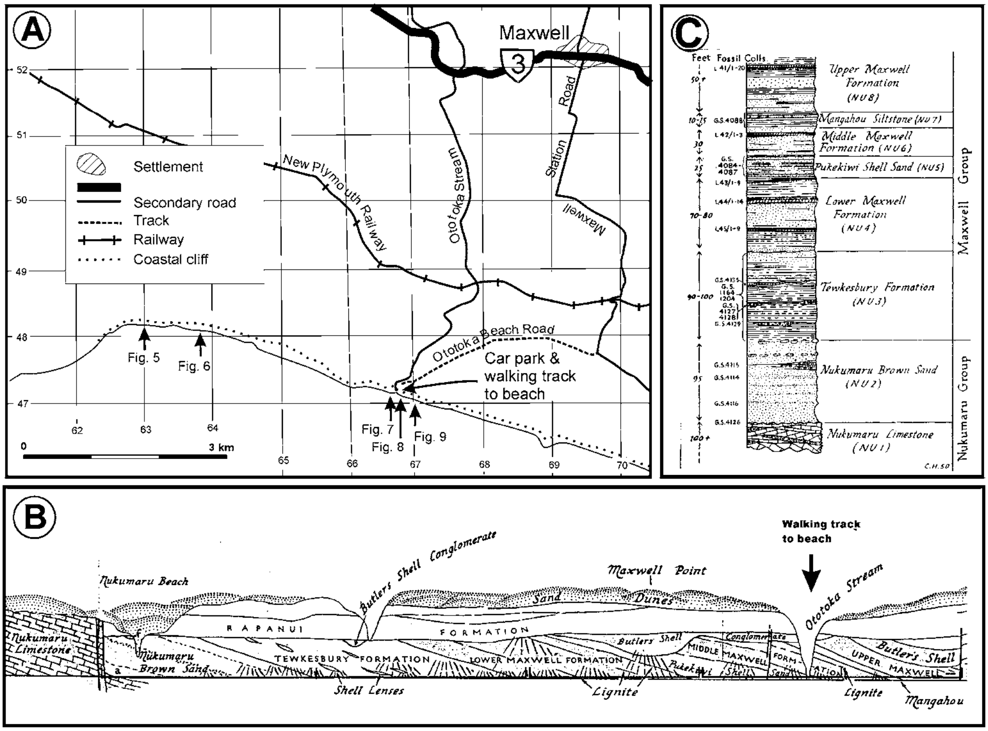


Fig. 2 **A**, Location of the Nukumaruan stratotype (after Topomap R22 Wanganui); **B**, disposition of outcrop in the coastal cliffs along Nukumaru and Ototoka beaches (adapted from Fleming 1953); **C**, formational lithostratigraphy of the Nukumaruan stratotype section (after Fleming 1953).

base of the Butlers Shell Conglomerate, to provide continuity with the sequence stratigraphic subdivision of the Castlecliffian stratotype by Abbott & Carter (1994, 1999).

Figure 3 is a composite measured section along the coast from the top of the Nukumaru Limestone to the basal Castlecliffian unconformity. This succession is c. 86 m thick, and comprises 11 depositional sequences (*sensu* Vail et al. 1991). Older Nukumaruan strata represented by undifferentiated formations of the Okiwa Group, together with the Hautawa Shellbed, Kuranui Limestone, Tuha Sand, and Ohingaiti Sand, do not crop out at the coast, and are not included in the present study. The Nukumaru Limestone outcrops on the coast but was not included in this study because sequences are cryptic and further work is required to resolve them.

The Butlers Shell Conglomerate rests unconformably on the upper Maxwell Group at an angle of c. 1° (Fleming 1953). The unconformity appears high in the cliff north of Ototoka Stream, and successively truncates the Pukekiwi Shell Sand, Middle Maxwell, Managahou, and Upper Maxwell formations before reaching beach level c. 2 km south-east of Ototoka Stream (Fig. 2B).

Wanganui Basin lithostratigraphy and cyclostratigraphy

A cyclostratigraphic synthesis of the Wanganui Basin by Naish et al. (1998) and Saul et al. (1999) revealed 58 sequences extending from the present to 3.6 Ma (OIS 1 to MG6). The Nukumaru section comprises basin sequences 12–21 (OIS 77–57). A local sequence nomenclature is based on the initials of the author or authors who documented the sequences. The sequences in the Nukumaru stratotype are designated NC1–NC11 (Fig. 3). This local sequence numbering will provide nomenclatural stability against any future renumbering of the basin-wide cyclostratigraphy. The context of the Nukumaru section within the formational lithostratigraphy and cyclostratigraphy of the Nukumaru Stage in the Wanganui Basin is shown in Fig. 4. To assist the identification of lithostratigraphic units and sequences in the field, five cliff views, annotated to show formational and sequence stratigraphy, are included (Fig. 5–9).

SEDIMENTARY FACIES ANALYSIS

Palaeoenvironmental interpretation of the Nukumaru section is based principally on standard sedimentary facies analysis. Eleven lithofacies are recognised on the basis of sedimentological and macrofossil features. The lithofacies are grouped into three associations: siliciclastic shoreline, shellbed, and non-marine. Facies characteristics are summarised (Table 1) and illustrated (Fig. 10–12). The distribution of facies in the Nukumaru section is indicated (Fig. 3).

The siliciclastic shoreline association (Fig. 10) comprises a spectrum of facies, ranging from open and protected shoreface sand and muddy sand, to innermost shelf mud. Mud rich facies in this association are characterised by their heterolithic character, that is, the interlamination or interbedding of mud and sand in various ratios to produce mud flasers, flaser bedding, and wavy bedding. Although heterolithic facies are often associated with tidal flat and other estuarine settings, the majority of heterolithic facies in the Wanganui Basin are regarded as having been deposited in a fully marine inner shelf location (see Abbott 1998 for discussion).

The shellbed association (Fig. 11) is characterised by high shell concentration relative to the enclosing facies (cf. Kidwell et al. 1986). Shellbed facies are distinguished on the basis of sedimentological characteristics (e.g., the presence of reworked versus *in situ* fossil assemblages) and taxonomic composition (especially the distinction between shoreline and shelf faunas). Shellbed facies comprise shellbeds that can be interpreted as having sequence stratigraphic significance (onlap, backlap, compound, and toplap shellbeds) as described in a later section.

The non-marine association (Fig. 12) consists of lignite, carbon-rich mudstone and sandstone, and palaeosols attributed to deposition in a mosaic of coastal plain environments.

MACROFOSSIL PALAEOECOLOGY

Uniformitarian interpretation of New Zealand Pliocene-Pleistocene macrofaunas is possible because their modern counterparts exist in modern New Zealand shoreline and continental shelf environments. Abbott & Carter (1997) identified statistical macrofossil associations from the Castlecliffian stratotype, and palaeocommunities within these associations were determined by comparison of their constituent taxa with modern New Zealand communities. In assemblages characterised by the presence of articulated valves, the palaeocommunity is clearly preserved in the environment in which it lived. In assemblages that are mixed and transported, several contributing palaeocommunities may be identified, and taphonomic attributes are then used to discriminate which of these (if any) lived in or near the enclosing facies.

The Castlecliff macrofossil associations have been widely recognised during subsequent stratigraphic studies in the Wanganui Basin, and qualitative abundance data from the Nukumaru section (Appendix 1) reveals the *Tiostrea*, *Cyclomactra*, and *Paphies* associations and their associated palaeocommunities (Table 2). The location of abundance observations, and the distribution of macrofossil associations in the Nukumaru section, are indicated in Fig. 3.

SEQUENCE STRATIGRAPHY

The Wanganui Basin fill is characterised by sedimentary cycles that generally range between a few and a few tens of metres in thickness. These cycles are regarded as high order depositional

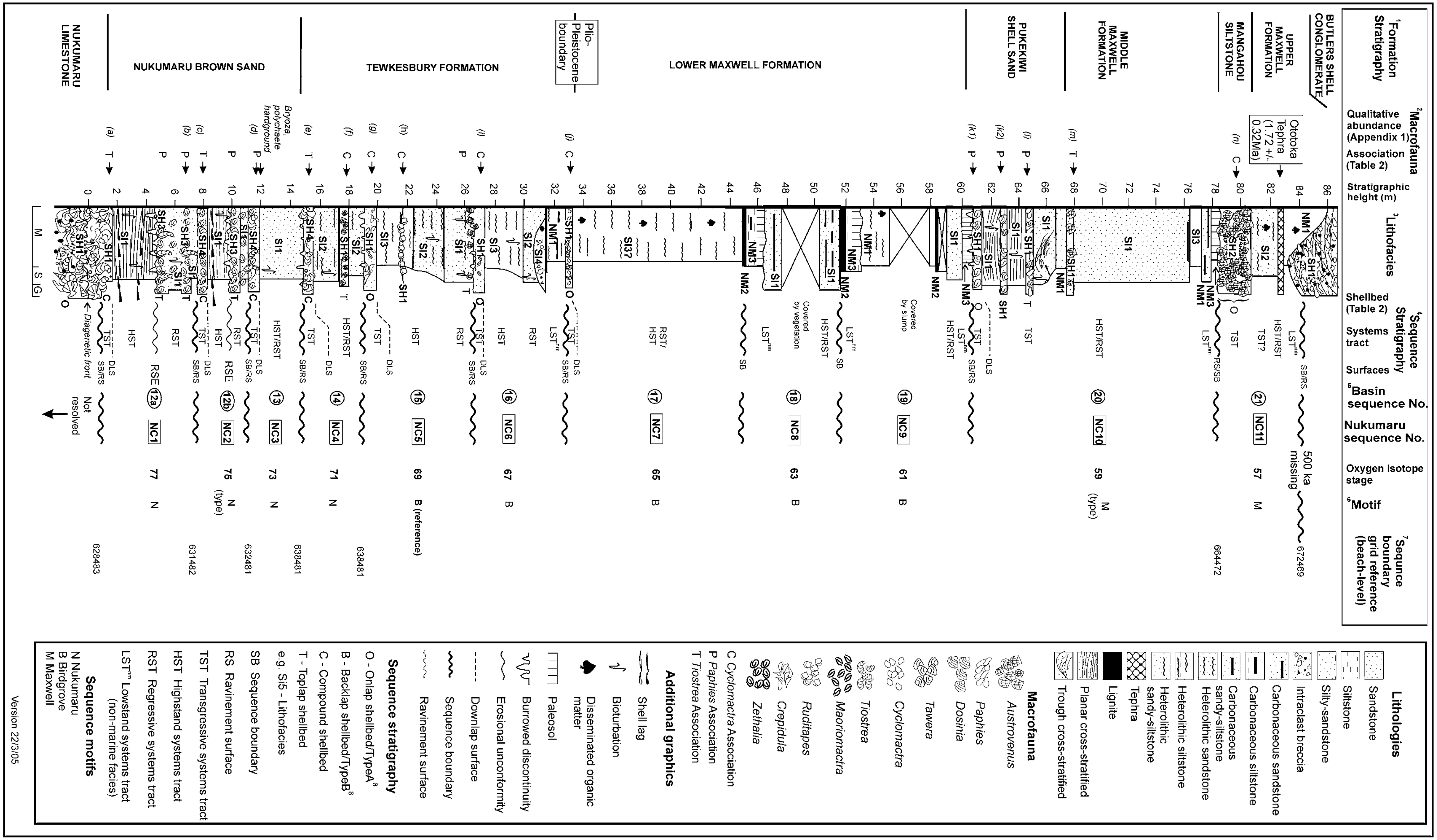


Fig. 3 Stratigraphic section of Nukumaruan (late Pliocene to early Pleistocene) strata exposed in the Nukumaru coastal section along Nukumaru and Ototoka beaches. Isothermal plateau fission track age on the Ototoka tephra is after Pillans et al. (2005 this issue). 1 = Formation lithostratigraphy modified from Fleming (1953). 2 = Macrofossil association of selected shell concentrations (Table 2 after Abbott & Carter 1997). 3 = Lithofacies as defined in Table 1. 4 = Sequence stratigraphic interpretation using terminology from Fig. 13. 5 = Basin sequence numbering scheme of Naish et al. (1998) and Saul et al. (1999). 6 = Sequence motifs from Saul et al. (1999) and this paper. 7 = Map grid references for the base of sequences that crop out at sea level. 8 = Shellbed terminology of Abbott & Carter (1994).

sequences in the terminology of Vail et al. (1991) and their origin is attributed to glacio-eustasy. A depositional sequence is defined as a package of genetically related strata, bounded by unconformities or their correlative conformities, that represents deposition during one complete cycle of relative sea-level change. High order sequences from the Wanganui Basin have also been referred to as cyclothems (Fleming 1953; Abbott & Carter 1994) following the classical terminology of Wanless & Weller (1932). The succession of sedimentary facies and unconformities in the Nukumaruan stratotype has been resolved into 11 depositional sequences (Fig. 3) that correspond to basin sequences 12–21 of Naish et al. (1998) and Saul et al. (1999).

Sequences can be divided into component systems tracts (Vail et al. 1991) that broadly correspond to segments of the controlling sea-level curve. Sequences deposited in continental shelf to basin margin settings generally comprise a transgressive, highstand, and regressive systems tracts associated with the rising, highstand, and falling segments of the sea-level curve, respectively. Such sequences are deposited dominantly during odd-numbered (interglacial) oxygen isotope stages. Sea-level lowstands (i.e., glacial stages) may be represented by non-marine facies, such as palaeosols and lignites.

Sequence-bounding surfaces recognised in Wanganui outcrops are of two types. Sequence boundaries represent subaerial exposure during sea-level lowerings, and rest on highstand or regressive systems tract sediments. Ravinement surfaces are cut by erosive shorefaces during transgression and occupy a sequence-bounding position when superimposed on sequence boundaries, as they often are.

The boundary between transgressive and highstand systems tracts are represented by downlap surfaces that form in response to higher rates of siliciclastic deposition following transgressive attenuation, and are characterised by sharp contacts of fine-grained siliciclastic sediment on shellbed facies. Some authors also refer to the boundary between transgressive and highstand systems tracts as the maximum flooding surface, the stratal surface that corresponds to the most landward extent of the palaeoshoreline (Vail et al. 1991). However, previous work in the Wanganui Basin has established that the maximum flooding surface, as determined by palaeobathymetric studies of foraminiferal faunas, does not neccessarily coincide with downlap surfaces (Haywick & Henderson 1992; Abbott 1997; Carter et al. 1998). We prefer to base our sequence analysis on surfaces that can be recognised in outcrop, and consequently follow Carter et al. (1998) in regarding the maximum flooding surface as a conceptual horizon. The boundary between highstand and regressive systems tracts may be conformable, or may be marked by a regressive surface of erosion that forms when wave-base scours underlying highstand sediments during sea-level fall.

Importance of shellbeds

Following the definition of Kidwell et al. (1986, p. 228) we regard a fossil concentration (or shellbed) as any relatively dense accumulation of biologic hardparts. Shellbed facies are of critical importance for resolving sequence architecture because shelly material is concentrated at sites within a depositional sequence where stratal surfaces converge (i.e., sequence and systems-tract bounding surfaces). Shellbeds regarded as significant in a sequence stratigraphic context are classified following the scheme applied by Naish & Kamp (1997) after Kidwell (1991, fig. 15), and elaborated upon by Kondo et al. (1998). Onlap, backlap, compound (a combination of onlap and backlap), and toplap shellbeds are recognised in the Nukumaruan stratotype, the characteristic features of which are summarised in the following.

Onlap shellbeds, or type A shellbeds of Abbott & Carter (1994), occur in transgressive settings where stratal surfaces converge against a ravinement surface or sequence boundary. Here, shell concentration results from siliciclastic sediment bypass. In the Nukumaru section,

Table 1 Sedimentary lithofacies of the Nukumaru section.

Facies code	Description	Macrofossil association	Sequence context	Environment of deposition
Siliciclastic shoreline association				
SI1	Fine to medium sand. Barren to sparsely fossiliferous (*Zethalia*, *Tawera*, *Paphies*, *Fellaster*). Vestiges of cross-bedding and ripple cross-lamination visible locally. Rare mud flasers.	*Paphies*	HST, RST	"Exposed" upper shoreface
SI2	Sand dominated heterolithic facies. Fine to medium sand with mud flasers and wavy laminae. Minor lenticular bedding. Bioturbated, sparsely fossiliferous to barren. Rare tephra.	*Paphies*	HST, RST	Lower shoreface
SI3	Mud-dominated heterolithic facies. Blue-grey, streaky laminated to lenticular-bedded mud and fine sand. Slightly to intensely burrowed and bioturbated, unfossiliferous.	Barren	HST	Innermost shelf
SI4	Intraformational mud-clast breccia. Channel fill.	Barren	RST	Intertidal
Shellbed association				
SH1	Close-packed to dispersed shells in a sand-rich matrix. Mixed, transported, and sometimes rounded assemblages (e.g., *Austrovenus*, *Maorimactra*, *Crepidula*). Mud-drapes, and cross-bedding developed locally. Some occurrences include greywacke pebbles.	*Cyclomactra*	Onlap shellbed, TST	Inner shelf
SH2	Close-packed to dispersed shells, mainly *Austrovenus*, in a matrix of mud and sand. Abundant paired valves. Bedding defined by shell concentration, including vestiges of cross-bedding. Fauna indicates a protected but not necessarily estuarine, environment.	*Cyclomactra*	Onlap shellbed, TST	"Protected" inner shelf
SH3	Abundantly fossiliferous, bioturbated fine sand; *Zethalia*, *Tawera*, *Paphies*, *Fellaster*. Shells and shell debris are dispersed, in bedding-parallel concentrations, and burrow-fill clumps. Near *situ* assemblages, paired valves present. Fauna indicates an exposed shoreface environment.	*Paphies*	Toplap shellbed, RST	"Exposed" upper shoreface
SH4	Close-packed bands, clumps and dispersed shell and shell debris in a matrix of bioturbated fine sand. *Tiostrea*, *Tawera*, *Perna*, *Lutraria*, *Purpurocardia*). *In situ* assemblages, paired valves common. Shellground substrate, rare hardground development.	*Tiostrea*	Backlap shellbed, TST	Inner shelf
Non-marine association				
NM1	Mudstone and sandstone. Purple to brown, laminated to structureless. Comminuted organic matter and intercalated lignite horizons.	Barren	LST^{nm}	Coastal lagoon
NM2	Lignite beds.	Not applicable	LST^{nm}	Coastal wetland
NM3	Palaeosol developed on NM facies or SI facies. Vertical plant roots, carbonaceous. Prismatic fractures in mud-rich occurrences. Iron staining in sands.	Not applicable	LST^{nm}	Coastal plain

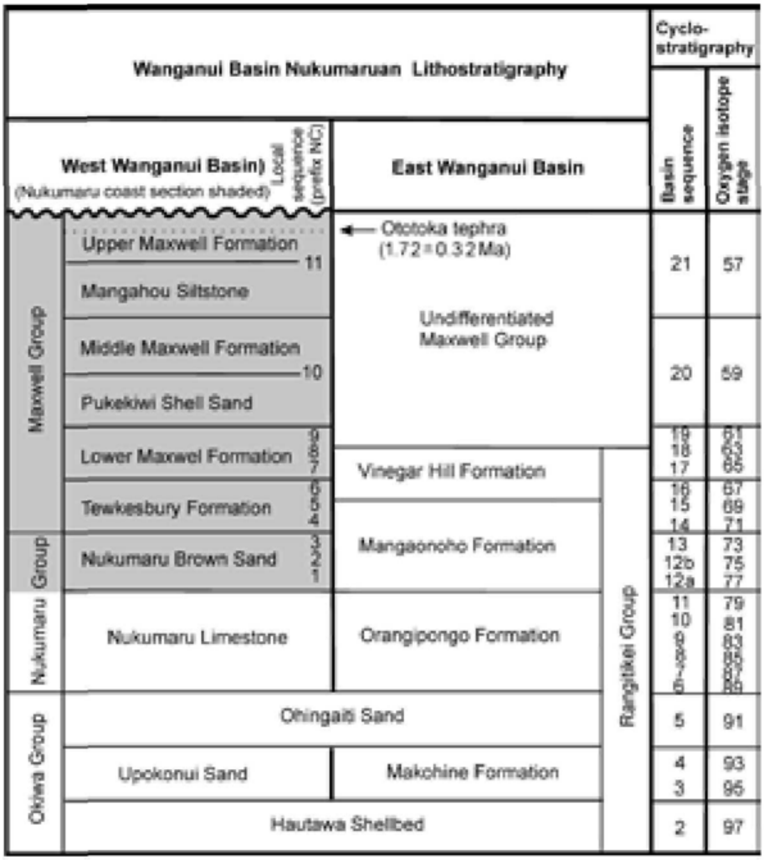


Fig. 4 Wanganui Basin Nukumaruan lithostratigraphy and cyclostratigraphy (emended from Naish et al. 1998). The base of the Ototoka tephra has recently been designated as the new section stratotype and point for the base of the Castlecliffian Stage by Cooper (2004). The Nukumaru section as discussed herein (shaded on the figure) extends to the historical top of the Nukumaruan Stage at the unconformity between the Upper Maxwell Formation and the overlying Butlers Shell Conglomerate.

such shellbeds usually comprise reworked and transported assemblages of taxa derived from open or protected sandy shorefaces, especially *Paphies*, *Austrovenus*, and *Zethalia*. Onlap shellbeds may be cross-bedded. Backlap shellbeds, or type B shellbeds of Abbott & Carter (1994), occur in the mid-cycle position where stratal surfaces converge along the seaward feather-edge (i.e., stratigraphic top) of the transgressive systems tract. Here, shelly material accumulates *in situ* in the near absence of siliciclastic sediment. In the Nukumaru section, backlap shellbeds are dominated by inner-shelf shellground taxa, especially *Tiostrea*, *Tawera*, and *Perna*. In attenuated transgressive successions, a backlap shellbed may directly overly an onlap shellbed, forming a compound shellbed *sensu* Naish & Kamp (1997). Toplap shellbeds form at the top of highstand or regressive systems tracts where stratal surfaces converge into the shoreface. As for onlap shellbeds, shelly material in this stratigraphic context is concentrated as a consequence of siliciclastic sediment bypass. In the Nukumaru section, these shellbeds are similar to onlap shellbeds, although shell assemblages may be more dispersed, such as occurs in the regressive portion of sequences NC1–4.

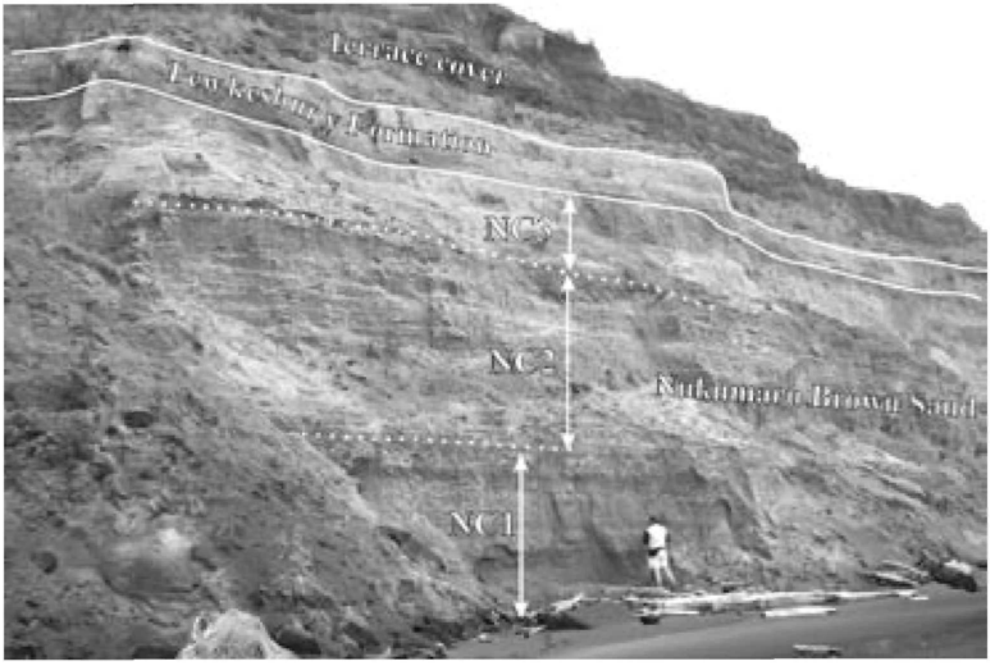


Fig. 5 Stratigraphy of the coastal cliffs at R22/630482 (see also Fig. 2A, 3). Sequence NC2 at this locality is the type Nukumaru sequence motif (Fig. 14A).

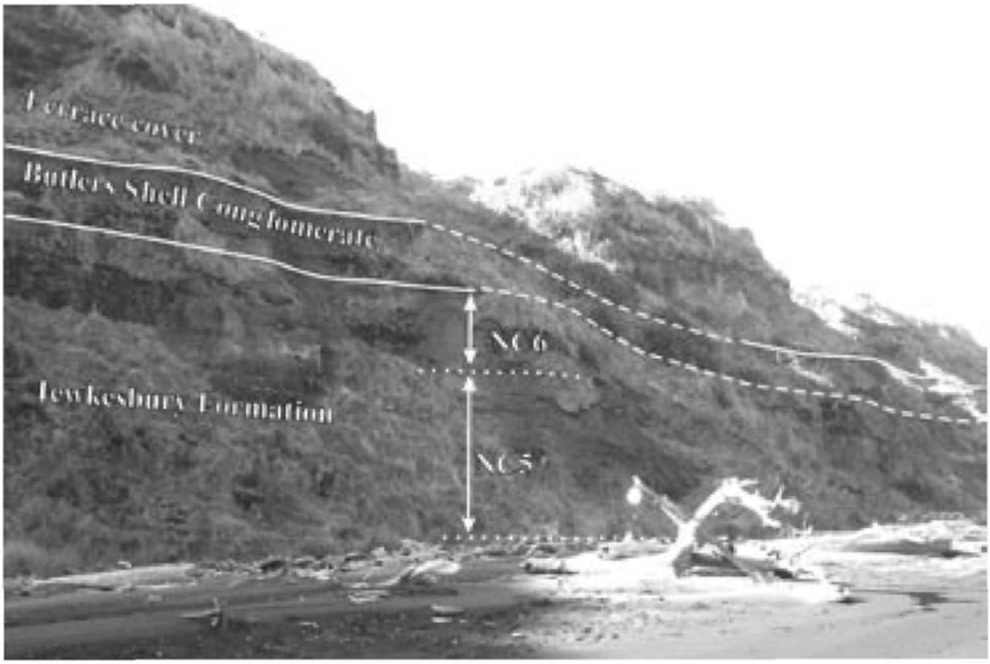


Fig. 6 Stratigraphy of the coastal cliffs at R22/638481 (see also Fig. 2A, 3). Sequence NC5 at this locality is a reference example of the Birdgrove motif (Fig. 14B).

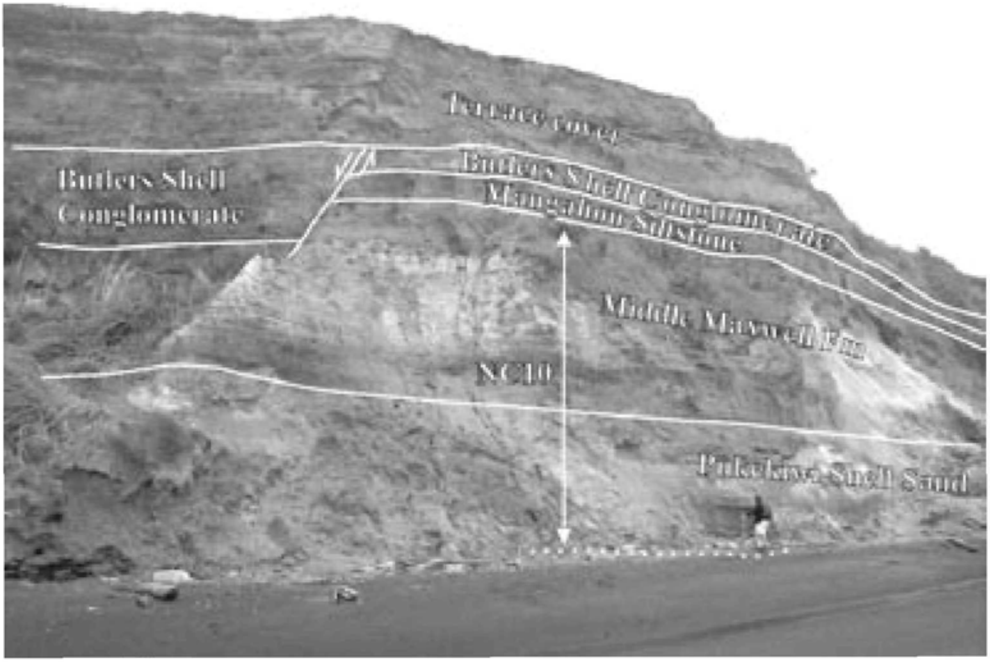


Fig. 7 Stratigraphy of the coastal cliffs at R22/667472 north-west of Ototoka Stream (see also Fig. 2A, 3). Sequence NC10 at this locality is the type Maxwell motif (Fig. 14C).

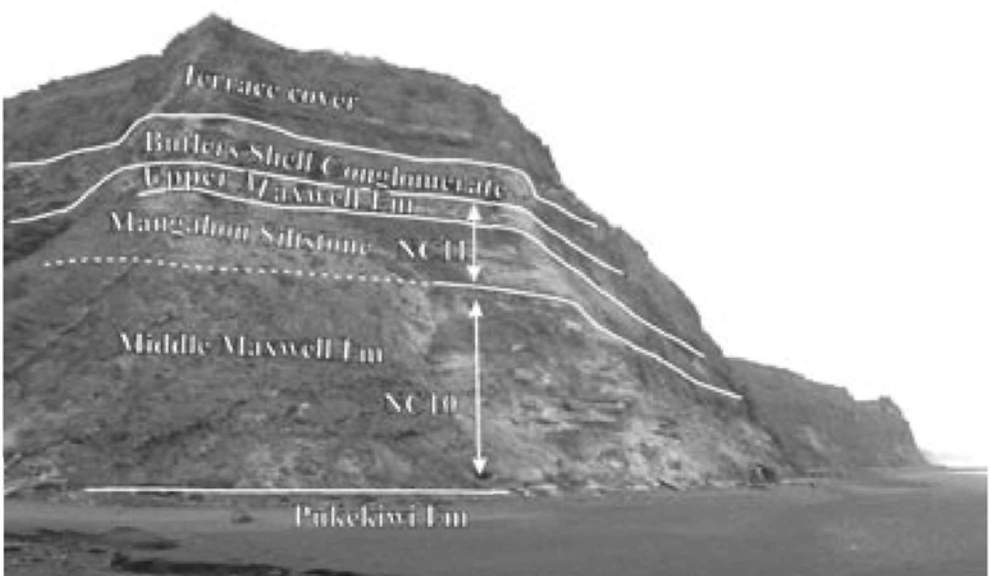


Fig. 8 Stratigraphy of the coastal cliffs at R22/668472, bluff on southern side of Ototoka Stream (see also Fig. 2A), showing sequences NC10 and NC11. The unconformity at the base of the Butler's Shell Conglomerate truncates the Upper Maxwell Formation at this locality.

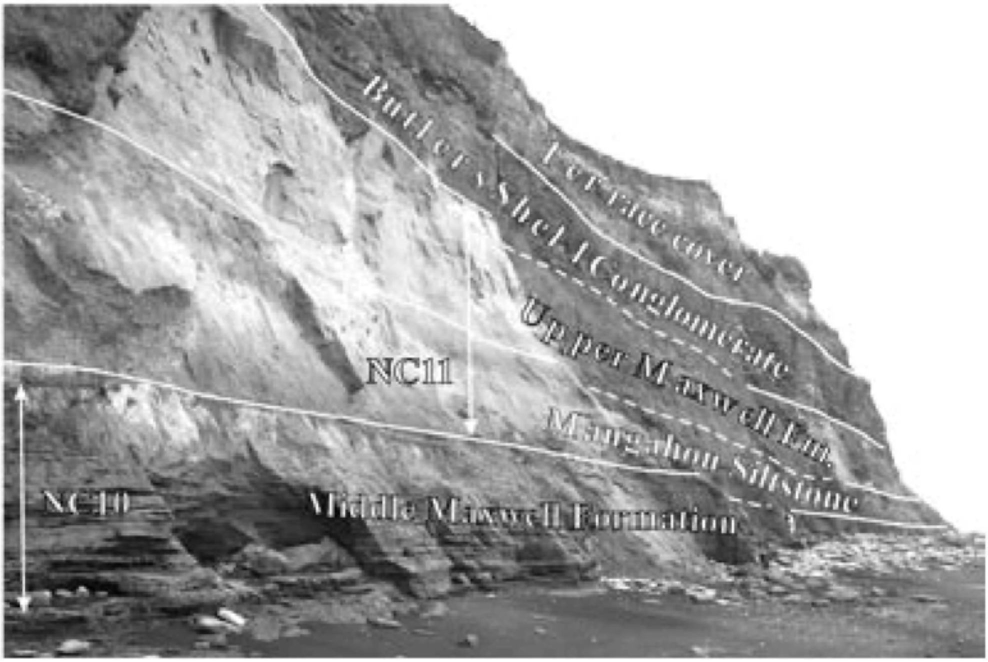


Fig. 9 Stratigraphy of the coastal cliffs at R22/670470 south-east of Ototoka Stream where the uppermost formations in the Nukukaruan stratotype approach beach level (see also Fig. 2A). The Ototoka tephra lies within the Upper Maxwell Formation.

Sequence stratigraphic architecture of the Nukumaruan stratotype

The sequence stratigraphic terminology as applied herein is summarised in Fig. 13. Sequences in the Nukumaru coast section and their component systems tracts and systems tract-bounding surfaces are indicated in Fig. 3 and described below.

Because the lowstand shoreline was situated many tens of kilometres west of the modern Wanganui coast, lowstand systems tracts are represented in the Nukumaru section exclusively by non-marine facies, especially lignites and palaeosols, formed in response to subaerial exposure. Following Saul et al. (1999), these non-marine assemblages are denoted LST^{nm} to distinguish them from the voluminous marine sediments inferred to have been deposited offshore, seaward of the contemporary lowstand shoreline (cf. Nodder 1995).

It is usually not possible to identify a single stratal surface that corresponds to sea-level lowstand, so sequence boundaries are nominally placed within LST^{nm} successions at the bases of substantial lignite beds or above palaeosols. We furthermore acknowledge that LST^{nm} deposits may include the non-marine portions of the sub- and superjacent highstand or transgressive deposits. The lower boundary of sequences NC6–NC9 have been placed following these conventions.

Ravinement surfaces represent transgressional marine erosion, and consist of a bored or burrowed disconformity. They are present in all Nukumaru sequences and occupy a sequence-bounding position in all but NC8 and NC9. When occupying a sequence-bounding position, erosion at ravinement surfaces has often removed evidence of subaerial exposure at the underlying sequence boundary (except sequences 10 and 11, where the ravinement surfaces rest on truncated palaeosols). For this reason, sequence-bounding disconformities showing these characteristics are designated SB/RS in Fig. 3.

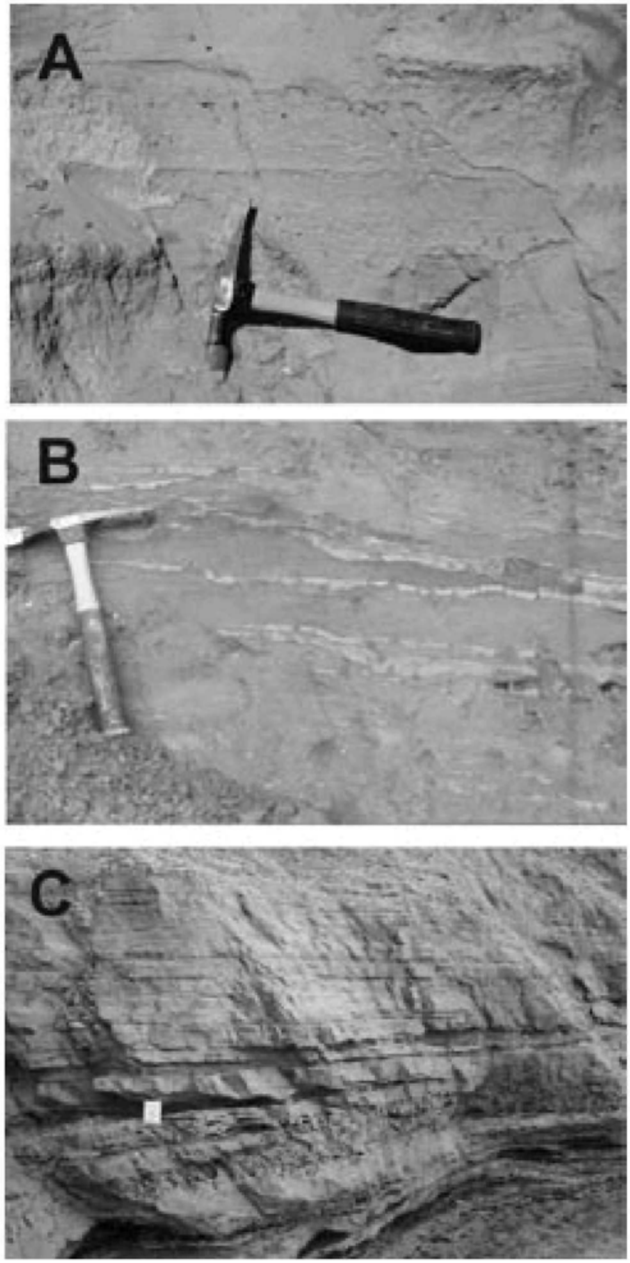


Fig. 10 Lithofacies from the siliciclastic shoreline association. **A**, bioturbated, barren sand of facies SI1 (Middle Maxwell Formation, HST/RST of sequence NC10); **B**, sand-dominated heterolithic facies SI2 (Tewkesbury Formation, HST of sequence NC5); **C**, mud-dominated heterolithic facies SI3 (Middle Maxwell Formation, HST of NC10).

Transgressive systems tracts overlie ravinement surfaces and generally begin with an onlap shellbed comprising shallow-marine or shoreline shells, mostly but not always reworked, in a sand-rich matrix (facies SH1, SH2). Onlap shellbeds may be overlain by sand-rich siliciclastic shoreline facies (facies SI1 or SI2), and capped by a backlap shellbed characterised by *in situ* innermost shelf fossils (facies SH4). In some sequences the siliciclastic facies may be absent such that the onlap shellbed is amalgamated with an overlying backlap shellbed. Such amalgamated intervals are referred to as compound shellbeds (e.g., sequences NC3, NC4).

Table 2 Nukumaruan palaeocommunities (adapted for Nukumaruan faunas after Abbott & Carter 1997).

Palaeo-community	Characteristic taxa	Community characteristics	Environment	Characteristic facies	Shellbed type	Systems tract
Paphies	*Amalda* sp., *Dosinia subrosea*, *Divaricella huttoniana*, *Fellaster*, *Paphies pliocenicum*, *Spisula aequilatera*, *Tawera* spp., *Zethalia zelandica*	Dominated by robust infaunal suspension feeders e.g., *Paphies*, with a high number of detritus-feeding gastropods (e.g., *Zethalia*)	Open ("exposed") sandy shoreline. Wave-dominated, high-energy environment. Mobile substrate of well sorted fine sand	SI1: autochthonous assemblages, slightly reworked	NA	HST/RST
				SH3: autochthonous assemblages, slightly reworked	Toplap	Upper HST/RST
				SH1: allochthonous assembages, mixed with taxa from various other palaeocommunities	Onlap	Basal TST
Cyclomactra	*Amphibola crenata*, *Austrovenus stutchburyi*, *Cominella glandiformis*, *Cyclomactra ovata*, *Nucula nitidula*, *Xymene expansus*, *Zeacumantus lutulentus*	Dominated by infaunal suspension feeders, tolerant of muddy substrate and brackish water (e.g., *Cyclomactra*)	"Protected" muddy shoreline. Low energy shoreline environment (sometimes estuarine?). Soft muddy substrate.	SH1: allochthonous assemblages, mixed with other taxa from various other palaeocommunities	Onlap	Basal TST
				SH2: autochthonous assembages (rare)	Onlap	Basal TST
Tiostrea	*Chlamys gemmulata*, *Cardita aoteana*, *Crepidula radiata*, *Barbatia novaezealandiae*, *Tucetona shrimptoni*, *Maoricolpus roseus*, *Neothyris lenticularis*, *Purpurocardia purpurata*, *Tawera* spp. *Tiostrea lutaria*, *Magasella sanguinea*	Dominated by suspension-feeding bivalves, although brachiopods are conspicuous. Members are shallow burrowers (e.g., *Purpurocardia*, *Tawera*) or epifaunal (e.g., *Tiostrea*, *Chlamys*, *Lima*, *Neothyris*)	Inner shelf. Bypassing of siliciclastic sediment sponsors *in situ* development of a stable shellground substrate	SH4: autochthonous assemblages	Backlap	Upper TST

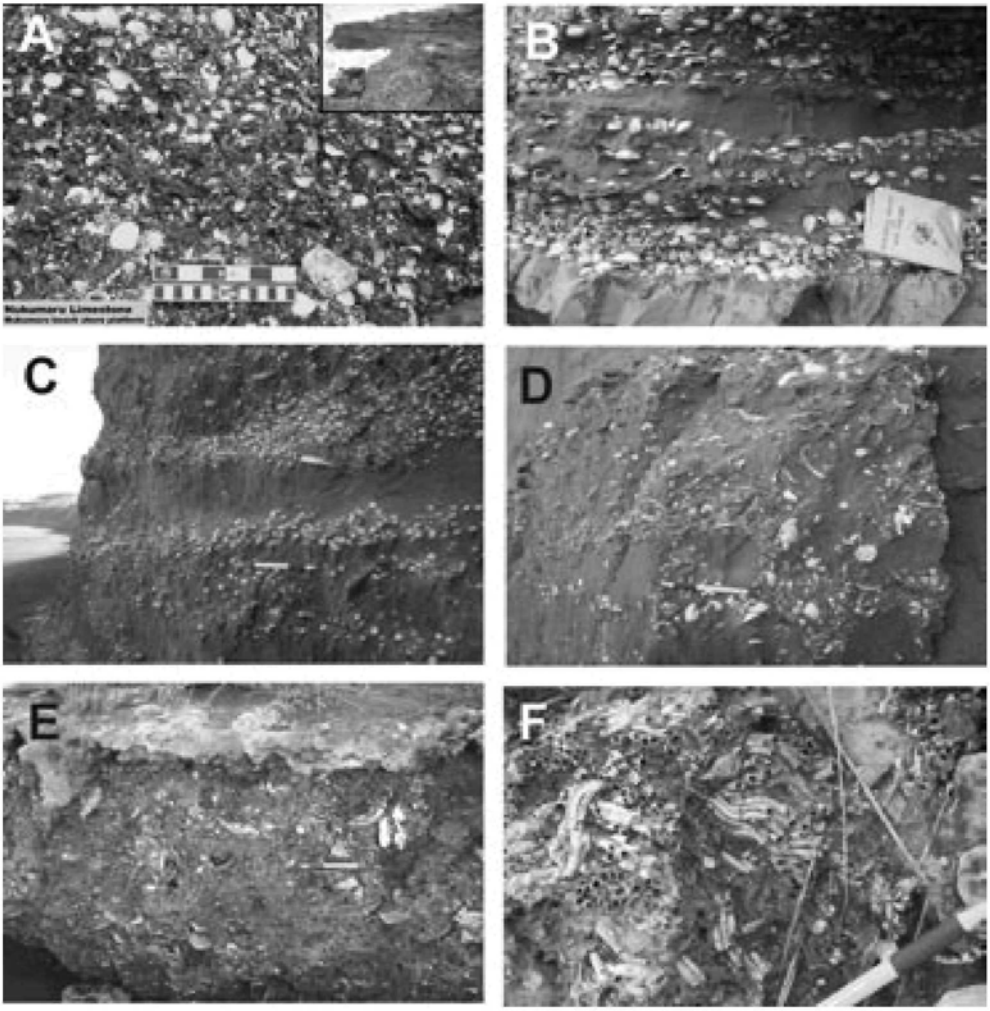


Fig. 11 Lithofacies from the shellbed association. **A**, Close-packed, broken, and abraded shell debris in a matrix of pebbly sand (facies SH1, Nukumaru Limestone); **B**, close-packed to dispersed *Austrovenus*—note paired valves—in heterolithic sand and mud (facies SH2, Mangahou Siltstone, onlap shellbed, TST of NC11); **C**, close-packed to dispersed *Zethalia* in well sorted fine to medium sand (facies SH3, Nukumaru Brown Sand, toplap shellbed, RST of NC2); **D**, close- to loosely-packed shells (*Tiostrea, Perna, Zethalia, Tawera*) in fine sand (facies SH4, Nukumaru Brown Sand, compound shellbed of NC2); **E**, close-packed shells (*Tiostrea, Zethalia, Lutraria*) in sand and capped by a polychaete-bryozoa hardground (facies SH4, compound shellbed, TST of NC3); **F**, bedding-plane view of hardground in E showing polychaete tubes.

Downlap surfaces in the Nukumaru section are marked by an abrupt termination of *in situ* shell accumulation and by an influx of highstand siliciclastic sediment. Highstand systems tracts and regressive systems tracts taken together are dominated by the siliciclastic shoreline association, some of which consist of distinctly shallowing-upward suites of facies (e.g., NC1, 2, 5, and 6). In siliciclastic shoreline successions containing a distinct two-fold subdivision of facies separated by an abrupt gradation or regressive surface of erosion, the highstand and regressive systems tracts can be resolved (e.g., NC1, 2, 5, and 6). Successions in which there is no distinction between highstand and regressive components, especially those consisting

Fig. 12 Palaeosol from the non-marine facies association showing vertical rootlets (facies NM3, LST^{nm} of NC10). Hammer head rests on the sequence-bounding ravinement surface at the base of sequence NC11.

of only one facies (e.g., NC3, NC10), are denoted highstand systems tract/lowstand systems tract (HST/RST).

Sequence stratigraphic motifs

Sequence architecture and facies composition vary according to palaeogeographic shelf setting. Saul et al. (1999) resolved such variation in the Wanganui Basin into seven sequence motifs into which all 58 sequences from sections across Wanganui Basin can be classified. These motifs represent palaeogeographic localities along a conceptual shore-normal palaeo-profile. The palaeogeographic locality for each motif is based on a combination of factors such as facies composition, maximum water depth, and the presence or absence of a backlap shellbed.

Three recurring sequence motifs, the Maxwell, Birdgrove, and Nukumaru, are present in the Nukumaru section (Fig. 3, 14). Two of these (Birdgrove, Nukumaru) were defined and briefly described by Saul et al. (1999). The Maxwell motif is new. Sequence motifs that reside in the Nukumaru section are described below.

Nukumaru motif (emended from Saul et al. 1999; Fig. 14A, Fig. 3 sequences NC1–NC4)

This motif is characterised by the dominance of sandy shoreface facies and a basal compound shellbed. Nukumaru sequence NC2 is the type example of the Nukumaru motif. Above a bioturbated and burrowed ravinement surface, the transgressive part of the NC2 begins with a compound shellbed consisting of open shoreline (*Paphies* palaeocommunity) and inner-shelf shellground (*Tiostrea* palaeocommunity) faunas. In sequence NC3, the top (backlap portion) of the shellbed is marked by a polychaete tube and bryozoa hardground (Fig. 11E,F). Above an abrupt downlap surface, the highstand sediments consist of sparsely fossiliferous, burrowed and bioturbated, lower shoreface sand. The regressive systems tract rests on a burrowed and bioturbated regressive surface of erosion, and consists of abundantly fossiliferous (*Paphies* palaeocommunity) upper shoreface sand. The concentration of shells in the regressive deposits represents stratal convergence in the context of toplap. Regressive deposits are truncated at the sequence-bounding ravinement surface at the base of the overlying sequence.

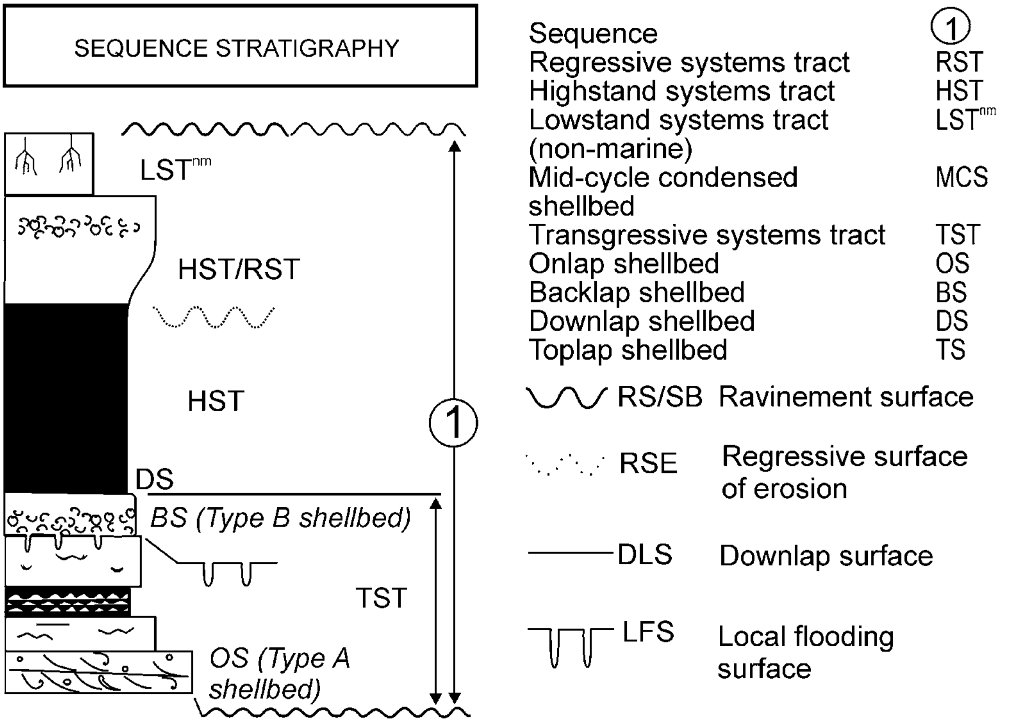


Fig. 13 Sequence stratigraphic terminology used in this paper (after Abbott & Carter 1994; Naish & Kamp 1997).

The abundance of shellground taxa (*Tiostrea* palaeocommunity) places the upper, backlap, part of the compound shellbed, the deepest lithofacies in the Nukumaru motif, at the landward limit of the inner shelf.

Birdgrove motif (Saul et al. 1999; Fig. 14B, Fig. 3 sequences NC5–NC9)

The Birdgrove motif is characterised by the dominance of heterolithic siltstone and sand of the siliciclastic shoreline facies association, and is often capped by assemblages of non-marine lowstand facies that include carbonaceous mudstone, lignite, and palaeosols. Sequence NC5 is nominated as a reference example of the Birdgrove motif in the Nukumaru section. Above a basal ravinement surface, the transgressive systems tract of NC5 comprises a cross-bedded onlap shellbed (*Cyclomactra* palaeocommunity). Above a sharp downlap surface, the highstand systems tract consists of structureless to laminated, blue-grey, barren, inner-shelf siltstone that grades up into sand-rich heterolithic facies. The highstand systems tract is truncated by a regressive surface of erosion, overlain by a regressive systems tract of fossiliferous (*Paphies* palaeocommunity) sand. Non-marine facies are absent from NC5 as this sequence is truncated by the sequence-bounding ravinement surface of NC6.

The maximum water depth in the Birdgrove motif is recorded in the highstand shelf siltstone (facies SI3). Consequently, the palaeogeographic position of this motif is relatively basinward of the Nukumaru motif. The type example of the Birdgrove motif is located in the Turakina Valley east of Wanganui (Saul et al. 1999).

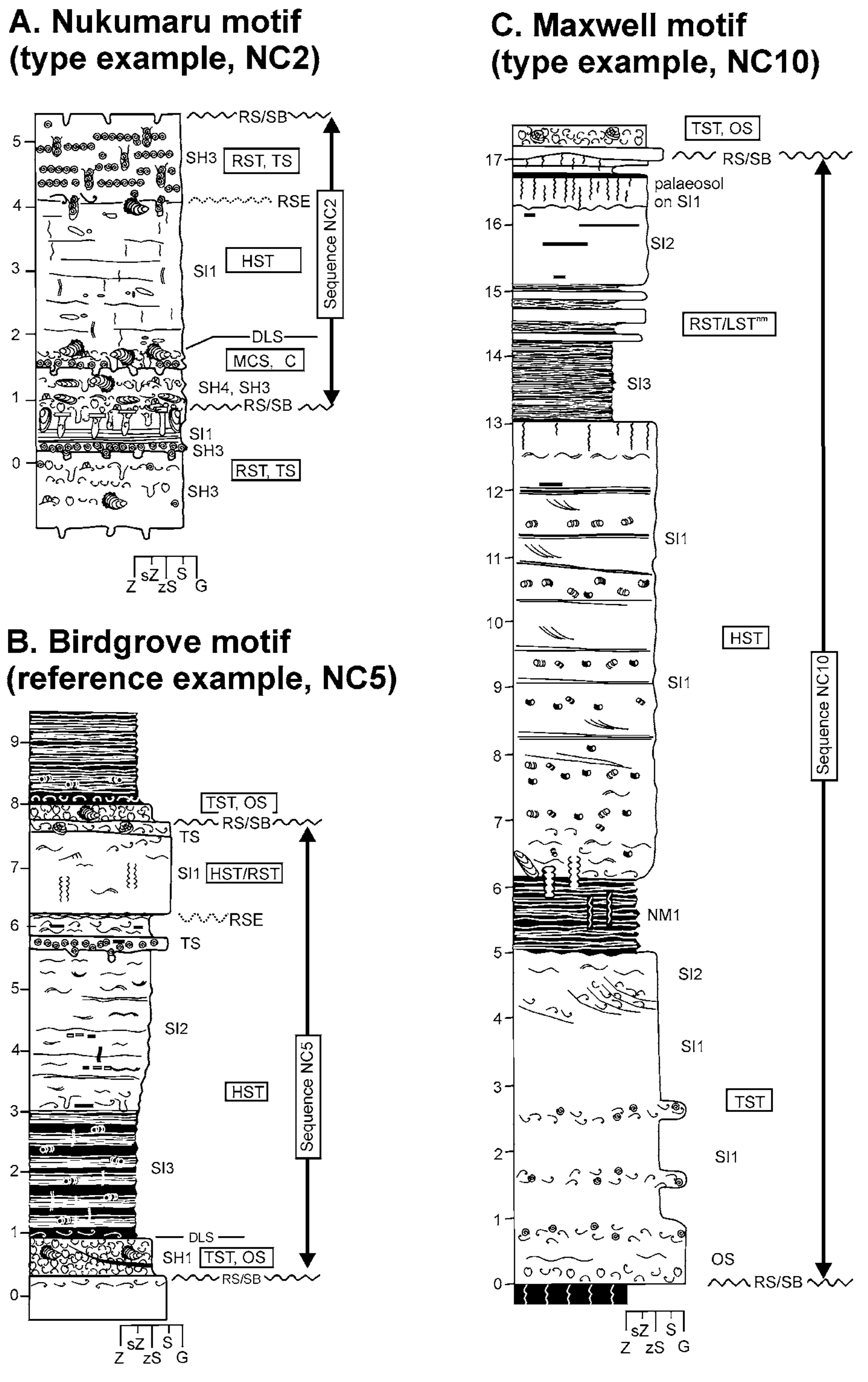


Fig. 14 Sequence motifs from the Nukumaru stratotype. See Fig. 15 for legend.

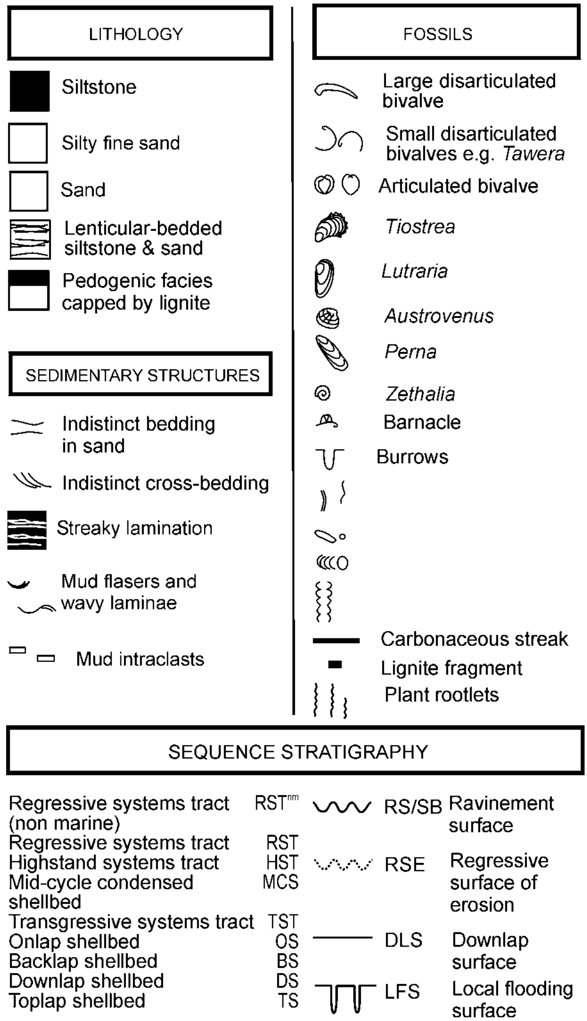
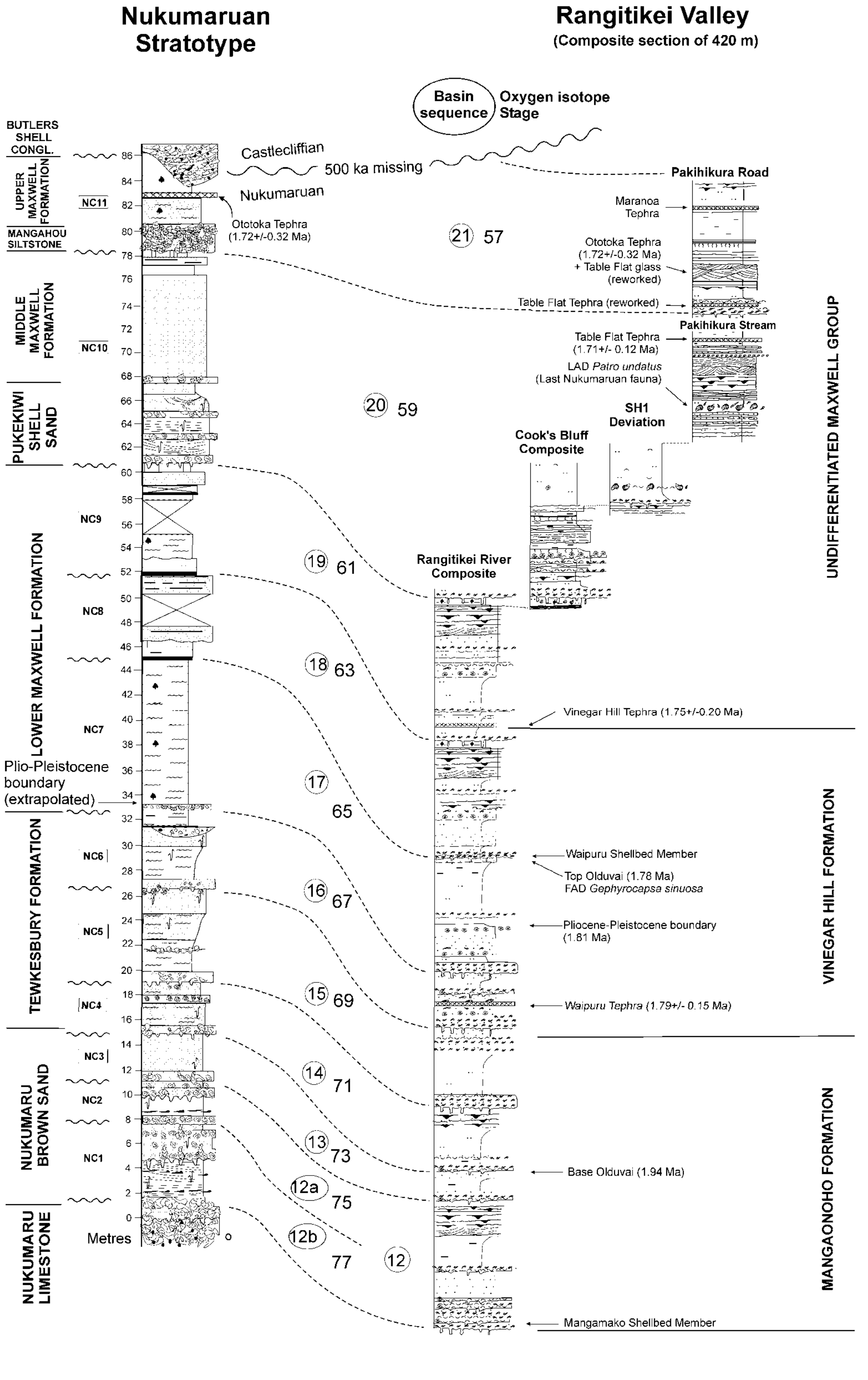


Fig. 15 Legend for Fig. 14.

Maxwell motif (new; Fig. 14C, Fig. 3 sequences NC10–NC11)

The Maxwell motif is characterised by a dominance of fine shoreface sand, sequence-capping non-marine facies, and the absence of a backlap shellbed. The type example of the Maxwell motif is sequence NC10 in the Nukumaru section. Transgressive deposits in NC10 consist of shelly shoreface sand with a basal onlap shellbed (*Paphies* palaeocommunity throughout). The absence of a backlap shellbed renders it difficult to resolve the highstand and regressive systems tract architecture in sequences of this type. The middle part of NC10 is dominated by barren sand assigned to the highstand systems tract. The upper part of NC10, comprising shoreline sand and mud, and capped by a palaeosol, is assigned as regressive/lowstand^{nm} systems tract. The absence of shelfal facies (i.e., backlap shellbed or marine mudstone) places the palaeogeographic position of the Maxwell motif relatively landward of the Nukumaru motif.


Nukumaruan Stratotype
Rangitikei Valley
(Composite section of 420 m)
Basin sequence
Oxygen isotope Stage
BUTLERS SHELL CONGL.
UPPER MAXWELL FORMATION
MANGAHOU SILTSTONE
MIDDLE MAXWELL FORMATION
PUKEKIWI SHELL SAND
LOWER MAXWELL FORMATION
Plio-Pleistocene boundary (extrapolated)
TEWKESBURY FORMATION
NUKUMARU BROWN SAND
NUKUMARU LIMESTONE
NC11
NC10
NC9
NC8
NC7
NC6
NC5
NC4
NC3
NC2
NC1
Metres
Castlecliffian
500 ka missing
Nukumaruan
Ototoka Tephra (1.72+/-0.32 Ma)
Pakihikura Road
Maranoa Tephra
Ototoka Tephra (1.72+/-0.32 Ma) + Table Flat glass (reworked)
Table Flat Tephra (reworked)
Pakihikura Stream
Table Flat Tephra (1.71+/- 0.12 Ma)
LAD Patro undatus (Last Nukumaruan fauna)
SH1 Deviation
Cook's Bluff Composite
Rangitikei River Composite
21 57
20 59
19 61
18 63
17 65
16 67
15 69
14 71
13 73
12a 75
12b 77
12
Vinegar Hill Tephra (1.75+/-0.20 Ma)
Waipuru Shellbed Member
Top Olduvai (1.78 Ma) FAD Gephyrocapsa sinuosa
Pliocene-Pleistocene boundary (1.81 Ma)
Waipuru Tephra (1.79+/- 0.15 Ma)
Base Olduvai (1.94 Ma)
Mangamako Shellbed Member
UNDIFFERENTIATED MAXWELL GROUP
VINEGAR HILL FORMATION
MANGAONOHO FORMATION

DISCUSSION AND CONCLUSIONS

The Nukumaru section is dominated by sand and mud facies deposited mainly in siliciclastic shoreline environments. Subordinate facies include non-marine lignite and palaeosols, and shallow-marine shellbeds. As for elsewhere in the Wanganui Basin, the succession of facies in the Nukumaru section can be resolved into depositional sequences following the sedimentary facies and shellbed approach developed by Abbott & Carter (1994), Naish & Kamp (1997), and Kondo et al. (1998). These sequences were deposited on the basin margin during successive interglacial sea-level highs. As a consequence of their basin margin palaeogeographic setting, only the late transgression, highstand, and early fall of the sea-level cycle left a sedimentary record. Glacio-eustasy during Nukumaruan time was dominated by the 41 ka orbital periodicity. The magnitude of glacio-eustatic variation for Nukumaruan time, inferred from deep-sea $\delta^{18}O$ records, ranges from 30 to 80 m (Naish 1997).

Sequences dominated by shoreline and non-marine facies represent distinctive motifs (Nukumaru, Birdgrove) within the suite of Wanganui Basin sequence motifs defined by Saul et al. 1999. The Nukumaru (type example) and Birdgrove motifs (reference example) are fully described herein. The new Maxwell motif is also fully described. The Maxwell motif is regarded as the most landward of the Nukumaru (and Wanganui Basin) motifs as it lacks a backlap shellbed or any other shelfal marine facies, and contains a high proportion of non-marine facies, including a palaeosol. The Nukumaru motif, dominated by shoreline sand, is relatively seaward. The Birdgrove motif, which includes marine mudstone in its highstand systems tract, represents the most basinward of the Nukumaru coast section motifs.

The vertical succession of Nukumaru sequence motifs (Fig. 3) reveals a low order accommodation cycle of the order of c. 450 ka duration. The upwards succession of Nukumaru motif sequences (NC1–NC4), Birdgrove sequences (NC5–NC9), and Maxwell motif sequences (NC10–NC11) records a long-term deepening-shallowing relative sea-level trend. As discussed by Saul et al. (1999), such low order cyclicity reflects tectonically-driven accommodation changes that modulate the stacking patterns of 41 ka and 100 ka glacio-eustatic sequences in the Wanganui Basin.

Saul et al. (1999) correlated stratigraphic sections between the Wanganui coast and the Rangitikei Valley, and recognised 58 "basin sequences" deposited since c. 3.6 Ma. The calibration of Wanganui Basin cyclostratigraphy using radiometric and palaeomagnetic data allowed Naish et al. (1998) to correlate the Wanganui cyclostratigraphic record directly with the orbitally-calibrated oceanic oxygen isotope record. Age estimates can thereby be made for stratigraphic horizons and events not used in establishing the correlations, e.g., individual sequence boundaries or biostratigraphic stage boundaries. In general, each sequence 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). Using the Ototoka tephra as a correlation tie-point, the 11 sequences in the Nukumaru section are correlated to odd-numbered OIS 77–57, representing a period of deposition of c. 450 k.y. between c. 2.08 and 1.63 Ma.

◄ **Fig. 16** Correlation between the Nukumaruan stratotype and the succession in Rangitikei Valley. Rangitikei sequence stratigraphy and lithostratigraphy from Naish & Kamp (1997). Oxygen isotope stage correlation, tephro- and magneto-stratigraphic tie-points, and basin cycle numbering are from Naish et al. (1998). Updated tephrostratigraphy by Pillans et al. (2005 this issue). The lithostratigraphic units Mangamako Shellbed Member, Mangaohono Formation, Vinegar Hill Formation, and Waipuru Shellbed are based on type localities in Rangitikei Valley, eastern Wanganui Basin (Superior Oil Company 1943; Naish & Kamp 1995).

There are correlations between the Nukumaru coast sequences and the Wanganui Basin cyclostratigraphy via the Rangitikei section compiled by Naish & Kamp (1995) (Fig. 16). The key tie-point is the Ototoka tephra, which has been geochemically characterised and dated (1.72 ± 0.32 Ma) by Pillans et al. (2005 this issue). This tephra occurs in basin sequence 21 in the Rangitikei section, and sequence NC11 at the coast. Using the Ototoka tephra tie-point, coastal sequences NC1–NC11 correspond to basin sequences 12–21 of the composite record and were deposited during OIS 77–57. The correlations allow the Pliocene-Pleistocene boundary (Zijderveld et al. 1991; Lourens et al. 1996) to be placed at the base of the Lower Maxwell Formation, at the top of the transgressive part of sequence NC7 (Fig. 3, 16).

Correlations also constrain the length of time missing in the coast section within the unconformity between the Butlers Shell Conglomerate and the Upper Maxwell Formation. The base of the Butlers Shell Conglomerate corresponds to basin sequence 31 (Alloway et al. 2004; Naish et al. 2005 this issue). Basin sequence 21 is the youngest sequence in the Nukumaruan stratotype, so basin sequences 22–30 are missing from the coast section. The missing sequences, documented in the Turakina and Rangitikei Valleys to the west of Wanganui, represent c. 500 ka, corresponding to $\delta^{18}O$ stages 56–34 on the timescale used by Naish et al. (1998). As noted by Fleming (1953), the unconformity represents erosion after a phase of gentle deformation (uplift and tilting) that affected the western part of the outcrop belt. It is not yet clear whether the unconformity formed in response to a single deformation event, or is the cumulative effect of several, smaller, events. New boreholes and reflection seismic profiles (Naish et al. 2005 this issue, unpubl. data) are expected to yield additional insights into the origin and extent of this unconformity.

ACKNOWLEDGMENTS

Funding for this project was provided by the Australian Research Council (grant A-39805139), New Zealand Foundation for Research, Science and Technology (CO5X0202 and CO5806), and the Southern Cross University Recruitment Grant Scheme (grant 305052). This contribution was finalised while SA was on study leave from Southern Cross University, and based at the School of Earth Sciences at the University of Tasmania. We thank Helen Neil and Avon MacIntyre for assistance with initial section development, and Peter King and Greg Browne for reviews of an early version of the manuscript. Journal reviewers Brad Field and Lucas Lourens provided thoughtful comments that informed the development of the final manuscript.

REFERENCES

Abbott ST 1997. Foraminiferal paleobathymetry and mid-cycle architecture of mid-Pleistocene depositional sequences, Wanganui Basin, New Zealand. Palaios: 267–281.

Abbott ST 1998. Transgressive systems tracts and onlap shellbeds from mid–Pleistocene sequences, Wanganui Basin, New Zealand. Journal of Sedimentary Research 68: 253–268.

Abbott ST, Carter RM 1994. The sequence architecture of mid–Pleistocene (ca. 1.1–0.4 Ma) cyclothems from New Zealand: facies development during a period of orbital control on sea level cyclicity. In: de Boer PL, Smith DG ed. Orbital forcing and cyclic sequences. International Association of Sedimentologists Special Publication 19: 367–394.

Abbott ST, Carter RM 1997. Macrofossil associations from mid-Pleistocene cyclothems, Castlecliff section, New Zealand: implications for sequence stratigraphy. Palaios 12: 188–210.

Abbott ST, Carter RM 1999. Stratigraphy of the Castlecliffian type section: 10 mid-Pleistocene sequences from the Wanganui coast, New Zealand. New Zealand Journal of Geology and Geophysics 42: 91–111.

Aguirre E, Pasini G 1985. The Pliocene–Pleistocene boundary. Episodes 8: 116–120.

Alloway BV, Pillans BJ, Naish TR, Westgate JA 2004. Appendix: Age and correlation of the Ototoka tephra. In: Beu AG. Marine mollusca of oxygen isotope stages of the last 2 million years in New Zealand. Part 1: Revised generic positions and recognition of warm-water and cool-water migrants. Journal of the Royal Society of New Zealand 34: 261–265.

Beu AG 2001. Local stages to be used for the Wanganui Series (Pliocene–Pleistocene), and their means of definition. New Zealand Journal of Geology and Geophysics 44: 113–125.

Beu AG, Edwards AR 1984. New Zealand Pleistocene and late Pliocene glacio–eustatic cycles. Palaeogeography, Palaeoclimatology, Palaeoecology 46: 119–142.

Beu AG, Grant-Taylor TL, Hornibrook N de B 1977. Nukumaruan records of the subantarctic scallop *Chlamys delicatula* and crab *Jacquinotia edwardsii* in central Hawke's Bay. New Zealand Journal of Geology and Geophysics 20: 217–248.

Beu AG, Edwards AR, Pillans BJ 1987. A review of New Zealand Pleistocene stratigraphy, with emphasis on the marine rocks. In: Itihara M, Kamei T ed. Proceedings of the First International Colloquium on Quaternary Stratigraphy of Asia and the Pacific Area, Osaka. Osaka, Science Council of Japan. Pp. 250–269.

Carter RM in press. The status of local "stages" in the New Zealand Plio-Pleistocene. New Zealand Journal of Geology and Geophysics.

Carter RM, Naish TR 1998. A review of the Wanganui Basin, New Zealand: global reference section for shallow-marine, Plio-Pleistocene (2.5–0 Ma) cyclostratigraphy. Sedimentary Geology 122: 37–52.

Carter RM, Fulthorpe CS, Naish TR 1998. Sequence concepts at outcrop and seismic scale: the distinction between physical and conceptual stratigraphic surfaces. Sedimentary Geology 122: 1–3.

Carter RM, Abbott ST, Naish TR 1999. Plio–Pleistocene cyclothems from Wanganui Basin, New Zealand: type locality for an astrochronologic timescale, or a template for recognising ancient glacio-eustasy? Philosophical Transactions of the Royal Society of London A 357: 1–12.

Cooper RA ed. 2004. The New Zealand geological timescale. Institute of Geological and Nuclear Sciences Monograph 22. 284 p. Wellington, Institute of Geological and Nuclear Sciences.

Fleming CA 1944. Molluscan evidence of Pliocene climatic change in New Zealand. Transactions of the Royal Society of New Zealand 74: 207–220.

Fleming CA 1947. Standard sections and subdivisions of the Castlecliffian and Nukumaruan Stages in the New Zealand Pliocene. Transactions of the Royal Society of New Zealand 76: 300–326.

Fleming CA 1953. The geology of the Wanganui Subdivision. New Zealand Geological Survey Bulletin 52: 361 p.

Fleming CA 1975. The Quaternary record of New Zealand and Australia. In: Suggate RP, Cresswell MM ed. Quaternary studies. Wellington, The Royal Society of New Zealand. Pp. 1–20.

Hays JD, Imbrie J, Shackleton NJ 1976. Variations in the Earth's orbit: pacemaker of the ice ages. Science 194: 1121–1132.

Haywick DWH, Henderson RA 1992. Foraminiferal paleobathymetry of Plio–Pleistocene cyclothemic sequences, New Zealand. Palaios 6: 586–599.

Journeaux TD, Kamp PJJ, Naish TR 1996. A lithostratigraphic framework for Middle Pliocene cyclothems, Mangaweka region, Wanganui Basin, New Zealand. New Zealand Journal of Geology and Geophysics 39: 135–149.

Kamp PJJ 1978. Stratigraphy and sedimentology of conglomerates in the Pleistocene Kidnappers Group, Hawke's Bay. Unpublished MSc thesis, University of Waikato, Hamilton, New Zealand.

Kidwell SM, Fursich FT, Aigner T 1986. Conceptual framework for the analysis and classification of fossil concentrations. Palaios 1: 228–238.

Kidwell SM 1991. The stratigraphy of shell concentrations. In: Briggs DEG, Allison PA ed. Taphonomy—releasing information from the fossil record. New York, Plenum Press. Pp. 21–290.

Kondo Y, Abbott ST, Kitamura A, Kamp PJJ, Naish TR, Kamataki T, Saul GS 1998. The relationship between shellbed type and sequence architecture: examples from Japan and New Zealand. Sedimentary Geology 122: 109–127.

McIntyre AP, Kamp PJJ 1998. Late Pliocene (2.8–2.4 Ma) cyclothemic shelf deposits, Parikino, Wanganui Basin, New Zealand: lithostratigraphy and correlation of cycles. New Zealand Journal of Geology and Geophysics 41: 69–84.

Lourens LJ, Antonarakou A, Hilgen FJ, Van Hoof AAM, Vergnaud-Grazzini C, Zachariasse WJ 1996. Evaluation of the Plio–Pleistocene astronomical timescale. Paleoceanography 11: 391–413.

Marshall P 1919. Tertiary rocks near Wanganui. Transactions of the New Zealand Institute 52: 115–128.

Marwick J 1924. Palaeontological notes on some Pliocene mollusca from Hawkes Bay. Transactions of the New Zealand Institute 55: 191–201.

Naish TR 1997. Constraints on the amplitude of late Pliocene eustatic sea-level fluctuations: new evidence from the New Zealand shallow-marine sediment record. Geology 25: 1139–1142.

Naish TR, Kamp PJJ 1995. Late Pliocene marine cyclothems, Wanganui Basin, New Zealand: a lithostratigraphic framework. New Zealand Journal of Geology and Geophysics 38: 223–243.

Naish TR, Kamp PJJ 1997. High-resolution sequence stratigraphy of 6th order (41 ka) Plio–Pleistocene cyclothems, Wanganui Basin, New Zealand: a case for the regressive systems tract. Geological Society of America Bulletin 109: 987–999.

Naish TR, Kamp PJJ, Alloway BV, Pillans BJ, Wilson GS, Westgate JA 1996. Integrated tephrochronology and magnetostratigraphy for cyclothemic marine strata, Wanganui Basin: implications for the Pliocene–Pleistocene boundary in New Zealand. Quaternary International 36: 29–48.

Naish TR, Abbott ST, Alloway BV, Beu AG, Carter RM, Edwards AR, Journeaux TD, Kamp PJJ, Pillans B, Woolfe K 1998. Astronomical calibration of a southern hemisphere Plio–Pleistocene reference section, Wanganui Basin (New Zealand). Quaternary Science Reviews 17: 695–710.

Naish TR, Field B, Zhu H, Melhuish A, Carter RM, Abbott ST, Edwards S, Alloway BV, Wilson GS, Niessen F, Baker A, Browne G, Maslen G 2005. Integrated behind-outcrop boreole and seismic stratigraphic architecture of a cyclothemic, shallow-marine depositional system, Wanganui Basin, New Zealand. Pp. 91–122 (this issue).

Nodder SD 1995. Late Quaternary transgressive/regressive sequences from Taranaki continental shelf, western New Zealand. Marine Geology 123: 187–214.

Orpin AR, Gammon PR, Naish TR, Carter RM 1998. Modern and ancient *Zyglochlamys delicatula* shellbeds in New Zealand, and their sequence stratigraphic implications. Sedimentary Geology 122: 267–284.

Park J 1887. On the Upper Wanganui and King Country. New Zealand Geological Survey Report 18: 167–182.

Pillans BJ 1983. Upper Quaternary marine terrace chronology and deformation, South Taranaki, New Zealand. Geology 11: 292–297.

Pillans BJ 1990. Late Quaternary marine terraces, south Taranaki–Wanganui (Sheet Q22 and part Sheets Q20, Q21, R21 and R22), 1:100 000. New Zealand Geological Survey Miscellaneous Series Map 18.

Pillans BJ 1991. New Zealand Quaternary stratigraphy: an overview. Quaternary Science Reviews 10: 405–418.

Pillans BJ, Alloway BV, Naish TR, Westgate J, Abbott ST, Palmer A 2005. Silicic tephras in Pleistocene shallow-marine sediments of Wanganui Basin, New Zealand. Pp. 43–90 (this issue).

Saul G, Naish TR, Abbott ST, Carter RM 1999. Sedimentary cyclicity in the marine Plio–Pleistocene of Wanganui Basin (New Zealand): sequence stratigraphic motifs of the last 2.5 Ma. Bulletin of the Geological Society of America 111: 524–537.

Shackleton NJ, Opdyke ND 1973. Oxygen isotope and palaeomagnetic stratigraphy of equatorial Pacific core V28–238: oxygen isotope temperatures and ice volumes on a 105 and 106 year scale. Quaternary Research 3: 39–59.

Shackleton NJ 1985. Neogene oxygen and carbon isotope stratigraphy. In: Snelling NJ ed. The chronology of the geological record. Geological Society of London Memoir 10: 206–208.

Stern TA, Davey FJ 1989. Crustal structure and origin of basins formed behind the Hikurangi subduction zone, New Zealand. In: Price RA ed. Origin and evolution of sedimentary basins and their energy and mineral resources. International Union of Geodesy and Geophysics and American Geophysical Union Geophysical Monograph 48. Pp. 73–85.

Superior Oil Company 1943. Geology of the Palmerston–Wanganui Basin, "West Side", North Island, New Zealand. In: Feldmeyer AE, Jones B, Firth CW, Knight J. Typescript and maps filed with the Institute of Geological and Nuclear Sciences Ltd, Lower Hutt.

Vail PR, Audemard F, Bowman SA, Eisner PN, Perez-Crus C 1991. The stratigraphic signatures of tectonics, eustasy and sedimentology—an overview. In: Ricken G, Seilacher A ed. Cycles and events in stratigraphy. Berlin, Heidelberg and New York, Springer-Verlag. Pp. 617–659.

Wanless HR, Weller JM 1932. Correlation and extent of Pennsylvanian cyclothems. Geological Society of America Bulletin 43: 1003–1016.

Zijderveld JDA, Hilgen FJ, Langereis CG, Verhallen PJJM, Zachariasse WJ 1991. Integrated magnetostratigraphy and biostratigraphy of the upper Pliocene–lower Pleistocene from Monte Singa and Crotone areas in Calabria, Italy. Earth and Planetary Science Letters 107: 697–714.

Appendix Qualitative macrofossil abundance data from the Nukumaruan stratotype, Wanganui Basin. D = Dominant, C = common, P = present, R = rare, d = reworked from older strata, x = present in the faunal lists of Fleming (1953), CAF = Fleming (1953), MMF = Middle Maxwell Formation

	Nukumaru Brown Sand					Tewkesbury Formation							Pukekiwi Shell Sand			MMF	Mangahou Siltstone	
Assemblage (see Fig. 3)	a	b	c	d	CAF	e	f	g	h	I	j	CAF	k	l	CAF	m	n	CAF
Rock platform																		
Mytilus aff. *edulis aoteanus*		P				P	P					x						
Aulacomya maoriana												x						
Barnea similes					x			R				x						
Estuarine (*Cyclomactra* Palaeocommunity)																		
Xenostrobus huttoni															xd		R	x
Barytellina tertia												x			xd		P	x
Paphies australis												x			x			
Austrovenus (*Crassitesta*) *stutchburyi*						C	D	R	R	C		x		Dd	xd	R	Dd	x
Cyclomactra ovata																	Cd	x
Lasaea aff. *maoria*																	P	x
Zeacumantus lutulentus			x		x		C					x						
Potamopyrgus antipodarum																	D	x
Cominella (*Josepha*) *glandiformis*							P					x			x			x
Amphibola crenata															x			x
Algal grazers (*Tiostrea* Palaeocommunity)																		
Trochus (*Coelotrochus*) *tiaratus*					x			R				x						
Micrelenchus tenebrosus		P			x							x						
Calliostoma puncticulatum			P		x				R									
Calliostoma ?pellucidum		P			x													
Modelia granosa						R						x						
Beach shallow shoreface (*Paphies* Palaeocommunity)																		
Nucula nitidula				R	x					R								
Nucula aff. *hartvigiana*					x													
Glycymeris (*Glycymerula*) *modesta*					x													
Cosa trigonopsis					x													
Isognomon zealandicus			P	Pd		R												

Appendix Qualitative macrofossil abundance data from the Nukumaruan stratotype, Wanganui Basin. D = Dominant, C = common, P = present, R = rare, d = reworked from older strata, x = present in the faunal lists of Fleming (1953), CAF = Fleming (1953), MMF = Middle Maxwell Formation

	Nukumaru Brown Sand					Tewkesbury Formation							Pukekiwi Shell Sand			MMF	Mangahou Siltstone	
Assemblage (see Fig. 3)	a	b	c	d	CAF	e	f	g	h	I	j	CAF	k	l	CAF	m	n	CAF
Lima zealandica					x													
Atrina pectinata zelandica	Pd				x	R												
Pteromyrtea dispar		Pd	Pd	Cd	x	Rd			R				Pd		x			
Divaricella (*Divalucina*) *huttoniana*					x													
Soletellina sp.															x			
Peronaea gaimardii								R							x			
Nemocardium (*Pratulum*) *pulchellum*										R								
Paphies donacina pliocenicum					x				R	R			C	D	x	D		
Mactra sp. (large)	P	P	R	P	x									C				
Spisula (*Spisulona*) *crassitesta*					x										x	P		x
Spisula (*Crassula*) *aequilatera*													P		x			
Maorimactra ordinaria						R		Dd	C	D		x						
Scalpomactra scalpellum									P	R								
Lutraria solida		Cd	C	Dd	x	Pd		Rd				x						
Dosinia (*Austrodosinia*) *horrida*		R	P	P	x	P			C						x			
Dosinia (*Phacosoma*) *subrosea*			P		x							x	D	C	x	C		
Dosinia (*Phacosoma*) *maoriana*			P			P			C									
Dosina zelandica		Rd		P	x					R								
Notocallista (*Striacallista*) *multistriata*								R							x			
Tawera spissa													Dd	C	x	D		
Tawera subsulcata	D	Dd	P	P	x	Cd		C	C	D		x			xd			
Bassina yatei		R	R	Cd	x	C		P	C									
Eumarcia plana	P	C	P	P	x	R									x			
Ruditapes largillierti									Dd									
Gari lineolata									R									
Panopea zelandica				R	x			Pd		Pd								
Myadora striata		P	C	P	x	R	R	P	P	Pd		x	C		x			
Myadora small									R			x				Pd		
Zethalia zelandica		D	D	D	x				P	R			D		x			

Stiracolpus sp.					x							x						
Struthiolaria frazeri							R											
Taniella planisuturalis					x													
Proxiuber australe												x						
Globisinum sp.					x													
Cirsotrema zelebori					x							x						
Acrillospira sp.												x						
Penion sulcatus						P												
Penion aff ormesi (= *cuverianus*)					x													
Buccinulum (*Euthrena*) sp.				R	x							x						
Cominella adspersa kereruensis		P	P		x										x			
Cominella excoriata					x								sp.					
Xymene expansus		P	P		x	P		P	C	R		x	C		x			
Xymene (*Zeatrophon*) *ambiguus*								P				x						
Xymenella oliveri (= *Xymene pusillus*)					x													
Paratrophon quoyi cheesemani					x													
Lepsithais sp.												x						
Alcithoe arabica		P	P		x	R		R		R								
Leporemax gatesi					x					R								
Leporemax fusus												x		P				
Amalda (*Baryspira*) *mucronata*					x							x	P		x			
Amalda (*Baryspira*) *australis*			P		x		R		R			x						
Amalda (*Baryspira*) *opima*				P	x			R	C	C		x						
Amalda (*Gracilispira*) *novaezelandiae*			P		x	R			R						x			
Neoguraleus sp.								P				x						
Duplicaria (*Pervicacia*) *tristis*															x			
Tenuiactaeon ambigua												x	P		x			
Fellaster		P		P	x	P	P		P			x						
Shell ground																		
(*Tiostrea* Palaeocommunity)																		
Patro undatus	P	P		P	x	P	P	P	R	P		x		D	x	C		
Barbatia novaezelandiae					x													x
Glycymeris shrimptoni					x							x						
Modiolus cf. *aereolatus*	Dd	P	C	Cd		Pd		P					R	P				
Perna				C		Cd												
Chlamys gemmulata									R	P		x						

Appendix Qualitative macrofossil abundance data from the Nukumaruan stratotype, Wanganui Basin. D = Dominant, C = common, P = present, R = rare, d = reworked from older strata, x = present in the faunal lists of Fleming (1953), CAF = Fleming (1953), MMF = Middle Maxwell Formation

	Nukumaru Brown Sand					Tewkesbury Formation							Pukekiwi Shell Sand			MMF	Mangahou Siltstone	
Assemblage (see Fig. 3)	a	b	c	d	CAF	e	f	g	h	I	j	CAF	k	l	CAF	m	n	CAF
Tiostrea chilensis lutaria	D	Cd	Cd	C	x	Dd	C	Dd	C	C		x		P		P		
Talabrica nummaria					x													
Purpurocardia purpurata	C			Rd	x	C	C			C		x						
Cardita aoteana					x													
Pleuromeris zelandica					x					R		x						
Maoricolpus roseus					x													
Zeacolpus sp.				R		R				R		x				R		
Crepidula radiata		P	P	P	x	D	D	D	R	P		x		P		R		
Zegalerus tenuis					x			P		R		x						
Sigapatella novaezelandiae		P	P	P	x	C	R	P		P						R		
Glaphyrina sp.					x													
Aeneator marshalli												x						
Notosaria nigricans												x						
Magasella sanguinea												x						
Barnacles	D	C		C		C	P		P	P								
encrusting brozoa				C		C												
Polydora, clioniids				C		C			P	P								