Sedimentary cyclicity in the marine Pliocene-Pleistocene of the Wanganui basin (New Zealand): Sequence stratigraphic motifs characteristic of the past 2.5 m.y.

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ABSTRACT

Earth's climatic history since 2.5 Ma has been controlled by Milankovitch variations in the planetary orbit, comprising alternate periods of glaciation and interglaciation with a dominant frequency of 41 000 yr. Concomitantly, eustatic sea level has fluctuated 70 to 130 m, causing rapid transgressions and regressions of the shoreline across the world's continental shelves. The resulting sedimentary record is cyclothemic, each cyclothem corresponding to a single climate and sea-level cycle. The Wanganui basin, New Zealand, contains a 2-km-thick, almost complete, composite record since isotope stage 100 (ca. 2.5 Ma) in the form of 47 superposed cyclothems of shelf origin. Each cyclothem corresponds to an unconformity-bound stratigraphic sequence, and typically contains a transgressive systems tract, sometimes a mid-cycle shell bed, a highstand systems tract, and sometimes a regressive systems tract. No advantage accrues from using transgressive-regressive units rather than cyclothems and/or sequences in description of the succession. Six basic sequence motifs represent deposition in locations between the shoreline and offshore shelf, i.e., the Hawera, Birdgrove, Turakina, Seafield, Castlecliff, and Rangitikei motifs. A seventh, the Nukumaru motif (which includes dominant coquina limestone), represents deposition in shallow-water areas of reduced terrigenous sediment on the flank of the basin. The sequence motifs represented in any section change systematically in sympathy with basin-scale changes in subsidence and sediment supply. In contrast with the 41 000 year length of individual glacio-eustatic sequences, these basin-wide tectonic cycles have a periodicity of many hundreds of thousands to a few million years, i.e., that of third- or fourth-order sequences of the Exxon type. This, coupled with the restriction of strongly cyclothemic sediments to geological periods of known glacio-eustasy (Permian-Carboniferous, Pliocene-Pleistocene), suggests that tectonic subsidence cycles rather than glacio-eustasy are the driving forces behind the development of the third- and fourth-order unconformity-bound sequences that are reported to occur throughout the stratigraphic record.

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INTRODUCTION

For at least the past 2.5 m.y. the pulse of Earth's environment has been influenced by systematic fluctuations in our planet's orbit, termed Milankovitch variations (Hays et al., 1976). Orbital variations on a time scale of 20 000 (precession), 41 000 (tilt), and 100 000 yr (either eccentricity, or inclination of the Earth's orbit; cf. Muller and MacDonald, 1997) in combination have caused changes in the distribution of solar radiation at different latitudes, the waxing and waning of ice sheets, and therefore changes in the volume of water in the global ocean and the position of sea level. The sedimentary record of the resultant sea-level cyclicity is manifest in the deep sea by the global oxygen isotope record (Emiliani, 1955; Shackleton and Opdyke, 1973; Shackleton et al., 1990, 1995a), and in shallow water by Pliocene-Pleistocene cyclothems (Fleming, 1953; Vella, 1963; Ueda, 1973). In remarkable anticipation of current stratigraphic concepts, Fleming (1953, p. 303) recognized that "the (New Zealand Pleistocene) cyclothems are typically separated by disconformities representing periods when the sea advanced and carved wave-cut platforms."

Sequence stratigraphy predicts the relationship between sea-level change and sedimentary architecture (Payton, 1977; Vail et al., 1991), and has become a dominant paradigm for the interpretation of ancient sedimentary successions. Sequence stratigraphy has led to a voluminous literature, widespread application in petroleum exploration and sedimentary basin studies (e.g., Wilgus et al., 1988), and a theoretical global sea-level curve (Haq et al., 1987). Initially applied at deep seismic scale with a resolution of tens of meters, from the mid-1980s the sequence stratigraphic model (Carter et al., 1991) was increasingly applied to higher resolution outcrop studies, and to studies of postglacial shelf sediments (e.g., Thorne and Swift, 1991).

The Wanganui basin, New Zealand, contains a largely undisturbed, 5-km-thick, complete Pliocene-Pleistocene record (Fleming, 1953; Anderton, 1981) (Fig. 1). The basin fill comprises cyclic, unconformity-bound strata of shelf origin, the last 2.5 m.y. part of which represents environments located entirely landward of the contemporaneous shelf edge. We present here the first detailed basin record of 43 cyclothems (sequences) that correspond to the shallow-marine, mostly interglacial, record of isotope stages 100–11 (2.5–0.4 Ma). We identify six fundamental types of terrigenoclastic cyclothem and one bioclastic motif, and interpret them in terms of sequence stratigraphy (Table 1) and basin evolution. The study of such high-resolution sequences, deposited during periods of undoubted glacio-eustasy, enable significant advances to be made in the theory and application of sequence stratigraphy.

CYCLOTHEM CONCEPT

The nonmarine to marine sedimentary cycles that recur in Pennsylvanian strata of the mid-

GSA Bulletin; April 1999; v. 111; no. 4; p. 524–537; 6 figures; 3 tables.

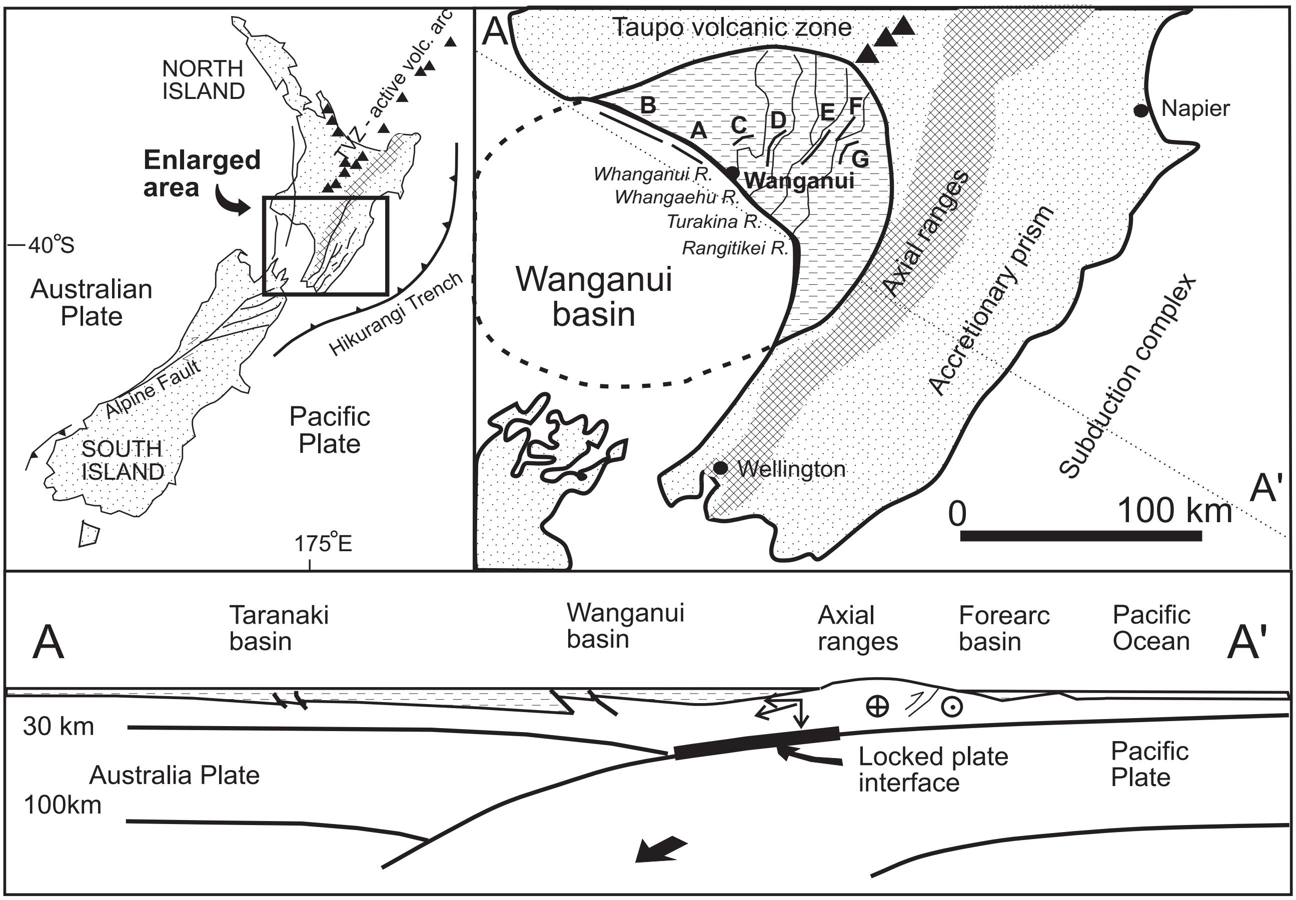


Figure 1. Location map and west-east tectonic cross section showing the location of the Wanganui basin.

western United States, that were later called cyclothems, were first described by Udden (1912). Studies by Weller (1930) and Wanless and Weller (1932) resulted in the recognition of a typical Illinois cyclothem (Fig. 2, column A), followed by Moore's (1936) description of the Kansas ideal cyclothem as a 10-unit model from which all midcontinent cyclothems could be derived by addition or subtraction of units. Udden (1912) recognized that the cyclothems represented "recurrent interruption of a progressive (marine) submergence," as did Weller (1930) and Moore (1936), but the latter authors attributed the cyclicity to recurrent tectonic uplift and downwarp. Wanless and Shepard (1935, 1936) first made a link between cyclothems, the eustatic rise and fall of ocean levels, and the waxing and waning of late Paleozoic Gondwana glaciations. Elias (1937) attributed the major facies within each cyclothem to deposition within an idealized, depth-related, paleogeography controlled by eustasy.

The 10 units of a characteristic Illinois style cyclothem can be grouped into 4 major parts (Fig. 2, column A): a lower, nonmarine interval of fining-

TABLE 1. SEQUENCE STRATIGRAPHIC TERMINOLOGY AND ABBREVIATIONS USED IN THIS PAPER

	Systems tract	Lower boundary	Sediment facies	Inferred sea level
LSTnm	Lowstand systems tract (nonmarine)	Transitional, from HST-RST of previous cycle	Terrigenous, nonmarine fluvial and lacustrine	Lowstand (glacial)
LST	Lowstand systems tract (marine)	Not seen in outcrop at Wanganui coast; occurs on offshore seismic as shelf-edge clinoforms	Lowstand (glacial)	
RST	Regressive systems tract	Transitional (i.e., gradational) from HST	Terrigenous, shoreface	Falling (postinterglacial)
HST	Highstand systems tract	Sharp/rapidly gradational (downlap surface)	Terrigenous, shallowing-upward shelf	Highstand to early fall (late interglacial)
MCCS	Mid-cycle condensed section	Transitional (i.e., gradational)	Sediment-starved shelf	Late rise, highstand (interglacial), early fall
MCS	Mid-cycle shell bed	Rapidly gradational (local flooding surface)	Shell-rich, sediment-starved shelf	Late rise, highstand (interglacial), early fall
TST	Transgressive systems tract	Sharp (ravinement surface)	Terrigenous, deepening-upward shelf	Rising (postglacial)

	Surfaces (occur in outcrop)	
DLS	Downlap surface	Contact between the TST or MCS and the HST
LFS	Local flooding surface	Contact between the TST and MCS
RS	Ravinement surface	Base of the TST (superposed upon the SB)
SB	Sequence boundary	Contact between HST/RST and overlying TST

	Horizons (theoretical levels)	
PEH	Peak eustatic sea-level horizon	Level corresponding to eustatic sea-level high
PRH	Peak relative sea-level horizon	Level corresponding to relative sea-level high
PWH	Peak paleowater depth horizon	Level corresponding to maximum water depth
MFH	Maximum flooding horizon	Level of peak shoreward position of the strand

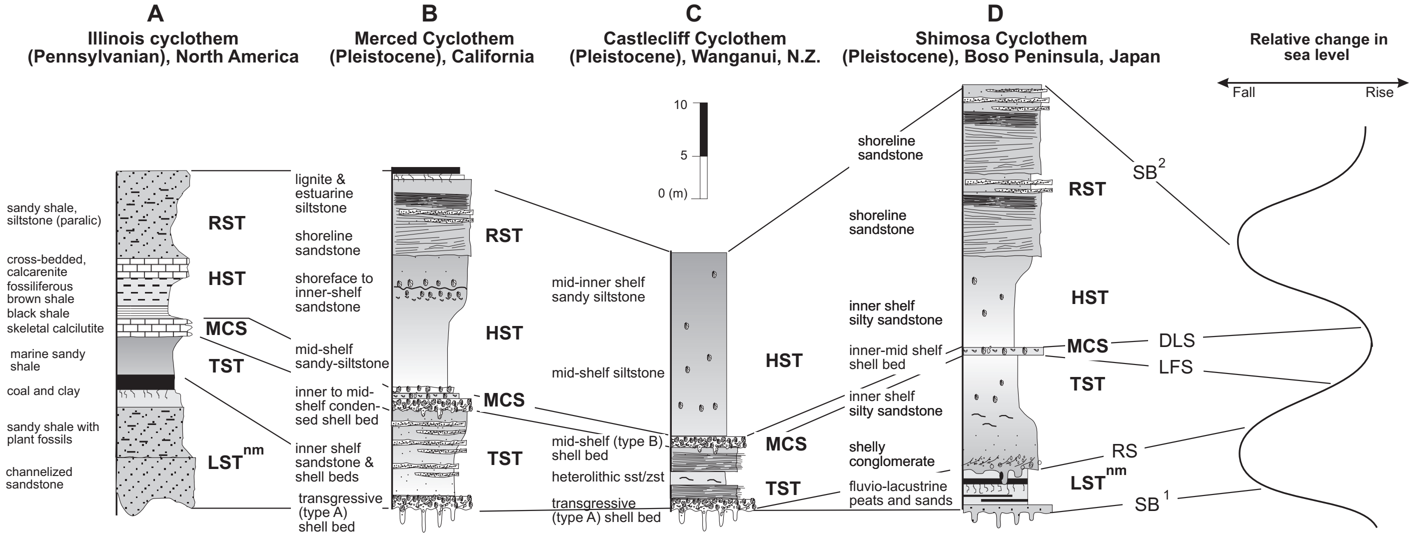


Figure 2. Comparison of four classic types of glacio-eustatic cyclothem (sequence). (A) Illinois motif (Pennsylvanian of North America; after Heckel, 1994; Klein and Willard, 1989). (B) Merced motif (mid-Pleistocene Merced Formation, California; after Clifton et al., 1988). (C) Castlecliff motif (mid-Pleistocene, Wanganui basin, New Zealand; after Abbott and Carter, 1994). (D) Shimosa motif (mid-Pleistocene of Boso Peninsula, Japan; after Tokuhashi and Kondo, 1989). Abbreviations in this and Figures 3–5 as follows. Systems tracts: LST^{nm}—lowstand systems tract, nonmarine; TST—transgressive systems tract; MCS—mid-cycle shell bed; HST—highstand systems tract; RST—regressive systems tract. Significant physical surfaces: SB—sequence boundary; SB (CC)—sequence boundary (correlative conformity); RS—ravinement surface; LFS—local flooding surface; DLS—downlap surface; sst—sandstone; zst—siltstone.

upward sand-silt capped by a seat earth (cf. Miller et al., 1996) and coal; a second interval of deepening-upward marine shale, which may include thin limestones with shallow-water fossils; a third interval of limestone containing offshore fauna, generally including fusulinids; and an upper interval of shallowing-upward marine shale. In terms of modern high-resolution sequence stratigraphy (e.g., Abbott and Carter, 1994), these intervals correspond to the lowstand (nonmarine), transgressive, mid-cycle shell bed, and highstand-regressive systems tracts, respectively. Elias (1937, p. 411) observed that "no single cycle of the Big Blue rocks shows all phases of the ideal cycle, but the missed phases in one cycle appear in proper position in neighboring cycles above and below." As a consequence, different types of cyclothem were recognized from the Illinois region, labeled with either arbitrary letters (e.g., types a–d of Weller, 1942), or names (e.g., the Macoupin, LaSalle, and Bogota motifs of Weller, 1958). Weller (1956, 1958) also argued for the recognition of an Illinois "megacyclothem," based on vertical groups of his cyclothem motifs, which he then correlated westward with the Kansas megacyclothem motif of Moore (1936). Wanless (1964) and Heckel et al. (1980) disagreed, believing that the Kansas cyclothem motif was the lateral, more marine equivalent of all of the varieties of cyclothem recognized in Illinois, the differences between which had only local rather than regional significance. Despite this dispute, by the 1960s there was general agreement as to the occurrence of three main types of cyclothem, the Kansas, Illinois, and Appalachian motifs, each of which represented progressively less marine influence within the cycle. Vigorous discussion continued, however, as to the nature of the controlling influence on cyclothem development, with autocyclic (delta switching; Moore, 1959; Ferm, 1970), tectonic (thrust loading; Klein and Willard, 1989), and Milankovitch-scale eustatic (Heckel, 1986, 1994) interpretations each having their proponents.

Given the complex historical controversy about the concept of Pennsylvanian cyclothems, and given the difficulty of locating the disconformity that separates cyclothems in the absence of a channelized sandstone at their base, it is not surprising that the use of cyclothem motifs largely fell into disuse after Weller's death in 1970. In its place has arisen an alternative subdivision of cyclic Pennsylvanian strata into transgressive-regressive units (Busch and Rollins, 1984; Weibel, 1996; Connolly and Stanton, 1992), also termed "modified cyclothems" by Weibel (1991). The boundary between such transgressive-regressive units is the marine flooding surface, which separates transgressive marine strata above from nonmarine or marginal marine strata below. For many of the sedimentary cycles in the Pliocene-Pleistocene strata of the Wanganui basin, the absence of channelized nonmarine sandstones (lowstand systems tracts) means that the marine flooding surfaces that bound transgressive-regressive units usually also correspond with the ravinement surfaces (and sequence boundaries) that bound the cyclothems; i.e., transgressive-regressive units, sequences, and cyclothems all coincide.

Similar sedimentary cyclicity to that of late Paleozoic time occurs within Pliocene-Pleistocene sediments, but has not been formalized previously in terms of cyclothem or sequence types. Interpretation of Pliocene-Pleistocene cyclothems is greatly aided by the presence of abundant shallow-marine fossils. Most of the fossils belong to extant species of known habitat, and they occur in characteristic shell beds that allow accurate paleodepth reconstruction, and often identify the sequence stratigraphic architecture (Abbott and Carter, 1994, 1997; Abbott, 1997a, 1997b; Naish and Kamp, 1997a, 1997b). We therefore agree with Riegel's (1991) comment that "It is time for the term cyclothem and its conception to regain their original meaning, stripping them of later metaphysical preoccupations and demonstrating their usefulness in designating a multi-elemental sequence of beds that is repeated many times and is commonly associated with certain paleogeographic settings and crustal conditions." This paper attempts to demonstrate the value of the cyclothem concept in the context of studies of late Neogene sediments, treated within a modern sequence strati-

graphic framework. The recognition of different types of descriptive Pliocene-Pleistocene cyclothems is an aid to sequence stratigraphic interpretation, and thereby adds to our understanding of the glacio-eustatic sediments of the Wanganui and other basins.

APPLICATION OF SEQUENCE INTERPRETATION TO PLIOCENE-PLEISTOCENE SEDIMENTS

It took more than 10 yr for the sequence stratigraphic model to be tested against onland Pliocene-Pleistocene sediments, the only part of the stratigraphic record for which an independent, accurate, high-resolution, surrogate sea-level curve is available in the form of the global oxygen isotope record (Ruddiman et al., 1989; Shackleton et al., 1995a). The first correlation of onland, unconformity-bounded, shallow-water sedimentary sequences with the oceanic oxygen isotope scale was that of Kamp (1978; Pleistocene of eastern North Island, New Zealand). Sedimentological studies of cyclothems (unconformity-bounded sequences) from California (Clifton et al., 1988), Japan (Tokuhashi and Kondo, 1989), and New Zealand (Abbott et al., 1989; Haywick et al., 1992) followed .

One reason it took so long for detailed studies of Pliocene-Pleistocene sequences to emerge is the rarity of suitable successions. In most parts of the world, the shallow-marine Pliocene-Pleistocene sedimentary record is concealed beneath the continental shelf. To elevate such strata homoclinally above sea level, without major disturbance, requires a rare combination of steady basin subsidence over several million years, followed by rapid but smooth tectonic uplift. Such conditions occur on the continental side of subduction zones (Boso Peninsula in Japan; Wanganui and Hawkes Bay basins in New Zealand), and occasionally in strike-slip regimes (Merced Formation, California). Shelf accumulations in the vicinity of subduction zones contain datable ash marker horizons, and are therefore particularly suitable for correlation with the isotope record. In Japan, the Kazusa and Shimosa Groups contain a record of isotope stages 82–13 (2.2–0.45 Ma) and stages 11–5 (0.4–0.13 Ma), respectively (e.g., Ito, 1992; Ito and Katsura, 1992).

The first detailed application of the sequence stratigraphic model to the interpretation of Pleistocene cyclothems was made by Abbott et al. (1989) and Abbott and Carter (1994), who described 10 superposed cyclothems from Wanganui, New Zealand, and correlated them with the interglacial parts of oxygen isotope stages 31–11 (0.95–0.35 Ma). The dominant sedimentary cycle recognized by Abbott and Carter (1994), termed the Castlecliff motif by Abbott and Carter (1999), comprises a lower interval of shallow-marine sands and transported shell beds (transgressive systems tract), an in situ or near situ mid-cycle shell bed, and an upper interval of shelf siltstone (highstand systems tract) (cf. Fig. 2).

WANGANUI BASIN

The south Wanganui basin is a 200 × 150 km, ovoid sedimentary basin situated in a backarc position with respect to the subducting plate boundary between the Pacific and Australian plates in North Island, New Zealand (Anderton, 1981) (Fig. 1). The modern continental shelf west of North Island is underlain from east to west by sediments of the Wanganui and Taranaki basins. Pliocene-Pleistocene subsidence and sedimentation have been concentrated in the vicinity of the Wanganui basin, and were attributed by Stern and Davey (1989, 1990) to the presence of a subjacent, locked, subducting plate interface, combined with foreland basin thrust loading at the zone of contact between the overriding Australian and subducting Pacific plates (Stern et al., 1992).

Sediments deposited in the northern Wanganui basin occur today beneath grassland hills on the western side of North Island, and have been uplifted at rates that increase eastward from ~0.3–0.5 m/k.y. at the coast to 1–3 m/k.y. along the forearc axial mountain range (Pillans, 1986). The sediments of the western and central parts of the basin, summarized herein (Fig. 3, insert), are well exposed in coastal cliffs to the northwest of Wanganui, and in four north-south river valleys, from west to east the Wanganui, Whangaehu, Turakina, and Rangitikei Rivers (Fig. 1). These sections are located roughly across depositional strike, and represent a basinal cross section from the western basin flank to the basin axis. Seven discrete types of cyclothem (sequence) occur within these sections, depending upon position in the basin (which determines the rate of subsidence), the rate of sediment supply, and the cycle of sea-level change.

The main Wanganui basin fill comprises a Pliocene-Pleistocene record of 43 cyclothems (sequences) that correspond to the shallow-marine, interglacial parts of isotope stages 100–11 (2.5–0.35 Ma) (Fig. 3). An overlapping and younger record of interglacial (odd-numbered) isotope stages 17–5 (0.68–0.09 Ma) is represented by a flight of 12 marine terraces that extend as far as 20 km inland and to 400 m above present sea level along the Wanganui coast. Pillans (1983, 1990) matched these terraces with the oxygen isotope scale, using radiocarbon, amino acid racemization, and tephrochronology for dating. Including the terrace record, we recognize 47 (rather than 50) cyclothems for the period covered by isotope stages 100–1 (2.5–0 Ma). The small sea-level change during three isotope stage pairs precludes their being represented by a full cyclothem in the sections studied. Cyclothems 12, 36, and 46 therefore each correspond to four isotope stages, i.e., stages 78–75, 26–23, and 6–3, respectively.

In addition to conventional biostratigraphy (Fleming, 1953; Beu and Edwards, 1984), newer correlation and dating methods are increasingly being applied to the study of the marine Pleistocene strata of the Wanganui basin. A paleomagnetic stratigraphy was established for the Rangitikei River by Seward et al. (1986), and for the Wanganui coast section by Turner and Kamp (1990). Ashes erupted from central North Island have been dated using fission-track, isothermal plateau–fission-track, and argon-argon methods (Seward 1974, 1976, 1979; Boellstorf and Te Punga, 1977; Kohn et al., 1992; Alloway et al., 1993; Pillans et al., 1994). Froggatt (1983; see also review in Froggatt and Lowe, 1990) developed a method of geochemical fingerprinting of individual eruptive events that allows precise correlation between separated sections. Although the earlier fission-track dates were not corrected for partial track annealing, and have proved to be too young, a combination of biostratigraphy, paleomagnetics, geochemical fingerprinting, and isothermal plateau fission-track and argon-argon dating now provides the high-quality chronologic framework (Pillans, 1994; Naish et al., 1996, 1998) on which we have based our stratigraphic study.

PLIOCENE-PLEISTOCENE SEQUENCE MOTIFS

The pre-terrace late Pliocene–Pleistocene fill of the northern Wanganui basin (Fig. 3, insert) comprises 43 superposed cyclothems or sequences, which total 1990 m in thickness in the Turakina River section in the axis of the basin. Strata thin westward, and cycles 23–32 are missing at an unconformity in the Wanganui coast section, where cycles 1–22 and 33–41 sum to only 670 m, a reduction of thickness from the basin axis of more than half. The 42 sequences span the period between isotope stage 100, just above the Gauss-Matuyama boundary (2.6 Ma), and isotope stage 11, which is in the mid-Brunhes chron (0.35 Ma). Paleomagnetic correlation between sequences in the five main sections, and with the oceanic oxygen isotope scale, is provided by the Brunhes-Matuyama boundary, the top and base of the Jaramillo and Olduvai boundaries, and the Gauss-Matuyama boundary (Pillans et al., 1994). In addition, 11 major silicic tephra horizons can be dated and traced throughout the basin (Pillans et al., 1994; Naish et al., 1996). Individual sequences can be traced laterally for as far as 70 km across the basin (Abbott, 1994).

Summary stratigraphic data for each basin cycle, and the designation of type sections, are presented in tabular form in Appendix 1.

The major sedimentary facies represented within the basin fill were deposited in a range of coastal plain, shoreface, and shelf marine environments during the late rise, highstand, and falling part of each glacio-eustatic cycle; i.e., the facies mostly represent interglacial oxygen isotope stages. In general, glacial stages are represented only by the surfaces of marine planation and bioerosion that mark the sequence boundaries at the base of each cyclothem . Marine ravinement and in situ boring pholad bivalves have removed all traces of nonmarine conditions at most such boundaries, apart from the rare preservation of subaerial surfaces (including soils) at some cycle boundaries near the inland edge of the basin (Abbott, 1992). In contrast to Permian-Carboniferous cyclothems, nonmarine facies are generally subordinate in the Wanganui basin Pliocene-Pleistocene, and the majority of the sections comprise sands, silts, and shell beds deposited in shoreface and shelf environments. Lowstand systems tract sediments deposited during glacial periods are sometimes thin nonmarine intervals between the marine cyclothems, and are referred to as LST^{nm} to distinguish them from the more voluminous marine lowstand systems tract deposits, LST, which accumulate far seaward, around the lowstand shoreline.

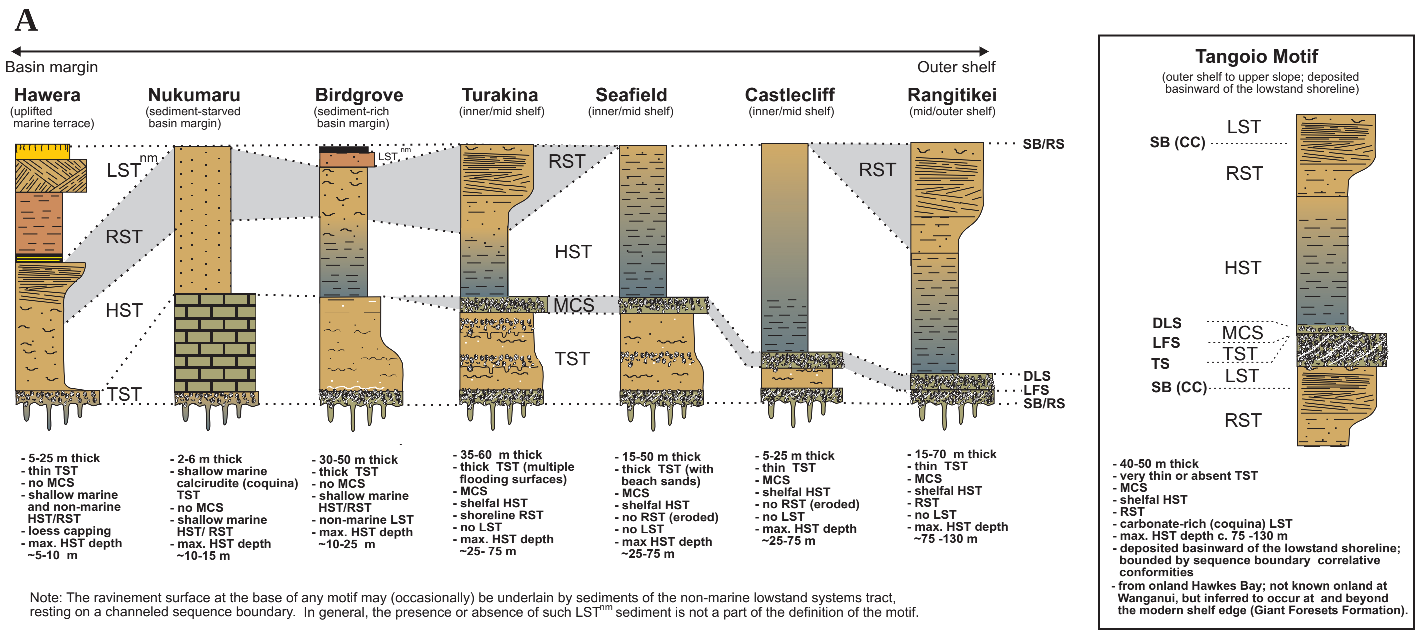
Seven major sequence motifs can be recognized (Table 2; Fig. 4) (Pillans, 1990; Abbott and Carter, 1994, 1997; Naish and Kamp, 1995, 1997a; Saul, 1994). Particular sequences may have a thin, often shelly transgressive systems tract (nondepositional transgression), a thicker, progradational transgressive systems tract (depositional transgression), or a transgressive systems tract containing more than one flooding surface (punctuated transgression). Systems tract terminology (see Table 1) is after Abbott and Carter (1994, 1997) and Naish and Kamp (1997a), and we follow Abbott and Carter (1994) in recognizing two main shell-bed types. Type A shell beds comprise cross-bedded, worn, and transported shell beds that occur within transgressive systems tracts, and not uncommonly directly overlie the basal sequence boundary. Similar shell beds were termed onlap shell beds by Naish and Kamp (1997a). Type B shell beds include well preserved, in situ faunal assemblages, including double-valved bivalves, and form the entire or major part of the mid-cycle shell bed that commonly straddles the junction between transgressive and highstand systems tracts. These shell beds represent the sediment-starved shelf surface, seaward of the shore-connected terrigenous sediment prism, and were called backlap shell beds by Naish and Kamp (1997a).

The seven sequence types summarized in Figure 4 all have boundaries with identifiable signs of subaerial exposure during glacial lowstands (soil, lignite, loess, karst formation), and/or marine ravinement during postglacial transgressions (sharp, eroded surfaces, sometimes with a transgressive shell lag; pholad borings or *Ophiomorpha* burrows). We therefore infer that most Wanganui cyclothems were deposited on the shelf, landward of the lowstand shoreline. Seaward of the lowstand shoreline, the subaerial sequence boundaries will pass into correlative conformities below the lowstand systems tract, and cyclothems will be delimited by flooding surfaces alone (cf. Galloway, 1989). In keeping with such a prediction, Haywick et al. (1992) described a Tangoio motif sequence (Fig. 4A, inset) that includes bioclastic marine sediment (coquina) which they inferred to have been deposited at the lowstand glacial shoreline. Similar terrigenous clastic sequences that culminate in lowstand sediments may occur rarely in the

TABLE 2. SEVEN CHARACTERISTIC CYCLOTHEM (SEQUENCE) MOTIFS FROM PLIOCENE-PLEISTOCENE TIME WHICH OCCUR IN THE WANGANUI BASIN

1. Hawera motif	Type: Sequence 44 (= stage 9a), at R22/785500, Kai-iwi Valley. Thin, shelly, TST, often with a basal conglomerate and including type A shell beds; overlain by a sandy, coarsening and shoaling upward HST, and shoreface sediments of the RST; overlying nonmarine sediments belong to the nonmarine LST, and generally include lignite and lacustrine mudstone. Thickness range, 4.4 –24 m; average 11.7 m. Coastal plain to innermost shelf; maximum HST water depth, 5–15 m.
2. Nukumaru motif	Type: Sequence NC-5, at R22/631483 in the Nukumaru coast section (Naish, Carter, unpublished data; correlated with cycle 9 of Table 4, = stage 83). TST (of trough cross-bedded coquina limestone with a mixed inner shelf–shoreface fauna, followed by a highstand systems tract of well sorted, fossiliferous, shoreface sand. Thickness range, 2.1–6.2 m; average, 3.9 m. Sediment-starved location on the inner shelf or offshore high; maximum HST water depth, about 10–15 m.
3. Birdgrove motif	Type: not designated; typical occurrence, Sequence 28 (= stage 43), near S22/102398, Turakina Valley. Thick, heterolithic TST, sometimes with inferred multiple flooding surfaces which separate prograding paracycles; MCS absent; HST dominated by bioturbated, sandy siltstones, with some estuarine faunas, passing up into RST-LST^{nm} fluvial heterolithic sandstone/siltstone, lacustrine mudstone, and lignite of coastal plain and swamp origin. Thickness range, 29–53 m; average 24.8 m. Coastal plain to inner shelf embayment; maximum HST water depth, about 10–25 m.
4. Turakina motif	Type: Sequence 17 (= stage 65), at T22/362385, Rangitikei Valley. Thick, heterolithic TST with associated estuarine and shoreface faunas, sometimes with inferred multiple flooding surfaces; MCS (type B shell bed) with in situ inner to middle shelf fauna; HST of massive bioturbated siltstone, coarsening upward and passing into RST shoreface sediment. Thickness range, 35–59 m; average (excluding one 185 m thick outlier cycle), 43.8 m. Sediment-rich location on the inner to middle shelf; maximum HST water depth, about 25–60 m.
5. Seafield motif	Type: Sequence 41 (= stage 15), at R22/756427, Castlecliff coast section. Moderately thick, sandy, progradational TST with shoreface faunas; MCS (type B shell beds) with middle shelf fauna; HST of massive siltstone. Equivalent to a top-truncated Turakina^{dt} sequence. Thickness range, 15–50 m; average, 25.9 m. Inner to middle shelf; maximum HST water depth, about 25–60 m. The TST of Seafield cyclothems represents shoreface progradation during a slow-down or reversal in sea-level rise, and/or an enhanced sediment supply.
6. Castlecliff motif	Type: Sequence 40 (= stage 17), at R22/750433, Castlecliff coast section. Thin, heterolithic TST, which often includes cross-bedded type A shell beds; MCS (type B shell bed) with offshore, middle shelf fauna; HST of massive siltstone. Equivalent to a top-truncated Turakina^{ndt} sequence, caused by RST erosion or nondeposition. Thickness range, 5–22 m; average, 13.4 m. Inner to middle shelf; maximum HST water depth, about 25–60 m.
7. Rangitikei motif	Type: Sequence 3 (= stage 95), at T22/433453, Rangitikei Valley. TST usually represented by a reworked shell lag, or thin basal shell bed, which grades up directly into an in situ MCS (type B shell bed); together, the basal lag and type B shell bed comprise a compound shell bed sensu Naish and Kamp (1997); HST of massive siltstone, coarsening upward into shallow shelf and shoreface sands of the RST. Thickness range, 15–68 m; average 34.3 m. Middle to outer shelf; maximum HST water depth about 50–130 m.

Note: LST—lowstand systems tract; TST—transgressive systems tract; MCS—mid-cycle shell bed; HST—highstand systems tract; RST—regressive systems tract. Water depths estimated using sedimentary facies analysis and comparison of fossil microfauna and macrofauna with their living counterparts.



B

	Average Systems Tract Thicknesses (m)					Sequence	
Count	Motif	TST	MCS	HST	RST	Range	Average
8	Hawera	0.9	0.0	10.8 (=HST+RST)		4.4-24	11.7
8	Birdgrove	19.3	0.0	5.5 (=HST+RST)		29-53	24.8
5	Turakina	17.0	0.6	12.3	14.0	35-185	43.9
15	Rangitikei	0.6	0.4	13.5	19.9	15-68	34.4
7	Castlecliff	2.8	0.8	9.9	0.0	5-22	13.5
8	Seafield	15.1	0.4	10.0	0.4	15-50	25.9

Figure 4. (A) Summary diagrams of the seven major sequence motifs represented among Wanganui basin cyclothems. Box: Eighth sequence motif (Tangoio) that incorporates lowstand marine sediments, from Hawke's Bay (after Haywick et al., 1992). Note that the motifs are based upon observed lithologies, shell beds, and the actual physical surfaces that separate them. For key to lettering, see caption to Table 1. Following Carter et al. (1998), we distinguish observable surfaces (SB—sequence boundary; RS—ravinement surface; LFS—local flooding surface; DLS—downlap surface) from the conceptual horizons of theoretical sequence stratigraphy (e.g., MFS, maximum flooding surface). (B) Summary of systems tract and sequence thicknesses for the motifs of A (extracted from Appendix 1). Cycle 1 is an abnormally thick Turakina motif sequence, and so is omitted from the calculated average.

Rangitikei section. For example, the surfaces between sequences 13 and 14 do not display clear evidence for subaerial erosion or ravinement (Naish and Kamp, 1995; 1997a).

Hawera motif cycles occur mainly in the tread of uplifted coastal terraces (isotope stages 5–17; Pillans, 1990). For older (higher) terraces, the lower terrace-tread marine cycle is overlain by the deposits of one or more younger climatic cycles, generally represented by a basal dune sand and a number of loesses (glacial) separated by soil or weathering horizons (interglacial) (e.g., Pillans and Wright, 1990; Palmer and Pillans, 1996). The fossil dune sands probably represent coastal sand blowout at highstand shorelines, when the interglacial terrace on which each rests was situated adjacent to the coast and was only a few tens of meters high. Similar Holocene dune sands occur along the last interglacial (Rapanui) terrace immediately inland from the present-day coast (Fleming, 1953). Sequences similar to the Hawera motif, but with thicker, sandy transgressive systems tracts, are characteristic of the late Pleistocene Shimosa Group in Japan (Tokuhashi and Kondo, 1989).

Faunal, sedimentological, and stratigraphic evidence indicates that the sequence types we have described represent successively more offshore locations on the paleoshelves that equate with each sequence (Fig. 5). The fluvial, lacustrine, lignitic, and shallow-marine facies within the Hawera and Birdgrove motifs correspond to coastal plain and innermost shelf depositional environments. Adjacent to the same shoreline but on the gradually emerging western flank of the basin, the coquina-dominated Nukumaru motif sequences also represent a shallow-water environment, here in a location starved of highstand terrigenous sediment. Farther offshore, on the middle shelf and on the basin flanks, Turakina, Castlecliff, and occasional Seafield motif sequences accumulated. Farthest offshore, toward the basin axis, Rangitikei motif sequences were deposited mostly inboard of the lowstand shoreline in outer shelf depths of 60 m or greater.

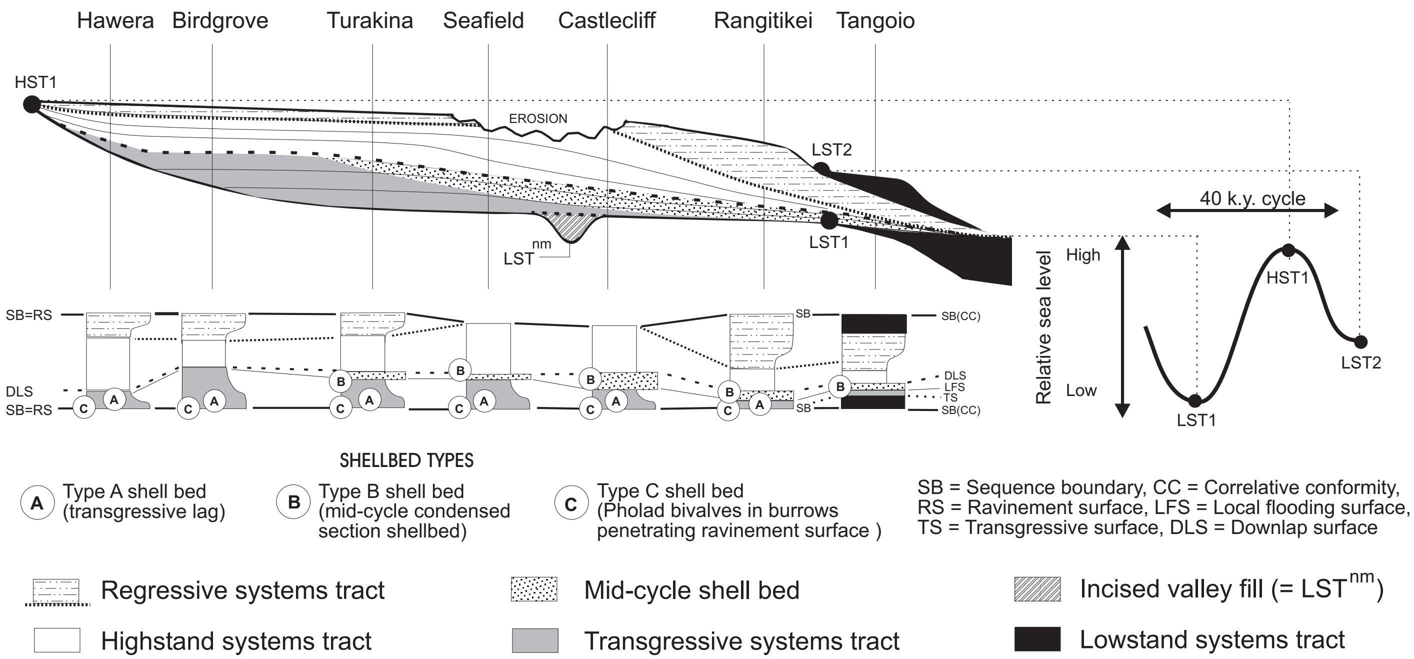


Figure 5. Wanganui and Tangoio cyclothem motifs depicted in relation to their paleogeographic position on the shelf, and their position with respect to sea-level highstand or lowstand. Key surfaces, shell beds, and systems tracts are indicated as appropriate. For the key to lettering, see the caption to Figure 2.

SURFACES, SHELL BEDS, AND THE RECOGNITION OF SEQUENCE ARCHITECTURE

Interpretation of the cyclicity in Pliocene-Pleistocene shallow-marine sequences, and recognition of the differing cyclothem motifs, depends on the correct identification of as many as five sediment-bounding surfaces associated with each cyclothem or sequence (Abbott and Carter, 1994). Accurate interpretation is also greatly aided by an understanding of the shell-bed types present, and the habitat of their faunas, as first appreciated by Fleming (1953) and as formalized by Carter et al. (1991). Naish (1996) and Naish and Kamp (1997a) presented a detailed genetic analysis of shell beds within the Pliocene part of the Rangitikei section, recognizing (partly after Kidwell, 1991) onlap, backlap, marine flooding, downlap, and compound shell-bed types.

In stratigraphic order, the important sediment-bounding surfaces are the lower sequence boundary, the ravinement surface, the local flooding surface, the downlap surface, and the upper sequence boundary (see Table 1 and Fig. 5). Sequence boundaries nearly always coincide with transgressive ravinement surfaces, and are sharply planed surfaces of marine erosion; when on siltstone, the boundaries are often penetrated by pholad borings, with shells sometimes preserved in situ (type C) shell bed; when on sandy substrate, the boundaries are often penetrated by *Ophiomorpha* and other burrows. Each sequence boundary is overlain by shallow marine, transgressive systems tract sands, or by a transgressive shell lag or a reworked (type A) shell bed. Local flooding surfaces are either sharp, burrowed surfaces or rapidly gradational contacts. They represent the level (or levels) in each cycle where rapid deepening and shoreline transgression (retrogradation) occurred. The uppermost, or single, local flooding surface is often marked by a superjacent, in situ (type B) shell bed with a relatively offshore, deeper water, fauna. The top of this mid-cycle shell bed is marked by the downlap surface, a rapidly gradational contact with siltstone of the overlying highstand systems tract.

In contrast with the intrasequence surfaces just described, and their associated shell beds, the theoretical maximum flooding horizon (equivalent to the maximum flooding surface of many authors), peak eustatic sea-level horizon, peak relative sea-level horizon, and the peak paleowater depth horizon. (Abbott and Carter, 1994; Carter et al., 1998) do not necessarily have any outcrop expression (Table 1). For example, Haywick and Henderson (1991), Abbott (1997a), and Naish and Kamp (1997b) presented faunal evidence that for some cyclothems the peak paleowater depth horizon occurs some distance above the downlap surface, within the basal highstand systems tract. Haywick showed that in late Pliocene sequences some systems tracts are separated across gradational contacts, notably the highstand systems tract–regressive systems tract and regressive systems tract–lowland systems tract. Understanding the difference between such theoretical (and therefore sometimes arbitrarily placed) horizons and the physical surfaces actually expressed in outcrop is an essential part of applying the lessons learned from the study of fifth- and sixth-order Pliocene-Pleistocene sequences to the interpretation of ancient third- and fourth-order sequences (Carter et al., 1998).

CONTROLS ON SEQUENCE PATTERN

The basic types of sequence motif described here (Fig. 4) are, to a degree, arbitrary generalizations in a spectrum of cyclothem types. The justification for their recognition and naming rests in the repetitive and robust recurrence of just these types over an extended stratigraphic and geographic range. But why these particular motifs and why are they so robust?

As sea level rises from a glacial low to an interglacial high, accommodation is created on the shelf within which sediment can accumulate. Terrigenous sediment supply is largely derived from the shoreline, and usually accumulates as a coastal, shore-connected sediment wedge. Seaward of this terrigenous wedge, the surface of the shelf is mantled by shell-hash facies. The rate

of change of accommodation is made up of two unequal parts: (1) space created by eustatic sea-level change, and (2) the rate at which the shelf substrate is subsiding, regional changes that also control the angle of slope of the shelf. Typical rates of sea-level rise during Pliocene-Pleistocene time were 10–30 m/k.y., and in the Wanganui basin the rates of subsidence varied from about 4 m/k.y. in the basin axis to less than half that on the flanks. Eustasy, aided by tectonics during periods of rising sea level, therefore results in very high rates of postglacial sea-level rise, and the rapid advance of transgressing shorelines across the shelf. On wide, shallowly sloping shelves, the shoreline may advance as rapidly as 10 km/k.y. Two results of this, well known from Holocene sediments on modern shelves, are the development of a thin, transgressive sand sheet, and the creation of drowned shorelines on the shelf at points where the rate of shoreline transgression abruptly outstrips the rate of sediment supply.

The key controls on the development of different types of sequence motif are as follows.

♦ The position on the paleoshelf where the sediment accumulates is a key control, because a particular location will control the total accommodation, and therefore the maximum water depth, and distance from the shoreline at highstand.

♦ The relationship between the rate of terrigenous sediment supply and the rate of change of sea level may change in magnitude during a eustatic cycle, and controls the thickness and nature of the transgressive and highstand systems tracts, and the presence or absence of a distinct mid-cycle shell bed.

Sequence types for different locations on the paleoshelf can therefore be represented by simple models that (ignoring tectonics) summarize the interaction between particular rates of sea-level rise or fall, and rates of sediment supply (Fig. 5) (Kamp and Naish, 1998). Noting that Wanganui cyclothems were deposited mostly during the interglacial parts of each climatic cycle, the following generalizations are drawn from the systematic variations in sequence motif across the Wanganui basin.

♦ Rangitikei motif sequences indicate deposition on the offshore shelf where subsidence rates were high, and highstand waters therefore relatively deep.

♦ Nukumaru motif sequences indicate deposition in a location starved of terrigenous sediment, for example on a basinal high, or in proximity to a deeply embayed shoreline.

♦ Castlecliff or Seafield motif sequences indicate that enhanced intercycle erosion occurred at their upper boundaries, which probably reflects slower or even reversed subsidence rates, i.e., decreasing accommodation through time.

♦ Birdgrove and Hawera motif sequences were deposited adjacent to a shoreline.

♦ Turakina motif sequences reflect an enhanced sediment supply, and were controlled by proximity to the sediment source.

Hawera motif sequences develop at locations within a few kilometers of the highstand shoreline, where rates of changing water depth, and shoreline transgression or regression, never outstrip the rate of terrigenous sediment supply. The transgressive and near-highstand sedimentary response, therefore, always represents positions within the contemporary shore-connected prism, and comprises a transgressive lag or deepening-up shoreface succession followed by a shallowing-up shoreface to coastal-plain succession. The highstand may be represented by a shell-rich facies, representing a relatively lower rate of sedimentation at distal shoreface depths, but a type B mid-cycle shell bed is usually absent. Because they represent locations within a few kilometers of the shoreline, Hawera motif cycles are particularly characteristic of the sediments preserved in latest Quaternary cycles, including on the treads of uplifted, late Quaternary terraces (Pillans, 1990; cf. Shimosa Group; Ito and O'Hara, 1994).

For locations on the paleoshelf that were seaward of the late transgressive and early highstand shore-connected sediment prism, the transgressive part of any sequence will be terminated above at a zone or surface of sediment starvation, above which is the local flooding surface and the highstand systems tract, with or without an intervening mid-cycle shell bed. For locations on the inner to middle shelf, moving from landward to seaward: (1) the mid-cycle shell bed will represent more time, and generally increase in thickness; and (2) the highstand and early regressive silts will generally become thinner, finer grained, and of deeper water aspect. Depending upon the nature of the transgressive systems tract, and the presence or absence of a mid-cycle shell bed, the sequence motif is Birdgrove or Turakina-Castlecliff-Seafield on the inner to middle shelf, and Rangitikei on the middle to outer shelf. All motifs may show a coarsening-upward trend in their highstand siltstones. Turakina and Rangitikei motif sequences are marked by the continuation of this trend to the point of development of a regressive shoreface (regressive systems tract).

Little terrigenous sediment accumulates on the outer shelf, beyond the seaward edge of the shore-connected sediment prism, during the interglacial portion of each eustatic cycle (e.g., Carter, 1975; Nelson et al., 1988). During highstands, therefore, the outer shelf is starved, and the cyclothems that develop can be predicted to be carbonate rich, lack a terrigenous highstand systems tract, and comprise stacked mid-cycle shell beds separated by thin transgressive shell beds (erosional transgression) or sandy transgressive systems tracts (depositional transgression). Such carbonate-rich, outer shelf cyclothems have not yet been recognized in the Pliocene-Pleistocene of either New Zealand or Japan.

SEQUENCE PATTERNS THROUGH SPACE AND TIME

Individual measured sections within the Wanganui basin are generally dominated by the presence of one persistent cyclothem motif (Fig. 3, insert). For example, the 10 cyclothems represented in the coastal Castlecliff section comprise 6 Castlecliff and 4 Seafield sequences (Abbott and Carter, 1994), and the 20 cyclothems described by Naish and Kamp (1995) from the middle Pliocene part of the Rangitikei section comprise 15 Rangitikei and 5 Turakina cycles. Similar bundling of cyclothem types has been described from Pennsylvanian strata (e.g., Heckel, 1994), and it is apparent that such systematic changes in cyclothem type are of basin-wide significance. Seismic and stratigraphic studies (Anderton, 1981; Fleming, 1953) show that during Pliocene-Pleistocene time the main depocenter of the Wanganui basin was located near the Turakina and Rangitikei Rivers, and the Wanganui coastal succession accumulated on the northwestern basin margin. The sequence motif changes that occur throughout the basin are consonant with the evolution of this architecture, and represent a high-frequency (mainly 40 k.y.) modulation superposed upon the tectonic cycles that created and shaped the basin on a time scale of hundreds of thousands of years. The tectonic control is reflected in the following way (Fig. 6).

1. As parts of the basin shallowed, i.e., as accommodation decreased through successive cycles, Rangitikei motif cycles were overlain successively by Castlecliff and Birdgrove or Hawera motif cycles. The inverse pattern Birdgrove-Castlecliff-Rangitikei is less clear, but probably characterizes basin deepening.

2. Gentle uplift affected the western basin margin during cycles 1–26 (Turakina passing to Nukumaru and Hawera motif cycles), at which time the margin became emergent for about 400 k.y. (1.55–1.10 Ma); a new cycle of subsidence, uplift, and eventual emergence occurred between 1.10 and 0.35 Ma (mainly Castlecliff motif cycles).

3. The tectonic-sedimentary phases recognized on the western basin margin propagated eastward across the basin with a time lag of ca. 80–200 k.y. between adjacent major sections, as best indicated by the systematically younger ages (from west to east) of the base and top of the basin-wide interval of Nukumaru-Hawera-Birdgrove motif cycles.

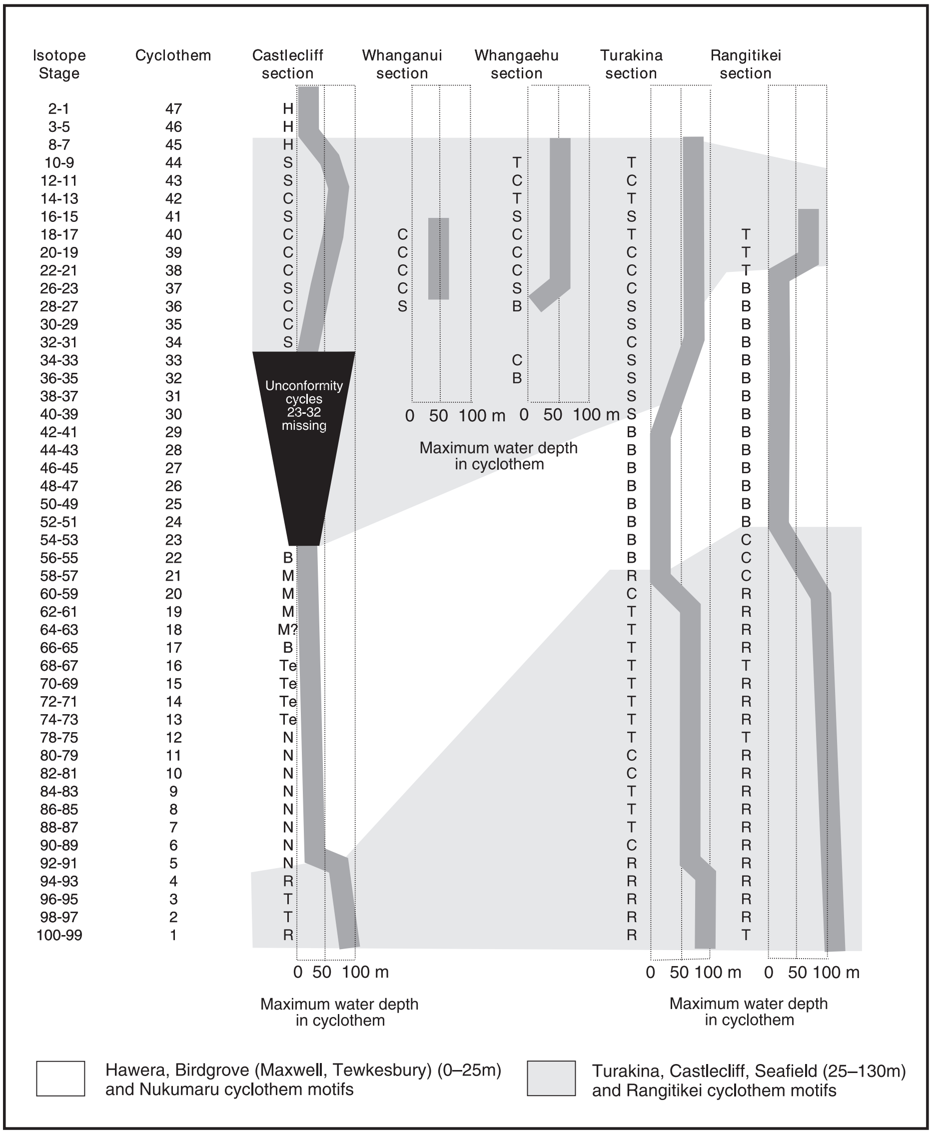


Figure 6. Time-space summary plot showing the distribution of the different types of cyclothem motif approximately along the line of section A–A′ (Fig. 1), Wanganui basin. Cyclothem motifs as follows: C—Castlecliff motif; H—Hawera motif; B—Birdgrove motif (variants, restricted to the coast section: Te—Tewkesbury; M—Maxwell); N—Nukumaru motif; R—Rangitikei motif; S—Seafield motif; T—Turakina motif.

The vertical and lateral changes in sequence motifs observed in the Wanganui basin correspond to phases of tectonic subsidence and inversion that are driven ultimately by plate tectonic forces (cf. Stern and Davey, 1989, 1990; Stern et al., 1992). These tectonic changes occur on a time scale of a few hundred thousand to a few million years, i.e., that of fourth- and third-order stratigraphic sequences of the Exxon type, and their effects may migrate in space and time within the basin. Tectonically driven cycles a few hundred thousand years long have also been documented from the accretionary prism on the eastern side of the New Zealand forearc (Lamb and Vella, 1987; Lamb, 1988), in the Banda arc (Fortuin and de Smet, 1991), in the Japanese forearc (Hiroki, 1994), and widely along the South American forearc (Flint et al., 1991). In studies of Pennsylvanian cyclothems of the cratonic interior, Chesnut (1994) and Heckel (1994) identified bundling of cyclothems into longer cycles on scales of 0.2–0.7 m.y. and 1.1–4.3 m.y., and attributed them to phases of flexural subsidence and unloading. Peper et al. (1992) showed by modeling that periodic tectonic movements caused by intraplate stresses may attain a vertical magnitude of tens of meters on time scales of a few hundred thousand years.

There is therefore no doubt regarding the widespread existence of natural tectonic-sedimentary cycles that overlap in duration with third- and fourth-order sequences of the Exxon type (Miall, 1996). There is also little doubt that strongly cyclothemic, fifth- and sixth-order cycle sediments, such as those described herein, are restricted to geological periods of known glacio-eustasy (e.g., Permian-Carboniferous, Pliocene-Pleistocene). The sequence stratigraphic model has been vindicated elsewhere as a powerful means of interpreting Pliocene-Pleistocene cyclothemic sediments (Abbott and Carter, 1994; Naish and Kamp, 1997a). We have shown (Figs. 3 and 6) that, although individual sequence motifs are controlled by glacio-eustasy, the longer scale bundling of motifs occurs in concert with basinal tectonic cycles with a length of a few hundred thousand to a few million years. For other parts of the stratigraphic column, where high-frequency glacio-eustasy is absent, onlapping and offlapping sedimentary cycles with a periodicity of 10^5 to 10^6 yr and a thickness of 10^2 to 10^3 m should be common, as is indeed observed to be the case for fourth- and third-order sequences of the Exxon type.

On the basis of rigorous tests of the sequence stratigraphic model as applied to Pliocene-Pleistocene cyclothemic strata, we conclude that cycles of tectonic subsidence and inversion, rather than glacio-eustasy, were the driving force behind the development of many ancient fourth- and third-order unconformity-bounded sequences. A similar conclusion was reached by Watts (1982, 1989) and Watts et al. (1982). Although it is clear that the fifth- and sixth-order sequences of Pliocene-Pleistocene time reflect glacio-eustasy, for longer period cycles "the availability of tectonic mechanisms to explain stratigraphic cyclicity of all types and at all geological time scales removes the need for global eustasy as a primary mechanism for the generation of stratigraphic architectures" (Miall, 1996, p. 270).

CONCLUSIONS

Our study of the Pliocene-Pleistocene cyclothems of the Wanganui basin leads to the following general conclusions.

1. As the Wanganui basin subsided and filled, changes in sequence motif occurred throughout the stratigraphic column. The basin fill comprises superposed groups of sequences that successively match the Rangitikei, Turakina-Castlecliff-Seafield, Birdgrove, Nukumaru, and Hawera cyclothem motifs. A shallowing succession is

marked by a change from Rangitiki through Castlecliff to Birdgrove-Hawera motifs, and a deepening succession by the opposite trend.

2. Changes in sequence motif occur through space and time as a basin deepens, or shallows, or its axis migrates. In contrast with the 41 000 year periodicity of most of the glacio-eustatic cyclothems, the driving tectonic cycles that shaped the Wanganui basin have a periodicity of several hundred thousand to more than a million years.

3. During Permian-Carboniferous and Pliocene-Pleistocene times there were repetitive, high-frequency, global sea-level changes. Accordingly, shelf sediments of those ages display striking cyclothem (or sequence) motifs, each of which represents deposition during an individual glacio-eustatic cycle. The lack of cyclothems throughout the rest of the stratigraphic record, combined with the widespread presence of unconformity-bounded sequences, suggests that tectonic subsidence is the primary cause of third- and fourth-order sequence development during nonglacial geological periods.

4. The cyclothem motifs so far recognized within the Wanganui basin all represent deposition landward of the lowstand shoreline, and are therefore bounded by marine ravinement surfaces that were superimposed upon preexisting sequence boundaries. Each cyclothem is therefore equivalent to a sequence, and also to a transgressive-regressive cycle.

In contrast, the Tangoio sedimentary motif from Hawkes Bay is inferred to represent deposition at and below a carbonate-rich lowstand shoreline, which results in an absence of transgressive ravinement surfaces, and sequence boundaries that are represented by correlative conformities beneath each marine lowstand systems tract (that are within the limestone units). The Tangoio cyclothem motif (limestone-siltstone couplet, as mapped by Haywick et al., 1992), thereby differs from the sequence motif (mid-limestone to mid-limestone). In circumstances like this, transgressive-regressive cycles correspond to the sequences but not the cyclothems.

We conclude that where the sequence stratigraphy is understood, the use of transgressive-regressive cycles offers no nomenclatural or other advantage over the recognition of cyclothems and sequences.

5. In contrast with the largely marine Pliocene-Pleistocene motifs describes so far from New Zealand, the widespread Illinois and Appalachian motif cyclothems from the Pennsylvanian strata of the United States include a well-developed nonmarine interval that often contains channelized sandstone and coal. This difference may be because the Pennsylvanian cyclothems were deposited by transgression of a 2000-km-wide intracratonic sea across a coastal plain with large, deeply incised meandering rivers, whereas the Pliocene-Pleistocene cyclothems are associated with smaller, shallowly incised braided rivers in small basins in active tectonic areas. Or, there may have been a significant difference in the frequency of eustasy between the two time periods, because apparently there was more time in the Pennsylvanian Epoch for the development of mature fluvial systems during glacial lowstands.

ACKNOWLEDGMENTS

We thank the landowners of properties in the Wanganui basin for their permission to access the sections described in this paper, and acknowledge financial support toward this research by the Australian Research Council, and James Cook University, Townsville. We also thank the referees for the constructive comments they offered. Poster versions of Figure 3 (insert) in various sizes may be purchased from the School of Earth Sciences, James Cook University, Townsville, New Zealand.

APPENDIX

See Table A1 on pages 534 and 535.

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TABLE A1. SUMMARY LOCATION AND SEQUENCE STRATIGRAPHIC DATA FOR THE 47 SEDIMENTARY CYCLES OF THE PLIOCENE-PLEISTOCENE OF THE WANGANNI BASIN

Cycle	Isotope stages	Grid reference: Sheet	Grid reference: GR	Location: Valley/coast (C)	Location: Description	Base: Type	Base: Burr.	Base: Lithology	Systems tract thickness					Sequence motif		Chronostratigraphic markers
									TST	HST/RST		Tot.	loess/dunesand		T = type cycle for motif	
47	3	Q22	390574	Whenuakura (C)	Low coastal cliff 100 m north of Whenuakura River mouth (Rakaupiko Terrace)	Sharp	—	Marine conglomerate on sandstone	2.4	2		4.4	1.5	Hawera		
46	5a	Q22	482521	Wairoa (C)	Low coastal cliff 200 m southeast of Wairoa Stream mouth (Hauriri Terrace)	Sharp	P	Shelly, pebbly lag on siltstone	0.7	6.1		6.8	0.7	Hawera		
46	5c	Q21	103794	Inaha (C)	Coastal cliff just northwest of Inaha Stream mouth (Inaha Terrace)	Sharp	P	Marine boulder bed on sandstone	2	22*		24	1.4	Hawera		*(thickness omits a 9 m lahar)
46	5e	Q21	465610	Kohi	Top of roadcut on north side of Kohi Stream (Rapanui Terrace)	Sharp	P	Pebbly sandstone on siltstone	0.2	6.7		6.9	4.7	Hawera		
45	7	R21	524637	Moumahaki	Roadcut at southwest-pointing bend of Omahina Road (Ngarino Terrace)	Sharp	—	Pebbly marine sandstone on sandy siltstone	0.1	8		8.1	5	Hawera		(thickness omits a 9-m-thick lahar)
44	9a	R22	785500	Kai-iwi	Roadcut on south side of Brunswick Road (Brunswick Terrace)	Sharp	—	Marine sandstone on siltstone	0.5	13		14	11	Hawera	T	
44	9c	S22	026380	Whangaehu	Roadcut on west side of Kauangaroa Rd, toward top of hill (Braemore Terrace)	Sharp	P	Pebbly marine sandstone on siltstone	0.2	18		17.8	9	Hawera		[Fordell T., Upper Griffins Road T.]
									TST	MCS	HST	RST	Tot.	—		
43	11	R22	769415	Castlecliff (C)	Above Tainui Shellbed Buttress, 4200 m southeast of Omapu Stream	Sharp	O	*Paphies* shell bed (A) on siltstone	8	1.8	7	0	17	Seafield		[Rangitawa T.]
42	13	R22	761424	Castlecliff (C)	Half-way up vegetated cliff slope, 3100 m southeast of Omapu Stream	Biot.	O	*Antisolarium* sandstone on siltstone	5.5	4.5	9	0	19	Castlecliff		
41	15	R22	756427	Castlecliff (C)	Ledge along top of Shag Rock, 2400 southeast of Omapu Stream	Sharp	P	Pebbly (Tom's) shell bed (A) on siltstone	21	1.5	1.5	0	24	Seafield	T	
40	17	R22	750433	Castlecliff (C)	Vegetated low cliff at back of beach, 1700 m southeast of Omapu Stream	Sharp	P	*Cyclomactra* shell bed (A) on siltstone	3.3	0.3	8	0	12	Castlecliff	T	Kupe T. (TST)
39	19	R22	740440	Castlecliff (C)	Bluff at beach level below high cliff, 450 m southeast of Omapu Stream	Sharp	P	*Paphies* shell bed (A) on siltstone	2.8	0.3	17	0	20	Castlecliff		B/M boundary
38	21	R22	734444	Castlecliff (C)	Southeast-dipping ledge to below beach level, 400 m northwest of Omapu Stream	Sharp	O	*Ophiomorpha* sandstone on siltstone	1	0.1	7	0	8.1	Castlecliff		Kaukatea T. (MCS)
37	25-23	R22	707458	Castlecliff (C)	Lower-middle slopes of high cliff just southeast of Okehu Stream	Sharp	P	Pebbly very coarse sandstone on siltstone	11	0.1	14	3	28	Seafield		Kaimatira T. (TST, rew.)
36	27	R22	707458	Castlecliff (C)	At base of high cliff just southeast of Okehu Stream	Sharp	P	Lower Okehu shell bed (A) on siltstone	2.8	0.3	5	0	8.1	Castlecliff		Top Jaramillo (Potaka T.)
35	29	R22	690464	Castlecliff (C)	Southeast dipping shell bed at beach level, 1700 m northwest of Okehu Stream	Sharp	—	Mowhanau shell bed (A) on siltstone	2	0.2	20	0	22	Castlecliff		
34	31	R22	667473	Castlecliff (C)	Halfway up south slope of Ototoka Stream, at coast	Sharp	O	Butlers shell bed (A) on siltstone	15	0	0	0	15	Seafield		Base Jaramillo
33	33	S22	092361	Turakina	Roadcut just south of small bridge, east side of Turakina Valley Road	Sharp	—	Pebbly shell bed (A) on siltstone with *Maorimactra* shell beds.	10	0	40	0	50	Seafield		
32	35	S22	095375	Turakina	On farm track, east of Turakina Valley Road	Sharp	—	Pebbly shelly sandstone (A) on sandy siltstone	13	0	18	0	30	Seafield		Rewa T. (TST)
31	37	S22	096385	Turakina	Roadcut, east side of Turakina Valley Road, south of farm-track bridge	Sharp	?P	Pebbly shell bed (A) on heterolithic sandstone/siltstone	18	0	0	0	18	Seafield		Unnamed ash (top TST)
30	39	S22	099393	Turakina	Near base of outcrop in northwest pointing bend, east side Turakina Valley Road	Not seen	—	Base inferred, not seen in outcrop	25	0	0	0	25	Seafield		
29	41	S22	103395	Turakina	Roadcut, east side of Turakina Valley Road	Sharp	—	Nonmarine mudstone on nonmarine mudstone and sandstone/siltstone.	2.5	0	10	20	33	Birdgrove		
28	43	S22	102398	Turakina	Below base of section in east bank of Turakina River, below road	Not seen	—	Base inferred, not seen in outcrop	11	0	5	10	26	Birdgrove	*	
27	45	S22	104403	Turakina	Farm track cutting, 30 m east of Turakina Valley Road	Sharp	—	Heterolithic with *Austrovenus* on reworked sandy ash	15	0	3	7	25	Birdgrove		
26	47	S22	116406	Turakina	High cliff above Turakina Valley Road, 50 m above Pahikura tephra	Sharp	—	Heterolithic sandstone/siltstone on nonmarine mudstone	22	0	3	7	32	Birdgrove		Mangapipi Ts. (TST and RST)
25	49	S22	114409	Turakina	1 m above road level, south end of large roadcut in Pahikura tephra	Sharp	—	Sandstone on nonmarine mudstone	32	0	7	14	53	Birdgrove		Pakihikura T. (TST)
24	51	S22	117413	Turakina	West end of river cliff on south bank, near water level just above bridge	Not seen	—	Undetermined; possibly coarse shelly sandstone on nonmarine siltstone.	35	0	4	9	48	Birdgrove		Birdgrove T. (TST)
23	53	S22	117421	Turakina	Small west bank promontery below farm track, 4 m above river level	Sharp	—	Sandstone on nonmarine mudstone	5	0	7	14	26	Birdgrove		Mangahou T. (RST)

TABLE A1. (*Continued*).

Cycle	Isotope stages	Grid reference Sheet	GR	Location Valley/coast (C)	Description	Base Type	Burr.	Lithology	Systems tract thickness TST	MCS	HST	RST	Tot.	Sequence motif		Chronostratigraphic markers
									TST	MCS	HST	RST	Tot.	—	T = type cycle for motif	
22	55	S22	133418	Turakina	Small road cut, on corner just north of stream	Sharp	—	Shell bed (A) on nonmarine mudstone	33	0	5	11	49	Birdgrove		Ototoka T. (TST)
21	57	S22	137427	Turakina	South end of long road cut, immediately east of river	Sharp	—	Shell bed (A), 2 m relief, large siltstone boulders, on nonmarine siltstone	2.2	0.5	15	30	48	Rangitikei		
20	59	S22	138428	Turakina	North end of long road cut, immediately east of river	Sharp	—	Sandy heterolithic sediment on nonmarine siltstone	2	0.2	3	0	5.2	Castlecliff		
19	61	T22	355376	Rangitikei	South end of high west bank cliff, near base	Grades?	—	Shell bed on silty sandstone	0.1	0.4	8	17	26	Rangitikei		Vinegar Hill T. (HST)
18	63	T22	350394	Rangitikei	At road level, midway along west side road cut	Sharp	O	Waipuru shell bed (A) on sandstone	0.5	1.5	6	20	28	Rangitikei		Top Olduvai
17	65	T22	362385	Rangitikei	Cutting on east side of farm track	Sharp	O	Shell bed (A) on heterolithic siltstone/sandstone	18	0.5	17	9	45	Turakina	T	Pliocene-Pleistocene boundary (DLS)
16	67	T22	359386	Rangitikei	South end of high east bank cliff, near base	Sharp	O	Shell bed (A) on sandstone	14	1.5	6	15	37	Turakina		Waipuru T. (TST)
15	69	T22	361387	Rangitikei	Midway along high east bank cliff, near base	Sharp	O	Shell bed (A) on sandstone	0.2	0.3	12	11	60	Rangitikei		
14	71	T22	376407	Rangitikei	North end of high east bank cliff, near base	Grades	—	Shell bed on sandy siltstone	0	0.3	18	19	61	Rangitikei		Base Olduvai
13	73	T22	410416	Waipuru	Midway along east side road cut, toward top	Sharp	O	Shell bed (A) on sandstone	0.2	0.3	12	2	15	Rangitikei		
12	77-75	T22	394417	Mangamako	North bank of stream, 500 m upstream from confluence	Sharp	—	Mangamako shell bed (A) on heterolithic siltstone/sandstone	27	0.3	12	20	59	Turakina		
11	79	T22	414424	Mangamako	South stream slope, just beneath terrace top and behind house	Sharp	—	Shell bed (A) on sandstone	9	0	14	12	35	Turakina		
10	81	T22	433427	Mangamako	Near base of east side road cut, in southeast corner of bend	Sharp	P	Shell bed (A) on heterolithic siltstone/sandstone	2	0.3	6	27	35	Rangitikei		
9	83	T22	393427	Rangitikei	Midway along high east bank cliff, at mid-height	Grades?	—	Shell bed on sandstone	0	0.2	8	20	28	Rangitikei		Ohingaiti T. (RST)
8	85	T22	394433	Rangitikei	North end of high east bank cliff, near base	Sharp	O	Shell bed on sandstone	0	0.2	11	8	19	Rangitikei		
7	87	T22	393435	Rangitikei	200 m south of north end of high east bank cliff, near base	Sharp	O	Shell bed (A) on sandstone (= Ohingaiti Sandstone)	0.3	0.2	8	20	29	Rangitikei		
6	89	T22	395447	Rangitikei	Southeast corner of meander, near base of high east bank cliff	Grades?	O	Shell bed (A) on sandstone	2.5	0.4	23	28	54	Rangitikei		
5	91	T22	427440	Rangitikei	400 m south of north end of high east bank cliff, near base	Sharp	O	Shell bed on silty sandstone	0.1	0.5	28	18	47	Rangitikei		
4	93	T22	440445	Rangitikei	East side roadcut, on corner 200m uphill from hairpin bend	Sharp	O	Shell bed (A) on silty sandstone	0.7	0.3	10	7	18	Rangitikei		
3	95	T22	433453	Rangitikei	Road cut near hilltop, Otara Road	Sharp	O	Shell bed (A) on sandstone (= Tuha Sandstone)	0.2	0.4	13	27	41	Rangitikei	T	
2	97	T22	436457	Rangitikei	Low cliff on east bank of river, north of Otara Bridge	Sharp	O	Hautawa shell bed on silty sandstone	0.1	0.3	24	44	68	Rangitikei		FAD *Zygochlamys delicatula*
1	99	T22	500474	Mangarere	Stream section, just below north side of road	Sharp	G	Shell bed (A) at base of Te Rimu Sandstone on siltstone	95	0	70	20	185	Turakina		

Note: Location information for the type locality of each of sequences 1 to 47, Wanganui basin. Grid references given apply to map series NZMS-260, and to the locations of the base of each sequence. Type cycles for five terrigenous cyclothem motifs are indicated by T. The asterisk against cycle 28 indicates a typical Birdgrove cycle with a well-exposed top boundary; a formal type locality designation for this motif awaits further work. Squared brackets around the names of some tephra indicate that they occur only within the tread of uplifted coastal terraces. Terrace stratigraphy is largely after Pillans (1990). Because of the difficulty of separating autocyclic and sea-level–controlled facies changes within the Birdgrove motif, post-transgressive system tract Birdgrove sediment is arbitrarily assigned one-third to the HST and two-thirds to the RST/LST^{nm} (see Table 2). Only rarely (e.g., top of cycle 28) is the LST^{nm} identifiable as a discrete nonmarine mudstone and/or lignite interval between an erosional sequence boundary and a marine ravinement surface. FAD—first appearance datum.

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Manuscript Received by the Society September 22, 1997
Revised Manuscript Received May 5, 1998
Manuscript Accepted May 22, 1998

Printed in U.S.A.