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 cycloithemic, 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 cyclothsms 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 41000 year length of individual glacio-

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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 terrigenous cyclothem and one biostratigraphic 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-
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-upward deposits, a midcycle condensed section, a regressive systems tract, and a transgressive systems tract. The sediments within each unit are described in terms of their sedimentary facies and the inferred sea-level positions at which they were deposited.

**Table 1. Sequence Stratigraphic Terminology and Abbreviations Used in This Paper**

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

**Surfaces (occur in outcrop)**

<table>
<thead>
<tr>
<th>Surface</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DLS</td>
<td>Downlap surface</td>
</tr>
<tr>
<td>LFS</td>
<td>Local flooding surface</td>
</tr>
<tr>
<td>RS</td>
<td>Ravinement surface</td>
</tr>
<tr>
<td>SB</td>
<td>Sequence boundary</td>
</tr>
<tr>
<td>PEH</td>
<td>Peak eustatic sea-level horizon</td>
</tr>
<tr>
<td>PRH</td>
<td>Peak relative sea-level horizon</td>
</tr>
<tr>
<td>PWH</td>
<td>Peak paleowater depth horizon</td>
</tr>
<tr>
<td>MFH</td>
<td>Maximum flooding horizon</td>
</tr>
</tbody>
</table>

**Horizons (theoretical levels)**

- **PEH**: Peak eustatic sea-level horizon
- **PRH**: Peak relative sea-level horizon
- **PWH**: Peak paleowater depth horizon
- **MFH**: Maximum flooding horizon

*Figure 1. Location map and west-east tectonic cross section showing the location of the Wanganui basin.*
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—lowstand systems tract, nonmarine; TST—transgressive systems tract; MCS—mid-cycle shell bed; HST—highstand systems tract; RST—regressive systems tract.

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 stratig-
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 sccale 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 hom клиnally 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 (Mered 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 Taraanki 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 sub-jacent, 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 (2.5–0.0 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; Boellstorff 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 1900 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 out through 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).
5. Seafield motif Type: Sequence 41 (= stage 15), at R22/756427, Castlecliff coast section.

6. Castlecliff motif Type: Sequence 40 (= stage 17), at R22/750433, Castlecliff coast section.

3. Birdgrove motif Type: not designated; typical occurrence, Sequence 28 (= stage 43), near S22/102398, Turakina Valley.

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).

7. Rangitikei motif Type: Sequence 3 (= stage 95), at T22/433453, Rangitikei Valley.

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Water depths estimated using sedimentary facies analysis and comparison of fossil microfauna and macrofauna with their living counterparts.

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 Ophio-morpha burrows). We therefore infer that most Wanganui cyclothem deposits were 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 cyclothsoms 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**

<table>
<thead>
<tr>
<th>Motif</th>
<th>Type</th>
<th>Sequence</th>
<th>Stage</th>
<th>Location</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hawera</td>
<td>Sequence 44 (= stage 9a), R22/785500</td>
<td>Kai-iwi</td>
<td>9a</td>
<td>Valley</td>
<td>Thin, shelly, TST, with cross-bedded type A shell beds; overlay by sandy coarsening and sh allowed upward HST, and shoreline facies of the RST; overlying nonmarine sediments belong to the nonmarine LST, and generally include lignite and lacustrine shale. Thickness range, 25–60 m; average, 40.2 m. Coastal plain to innermost shelf; maximum HST water depth, about 5–15 m.</td>
</tr>
<tr>
<td>Nukumaru</td>
<td>Sequence NC-5, R22/631483</td>
<td>Nukumaru</td>
<td>5</td>
<td>Coast section</td>
<td>Thick, heterolithic TST, with cross-bedded type A shell beds; overlay by sandy coarsening and shallowed upward HST, and shoreline facies of the RST; overlying nonmarine sediments belong to the nonmarine LST, and generally include lignite and lacustrine shale. Thickness range, 25–60 m; average, 40.2 m. Coastal plain to innermost shelf; maximum HST water depth, about 5–15 m.</td>
</tr>
<tr>
<td>Birdgrove</td>
<td>Type not designated; Sequence 28 (= stage 43), R22/102398, Turakina Valley</td>
<td>Turakina</td>
<td>6</td>
<td>Valley</td>
<td>Thick, heterolithic TST, with cross-bedded type A shell beds; overlay by sandy coarsening and shallowed upward HST, and shoreline facies of the RST; overlying nonmarine sediments belong to the nonmarine LST, and generally include lignite and lacustrine shale. Thickness range, 25–60 m; average, 40.2 m. Coastal plain to innermost shelf; maximum HST water depth, about 5–15 m.</td>
</tr>
<tr>
<td>Seafield</td>
<td>Sequence 41 (= stage 15), R22/756427</td>
<td>Castlecliff coast section</td>
<td>15</td>
<td>Valley</td>
<td>Moderately thick, sandy, progradational TST with shoreline facies; overlay by sandy coarsening and shallowed upward HST, and shoreline facies of the RST; overlying nonmarine sediments belong to the nonmarine LST, and generally include lignite and lacustrine shale. Thickness range, 25–60 m; average, 40.2 m. Coastal plain to innermost shelf; maximum HST water depth, about 5–15 m.</td>
</tr>
<tr>
<td>Castlecliff</td>
<td>Sequence 40 (= stage 17), R22/750433</td>
<td>Castlecliff coast section</td>
<td>17</td>
<td>Valley</td>
<td>Thick, heterolithic TST, with cross-bedded type A shell beds; overlay by sandy coarsening and shallowed upward HST, and shoreline facies of the RST; overlying nonmarine sediments belong to the nonmarine LST, and generally include lignite and lacustrine shale. Thickness range, 25–60 m; average, 40.2 m. Coastal plain to innermost shelf; maximum HST water depth, about 5–15 m.</td>
</tr>
<tr>
<td>Rangitikei</td>
<td>Sequence 3 (= stage 95), T22/433453</td>
<td>Rangitikei Valley</td>
<td>95</td>
<td>Valley</td>
<td>Thin, heterolithic TST, with cross-bedded type A shell beds; overlay by sandy coarsening and shallowed upward HST, and shoreline facies of the RST; overlying nonmarine sediments belong to the nonmarine LST, and generally include lignite and lacustrine shale. Thickness range, 25–60 m; average, 40.2 m. Coastal plain to innermost shelf; maximum HST water depth, about 5–15 m.</td>
</tr>
</tbody>
</table>

**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.
SEDIMENTARY CYCLICITY, WANGANUI BASIN, NEW ZEALAND

A

B

Average Systems Tract Thicknesses (m)

<table>
<thead>
<tr>
<th>Count</th>
<th>Motif</th>
<th>TST</th>
<th>MCS</th>
<th>HST</th>
<th>RST</th>
<th>Range</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>Hawera</td>
<td>0.9</td>
<td>0.0</td>
<td>10.8</td>
<td>(+HST+RST)</td>
<td>4.4-24</td>
<td>11.7</td>
</tr>
<tr>
<td>8</td>
<td>Birdgrove</td>
<td>19.3</td>
<td>0.0</td>
<td>5.5</td>
<td>(+HST+RST)</td>
<td>29-53</td>
<td>24.8</td>
</tr>
<tr>
<td>5</td>
<td>Turakina</td>
<td>17.0</td>
<td>0.6</td>
<td>12.3</td>
<td></td>
<td>35-185</td>
<td>43.9</td>
</tr>
<tr>
<td>15</td>
<td>Rangitikei</td>
<td>0.6</td>
<td>0.4</td>
<td>13.5</td>
<td></td>
<td>15-68</td>
<td>34.4</td>
</tr>
<tr>
<td>7</td>
<td>Castlecliff</td>
<td>2.8</td>
<td>0.8</td>
<td>9.9</td>
<td></td>
<td>5-22</td>
<td>13.5</td>
</tr>
<tr>
<td>8</td>
<td>Seafield</td>
<td>15.1</td>
<td>0.4</td>
<td>10.0</td>
<td></td>
<td>15-50</td>
<td>25.9</td>
</tr>
</tbody>
</table>

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.

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SHELLBED TYPES

A Type A shell bed (transgressive lag)
B Type B shell bed (mid-cycle condensed section shellbed)
C Type C shell bed (Pholad bivalves in burrows penetrating ravinement surface)

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, ravinement, and incised valley fill (= LST<sup>nm</sup>) surfaces. For key to lettering, see caption to Figure 2. Erosion and Kamp (1997b) presented faunal evidence that for some cyclothems the peak eustatic sea-level horizon, peak palaeowater depth horizon, and 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 palaeowater 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 palaeowater 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.

1. **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.**

2. **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 cyclothemcs 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 shelf bed. For locations on the inner to middle shelf, moving from landward to seaward: (1) the mid-cycle shelf 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 shelf 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 tracts).

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 cyclothsms 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 cyclothsms 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 cyclothsms represented in the coastal Castlecliff section comprise 6 Castlecliff and 4 Seafield sequences (Abbott and Carter, 1994), and the 20 cyclothsms 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 Pennsylvania 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.
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-stratigraphic 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 described so far from New Zealand, the widespread Illinois and Appalachian motif cyclothems from the Pennsylvania 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 Pennsylvania 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.  

Appendix  

See Table A1 on pages 534 and 535.  

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### Table A.1. Summary Location and Sequence Stratigraphic Data for the 47 Sedimentary Cycles of the Pliocene-Pleistocene of the Wanganui Basin

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Isotope stages</th>
<th>Grid reference</th>
<th>Valley/coast (C)</th>
<th>Location</th>
<th>Description</th>
<th>Type</th>
<th>Burr.</th>
<th>Lithology</th>
<th>Systems tract thickness</th>
<th>Sequence motif</th>
<th>Chronostratigraphic markers</th>
</tr>
</thead>
<tbody>
<tr>
<td>47</td>
<td>3</td>
<td>Q22 390574</td>
<td>Whenuakura (C)</td>
<td>Low coastal cliff 100 m north of Whenuakura River mouth (Rakau Stream)</td>
<td>Sharp —</td>
<td>Marine conglomerate on sandstone</td>
<td>2.4</td>
<td>2</td>
<td>4.4 1.5</td>
<td>Hawera</td>
<td>T = type cycle for motif</td>
</tr>
<tr>
<td>46</td>
<td>5a</td>
<td>Q22 482521</td>
<td>Wairoa (C)</td>
<td>Low coastal cliff 200 m southeast of Wairoa Stream mouth (Hauriri Terrace)</td>
<td>Sharp P</td>
<td>Shelly, pebbly lag on silstone</td>
<td>0.7</td>
<td>6.1</td>
<td>6.8 0.7</td>
<td>Hawera</td>
<td></td>
</tr>
<tr>
<td>46</td>
<td>5c</td>
<td>Q21 103794</td>
<td>Inaha (C)</td>
<td>Coastal cliff just north of mouth of Inaha Stream (Inaha Terrace)</td>
<td>Sharp P</td>
<td>Marine boulder bed on sandstone</td>
<td>2.22</td>
<td>24</td>
<td>24 1.4</td>
<td>Hawera</td>
<td><em>(thickness omits a 9.3 m lahar)</em></td>
</tr>
<tr>
<td>46</td>
<td>5e</td>
<td>Q21 465610</td>
<td>Kohi</td>
<td>Top of roadcut on north side of Kohi Stream (Rapanui Terrace)</td>
<td>Sharp P</td>
<td>Pebbly sandstone on silstone</td>
<td>0.2</td>
<td>6.7</td>
<td>6.9 4.7</td>
<td>Hawera</td>
<td>T</td>
</tr>
<tr>
<td>47</td>
<td>7</td>
<td>R21 524637</td>
<td>Murnahaki</td>
<td>Roadcut at southeast pointing bend of Omahina Road (Ngarino Terrace)</td>
<td>Sharp —</td>
<td>Pebbly marine sandstone on sandy silstone</td>
<td>0.1</td>
<td>8</td>
<td>8.1 5</td>
<td>Hawera</td>
<td><em>(thickness omits a 9.3-m-thick lahar)</em></td>
</tr>
<tr>
<td>44</td>
<td>9a</td>
<td>R22 785500</td>
<td>Kai-iwi</td>
<td>Roadcut on south side of Brunswick Road (Brunswick Terrace)</td>
<td>Sharp —</td>
<td>Marine sandstone on silstone</td>
<td>0.15</td>
<td>13</td>
<td>14 11</td>
<td>Hawera</td>
<td>T</td>
</tr>
<tr>
<td>44</td>
<td>9c</td>
<td>S22 026390</td>
<td>Whangaehu</td>
<td>Roadcut on west side of Kauhanga Rd, toward top of hill (Brasemore Terrace)</td>
<td>Sharp P</td>
<td>Marine sandstone on silstone</td>
<td>0.2</td>
<td>18</td>
<td>17.8 9</td>
<td>Hawera</td>
<td></td>
</tr>
<tr>
<td>43</td>
<td>11</td>
<td>R22 769415</td>
<td>Castlecliff (C)</td>
<td>Above Tainui Shellbed Buttress, 4200 m southeast of Omakau Stream</td>
<td>Sharp O</td>
<td>Paphies shell bed (A) on silstone</td>
<td>8.0</td>
<td>1.8</td>
<td>7 17</td>
<td>Seafield</td>
<td>[Rangitawa T. ]</td>
</tr>
<tr>
<td>42</td>
<td>13</td>
<td>R22 761424</td>
<td>Castlecliff (C)</td>
<td>Halfway up vegetated cliff slope, 3100 m southeast of Omakau Stream</td>
<td>Biot. O</td>
<td>Antisolarium sandstone on silstone</td>
<td>5.5</td>
<td>4.5</td>
<td>9 0</td>
<td>Castlecliff</td>
<td></td>
</tr>
<tr>
<td>41</td>
<td>15</td>
<td>R22 756427</td>
<td>Castlecliff (C)</td>
<td>Ledge along top of Shag Rock, 2400 m southeast of Omakau Stream</td>
<td>Sharp P</td>
<td>Pebbly (Tom's) shell bed (A) on silstone</td>
<td>21.5</td>
<td>1.5</td>
<td>1.5 0.4</td>
<td>Seafied T</td>
<td>T</td>
</tr>
<tr>
<td>40</td>
<td>17</td>
<td>R22 750433</td>
<td>Castlecliff (C)</td>
<td>Vegetated low cliff at back of beach, 1700 m southeast of Omakau Stream</td>
<td>Sharp P</td>
<td>Cyclomactra shell bed (A) on silstone</td>
<td>3.3</td>
<td>0.3</td>
<td>8 0</td>
<td>Castlecliff</td>
<td>T</td>
</tr>
<tr>
<td>39</td>
<td>19</td>
<td>R22 740440</td>
<td>Castlecliff (C)</td>
<td>Bluff at beach level below high cliff, 450 m southeast of Omakau Stream</td>
<td>Sharp P</td>
<td>Paphies shell bed (A) on silstone</td>
<td>2.8</td>
<td>0.3</td>
<td>17 20</td>
<td>Castlecliff</td>
<td>T</td>
</tr>
<tr>
<td>38</td>
<td>21</td>
<td>R22 734444</td>
<td>Castlecliff (C)</td>
<td>Southeast-dipping ledge to below beach level, 400 m northwest of Omakau Stream</td>
<td>Sharp O</td>
<td>Ophromorpha sandstone on silstone</td>
<td>1.0</td>
<td>1</td>
<td>7 0.1</td>
<td>Castlecliff</td>
<td>T</td>
</tr>
<tr>
<td>37</td>
<td>23-23</td>
<td>R22 707458</td>
<td>Castlecliff (C)</td>
<td>Lower-middle slopes of high cliff just southeast of Okehu Stream</td>
<td>Sharp P</td>
<td>Pebbly very coarse sandstone on silstone</td>
<td>11.0</td>
<td>0.1</td>
<td>14 3</td>
<td>Seafied T</td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>27</td>
<td>R22 707458</td>
<td>Castlecliff (C)</td>
<td>At base of high cliff just southeast of Okehu Stream</td>
<td>Sharp P</td>
<td>Lower Okehu shell bed (A) on silstone</td>
<td>2.8</td>
<td>0.3</td>
<td>5 8</td>
<td>Castlecliff T</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>29</td>
<td>R22 690446</td>
<td>Castlecliff (C)</td>
<td>Southeast dipping shell bed at beach level, 1700 m northwest of Ototoka Stream</td>
<td>Sharp —</td>
<td>Mowhanau shell bed (A) on silstone</td>
<td>2.0</td>
<td>0.2</td>
<td>20 0</td>
<td>Castlecliff</td>
<td>T</td>
</tr>
<tr>
<td>34</td>
<td>31</td>
<td>R22 667473</td>
<td>Castlecliff (C)</td>
<td>Halfway up south slope of Ototoka Stream, toward coast</td>
<td>Sharp O</td>
<td>Butlers shell bed (A) on silstone</td>
<td>15.0</td>
<td>0</td>
<td>0 15</td>
<td>Seafield</td>
<td>Base Jaramillo</td>
</tr>
<tr>
<td>33</td>
<td>33</td>
<td>S22 092361</td>
<td>Turakina</td>
<td>Roadcut just south of small bridge, east side of Turakina Valley Road</td>
<td>Sharp —</td>
<td>Pebbly shell bed (A) on silstone with Montmactra shell beds.</td>
<td>10.0</td>
<td>0</td>
<td>40 50</td>
<td>Seafied</td>
<td></td>
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<tr>
<td>32</td>
<td>35</td>
<td>S22 095375</td>
<td>Turakina</td>
<td>On farm track, east of Turakina Valley Road</td>
<td>Sharp —</td>
<td>Pebbly shell bed (A) on sandstone</td>
<td>13.0</td>
<td>0</td>
<td>18 30</td>
<td>Seafied</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>37</td>
<td>S22 096385</td>
<td>Turakina</td>
<td>Roadcut, east side of Turakina Valley Road, south of farm-track bridge</td>
<td>Sharp ?P</td>
<td>Pebbly shell bed (A) on heterolithic sandstone/siltstone</td>
<td>18.0</td>
<td>0</td>
<td>0 0</td>
<td>Seafied</td>
<td></td>
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<tr>
<td>30</td>
<td>39</td>
<td>S22 099390</td>
<td>Turakina</td>
<td>Near base of outcrop in northwest pointing bend, east side Turakina Valley Road</td>
<td>Not seen — Base inferred, not seen in outcrop</td>
<td>25.0</td>
<td>0</td>
<td>0 25</td>
<td>Seafied</td>
<td></td>
<td></td>
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| 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     | Birdgrove    | *
<p>| 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     | Birdgrove T | |
| 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 | 0      | 3 7      | 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 | 0      | 3 7      | Birdgrove    | Mangapipi T. (TSST 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 | 0      | 7 14     | Birdgrove    | Pakihiku T. (TSST) |
| 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 silstone | 35.0 | 0      | 4 9      | Birdgrove    | Birdgrove T. (TSST) |
| 23    | 53             | S22 117421     | Turakina        | Small west bank promontory below farm track, 4 m above river level | Sharp — | Sandstone on nonmarine mudstone | 5.0  | 0      | 7 14     | Birdgrove    | Mangahou T. (RST) |</p>
<table>
<thead>
<tr>
<th>Cycle</th>
<th>Isotopic stages</th>
<th>Grid reference</th>
<th>Location</th>
<th>Description</th>
<th>Base</th>
<th>Lithology</th>
<th>Systems tract thickness</th>
<th>Sequence motif</th>
<th>Chronostratigraphic markers</th>
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<td>Type</td>
<td>Burr.</td>
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<tr>
<td>22</td>
<td>55</td>
<td>S22 133418</td>
<td>Turakina</td>
<td>Small road cut, on corner just north of stream of river</td>
<td>Sharp</td>
<td>—</td>
<td>Shell bed (A) on nonmarine mudstone</td>
<td>33</td>
<td>5</td>
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<tr>
<td>21</td>
<td>57</td>
<td>S22 137427</td>
<td>Turakina</td>
<td>South end of long road cut, immediately east of river</td>
<td>Sharp</td>
<td>—</td>
<td>Shell bed (A), 2 m relief, large siltstone boulders, on nonmarine siltstone</td>
<td>2.2</td>
<td>0.5</td>
</tr>
<tr>
<td>20</td>
<td>59</td>
<td>S22 138428</td>
<td>Turakina</td>
<td>North end of long road cut, immediately east of river</td>
<td>Sharp</td>
<td>—</td>
<td>Sandy heterolithic sediment on nonmarine siltstone</td>
<td>2</td>
<td>0.2</td>
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<tr>
<td>19</td>
<td>61</td>
<td>T22 355376</td>
<td>Rangitikei</td>
<td>South end of high west bank cliff, near base</td>
<td>Grades?</td>
<td>—</td>
<td>Shell bed on silty sandstone</td>
<td>0.1</td>
<td>0.4</td>
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<tr>
<td>18</td>
<td>63</td>
<td>T22 350394</td>
<td>Rangitikei</td>
<td>At road level, midway along west side road cut</td>
<td>Sharp</td>
<td>O</td>
<td>Waipuru shell bed (A) on sandstone</td>
<td>0.5</td>
<td>1.5</td>
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<td>17</td>
<td>65</td>
<td>T22 362385</td>
<td>Rangitikei</td>
<td>Cutting on east side of farm track</td>
<td>Sharp</td>
<td>O</td>
<td>Shell bed (A) on heterolithic siltstone/sandstone</td>
<td>18</td>
<td>0.5</td>
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<tr>
<td>16</td>
<td>67</td>
<td>T22 359386</td>
<td>Rangitikei</td>
<td>South end of high east bank cliff, near base</td>
<td>Sharp</td>
<td>O</td>
<td>Shell bed (A) on sandstone</td>
<td>14</td>
<td>1.5</td>
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<tr>
<td>15</td>
<td>69</td>
<td>T22 361387</td>
<td>Rangitikei</td>
<td>Midway along high east bank cliff, near base</td>
<td>Sharp</td>
<td>O</td>
<td>Shell bed (A) on sandstone</td>
<td>0.2</td>
<td>0.3</td>
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<tr>
<td>14</td>
<td>71</td>
<td>T22 376407</td>
<td>Rangitikei</td>
<td>North end of high east bank cliff, near base</td>
<td>Grades</td>
<td>—</td>
<td>Shell bed on sandy siltstone</td>
<td>0</td>
<td>0.3</td>
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<tr>
<td>13</td>
<td>73</td>
<td>T22 410416</td>
<td>Waipuru</td>
<td>Midway along east side road cut, toward top</td>
<td>Sharp</td>
<td>O</td>
<td>Shell bed (A) on sandstone</td>
<td>0.2</td>
<td>0.3</td>
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<tr>
<td>12</td>
<td>77-75</td>
<td>T22 394417</td>
<td>Mangamako</td>
<td>North bank of stream, 500 m upstream from confluence</td>
<td>Sharp</td>
<td>—</td>
<td>Mangamako shell bed (A) on heterolithic siltstone/sandstone</td>
<td>27</td>
<td>0.3</td>
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<tr>
<td>11</td>
<td>79</td>
<td>T22 414424</td>
<td>Mangamako</td>
<td>South stream slope, just beneath terrace top and behind house</td>
<td>Sharp</td>
<td>—</td>
<td>Shell bed (A) on sandstone</td>
<td>9</td>
<td>0</td>
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<tr>
<td>10</td>
<td>81</td>
<td>T22 433427</td>
<td>Mangamako</td>
<td>Near base of east side road cut, in southeast corner of bend</td>
<td>Sharp</td>
<td>P</td>
<td>Shell bed (A) on heterolithic siltstone/sandstone</td>
<td>2</td>
<td>0.3</td>
</tr>
<tr>
<td>9</td>
<td>83</td>
<td>T22 393427</td>
<td>Rangitikei</td>
<td>Midway along high east bank cliff, at mid-height</td>
<td>Grades?</td>
<td>—</td>
<td>Shell bed on sandstone</td>
<td>0</td>
<td>0.2</td>
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<tr>
<td>8</td>
<td>85</td>
<td>T22 394433</td>
<td>Rangitikei</td>
<td>North end of high east bank cliff, near base</td>
<td>Sharp</td>
<td>O</td>
<td>Shell bed on sandstone</td>
<td>0</td>
<td>0.2</td>
</tr>
<tr>
<td>7</td>
<td>87</td>
<td>T22 393435</td>
<td>Rangitikei</td>
<td>200 m south of north end of high east bank cliff, near base</td>
<td>Sharp</td>
<td>O</td>
<td>Shell bed (A) on sandstone</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>6</td>
<td>89</td>
<td>T22 395447</td>
<td>Rangitikei</td>
<td>Southeast corner of meander, near base of high east bank cliff</td>
<td>Grades?</td>
<td>—</td>
<td>Shell bed (A) on sandstone</td>
<td>2.5</td>
<td>0.4</td>
</tr>
<tr>
<td>5</td>
<td>91</td>
<td>T22 427440</td>
<td>Rangitikei</td>
<td>400 m south of north end of high east bank cliff, near base</td>
<td>Sharp</td>
<td>O</td>
<td>Shell bed on silty sandstone</td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>4</td>
<td>93</td>
<td>T22 440445</td>
<td>Rangitikei</td>
<td>East side roadcut, on corner 200m uphill from hairpin bend</td>
<td>Sharp</td>
<td>O</td>
<td>Shell bed (A) on silty sandstone</td>
<td>0.7</td>
<td>0.3</td>
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<tr>
<td>3</td>
<td>95</td>
<td>T22 433433</td>
<td>Rangitikei</td>
<td>Road-cut near hilltop, Otara Road</td>
<td>Sharp</td>
<td>O</td>
<td>Shell bed (A) on sandstone (= Tuha Sandstone)</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>2</td>
<td>97</td>
<td>T22 436457</td>
<td>Rangitikei</td>
<td>Low cliff on east bank of river, north of Otara Bridge</td>
<td>Sharp</td>
<td>O</td>
<td>Hautawa shell bed on silty sandstone</td>
<td>0.1</td>
<td>0.3</td>
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<tr>
<td>1</td>
<td>99</td>
<td>T22 500474</td>
<td>Mangarere</td>
<td>Stream section, just below north side of road</td>
<td>Sharp</td>
<td>G</td>
<td>Shell bed (A) at base of Te Rimu Sandstone on siltstone</td>
<td>95</td>
<td>0</td>
</tr>
</tbody>
</table>

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/LSTnm (see Table 2). Only rarely (e.g., top of cycle 28) is the LSTnm identifiable as a discrete nonmarine mudstone and/or lignite interval between an erosional sequence boundary and a marine ravinement surface. FAD—first appearance datum.

TABLE A1. (Continued).
Heckel, P. H., 1986, Sea-level curve for Pennsylvanian eustatic.


Moore, R. C., 1936, Striation classification of the Pennsylvani.


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Seward, D., 1976, Tephrostratigraphy of the marine sediments in the Wanganui basin, New Zealand: New Zealand Jour.


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