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Late Pleistocene sea-level oscillations (MIS 10–2) recorded in shallow marine and coastal plain sediments of the southern Wanganui Basin, New Zealand

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ABSTRACT

The northern Wanganui Basin, New Zealand, is one of the key global sites for understanding marine cyclic sedimentation during the Quaternary. This paper presents the first evidence of marine cyclic sedimentation from its central-southern parts. Sedimentological, micropalaeontological and palynological analyses on a 280-m-deep borehole encountered units dating back to MIS 10. The sequence includes four marine cycles spanning MIS 9–5, which are overlain by terrestrial fluvial aggradation surfaces dating from MIS 4–2. Each marine unit represents a progressively shallowing depositional environment from the mid-shelf to coastal plain. This is overlain by a terrestrial sequence of lowstand fluvial terraces. Localized fault movements appear to have influenced the sedimentary character of the sequence during MIS 7a and 5e producing basement highs which provided protection to the shoreline. The cyclothems described in this paper now extend the already extensive, previously described record from MIS 17–10 to produce a combined eustatic record of Quaternary sea level change within the basin to MIS 5. They also provide an excellent example of the sedimentary response of a coastal basin to a progressive loss of sedimentation accommodation space.

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Introduction

Sedimentary records of eustatic cycles are well preserved in a variety of depositional environments from the deep ocean (e.g., Shackleton, 1987) to coral terraces (e.g., Chappell et al., 1996). On continental shelves, with abundant sediment supply and ample accommodation space, the regression and transgression of shorelines leads to the deposition of cycles of marine and terrestrial sedimentation. On tectonically active coasts, these sequences can be well preserved as they are raised above modern sea level such as found in the Spencer Gulf, Southern Australia (Murray-Wallace, 2002), San Francisco, California (Clifton et al., 1988) and the Boso Peninsula, Japan (Tokuhashi and Kondo, 1989).

One of Earth's most complete late Neogene marine stratigraphic sequences occurs in the Wanganui Basin, New Zealand. There, approximately 2 km of basin-infill dating from about 2.5 Ma occurs recording glacio-eustatic sea-level fluctuations back to Marine Isotope Stage (MIS) 100 (Naish et al., 1998; Saul et al., 1999). This record is considered to be one of the few places globally that can provide direct evidence of Pliocene–Pleistocene eustatic variations inferred from deep-ocean isotope records (N. Shackleton pers. comm.; in Naish, 2005). The youngest part of the sequence (MIS 17–3) is characterized by a sequence of uplifted marine terraces that represent late Pleistocene eustatic cycles over a coevally uplifting shoreline (Pillans, 1983).

At the basin's southern edge, subsidence on the order of 4 mm/yr is occurring (Berryman and Hull, 2003), and in the central parts close to 700 m of sediment have been deposited below sea level (Aharoni, 1991). This sedimentation has formed a 30-km-wide coastal plain extending from the central axial ranges. Given the depth of sediments found in these central parts, the question arises whether depositional sequences equivalent to the erosional terraces occur. This paper therefore sets out to explore these sedimentary sequences through an examination of borehole sediments at the township of Levin, Horowhenua, in the southern part of the basin (Fig. 1).

Regional setting

The Wanganui Basin forms a back-arc sedimentary basin resulting from the convergence of the Indo-Australian and Pacific Plates (Begg and Johnston, 2000) (Fig. 1). Gradual emergence to the north during the Pleistocene has produced a 4–6° southward regional tilt of strata as the basin's depocenter has migrated slowly south (Anderton, 1981). At the study site recent uplift is estimated at be occurring at 0.3 mm/yr based on the elevation of mid-Holocene estuarine deposits (Shepherd, 1987).

The basement geology of the Basin consists of indurated greywacke and argillites similar to Torlesse Terrane, which composes the adjacent Tararua Range (Anderton, 1981). Overlying this are successions of shallow marine and terrestrial sediments, grouped into the upper Wanganui Series (Fleming, 1953; Beu and Edwards, 1984). The Nukumaruan (2.4–1.71 Ma) and Castlecliffian (1.71–0.43 Ma) stages comprise 47 superimposed marine cyclothems, developed from

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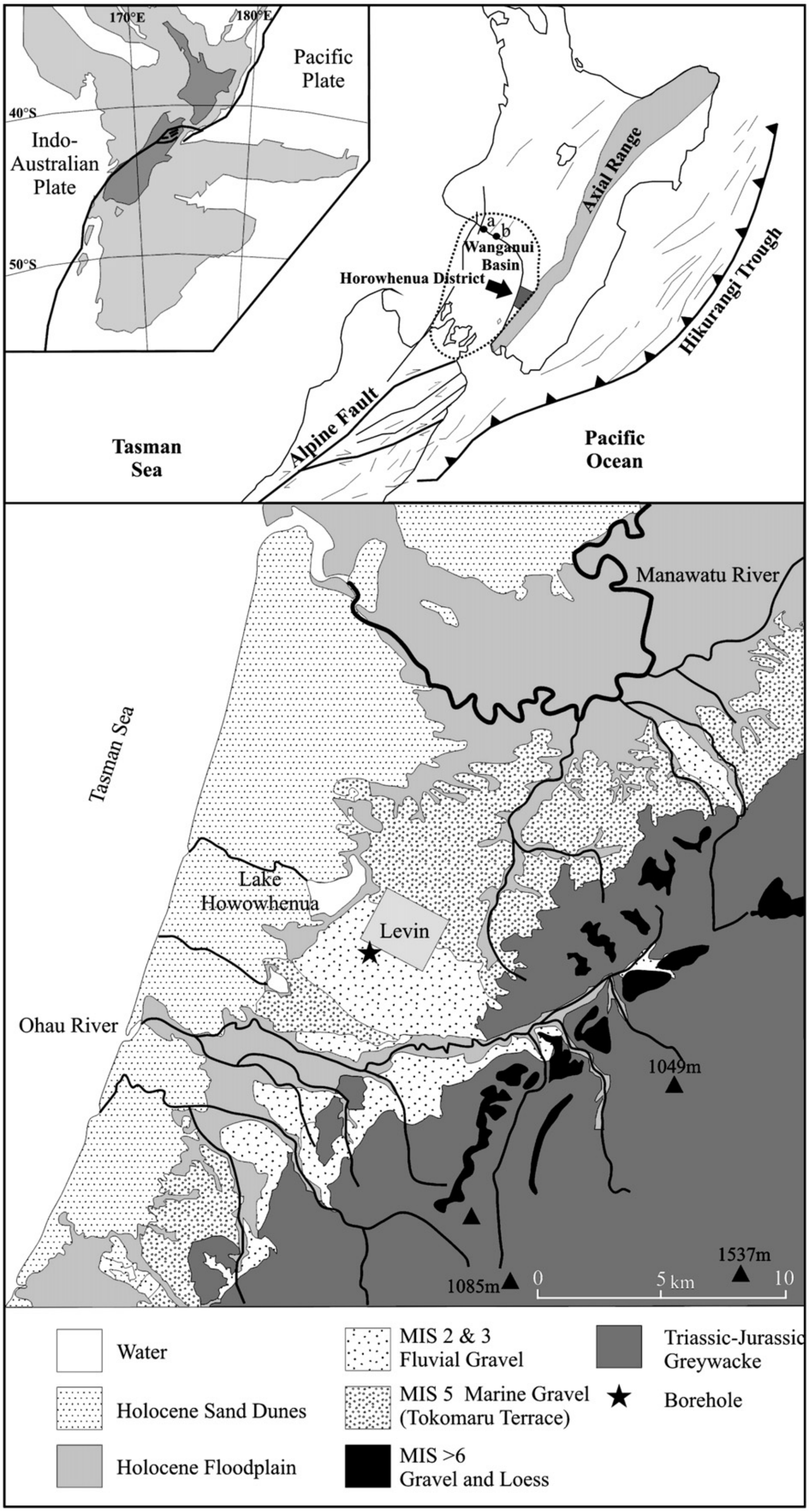

Figure 1. Location of the study site, showing a) New Zealand's relation to the Pacific and Indo-Australian plates, b) the position of the Wanganui Basin in relation to the major fault zones, and c) the surface geology of the Horowhenua Region. The Haweran (a) and Castlecliff (b) motifs are found in the northern part of the basin.

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glacioeustatic fluctuations over the shelf (Carter et al., 1991; Abbott and Carter, 1994; Naish and Kamp, 1997a,b). The younger Haweran Stage (0.34–0.01 Ma) is represented by a flight of 13 marine terraces (Pillans, 1983, 1994), the youngest of which is the Tokomaru marine terrace (MIS 5), which contains the Otaki Formation.

The oldest Quaternary sediment exposed in the Horowhenua region is the MIS 6 Marton Alluvium gravels, consisting of moderately weathered, poorly to moderately-sorted clasts (Fleming, 1972). Truncating these gravels is the Otaki Formation, composed of three distinct lithological units: 1) a basal beach gravelly-sand (Otaki beach sand), 2) a thin lignite band (Awatea lignite), and 3) an overlying dune sand (Otaki dune sand). This is in turn buried by aggradational lowstand terraces (Ohaken, Ratan and Porenan) composed of fluvial gravel and loess during MIS 2–4, with the youngest Ohakean terrace (12–25.5 ka) (Barnett, 1994) forming at the ground surface at the borehole site. Holocene sedimentation in the region is characterized by a prograding gravel plain overlain by a series of dune sequences dating back to 5 ka (Cowie, 1963; Hesp and Shepherd, 1978), this occurring several kilometers seaward of the study site.

Materials and methods

Seventy samples were analysed from a 280-m-deep borehole drilled between October 2003 and April 2004, using a cable-tool percussion rig. Unconsolidated sediment was collected where a change in lithology occurred or at regular intervals in thick, relatively uniform, sediment units. All samples were analysed for grain size with 30–40 g of material being initially treated with 10% HCl, disaggregated with 0.1% sodium hexametaphosphate and wet-sieved through a 63-μm mesh. The mud size fraction was analysed on a Sedigraph 5100 and the coarser fraction was dry sieved at 0.5-ϕ intervals. Foraminiferal sediment samples were processed according to the procedures of Kummel and Raup (1965) using the sand fraction. Forams were identified through comparison with Hayward et al. (1999), and counted under a binocular microscope until 100 tests were completed. This sampling density provided accurate assessment of faunal compositions in identifying shallow marine associations (Hayward and Hollis, 1994; Naish and Kamp, 1997b). Standard procedures were used to process the sediment for palynological analysis (hot 10% KOH, 40% HF, and acetolysis) as outlined in Moore et al. (1991). Slides were counted until at least 300–400 palynomorphs were observed. Grains were identified through comparison with the Victoria University of Wellington, School of Geography, Environment and Earth Sciences reference slide collection and from reference descriptions in Cranwell (1953), Pocknall (1981), and Moar (1993). Geochemical analyses employed a Jeol-733 superprobe using the techniques prescribed by Froggatt (1983). Values for major oxide compositions were determined using a beam current of 8.0 nA at 15 kV and beam diameter of 10 μm. Two radiocarbon ages were obtained from the Waikato Radiocarbon Dating Laboratory, New Zealand. In addition uranium series disequilibrium dating was attempted on several samples at the Australian National University; however, the carbonate system had not remained closed and reliable ages could not be determined.

Results

Sedimentary facies

Based on changes in sedimentology, 36 depositional units and nine recurrent lithofacies were identified in the 280-m borehole (Table 1a). The lower 110 m consists of alternating mud, silt and sand units each 5–30 m thick, while between 120–170 m depth silty sand and sand units occur in association with thick gravels. The upper 120 m are dominated by thick gravels separated by thin silt and sand units (Fig. 2).

Table 1a
Lithofacies for sediments within the borehole, summarizing the lithology and depositional environment

Facies code	Lithology	Depositional environment
M	Blue grey mud	Mid to inner-shelf, or deep marine embayment
FZS	Fossiliferous silty sand	Mid to outer-shoreface/marginal marine (estuarine embayment)
FS	Fossiliferous fine sand	Mid to inner-shoreface
SL	Bioclastic sand carbonate	Shoreface
SG	Sandy shelly gravel	Inner-shoreface
S (Sd, Sb)	Fine, well sorted barren sand. Sd is very well sorted and positive skew, Sb well sorted and negative skew.	Littoral coastal sand deposits. Sd = dune, Sb = beach.
IGM	Interbedded gravel and mud	Fluvio-delatic
Z	Silt	Fluvial overbank (floodplain)
G	Coarse gravel	Braided river channel

Facies (M) is composed of blue to grey, consolidated, fossiliferous mud units, occurring below 190 m depth with beds up to 26 m thick (Fig. 3a). The mudstone is poorly sorted, containing 48–52% silt, 41–47% clay and 4–5% sand, with in situ molluscs *Chlamys gemmulata* and reworked fragments of other species such as *Austrovenus stutchburyi* and *Nucula hartvigiana*. These units are bioturbated between 245 and 260 m depth with in situ siliceous *Polychate* worm tubes (*Cruziana ichnofacies*) and the marine bivalve *C. gemmulata* basally attached to those tubes. They likely represent an inner-shelf environment or large protected embayment below fair weather wave base. The reworked broken fragments of the estuarine-dwelling species are allochthonous, likely derived from more shoreward environments. These units represent the deepest marine environment encountered in the borehole.

The next facies (FZS) occurs between 128 and 270 m depth, forming beds up to 9 m thick (Fig. 3b). It is composed of silty sandstone units with thin laminations of blue mud and micaceous sand. The units contain a mixture of estuarine and open-ocean salinity molluscs, such as *A. stutchburyi*, *Paphies* sp. and *Zenatia acinaces*, as well as traces of peat and wood with the occasional rounded greywacke pebble. The bimodal distribution of sand and silt suggests that these units may either represent a wave graded shoreline on the middle to outer shoreface (e.g., Dunbar and Barrett, 2005) or a tide-dominated estuary (e.g., Reinson, 1992). The presence of in situ macrofossils in many of the beds suggests the latter interpretation to be more likely. A shallower environment of the inner shoreface is interpreted to relate to the next facies (FS), which is composed of grey-brown fossiliferous, fine, moderately sandy units (88–90%) up to 14 m thick. They occur intermittently from the base of the borehole up to 180 m depth and contain detrital fragments of *A. stutchburyi* and *Amalda depressa*.

A distinct shell hash bed occurs between 223 and 224 m depth, where well-rounded greywacke pebbles are mixed with shelf and intertidal mollusc species that define facies SL (Fig. 3c). The high carbonate content is suggestive of terrigenous-starved conditions with the faunal composition indicating nearby estuaries (Abbott and Carter, 1994; Naish and Kamp, 1997a). It is likely this facies represents a period of sea-level rise. Detrital shell material also dominates units comprising facies SG (Fig. 3d), which occurs between 145–146 m and 201–202 m, and is composed of dark grey to brown poorly-sorted sandy gravel. Greywacke pebbles also occur with whole shells of *Z. acinaces* and/or *Pleuromeris finlayi*. Deposition probably occurred in a high-energy inner shoreface environment.

Further shallowing of the depositional environment within the borehole is represented in facies S, which consists of 4–5 m thick units of micaceous sandstone. The sand is medium to fine-grained, very well to well-sorted. Differentiating between dune (S_d) and beach (S_b) sands was based on skewness and sorting values. The high proportion of mica and volcanic minerals suggests a littoral source with grains

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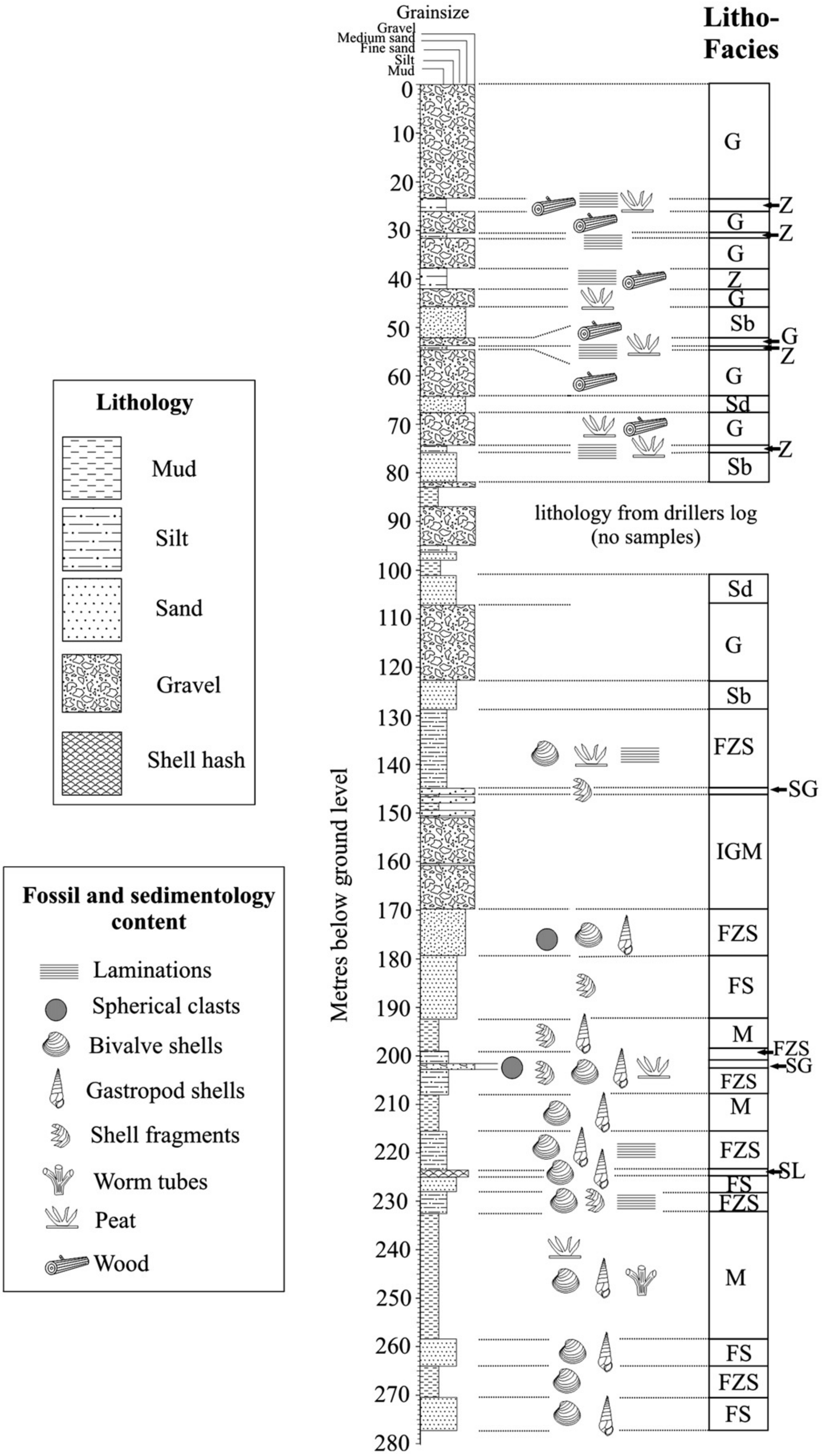

Figure 2. Sedimentary log of the borehole showing the major lithofacies identified. See Table 1a for lithofacies descriptions.

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Figure 3. Photographs of a range of units identified within the hole; a) blue-grey fossiliferous mud of facies M containing siliceous *Polychaete* tubes; b) mica rich unconsolidated silty sand from facies FZS; shelly gravel of c) facies SL and d) facies SG; and e) subangular–subrounded greywacke clasts of facies G.

having a similar composition to uplifted beds in the north of the basin (Holgate, 1985).

The top 160 m of the borehole are dominated by coarse-grained gravel units composed of sub-rounded to sub-angular greywacke clasts with minor occurrences of argillite and quartz pebbles. From 147–171 m depth, the gravels are interbedded with silty sands (facies IGM). This unit most likely represents a fluvio-deltaic environment with material derived from the uplifting axial ranges. From 0–123 m depth, the gravel units are poorly sorted with some containing strongly weathered clasts while others appear fresh (facies G) (Fig. 3e). The gravels have a similar texture to gravels on the present aggradation surface at the top of the borehole. Large pieces of wood and other organic fibrous debris are commonly found, along with small (2–3 m) sandy or clayey silt units often containing thin ripple laminations. This is interpreted as being deposited within abandoned channels of a gravel bed river during high flood stage flows and is termed facies Z.

Foraminiferal stratigraphy

In order to further refine the palaeoenvironmental interpretation of the facies, foraminiferal analysis was undertaken to determine benthic species present in the lower 120 m of the borehole within the marine-dominated units. Approximately 1900 examinations detected 46 different species from 21 samples. Of the main (>4% abundance) benthic species identified, six distinct sample associations are apparent (Fig. 4, Table 1b). Each association can be related to the faunal zonations identified by Hayward et al. (1999) for New Zealand coastal environments. The first three associations are dominated by *Ammonia parkinsoniana* and represent brackish-water environments. In the first (association A), occurring between 172–182 m and 223–224 m depth, *A. parkinsoniana* accounts for 87% of the species and is dominant within facies FS. Within association AE, *A. parkinsoniana* constitutes 50% of the tests with sub-dominant *Elphidium crispum* (14%), *E. advenum* (13%) and *Haynesina depressula* (9%). This

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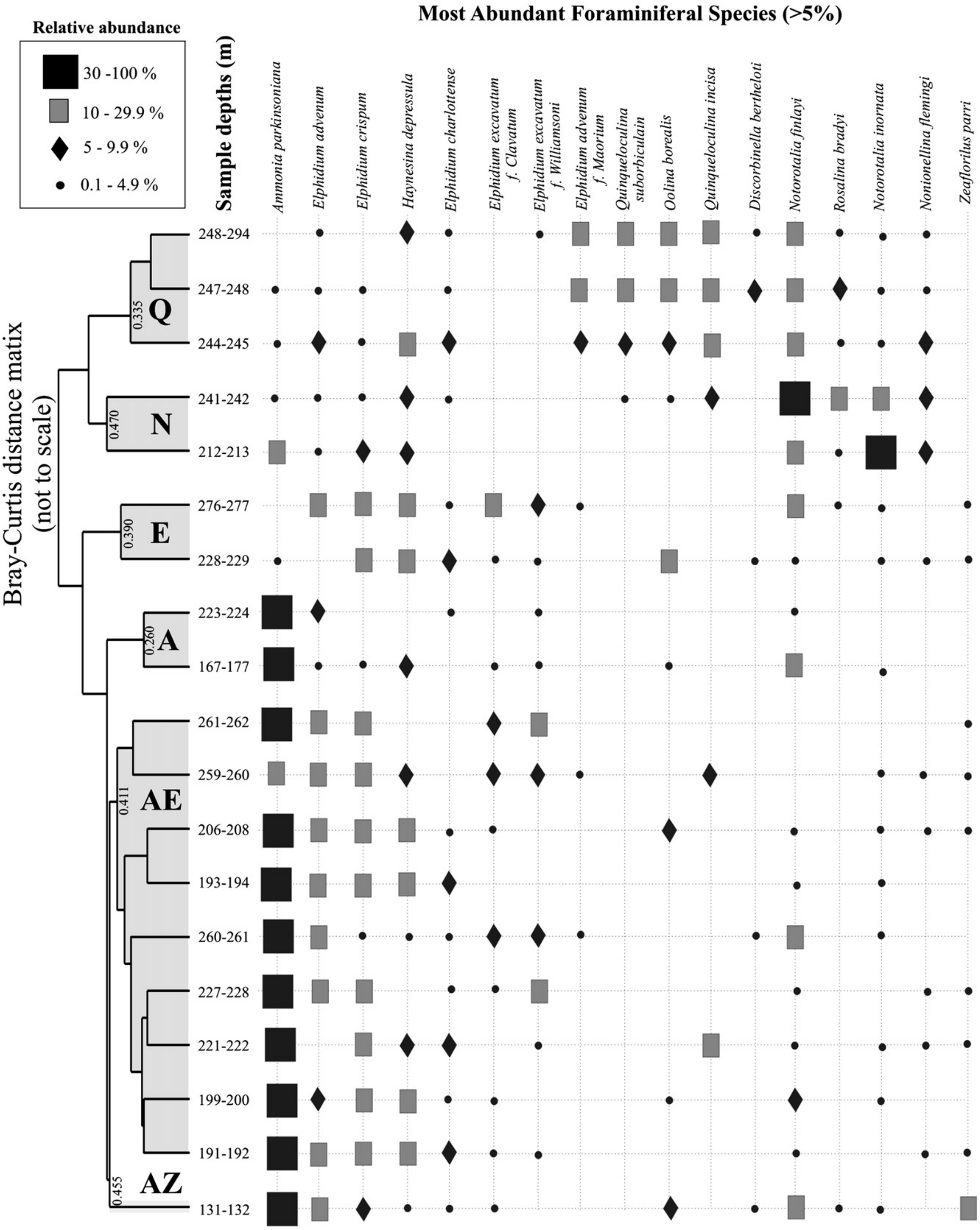

Figure 4. Dendrogram classification and relative species abundance of the Levin borehole foraminiferal sample associations produced by cluster analysis using Bray–Curtis distance matrix.

association is scattered through the marine units between 182 and 264 m depth that belong to facies FZS and M. The presence of association AE with sedimentary facies M suggests it is unlikely to be an open shoreline/inner shelf environment. The abundance of *A. parkinsoniana* continues to decrease in the third association (AZ) where it accounts for 36% of the species and is co-dominant with *Zeaflorilus parri* (24%) and *Notorotalia finlayi* (14%). This association occurs between 130–145 m depth within facies FS. A certain degree of

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Table 1b
Foraminiferal zonation within the sediments and the inferred palaeoenvironment

Foram zone	Dominant species	Palaeoenvironment
A	*Ammonia parkinsoniana*	Brackish subtidal (MSL — c. 2 m depth)
AE	*Ammonia parkinsoniana*	Intertidal – subtidal (MLW — c. 6 m depth)
AZ	*Ammonia parkinsoniana, Zeaflorilus parri*	Shallow subtidal (5–15 m depth)
E	*Elphidium advenum, E. crispum*	Mid shoreface (c. 20 m depth)
N	*Notorotalia inornata, N. finlayi*	Inner shelf (25–40 m depth)
Q	*Quinqueloculina incise, N. finlayi*	Inner shelf (30–50 m depth)

reworking and mixing of species can be expected within these brackish-water assemblages as they commonly occur in shallow-water environments (Hayward and Hollis, 1994; Hayward et al., 1999), but all appear unique to environments such as harbors and estuaries (e.g., Hayward and Hollis, 1994).

Three other benthic associations represent open-marine environments dominated by *Quinqueloculina*, *Notorotalia* and *Elphidium* species. Association E is co-dominated by *E. advenum* (35%), *E. crispum* (22%) and *H. depressula* (17%), and occurs between 228–232 and 270–278 m depth. Association N is found between 208–218 and 232–244 m depth within the mud units. *Notorotalia* species, which are often found in deep sheltered embayments (Hayward et al., 1999), are abundant with *N. inornata* (33%) and *N. finlayi* (32%) being the most common and *Nonionellina flemingi* (9%) and *H. depressula* (7%) being subdominant species. The final association identified, Q, is co-dominated by *Quinqueloculina incisa* (21%), *N. finlayi* (20%) and *Q. suborbicularis* (16%) being found at 244–258 m depth. Modern foraminiferal associations dominated by *Quinqueloculina* have not been documented from the New Zealand region, although an informal biofacies containing both *Q. incisa* and *N. finlayi* has been noted living in water depths of 35 m off the Kapiti coast (Perrett, 1990).

Palynology

Pollen analysis was conducted on sedimentary units that contained over 80% sand and silt particles and were most likely to preserve palynomorphs. A total of 28 samples representing horizons between 24 and 263 m depth produced 47 pollen and spore species that differentiate 10 zones within the borehole (Fig. 5, Table 1c). Spores from the tree ferns *Cyathea* and *Dicksonia*, as well as monolete fern spores, dominate, composing up to 50% of the total pollen sum. Similarly *Nothofagus fusca* pollen is prevalent through the sequence.

The first pollen zone occurs from 233–263 m depth, corresponding to a deep-marine depositional environment, which means the signal preserved is likely to represent a regional vegetation pattern (e.g., McGlone, 2001). The tree species *Metrosideros* and *Dacrydium cupressinum* are common (each 10%) with *Podocarpus* sp. and *Fuscospora*-type each accounting for 5% of the pollen sum, with the frost intolerant *Ascarina lucida* having a composition of <3%. Within zone 2 (225–233 m depth) there is an expansion of *Fuscospora*-type and *Nothofagus fusca* pollen (up to 20%) and *D. cupressinum* (13%), with a decrease in the other tree species present. Notable is the disappearance of *A. lucida*. This change is typical of a cooling from an interglacial conifer–broadleaf forest (zone 1) found in Pleistocene strata of the SW North Island (e.g., Bussell and Pillans, 1997) to a glacial environment dominated by grass and shrubland (Bussell, 1986).

A replacement of the beech–podocarp forest occurs in zone 3 (205–225 m), with the assemblages being characteristic of a stadial–interstadial transition (Bussell, 1986). An upward decrease in *Fuscospora*-type (9%), *N. menziesii* (3%), and *D. cupressinum* (2%) and an increase in pollen from *Metrosideros* (5%), *Podocarpus* sp. (5%), and *Ascarina* (5%) compared to zone 2 defines the base of this zone. However, relative abundances of *Fuscospora*-type and *D. cupressinum* all increase again in the latter part of this zone at an expense of *Metrosideros* and *Podocarpus* species. *Ascarina* reappears here, but it is again absent from zone 4 (196–205 m) as a deterioration in climate is recorded with an associated increase in *Fuscospora*-type (25%) and *N. menziesii* (5%) pollen. Full interglacial conditions again reoccur in zone 5 (184–196 m) as *Fuscospora* decreases to 14% and *N. menziesii* almost completely disappears, associated with *Ascarina* and *Pseudopanax* each constituting 3% of the pollen sum. A large increase in *Fuscospora* (to 31%), shrub and grass pollen, and reappearance of *N. menziesii* (2%) in zone 6 (170–184 m) indicate an expansion of beech forest and scrubland–grassland vegetation compared to zone 5. However, the prevalence of *D. cupressinum* (4%) and *Metrosideros* (7%) suggests that mixed conifer and broadleaf forests may have continued growing in lowland coastal sites.

Zone 7 (131–147 m) is bounded by barren gravels and sands, and is characterised by large amounts of conifer and broadleaf tree pollen including *D. cupressinum* (8%), *Podocarpus* sp. (3%), *Metrosideros* (4%), *Cyathea*-type (40–53%), and *Dicksonia*-type (8–15%) with an absence of *Fuscospora* and *N. menziesii*. These associations indicate full interglacial conditions. There is also an increase in wetland taxa and *Chenopodium* which prefers saline environments (Macphail and McQueen, 1983). These taxa suggest the presence of nearby estuaries. From 35–75 m depth, interglacial conditions are still represented with zone 8 having a similar floristic composition to zone 7, although small tree and shrub species are of greater prevalence. The final two pollen zones are characterised by a dominance of fern palynomorphs with typical tree species being almost absent in zone 9 (30–32 m) and only a minor proportion of zone 10 (23–26 m). It is possible fern spores originated from forests growing within the catchment of the Ohau River and were hydraulically transported to the drill site and deposited in overbank deposits. However, wind pollinated tree species from these forests should also be present, but are absent. It is therefore postulated that the fern spores came from old soil deposits located within the Ohau River catchment, which was unvegetated, where other pollen species had been degraded through biological activity (e.g., Bryant et al., 1994).

Cyclostratigraphy and borehole chronology

A sequence of four marine cyclothems is evident in the lower part of the borehole (263–100 m) (Table 2). Below 263 m depth, estuarine silty sands overlie inner-shoreface sands that most likely represent part of a preceding cycle that was not fully sampled within the borehole (Fig. 6). A maximum age of 340 ka is inferred for the cycles based on the age of first appearance (FAD) of several molluscan fauna in the Wanganui Basin. An in situ shell bed containing the remains of *Xymene plebeius* (Hutton), *Tawera spissa* (Deshayes) and broken valves of *Barytellina crassidens* (Marwick) was found at 223 m depth. The former two have a FAD of Castlecliffian Stage (1.71–0.340 Ma) while the latter is first found at around 300 ka (MIS 9) (Beu and Maxwell, 1990).

The first cycle (cycle 1) occurs between 263–228 m depth. It contains a 10-m-thick transgressive systems tract (TST) consisting of shoreface sand (facies FS) and bioturbated inner-shelf mud deposits (facies M). These deposits represent a fining-upward succession related to an abrupt increase in water depth over a wave graded shoreface environment (i.e., Posamentier and Vail, 1988). A highstand systems tract (HST) consisting of inner shelf mud deposits (facies M) overlies the TST. The boundary between the TST and HST is a down-lap surface (DLS) that occurs at 245–242 m depths. The DLS represents maximum flooding of the sea floor and is represented by a change from *Quinqueloculina*- to *Notorotalia*-dominated foraminifera and the appearance of an in situ marine faunal assemblage. Cycle 1 contains a thin regressive systems tract (RST) consisting of outer shoreface silty sand deposits (facies FZS). A regressive surface of erosion (RSE) is

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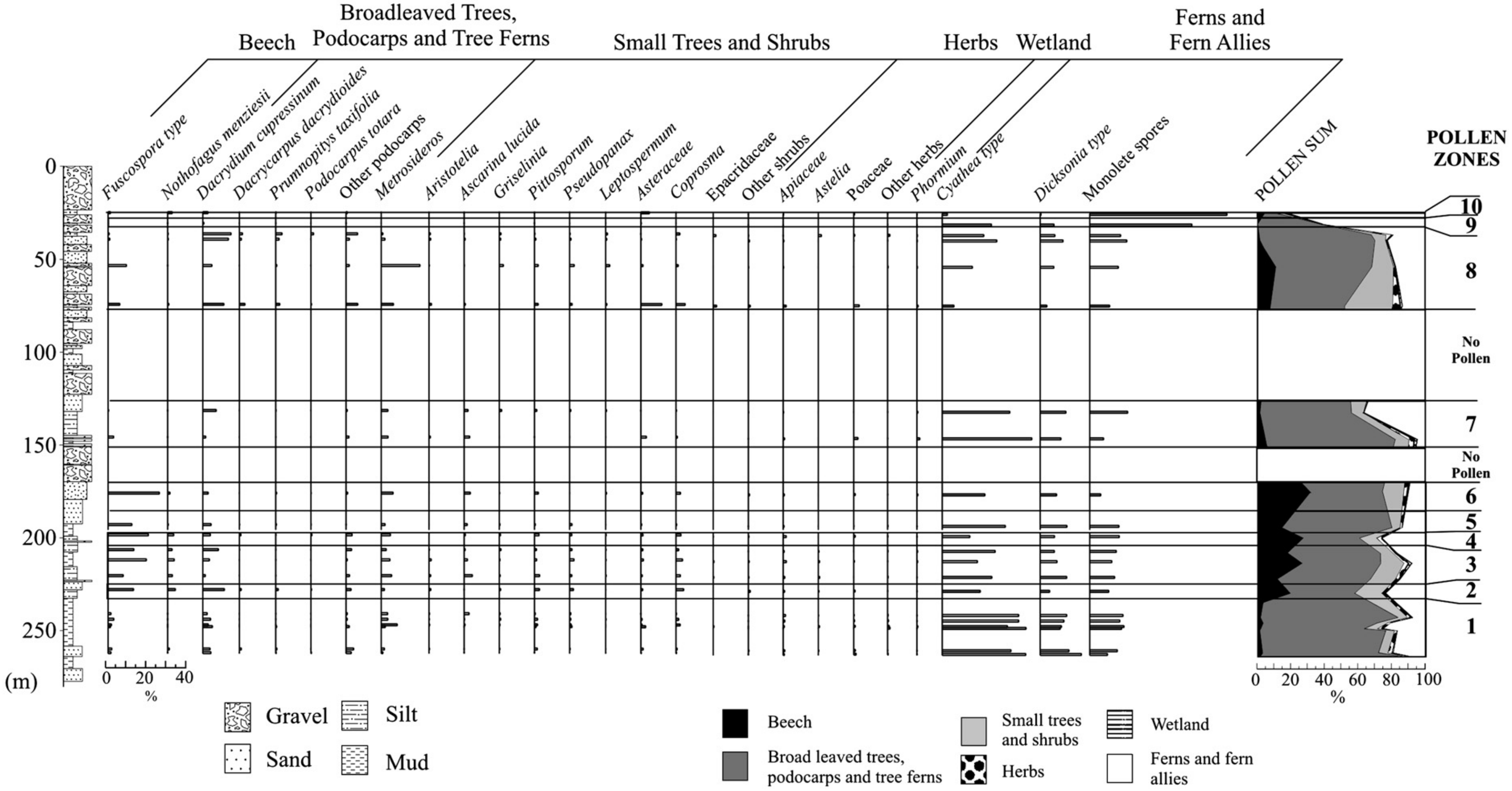

Figure 5. Percentage frequency bar graphs of most common pollen and spore encountered within Levin borehole. Pollen sum diagram shows relative proportions of beech (*Nothofagus*) trees, broadleaved trees, podocarps, small trees and shrubs, herbs, wetland, and ferns and fern allies.

Table 1c
Vegetation and climatic characteristics for each palynological zone within the core

Pollen zone	Vegetation	Inferred climate
1	Conifer–broadleaf forest	Full interglacial
2	Beech forest	Stadial (cooling)
3	Podocarp forest	interglacial
4	Beech forest and scrubland	Stadial (cooling)
5	Conifer–broadleaf forest	Full interglacial
6	Conifer–broadleaf and beech forest with scrubland	Stadial (cooling)
7	Conifer–broadleaf forest	Full interglacial
8	Podocarp-conifer broadleaf forest	Interglacial (cooling)
9	Treeless grass and shrubland	Full glacial
10	Partial beech forest	Glacial interstadial

inferred to lie between the HST and RST at approximately 235 m depth. No lowstand systems tract (LST) was identified in the borehole as the shelf most likely became sub-aerially exposed during sea-level lowstands, and these sediments were ephemeral and were removed or reworked during a later sea-level rise.

Two distinct tephras are found within strata between 229–228 m depths, though like all tephras identified within the borehole they are composed of multiple glass shards and are not considered to be primary air fall deposits (Fig. 7). The two tephras have similar geochemical signatures to the Rangitawa (350 ± 40 ka; Kohn et al., 1992) and Lower Finnis Road Tephras (320 ± 70 ka; Seward, 1976) in Wanganui Basin (Fig. 7). Two samples taken from 249–248 m and 229–228 m contained a nannofloral assemblage typical of the *Coccolithus pelagicus* zone (Anthony Edwards, Strat. Solutions Ltd, NZ, pers. comm., 2005) that has an age of ca. 60–500 ka that is based on the absence of *Pseudoemiliania lacunosa* (FAD MIS 12; Beu and Edwards, 1984). Strata in this cycle were deposited during an interglacial period (i.e., pollen zone 1) that corresponds to either warm MIS 5, 7, 9, or 11. The nannofossil *Emiliania huxleyi* (FAD MIS 8; Beu and Edwards, 1984) was absent from both samples suggesting an age of MIS 9 or 11. Based on the recognition of Rangitawa tephra (MIS 10) the strata must be younger than MIS 11 so an age of ca. 340–300 ka (MIS 9) is inferred.

Cycle 2 (228–202 m depth) truncates cycle 1 at the very top, and the sandy gravel found at the cycle boundary is similar in composition to deposits found on the uplifted terraces in the Wanganui Basin interpreted by Pillans (1983; 1994) to represent a ravinement surface (RS). The TST contains shoreface sand deposits (facies FS) and a mid-cycle shell bed that contains an in situ shelf–shoreface faunal assemblage (facies SL) (cf. Abbott, 1997). There is a DLS above the shell bed that separates it from overlying outer shoreface silty sand and inner shelf mud deposits that compose the HST (facies FZS and M, respectively). A RSE overlies the HST that separates shelf mud from estuarine silty sand deposits (facies FZS) that compose the RST. There is no LST associated with this cycle for those same reasons stated for cycle 1.

Cycle 3 (202–147 m depth) is the most complete sequence preserved within the borehole. The cycle boundary is a RS, and TST consists of shelly gravel and estuarine silty sand deposits (facies SG and FZS, respectively). The HST is composed of estuarine mud and sand deposits (facies M and FS, respectively) deposited in a marine embayment. Overlying the HST are estuarine silty sand deposits (facies FZS) that compose the RST. The cycle also contains a LST that is composed of interbedded mud and gravel deposits (facies IGM) that represent a lowstand fluvio-deltaic environment. The contact between the RST and LST is a marine–terrestrial boundary and may be time transgressive, as fluvial sediments prograded directly over marginal marine strata as the shoreline prograded under a dominant sediment supply regime as sea level fell (i.e., Shepherd, 1987; Naish and Kamp, 1997a).

Cycles 2 and 3 have an inferred age of MIS 7 through 6 (245–130 ka). Oxygen isotope curves suggest MIS 7 was characterised by two closely spaced highstands that were separated by a marked sea-level fall around 230 ka (Shackleton et al., 1990). The cyclostratigraphy of cycles 2 and 3 reflects two highstand periods, with the pollen record recording a slight climate deterioration within a warm period when scrubland and beech forest expanded at the expense of conifer–broadleaf forests (i.e., pollen zone 4). This sequence therefore appears equivalent to the Wanganui Landguard Bluff sequence of Pillans et al. (1988), which preserves highstands at MIS 7a and 7c.

An age of MIS 7c is suggested for cycle 2 based on the identification of a tephra at 208–206 m depth that has a similar geochemical composition to Middle Griffins Road tephra in Rangitikei Valley (ca. 300 ka; Pillans, 1988) and a tephra found within Waipuna Conglomerate (MIS 7) in Wanganui Basin (Holgate, 1985) (Fig. 7). The correlative tephra in the borehole is likely to have been reworked and have a maximum age of ca. 300 ka. A sample taken from 208–206 m depth was analyzed for nannoflora and found to contain *E. huxleyi* (FAD MIS 8). Therefore an age estimate of MIS 7a–6 is inferred for cycle 3.

Cycle 4 (147–100 m depth) is the shallowest cycle in the borehole. The TST contains basal marine gravel deposits (facies SG) that overlie lowstand fluvial deposits (facies IGM) and the cycle boundary is a transgressive surface. The HST consists of estuarine silty sand deposits. The TST and HST are considered to be valley fill deposits that accumulated in channels carved during the preceding lowstand. The RST and LST are represented by shoreface and beach sand (facies S) and gravel deposits (facies G). The transition between the HST, RST, and LST was most likely time transgressive and represents gradual depletion of accommodation space and coastal progradation under an abundant sediment supply regime. The presence the nannofossil *E. huxleyi* (FAD MIS 8) (Beu and Edwards, 1984) at 132–131 m depth places at maximum age on this cycle and it was likely deposited during the last interglacial period (MIS 5d–5b), based on its stratigraphic position in the borehole.

Between 100–40 m depths, thin beach and dune sand deposits (subfacies Sb and Sd) are interbedded with floodplain silt (facies Z) and thick fluvial gravel deposits (facies G). This succession represents a siliciclastic strandplain that commonly develops during late highstands or during regressions on coastlines where rate of sediment supply exceeds tectonic subsidence (Thom, 1983). Pollen within these sediments indicate an abundance of broadleaf tree species, suggesting climate was still warm. The succession most likely represents the regression that occurred during the last interglacial period (MIS 5b–5a) and wood from 75 m depth returned a background radiocarbon age (>40,000 ^{14}C yr BP, Lab number Wk13831). Sand deposits between 55–40 m depths are correlative to the Otaki Formation that compose the Tokomaru marine terrace in Horowhenua, based on sedimentology and regional stratigraphy (MIS 5b) (Barnett, 1994).

The top 40 m of the borehole strata consists of fluvial gravels and silts that comprise regional aggradation surfaces from the last glacial period (MIS 4–2) (Barnett, 1994). The uppermost gravel unit from ground level to 23 m depth correlates to the Ohakean aggradation surface that was deposited during the last glacial maximum

Table 2
Sequence stratigraphic terms and abbreviations used within this paper

Abbreviation	Systems tract	Inferred sea level
HST	Highstand systems tract	Highstand to early fall
LST	Lowstand systems tract	Lowstand
MCS	Mid-cycle shell bed	Late rise, highstand, early fall
RST	Regressive systems tract	Falling
TST	Transgressive system tract	Rising
	Description	
DLS	Down-lap surface	
RS	Ravinement surface	
RSE	Regressive surface of erosion	
FAD	First appearance datum	
OIS	Marine oxygen isotope stage	

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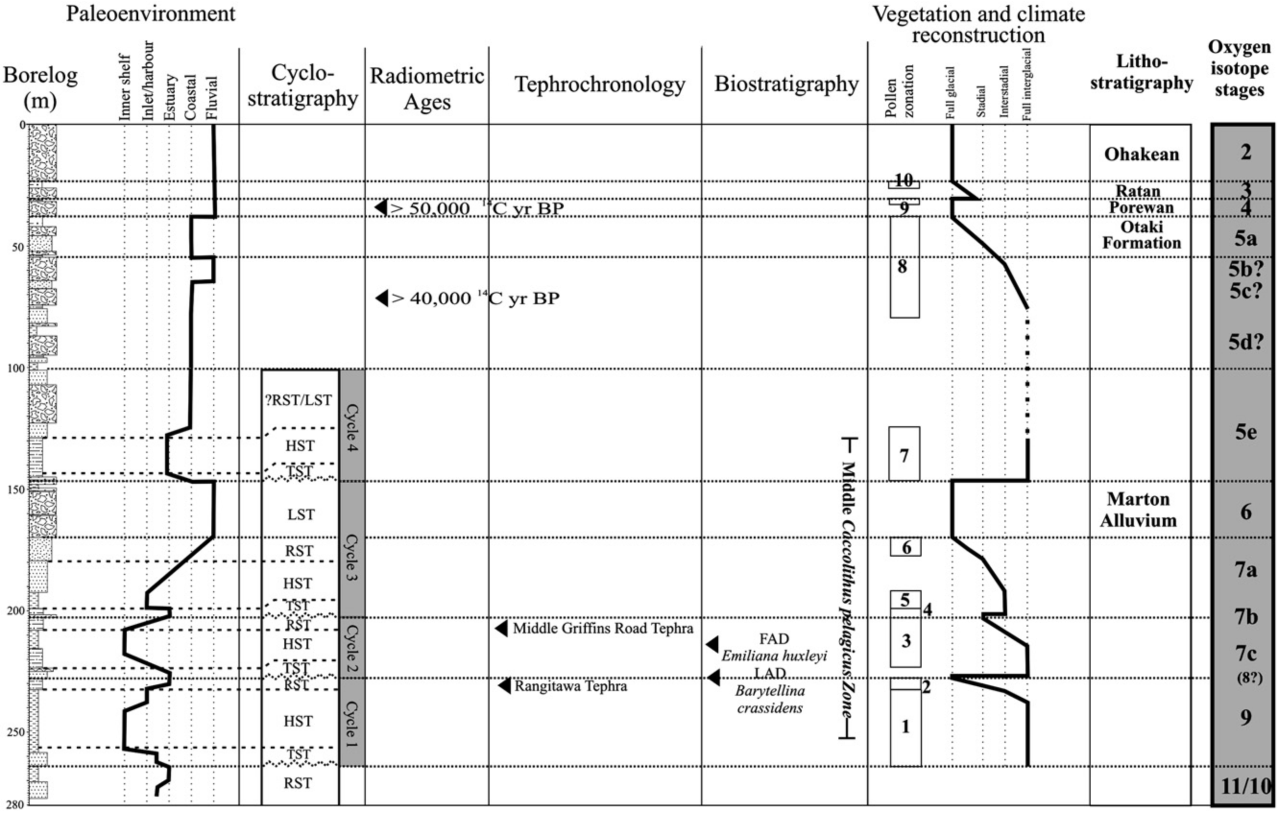

Figure 6. Chronostratigraphy of the Levin borehole based on recognition of chronologic markers from the Wanganui Basin (after Pillans, 1994) and correlation with marine oxygen isotope stages (Shackleton et al., 1990).

(14–24 ka; MIS 2). Pollen from silt beds within the gravel is suggestive of a largely barren landscape and large amounts of reworking. Two older aggradation surfaces that are correlative with the Ratan (24–59 ka; MIS 2) and Porewan (59–71 ka; MIS 3) sub-stages have also been tentatively identified within the borehole between 23–30 m depth and 30–42 m depth, respectively. This correlation is based on regional stratigraphy where a brief reappearance of broadleaf and *Nothofagus* trees indicates a slight climate amelioration occurred around MIS 3 (Cowie, 1963). A background radiocarbon age at 30 m depth also indicates the material to be older than MIS 2 (>50,000 ^{14}C yr BP, Lab number Wk13830).

Discussion

The sedimentary sequences cored within the central part of the Wanganui Basin represent the youngest marine depositional sequences found in the region. Four cyclothems were identified and interpreted to range in age from MIS 9–5, with each successively younger cycle being deposited in a shallower environment than the previous one. Cycles of this age have not been previously described within the basin, with uplifted marine terraces characterizing the sedimentary environments during this time in the well-described northern part of the basin (Pillans, 1983). It would therefore appear that while the coast around Wanganui was uplifting during the late Pleistocene, cyclic marine sediment continued to be deposited in the offshore part of the basin in the vicinity of Levin where accommodation space was still available. Seismic profiling close to the borehole described herein reveals that this local sedimentary depocenter was formed in basement anticlines and depressions. The largest of these, the Ohau Trough, is bounded on the seaward side by the Levin Fault and Poroutawhao High and contains some 900 m of sediment (Aharoni, 1991).

The depositional environment of the four cyclothems found in the Levin borehole is inferred by comparing their architecture to the youngest cycles from northern Wanganui Basin (MIS 10–17), which are now deeply buried and inaccessible in the southern sector. The architecture of these cyclothems is found to closely reflect eustatic cycles over a middle to inner shelf environment, with strata having a gentle southward dip and outcrop along the coast near Wanganui. The deepest and oldest cycles in the borehole (cycles 1 and 2) have similar architecture to Castlecliff cyclothem, especially those from MIS 7–10 (Saul et al., 1999) (Fig. 8). These are generally between 5–25 m thick and contain a thin sandy TST with mid-cycle shell bed, an upper HST consisting of shelfal massive or bedded siltstone, thin RST, and absent LST (Abbott, 1997). Maximum HST depth is between 25–75 m based on foraminiferal paleobathymetry (Naish and Kamp, 1997a). These cyclothems are the result of 5th-order stratigraphic sequences driven by glacioeustatic fluctuations over the middle to inner shelf (Carter and Naish, 1998).

The architecture of cycles 3 and 4 is similar to Haweran cyclothems that comprise uplifted marine terraces in Wanganui Basin. The individual terraces are between 10–20 m relief and underlying sediments contain a thin TST of shelly conglomerate, a shallow marine of estuarine HST with maximum water depth of 5–10 m, a shoreface RST, and non marine LST (Pillans, 1994). These cycles are also thought to be the result of 5th-order stratigraphic sequences driven by glacioeustatic fluctuations over a smoothly uplifting shoreline (Pillans, 1994). In the Levin borehole, these cycles represent progressive loss of accommodation space due to the infilling of the Ohau Trough or gradual uplift or a combination of both. Cycle 4 is correlated to the last interglacial (MIS 5) transgression and represents infilling of valleys incised during the previous glacials.

Cycle 4 represents that last marine incursion in the area with progradation of a coastal strandplain occurring during MIS 5d to 5a, culminating with infilling of the marine embayment during the MIS 5e last interglacial transgression. These sediments are represented

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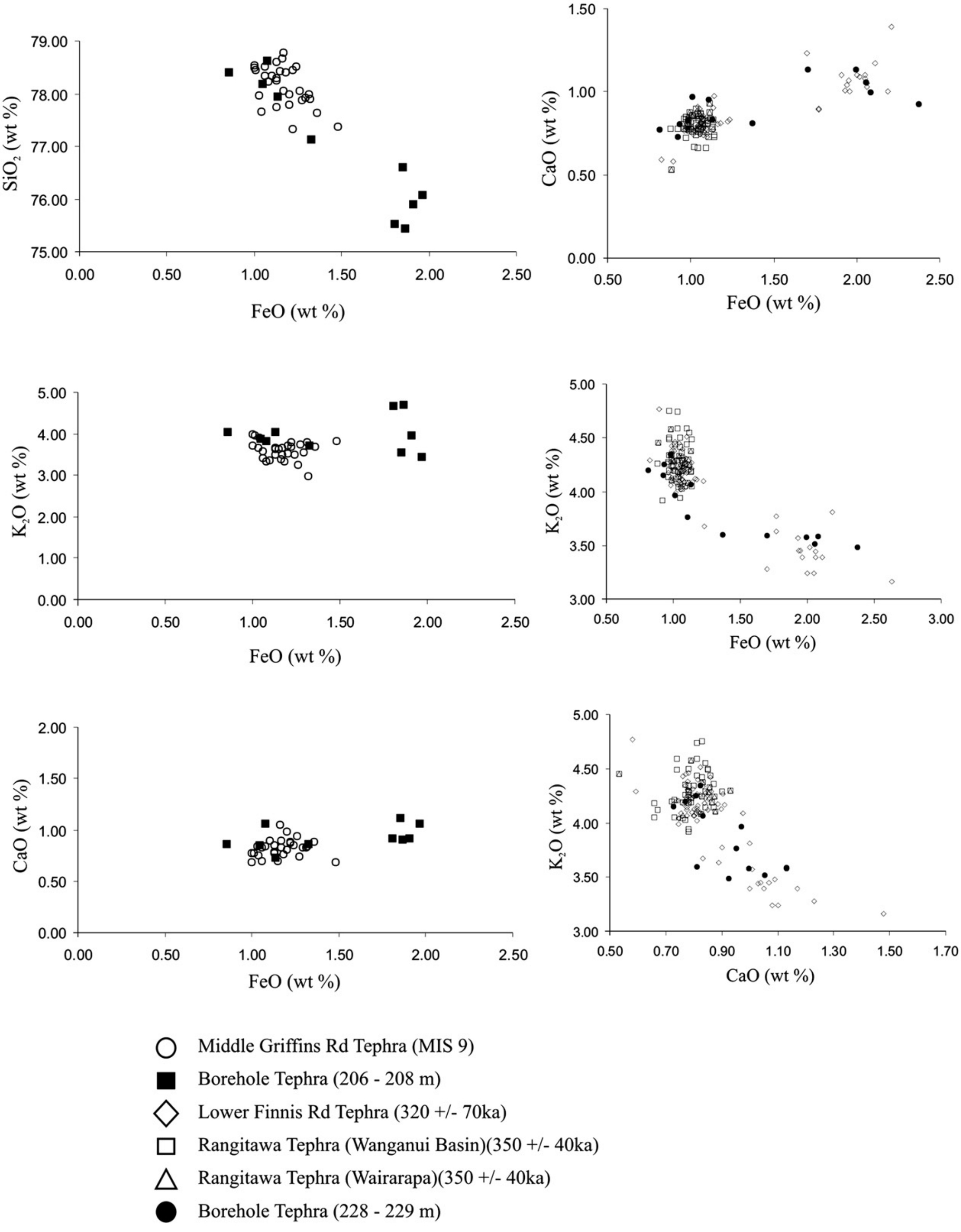

Figure 7. Geochemistry of glass shards showing biaxial plots of tephra within the marine units compared with the Middle Griffins Road Ash (data from Brad Pillans, Australian National University, pers. comm., 2005) and the Rangitawa Tephra (data from Brent Alloway, GNS Science, pers. comm., 2005).

between 100 and 40 m depths in the borehole, where estuarine deposits are gradually overlain by beach, dune, and fluvial sediments. Sand units in the upper part of this sequence are correlative with the Otaki Formation (MIS 5) underlying the Tokomaru marine terrace elsewhere in the region.

Borehole stratigraphy indicates that tectonic activity of the Levin Fault and associated Poroutawhao High had an affect on marine sedimentation that is somewhat restricted, although a maximum age for the Levin Fault is unknown. The Poroutawhao High probably remained submerged below sea level until MIS 7a. Prior to this time, a wave-graded open shelf environment appears to have dominated sedimentation. After MIS 7a, a protected marine embayment characterized deposition during sea-level highstand periods. The Levin Fault is considered to be no longer

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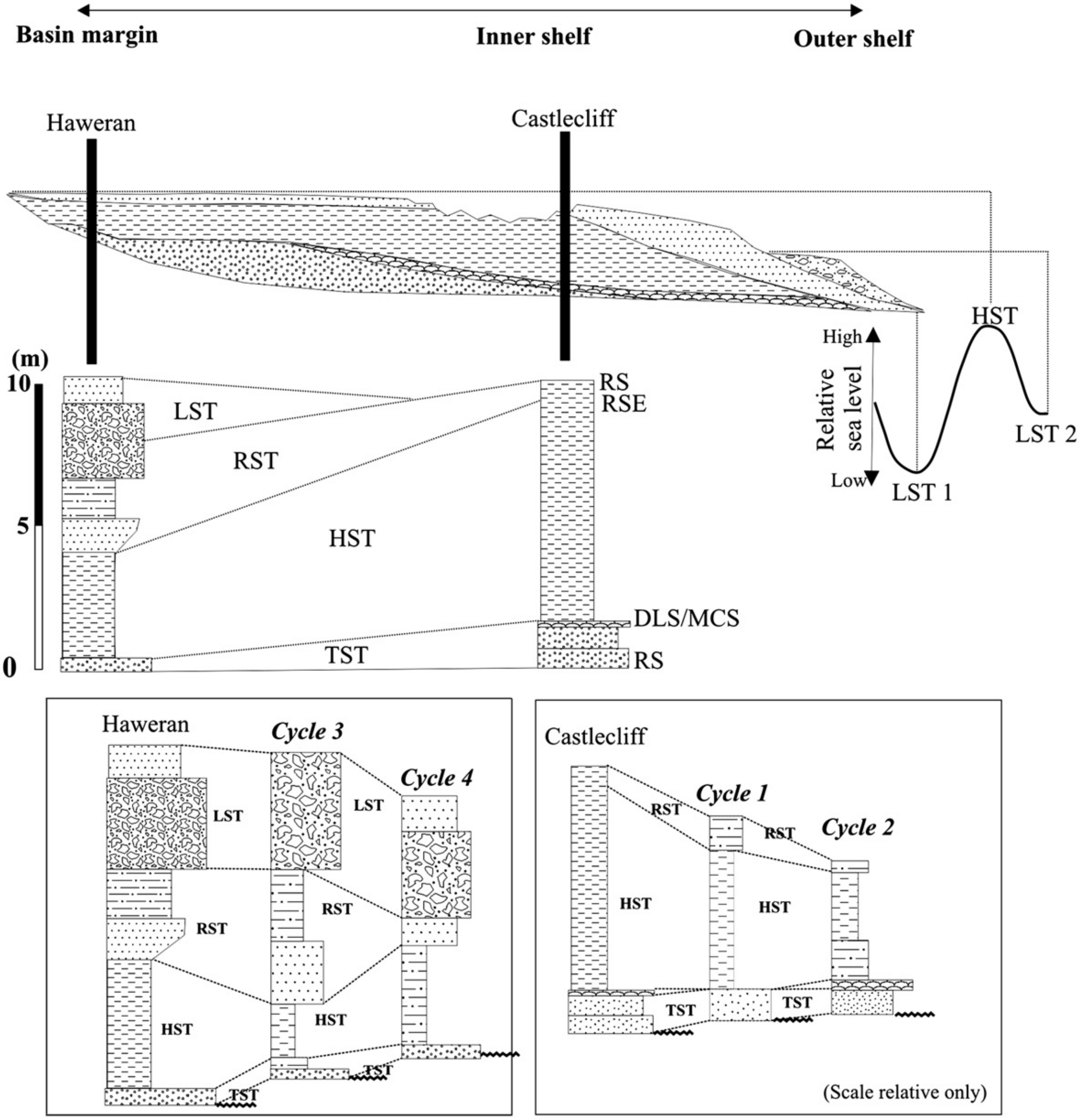

Figure 8. Summary stratigraphic model for the Wanganui Basin showing location and architecture of Castlecliff and Haweran motifs (after Saul et al., 1999) Also shown are sedimentary cycles from this study and their suggested origin. Cycles 1 and 2 correlate well with Castlecliff cyclothems and cycles 3 and 4 correlate well with Haweran cyclothems. See Figure 2 for sedimentary units legend. See Figure 1 for the location of the Castlecliff and Haweran motifs.

active as the Ohakean aggradation surface is not crossed by the fault.

Conclusion

Four marine cyclothems have been identified from strata found in a 280-m-deep borehole drilled near sea level near Levin in south eastern Wanganui Basin. Molluscan and nannofossil biostratigraphy and tephrostratigraphy indicate these cycles span MIS 9 through 5 and represent an extension of the marine record found within the uplifted part of Wanganui Basin. The newly described cyclothems indicate that while the Wanganui Basin was uplifting and forming marine terraces in the northern sector during the late Pleistocene, a shallow marine shelf environment existed over the Horowhenua District to the south where accommodation space for sedimentation was available. The sedimentary character of the borehole sediments representing the Levin area indicates a progressive shallowing of an inner shelf environment through multiple sea level cycles as accommodation space was infilled. Superimposed on the deposition were the effects of localized basement thrust faults and anticlines that created protected marine environments during MIS 7a and 5e. Progradation of coastal plain during the last interglacial period (MIS 5d–5a) and fluvial aggradation during the last glacial period (MIS 4–2) are represented in the upper part of the sequence.

The cyclostratigraphic pattern observed in the borehole sequence is similar to those recognized in the uplifted parts of the basin to the north that were deposited during MIS 17–10. This combined record now means eustatic history of the basin extends from MIS 17 to 5. The occurrence of much younger cycles within the borehole supports a southward shift in deposition within the basin during the Pleistocene. Such deposition extends the already long record present within Wanganui Basin, and also provides a stratigraphic relationship between the northern and south eastern parts of the basin.

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