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Anatomy and origin of autochthonous late Pleistocene forced regression deposits, east Coromandel inner shelf, New Zealand: implications for the development and definition of the regressive systems tract

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Abstract High-resolution seismic reflection data from the east Coromandel coast, New Zealand, provide details of the sequence stratigraphy beneath an autochthonous, wave dominated inner shelf margin during the late Quaternary (0–140 ka). Since c. 1 Ma, the shelf has experienced limited subsidence and fluvial sediment input, producing a depositional regime characterised by extensive reworking of coastal and shelf sediments during glacio-eustatic sea-level fluctuations. It appears that only one complete fifth-order (c. 100 000 yr) depositional sequence is preserved beneath the inner shelf, the late Pleistocene Waihi Sequence, suggesting any earlier Quaternary sequences were mainly cannibalised into successively younger sequences. The predominantly Holocene-age Whangamata Sequence is also evident in seismic data and modern coastal deposits, and represents an incomplete depositional sequence in its early stages of formation.

A prominent aspect of the sequence stratigraphy off parts of the east Coromandel coast is the presence of forced regressive deposits (FRDs) within the regressive systems tract (RST) of the late Pleistocene Waihi Sequence. The FRDs are interpreted to represent regressive barrier-shoreface sands that were sourced from erosion and onshore reworking of underlying Pleistocene sediments during the period of slow falling sea level from isotope stages 5 to 2 (c. 112–18 ka). The RST is volumetrically the most significant depositional component of the Waihi Sequence; the regressive deposits form a 15–20 m thick, sharp-based, tabular seismic unit that downsteps and progrades continuously across the inner shelf. The sequence boundary for the Waihi Sequence is placed at the most prominent, regionally correlative, and chronostratigraphically significant surface, namely an erosional unconformity characterised in many areas by large incised valleys that was generated above the RST. This unconformity is interpreted as a surface of maximum subaerial erosion generated during the last glacial lowstand (c. 18 ka). Although the base of the RST is associated with a prominent regressive surface of erosion, this is not used as the sequence boundary as it is highly diachronous and difficult to identify and correlate where FRDs are not developed. The previous highstand deposits are limited to subaerial barrier deposits preserved behind several modern Holocene barriers along the coast, while the transgressive systems tract is preserved locally as incised-valley fill deposits beneath the regressive surface of erosion at the base of the RST.

Many documented late Pleistocene RSTs have been actively sourced from fluvial systems feeding the shelf and building basinward-thickening, often stacked wedges of FRDs, for which the name **allochthonous FRDs** is suggested. The Waihi Sequence RST is unusual in that it appears to have been sourced predominantly from reworking of underlying shelf sediments, and thus represents an **autochthonous FRD**. Autochthonous FRDs are also present on the Forster-Tuncurry shelf in southeast Australia, and may be a common feature in other shelf settings with low subsidence and low sediment supply rates, provided shelf gradients are not too steep, and an underlying source of unconsolidated shelf sediments is available to source FRDs. The preservation potential of such autochthonous FRDs in ancient deposits is probably low given that they are likely to be cannibalised during subsequent sea-level falls.

Keywords sequence stratigraphy; forced regressive deposits; regressive systems tract; incised-valley fill; sea-level change; Coromandel shelf; New Zealand; late Pleistocene; Forster-Tuncurry shelf; Australia

INTRODUCTION

Sequence stratigraphy is a valuable tool for analysing depositional cycles associated with the infilling of modern and ancient sedimentary basins. The geometric arrangement and hierarchy of depositional sequences reflects an interplay between fluctuations in accommodation versus sediment supply at a variety of scales. Early sequence stratigraphic models assumed that no sediment was deposited on the shelf during most of the falling part of a sea-level cycle because of an overall erosive regime (Mitchum et al. 1977; Vail 1987; Van Wagoner et al. 1987). However, it has since been recognised that often a distinct phase of deposition occurs during falling sea-level conditions, before the lowest point of sea level. The concept of shoreface progradation driven by falls in relative sea level, a process termed forced regression, was documented by Plint (1988, 1991) and Plint & Norris (1991) from studies of subsurface and outcrop sections in the Cretaceous Western Interior of Canada. Deposits generated during forced regressions have been variously described as sharp- or erosive-based shoreface

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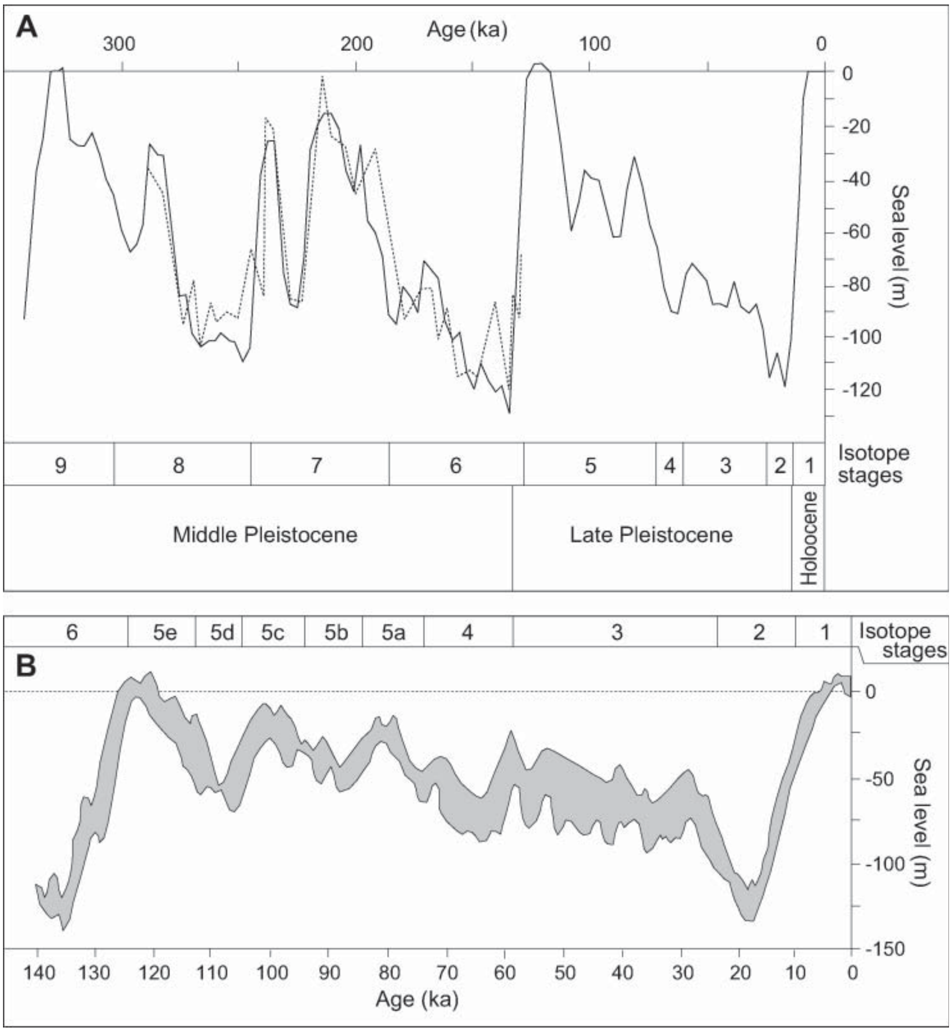


Fig. 1 **A**, Oxygen isotope-based glacio-eustatic sea-level record for the past 350 000 yr highlighting the asymmetrical nature of the fifth-order (c. 100 ka) cycles, with short highstands and lowstands, rapid transgressions, and prolonged sea-level falls (solid line from Chappell & Shackleton (1986) and Shackleton (1987); dotted line from Martinson et al. (1987)). **B**, Late Pleistocene sea-level envelope showing the prolonged and episodic nature of falling sea level prior to the maximum lowstand at c. 20 ka, conditions favourable to the development of forced regressive deposits (FRDs; based on sea-level curves published by Chappell & Shackleton 1986; Shackleton 1987; Bard et al. 1990, 1992; Bond et al. 1993; Dansgaard et al. 1993).

deposits, shelf-perched lowstand deposits, shelf-edge lowstand deposits, shoreline-detached shelf deposits, and forced regression deposits (Hunt & Tucker 1992; Posamentier et al. 1992; Posamentier & Allen 1999; Plint & Nummedal 2000).

Attempts to place forced regressive deposits (FRDs) within a sequence stratigraphic framework have generated controversy regarding the placement of sequence boundaries in relation to the FRDs, and whether a new depositional systems tract should be added to the well-established tripartite sequence stratigraphic scheme involving lowstand (LST), transgressive (TST), and highstand (HST) systems tracts (Hunt & Tucker 1992, 1995; Posamentier et al. 1992; Kolla et al. 1995; Posamentier & Allen 1999; Posamentier & Morris 2000; Plint & Nummedal 2000). FRDs have been ascribed to the LST (Posamentier et al. 1992; Kolla et al. 1995) where they are interpreted to overlie the sequence boundary. However, several workers have proposed a new systems tract for FRDs with the sequence boundary above (e.g., Nummedal et al. 1993; Mellere & Steel 1995; Van Wagoner 1995; Hart & Long 1996; Naish & Kamp 1997; Haywick 2000; Hernández-Molina et al. 2000; Kolla et al. 2000; Plint & Nummedal 2000). These include the regressive systems tract (RST; Naish & Kamp 1997), falling stage systems tract (FSST; Plint & Nummedal 2000), and the offlapping systems tract (OST; Pomar & Ward 1995). Van Wagoner (1995) adapted the late highstand prograding complex of Vail (1987) to include FRDs. Naish & Kamp (1997) originally ascribed the RST to gradationally based FRDs. However, the RST definition has subsequently been abridged to include both sharp-based and gradationally based FRDs (Saul et al. 1999; Kitamura et al. 2000; Browne & Naish 2003). For this study, we use the RST terminology to place FRDs within a sequence stratigraphic framework.

The strongly asymmetric nature of glacio-eustatic sea-level cycles during the Pleistocene (Fig. 1A), when gradual and prolonged falling sea-level conditions occupied c. 80% of the time, ought to potentially favour the formation of extensive FRDs on many continental shelves. Indeed, because they are shallow enough to be imaged by high-resolution seismic reflection profiles and can be related to a known sea-level record (Fig. 1B), there have been several recent studies of late Pleistocene FRDs beneath modern shelves, such as those bordering the Mediterranean Sea (Trincardi & Field 1991; Tesson et al. 1993; Chiocci 2000; Hernández-Molina et al. 2000), in the Gulf of Mexico (Kolla et al. 2000), and on the Canterbury shelf in New Zealand (Browne & Naish 2003). However, most published examples of late Pleistocene FRDs are offshore from large river systems where they formed under conditions involving a combination of

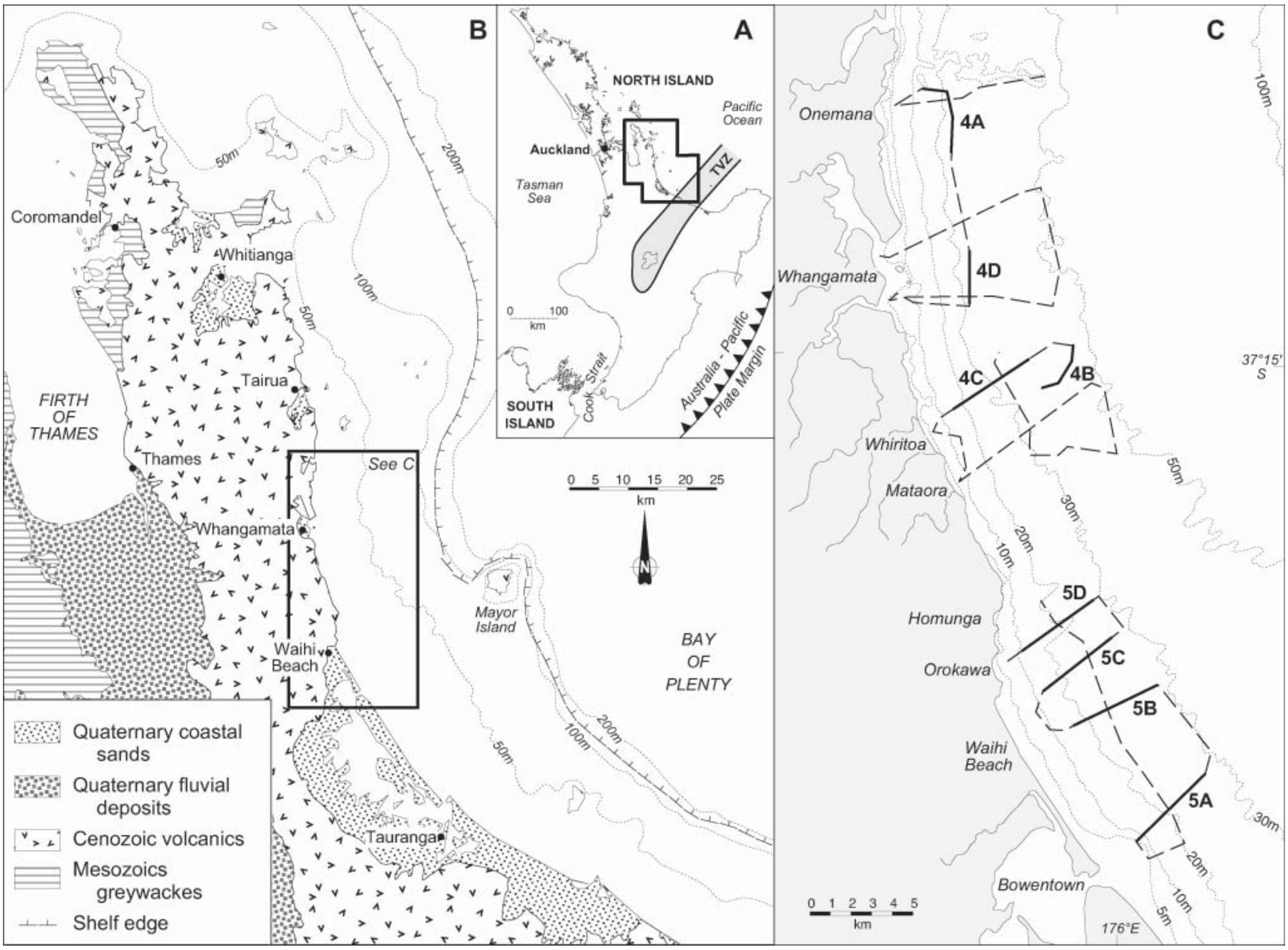


Fig. 2 **A**, Location of the east Coromandel shelf in the back-arc region of northeast New Zealand, behind the modern Taupo Volcanic Zone (TVZ). **B**, Regional geology (after Schofield 1967) highlighting the rocky, embayed nature of the east Coromandel coast, and the wide coastal plain that dominates the Bay of Plenty coastline to the southeast. **C**, Location of inner shelf seismic profiles with figured transects bolded and numbered.

relatively high sediment supply and subsidence rates during falling sea level, producing for example the outer-shelf perched FRDs on the Rhône shelf, Mediterranean (Tesson et al. 1993), fluvio-deltaic FRDs on the Canterbury shelf, New Zealand (Browne & Naish 2003), or the across-shelf FRD lobes atop the Lagniappe delta, Gulf of Mexico (Kolla et al. 2000).

This study describes and interprets the seismic stratigraphy from beneath the inner shelf off a portion of the east coast of the Coromandel Peninsula in northeastern New Zealand (Fig. 2). Here, there are no major river systems supplying sediment directly onto the shelf, but what we infer to be late Pleistocene FRDs appear to dominate the subsurface geology of this age across the imaged inner shelf zone. We develop a conceptual model to explain the evolution of the late Pleistocene and Holocene seismic units that is linked to a record of eustatic sea-level change for the period. The nature of the east Coromandel FRDs in this model is used to provide some additional insights about the sequence stratigraphy and origin of FRDs, particularly in autochthonous depositional settings where sediments are sourced through reworking of underlying deposits by wave and wind-generated currents.

REGIONAL SETTING

Geology

The Coromandel Peninsula is a prominent horst block within the back-arc region above the westward-subducting Pacific plate under the North Island (Fig. 2A,B). Arc volcanism dominated the region throughout the Miocene and Pliocene and produced the andesites, rhyolites, dacites, and ignimbrites of the Coromandel Group that form the peninsula (Table 1; Fig. 2B). Back-arc extension was initiated off the east Coromandel coast c. 4 Ma and continued until c. 1 Ma (Table 1) (Wright 1992). This period of back-arc extension produced a series of basins flanking the Coromandel Peninsula that infilled with up to 1 km of volcaniclastic sediments (Thrasher 1986; Wright 1992). Onshore equivalents of these Pliocene–Pleistocene back-arc deposits are represented by coastal terrace deposits t_1 and t_2 near Waihi Beach, dated at 1.5–1.7 Ma, that are part of the Tauranga Group (Fig. 3) (Brathwaite & Christie 1996).

About 1 Ma, the volcanic arc migrated east and south away from Coromandel Peninsula to establish the Taupo Volcanic Zone (Wright 1992). Back-arc basin infilling ceased

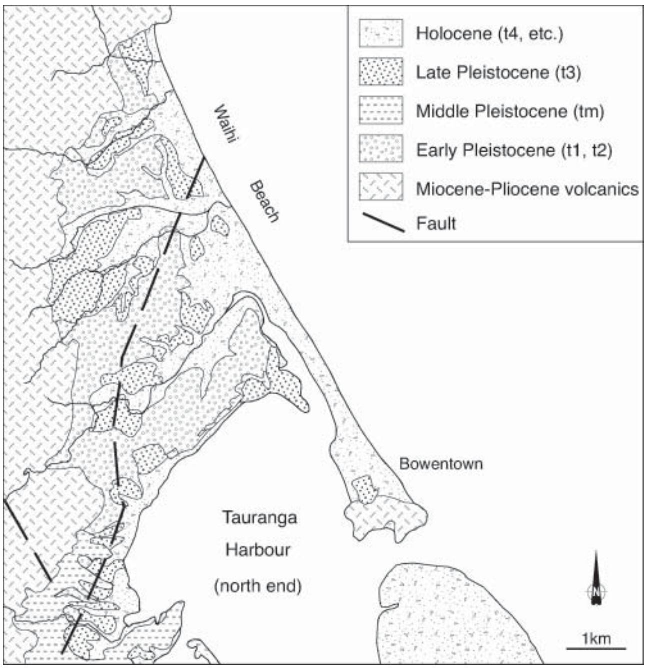


Fig. 3 Quaternary sedimentary units mapped onshore in the vicinity of Waihi Beach, northern Tauranga Harbour (see Fig. 2B). Units and lithologies are defined in Table 1. (Adapted from Brathwaite & Christie 1996.)

on the east Coromandel margin as thermal subsidence slowed to a rate of c. 4 cm/ka (Abrahamson 1987). Mid–late Pleistocene sedimentation on the east Coromandel shelf has thus been characterised by only limited supply of fluvial sediments derived from erosion of the peninsula. Back-arc basin extension shifted to the Tauranga Basin to the south of Waihi Beach, which has continued to infill with up to 500 m of terrestrial and coastal sediments included also within the Tauranga Group (Table 1) (Harmsworth 1983; Brathwaite & Christie 1996).

Coastal morphology and oceanography

Eastern Coromandel Peninsula is drained by short, steep-gradient, small streams discharging onto a rocky, embayed coastline supporting stationary, Holocene-age mainland beaches along some rocky coastal sectors, and Holocene and late Pleistocene-age highstand barriers enclosing estuaries in local drowned river valleys (Fig. 2B) (Marks & Nelson 1979; Gibb & Aburn 1986; Abrahamson 1987; Davis & Healy 1993). The east Coromandel coast is sediment starved, with the bulk of Holocene barrier systems formed during an onshore mass transfer of shelf sediments in the early Holocene (Abrahamson 1987). For example, the Pauanui barrier system at the mouth of Tairua Harbour (Fig. 1B) prograded c. 620 m through reworking of shelf deposits by 2.0 ka, while there has been only 120 m of progradation from fluvially sourced sediments between 2.0 and 0 ka (Gibb & Aburn 1986). The east Coromandel shelf is wave dominated

Table 1 Major geological map units on east Coromandel Peninsula, based on Schofield (1967) and Brathwaite & Christie (1996), and their suggested correlation with offshore seismic units. ASL = above sea level.

Age	Geological unit	Lithology	Shelf geology	Basin evolution
Holocene (12–0 ka)	Modern coastal terraces (tr, te, td, tb, and t4) in the Tauranga Group at <3 m ASL	Fluvial sand, gravel, and mud; coastal and dune sand; estuarine sand, silt, and clay; rhyolitic pebbles and pumice (Taupo eruption, 1.8 ka)	Seismic units 5 and 6 (Whangamata Sequence), possibly equivalent to Thrasher's (1986) upper seismic unit on slope	Slow thermal subsidence on east Coromandel shelf; back-arc extension, subsidence, and sedimentation in Tauranga Basin
Late Pleistocene (120–12 ka)	Coastal terraces (t3) in the Tauranga Group at 4–5 m ASL	Fluvio-estuarine clayey sand, sandy clay; paleosols; Rotoehu Ash (?c. 60 ka)	Seismic units 3 and 4 (Waihi Sequence), possibly equivalent to Thrasher's (1986) upper seismic unit on slope	Slow thermal subsidence on east Coromandel shelf; back-arc extension, subsidence, and sedimentation in Tauranga Basin
Middle Pleistocene	Matua Subgroup (tm) of Tauranga Group	Alluvial gravel, sand, silty clay, and peat; estuarine silt and mud; minor beach sand interbedded with tephra (0.22–0.84 Ma)	Possibly forms the upper part of seismic unit 2 offshore from Bowentown; may form part of Thrasher's (1986) lower seismic unit on slope	Slow thermal subsidence on east Coromandel shelf; back-arc extension, subsidence, and sedimentation in Tauranga Basin
Early Pleistocene	Coastal terraces (t1 and t2) in the Tauranga Group at 15–40 m ASL	Rhyolite pebbles; paleosols, weathered rhyolite, red clay; tephra (1.5–1.7 Ma)	Seismic unit 2, possibly equivalent to Thrasher's (1986) lower seismic unit on slope	Back-arc extension, rapid subsidence, and sedimentation on east Coromandel shelf
Early Miocene–Pliocene	Coromandel Group Volcanics (cover much of Coromandel Peninsula)	Rhyolites, dacites, ignimbrites, and sediments	Seismic unit 1 (igneous basement)	Arc volcanism

(Bradshaw et al. 1991, 1994), with sediment entrainment restricted to depths <20 m under fair-weather wave conditions (H_S = 0.9–1.7 m; T = 4–13 s). Periodic extratropical storm waves (H_S = 1.0–5.0 m; T = 4–10 s) and their associated storm currents (velocity up to 0.4 m/s) mobilise sediments in depths down to 50 m where they are transported offshore by downwelling currents and northwards by geostrophic flows (Bradshaw et al. 1991, 1994).

METHODOLOGY

Some limited geophysical surveys in support of an inner shelf sedimentation study were undertaken in June 1990 using an EG and G Uniboom (Model 230-1) high-resolution sub-bottom profiler. Approximately 135 km of 3.5 kHz high-resolution seismic records were obtained off Waihi Beach, Whiritoa, Whangamata, and Onemana in water depths of 10–50 m (Fig. 2C). Tracklines were positioned with precise satellite navigation. Signal penetration reached 30–50 m sub-bottom at a maximum vertical resolution of 0.5 m before the first multiple reflection appeared. Ground truthing of some seismic units exposed on the seafloor was possible using side-scan sonographs, box cores, and surface grab-samples collected along the sub-bottom tracklines (Bradshaw 1991; Bradshaw et al. 1994). Two-way travel time on seismic profiles was converted into metres assuming a seismic wave velocity of 1500 m/s in water and 1800 m/s in sediments (McQuillin & Ardos 1977).

INNER SHELF SEISMIC UNITS

The definition of seismic units beneath the east Coromandel inner shelf is based on distinct seismic facies and bounding surfaces. Geological interpretations of the seismic units are possible using established seismic sequence stratigraphy methods (e.g., Vail 1987; Emery & Myers 1996; Posamentier & Allen 1999). The relative age of the seismic units has been interpreted from the superposition of various truncation, toplap, onlap, and downlap surfaces. The actual geologic age of each seismic unit cannot be directly determined because there are no long sediment cores through the imaged sections. Instead, an estimate of the most likely age range for each unit has been made by comparing the superposed seismic evidence for relative falls and rises in sea level with an established eustatic sea-level record for the last 140 000 yr (Fig. 1B) (Chappell & Shackleton 1986; Martinson et al. 1987; Shackleton 1987). Additional support for the chosen ages has come from comparing the seismic character and juxtaposition of the east Coromandel units with similar seismic profiles from the southeastern Australian shelf, where some absolute age control is available (Roy et al. 1997).

Up to six distinct seismic units have been identified, each separated by a seismic discontinuity representing a significant sequence stratigraphic surface (Fig. 4, 5). Their essential characteristics are summarised in Table 2.

Seismic unit 1

Seismic unit 1 is an acoustically opaque unit that crops out on the inner shelf off Onemana (Fig. 4A). The upper bounding surface of unit 1 is an irregular erosion surface that is interpreted as representing a major unconformity. Seafloor dredging and side-scan sonar surveys of the seafloor (Bradshaw et al. 1994) indicate that unit 1 represents local Neogene volcanic basement (Tables 1, 2). Unit 1 is generally only shallow enough to be seismically imaged in the northern profiles. Farther south the volcanic basement descends steeply beneath a thick sedimentary section. Interpretations of deeper multi-channel seismic data by Thrasher (1986) indicate that volcanic basement is c. 200 m beneath the shelf surface south of Onemana. The sudden appearance of unit 1 off Onemana coincides with an igneous platform which extends from the coast (Thrasher 1986), and defines the northwestern boundary of an early Pliocene-age back-arc basin complex on the east Coromandel shelf.

Seismic unit 2

Unit 2 is the thickest and most extensive of the seismic units beneath the east Coromandel inner shelf. The base of unit 2 is rarely imaged and it is typically at least 20 m thick before the first seafloor multiple degrades the seismic signal. An exception is off Onemana where seismic reflectors from unit 2 can be seen onlapping against volcanic basement (unit 1; Fig. 4A). The upper boundary of unit 2 varies from an angular unconformity on the Whiritoa inner shelf (Fig. 5B) to an erosional unconformity in most areas. Unit 2 has a highly variable seismic character ranging from irregular chaotic reflectors to semi-continuous subparallel reflectors (Fig. 4C,D, 5B,C). More continuous, offlapping and onlapping seismic reflectors appear to be present off Bowentown (Fig. 5A). This significant change in seismic character at the southern limit of the study area may represent a younger middle Pleistocene sequence from the northern margin of the Tauranga Basin. Gas-rich muds may be responsible for the presence of common opaque acoustic zones imaged in unit 2 (Fig. 4B,C, 5C). Most profiles from unit 2 do not show any clear seismic geometry to indicate possible internal bounding surfaces and subunits.

Overall, the seismic character and superposition of unit 2 are similar to an early Pliocene–Pleistocene sequence identified by Thrasher (1986) from multi-channel seismic observations which extends across the east Coromandel shelf and slope from subsurface depths of a few hundred metres to >2 km. Thrasher (1986) described syndepositional growth within this sequence, which appears to be tilted to the east. He correlated this sequence with early Pliocene–Pleistocene-age sediments that form coastal terraces t_1 and t_2 behind Waihi Beach (Fig. 3). The syndepositional growth and regional eastward tilting described by Thrasher (1986), and deformation apparent in high-resolution seismic sections from the Whiritoa shelf region (Fig. 4B), indicate that unit 2 was associated with a regional tectonic event. This is likely to be back-arc basin extension and subsidence that began off the east Coromandel Peninsula at c. 4 Ma (Wright 1993). It is uncertain exactly when deposition of seismic unit 2 ceased. However, dating of deposits from t_1 and t_2 at 1.5–0.7 Ma (Brathwaite & Christie 1996) suggests that deposition of unit 2 ended in the early Pleistocene, by which time the axis of back-arc extension had migrated southeast (Fig. 2) (Wright 1993).

Seismic unit 3

Seismic unit 3 is only partially preserved in profiles from the innermost shelf region between Bowentown and north Waihi Beach (Fig. 5). Here, it reaches a maximum thickness of 10 m off Waihi Beach, but is generally <5 m thick due to truncation by an overlying erosion surface (Fig. 5, 6).

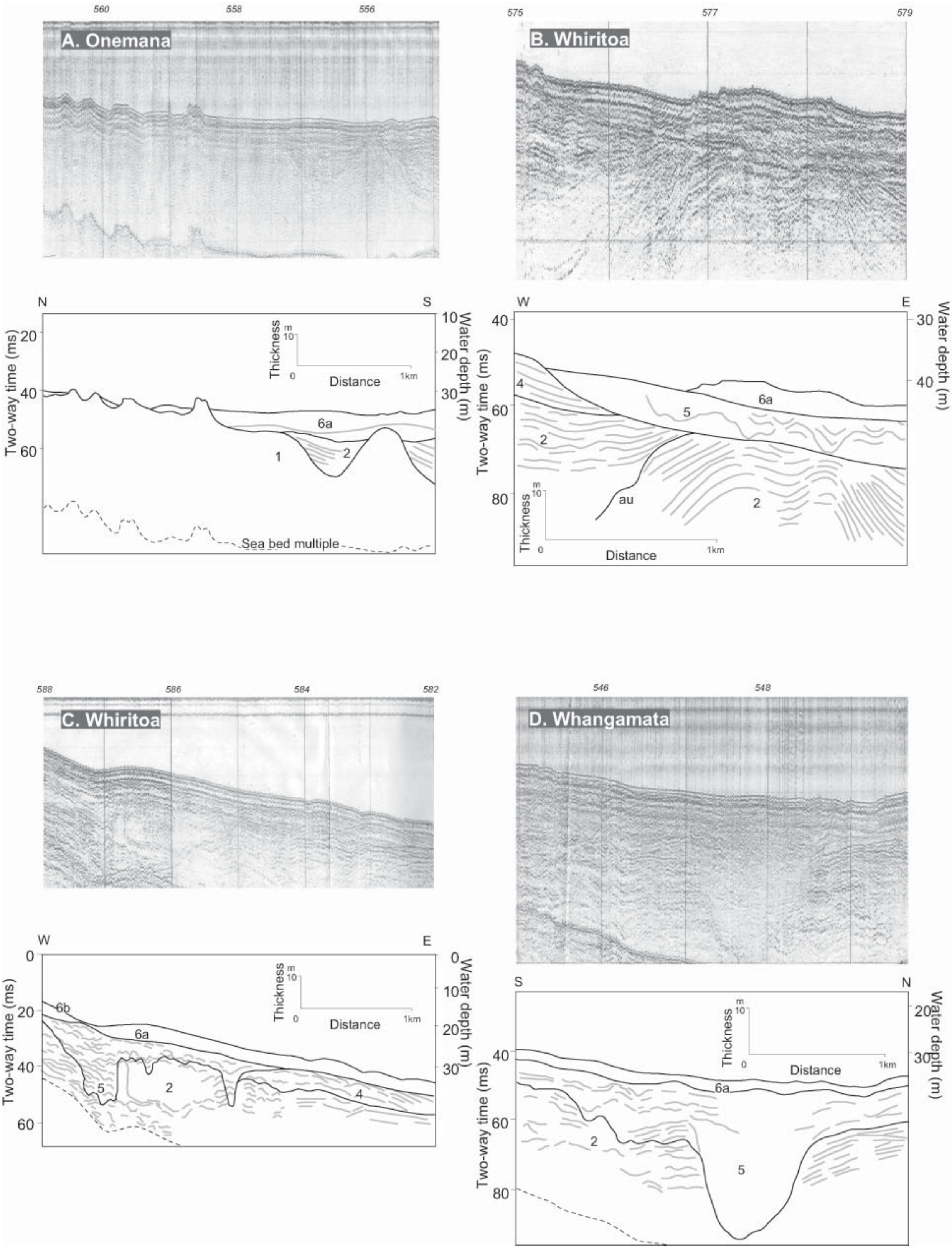


Fig. 4 High-resolution seismic profiles from the northern survey area (see Fig. 2C). **A**, Offshore Onemana Beach showing shallow igneous basement and thin development of seismic unit 2. **B**, Offshore Whiritoa Beach showing thick and structurally deformed seismic unit 2, including intra-angular unconformity (au), northern limit of seismic unit 4, and broad incised valley infilled with seismic units 5 and 6a. **C**, Offshore Whiritoa Beach showing poorly developed seismic unit 4 and extensive incised-valley erosion. **D**, Offshore Whangamata Beach showing very large incised-valley feature infilled with seismic unit 5. Seismic units defined in Table 2.

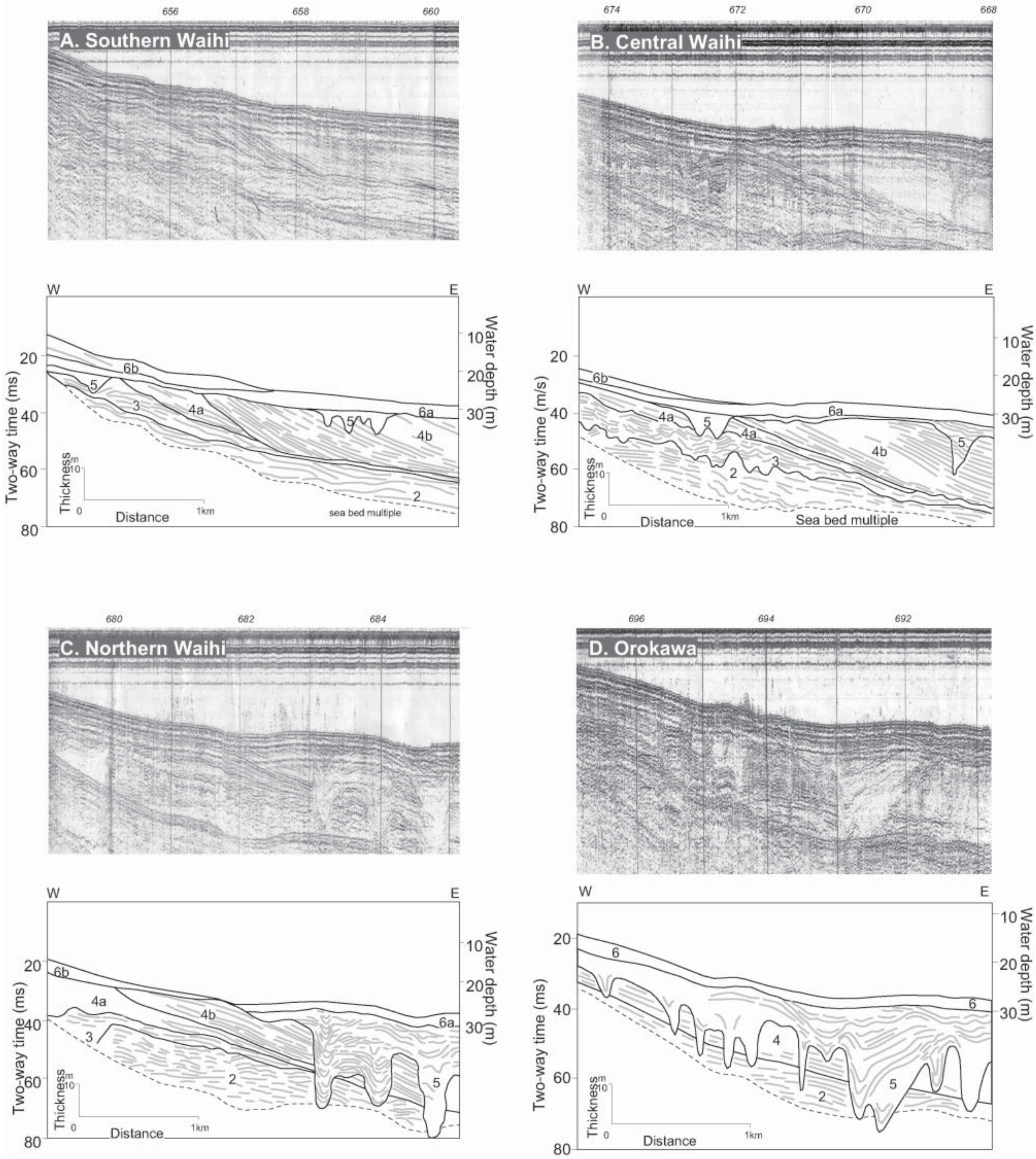


Fig. 5 High-resolution seismic profiles from the southern survey area (see Fig. 2C). **A**, Offshore Bowentown showing well-preserved late Pleistocene forced regressive deposit (FRD) in seismic unit 4. **B**, Offshore central Waihi Beach showing well-preserved seismic unit 3 and late Pleistocene FRD represented by seismic unit 4. **C**, Offshore northern Waihi Beach showing deep incised valleys eroding into seismic unit 4 and infilled with seismic unit 5. **D**, Offshore Orokawa Bay showing almost complete destruction of late Pleistocene FRD by extensive and deep incised valleys infilled by seismic unit 5. Seismic units defined in Table 2.

Elsewhere, unit 3 was either never deposited on the shelf or was subsequently completely eroded. Seismic unit 3 occurs above an incision surface that truncates at least 5 m of strata from unit 2 (Fig. 5B). This incision surface is interpreted to have formed during the c. 130 m fall in relative sea level that occurred during the glacial lowstand accompanying isotope stage 6 (c. 140 ka; Fig. 1). Unit 3 varies from chaotic discontinuous reflections which infill small (c. 5 m deep) incision surfaces off Waihi Beach (Fig. 5B), to discontinuous reflections which onlap unit 2 off Bowentown (Fig. 5A). This seismic facies is interpreted as representing transgressive sediments (shelf, barrier-shoreface, and fluvio-estuarine) deposited during the marine transgression at the end of isotope stage 6 (c. 128 ka; Fig. 1).

Seismic unit 4—a forced regressive deposit (FRD)

Seismic unit 4 forms a very prominent, sharp-based, tabular unit off Bowentown and Waihi Beach (Fig. 5, 6). It is well preserved off Bowentown where it is up to 20 m thick (Fig. 5A, 6), but becomes increasingly truncated by a prominent incision surface towards the north (Fig. 5C,D, 6). Farther north, unit 4 is hard to recognise, but may be present off Whiritoa where seismic sections image a thin offlapping unit (Fig. 4C). Unit 4 stands out on seismic sections as a sharp-based, tabular unit with offlapping seismic reflections (clinoforms) that downstep progressively basinwards. The offlapping clinoforms dip at the same gradient as modern shoreface deposits along the east Coromandel coast, and are thus interpreted as progradational shoreface sands. Clinoforms terminate up-dip at a near-flat upper surface, and down-dip by downlap against a seaward-dipping, sharp-based erosion surface that extends from depths of 35–50 m below present sea-level. At least two distinct disjunct, progradational wedges separated by truncation surfaces are evident in seismic sections. The oldest, unit 4a, is only partially preserved beneath the innermost shelf where it rests above and truncates unit 3 (Fig. 5A–C). The second wedge, unit 4b, is thicker and extends more continuously across the inner shelf zone. The base of unit 4b is a seaward-dipping erosional surface that truncates strata from units 4a, 3, and 2 (Fig. 5A–C).

The seismic geometry of unit 4 indicates at least two major phases of submarine erosion followed by shoreface progradation. Late Pleistocene-age coastal sediments (isotope stage 5) occur behind several modern barrier systems along the east Coromandel coast (Abrahamson 1987), and may represent highstand deposits that immediately preceded

Table 2 Some properties of seismic units 1–6 beneath the inner Coromandel shelf.

Seismic unit and inferred age	Seismic character	Location	Thickness	Upper contact	Lithology (inferred) and systems tract[1]
6 Holocene <6.5 ka Late isotope stage 1	Sheet-like, but mainly obscured by first bubble pulse	All profiles	**6b** – only nearshore, landward thickening **6a** – thin (<5 m) but extensive	Modern seabed	**6b** – vf sands of modern shoreface (**HST**) **6a** – transgressive shelf sands (fs over cs) (**TST**)
5 Postglacial 15–6.5 ka Late isotope stage 2 and 1	Channel-like features and lateral progradation of reflectors over seismic opaque zones	N Waihi to Whiritoa (deep valleys), Whangamata (broad valley)	Highly variable (0 to >20 m)	Planar erosive surface	Incised-valley fills with gaseous muds, fluvial and tidal delta sands (**TST**)
4 Late Pleistocene 112–18 ka Isotope stages late 5, 4, 3, 2[2]	Sharp-based tabular unit, offlapping reflectors downstep basinwards	Bowentown to Waihi, less well preserved farther north	4b – Thick across inner shelf 4a – Partly preserved beneath innermost shelf	Major incision surface	Progradational shoreface sands (clinoforms) (**RST**)
3 Late Pleistocene 140–125 ka End isotope stage 6	Chaotic reflectors infilling incisions, to discontinuous reflectors onlapping unit 2	Bowentown to N Waihi	Mainly <5 m, up to 10 m	Irregular erosive unconformity	Transgressive back-barrier and fluvio-estuarine sediments (**TST**)
2 Early Pleistocene–Pliocene	Irregular chaotic to semi-continuous subparallel reflectors	All profiles	Extensive and thick (>20 m)	Angular erosive unconformity	Tauranga Group sediments, locally deformed and gaseous
1 Pliocene–Miocene	Acoustically opaque	Onemana (elsewhere too deep)	Local basement rocks	Irregular erosive unconformity	Coromandel Group volcanic rocks

[1]vf, very fine; fs, fine sand; cs, coarse sand; HST, highstand systems tract; TST, transgressive system tract; RST, regressive systems tract.
[2]Based on comparison with dated southeast Australian shelf examples (Roy et al. 1997) (see Fig. 7), possibly mainly stage 3.

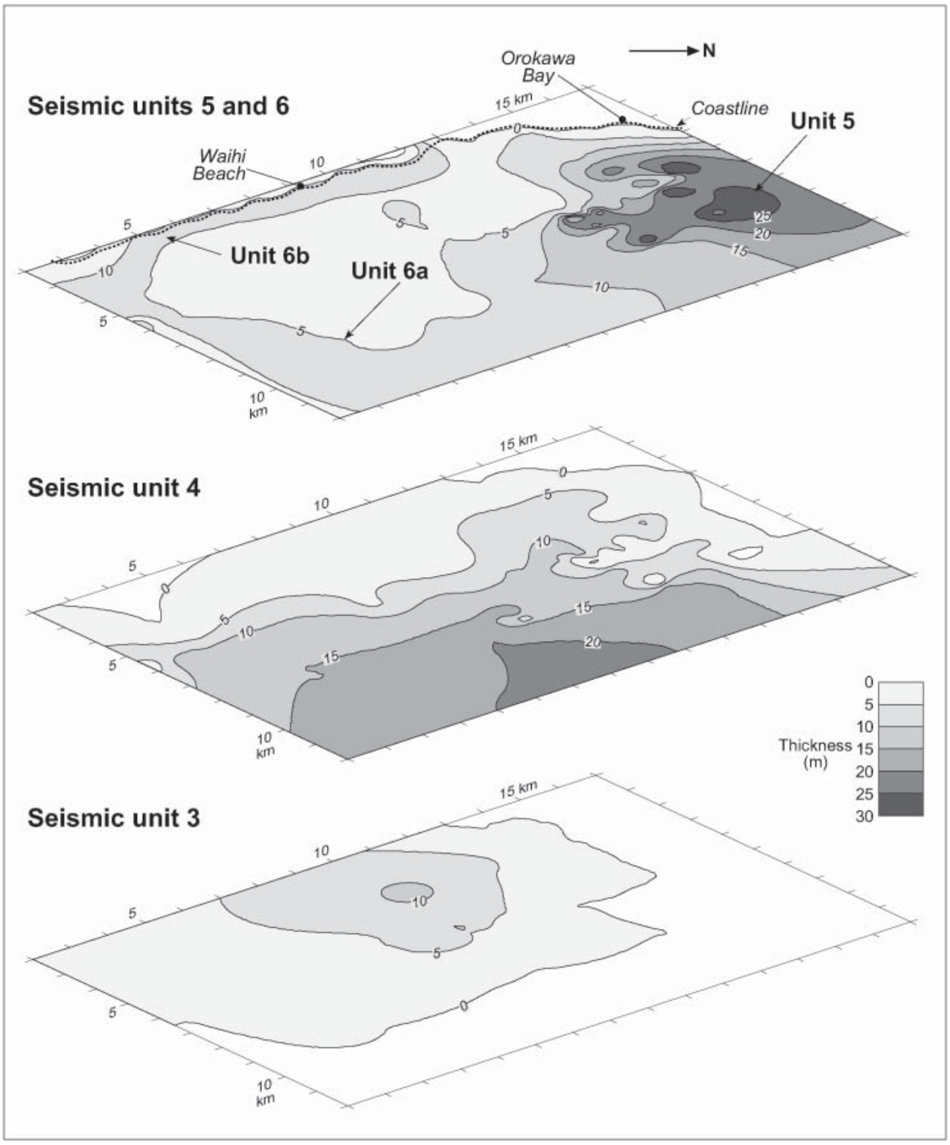


Fig. 6 Isopach maps for late Pleistocene transgressive and incised-valley fill deposits (seismic unit 3), late Pleistocene forced regressive deposit (FRD; seismic unit 4), Holocene incised-valley fill (seismic unit 5), Holocene transgressive shelf sands (seismic unit 6a), and Holocene shoreface sands (seismic unit 6b). Note the well-developed Holocene incised-valley system in the north which correlates onshore with small fluvial systems behind Waihi Beach.

deposition of seismic unit 4. The prominent incision surface on the top of unit 4 is correlated to the c. 120 m maximum sea-level fall associated with last glacial isotope stage 2 (c. 18 ka). The formation of seismic unit 4 is therefore linked to the period of incremental falls in relative sea level that occurred between c. 112 and 18 ka (Fig. 1), and is interpreted to represent a late Pleistocene-age FRD. Not only do such falling sea-level conditions promote the generation of FRDs, but several of the distinguishing criteria for FRDs noted by Posamentier & Allen (1999) are associated with seismic unit 4, including the following:

(1) Unit 4 thins or pinches out beneath the modern shoreface wedge (Fig. 5A–C) and is therefore detached from inland late Pleistocene-age (isotope stage 5) highstand barrier/shoreface deposits by a narrow zone of sedimentary bypass.

(2) Unit 4 regressive deposits extend offshore continuously from the base of the modern shoreface to the limit of the seismic record in 30 m water depth off Waihi, and probably continue much farther across the shelf judging from their seismic geometry and thickness (Fig. 5B,C, 6).

(3) The basal erosion surfaces upon which units 4a and b rest are planar, seaward-dipping, and most pronounced beneath the landward portion of the regressive wedges (Fig. 5A,B), suggesting they are associated with shoreface erosion due to a lowering of wave-base level during incremental falls in relative sea level (i.e., are regressive surfaces of erosion).

(4) The top of unit 4 is a seaward-dipping surface across the inner shelf off Bowentown (Fig. 5A), consistent with a forced regressive wedge formed by successive small downsteps of offlap wedges. Farther north, the top of unit 4 has been extensively modified by subaerial erosion and a subsequent ravinement surface (Fig. 5B–D).

(5) Successively younger progradational wedges (units 4a and 4b) are downstepping towards the last glacial (isotope stage 2) shoreline.

Seismic unit 5

Seismic unit 5 infills a prominent incision surface evident in most seismic profiles from the east Coromandel shelf (Fig. 4, 5). The incision surface varies from a series of narrow and deep features (each c. 250 m wide and 20 m deep) between northern Waihi and Whiritoa (Fig. 4C, 5C,D, 6), to a single, very broad and deep feature (2 km wide, 30 m deep) off Whangamata (Fig. 4D). The infill pattern associated with unit 5 is often difficult to image due to a seismically opaque zone, which is interpreted as indicating biogenic gas emanating from estuarine basin muds. Where resolvable, unit 5 displays a channel fill geometry, and is terminated c. 5 m beneath the present seafloor by an erosion surface at the base of unit 6 (Fig. 5C,D). Seismic unit 5 is interpreted to represent an incised-valley fill deposit formed during the postglacial marine transgression from c. 15 to 6.5 ka (Fig. 1). The major incision surface at the base of unit 5 is interpreted as representing a surface of maximum subaerial erosion, as defined by Kolla et al. (2000), which formed during the last glacial lowstand (c. 18 ka). Alternatively, it may represent a tidal ravinement surface formed by the landward migration of disconnected tidal channel segments that established and incised during the postglacial marine transgression (c. 15–6.5 ka). A maximum subaerial erosion surface origin is favoured for the following reasons:

(1) Large incision surfaces off Waihi can be correlated onshore to small fluvial valleys located behind Waihi Beach (Fig. 3), while there are no large incision surfaces off the main present-day tidal inlet at Bowentown.

(2) The single large incision feature on the Whangamata inner shelf is associated onshore with a relatively large drowned river valley, while the numerous, narrow incision features off Waihi are associated with a series of much smaller fluvial systems that discharge behind Waihi Beach. There is thus an apparent correlation between the size of offshore incision features and the size of onshore fluvial systems.

(3) Modern tidal inlets along the east Coromandel coast are typically <5 m deep (Abrahamson 1987), while the incision surfaces are up to 20–30 m deep.

Seismic unit 6

Seismic unit 6 is the youngest depositional unit on the east Coromandel shelf. Two subunits are evident, 6a and 6b. Unit 6a is a widespread and thin package (<5 m thick; Fig. 6) whose seismic character is usually obscured by the first bubble pulse. However, it is often seen overlying a relatively planar erosion surface that truncates strata from units 4 and 5 (Fig. 5, 6). Sediment samples and side-scan sonar surveys (Bradshaw et al. 1994) show that unit 6a consists predominantly of very coarse to medium grained sands which represent a transgressive shelf lag deposit generated by erosional shoreface retreat during the postglacial marine transgression. These shelf sands are often covered by more recent fine-grained sands that have been reworked by modern wind-generated currents into a series of shore-normal submarine dunes. The fine-sand sheet is particularly extensive off Whiritoa, where currents decelerate and deposit sands transported along-shelf from the Bay of Plenty (Bradshaw et al. 1994).

Unit 6b is only partly imaged by seismic profiles that extend onto the shoreface (Fig. 5A–C). It represents a landward-thickening sediment wedge that appears to downlap onto unit 6a (Fig. 5A), corresponding with the basinward toe of modern barrier systems. Bottom sampling shows that it consists of very fine grained sands comprising abundant volcanic glass fragments (Bradshaw et al. 1994). Unit 6b is a currently accreting shoreface deposit that is locally sourced from fluvial sediments bypassing infilling estuaries (Bradshaw et al. 1994).

A SOUTHEASTERN AUSTRALIAN ANALOGUE

Like the east Coromandel coastal situation, the southeast coast of Australia has no major river systems supplying sediments to the coast, and the continental margin has very low subsidence rates of 0.01 m/ky (Marshall & Thom 1976). Studies of the geomorphology and sedimentology of the late Pleistocene and Holocene barrier and estuary systems of the east Coromandel Peninsula (e.g., Marks & Nelson 1979; Gibb & Aburn 1986; Abrahamson 1987; Davis & Healy 1993) suggest they have a similar morphostratigraphy to coastal deposits described in more detailed investigations from southeastern Australia (e.g., Thom et al. 1978, 1981a,b; Roy & Thom 1981; Roy et al. 1995). Both the northeastern New Zealand and southeastern Australian coastlines are compartmentalised, wave dominated, and sediment starved settings, in which existing coastal and shelf sediments are frequently reworked by waves and geostrophic currents under present sea-level conditions (i.e., autochthonous depositional settings).

Roy et al. (1997) have documented in detail the Quaternary geology of the Forster-Tuncurry coast and shelf off southeastern Australia using high-resolution seismic imaging, long sediment vibrocores, and carbon and thermoluminescent dating of samples. Neither long cores nor absolute dating were available for the east Coromandel study, but given the strong parallels in sedimentation controls noted above between the two regions, it is not surprising that similar seismic stratigraphic units occur in the shallow subsurface coastal and shelf deposits from both regions. A dated, shore-normal sequence stratigraphic section for the Forster-Tuncurry coast and shelf is reproduced in Fig. 7. Noticeably, it contains a prominent late Pleistocene FRD described by Roy et al. (1995, 1997) as a 15 m thick “drowned regressive barrier system” that extends continuously as a tabular wedge across the shelf from water depths of 30–80 m (Fig. 7). This feature is similar to the unit 4 FRD at east Coromandel, which is also c. 15–20 m thick and extends continuously across the inner shelf surface from water depths of 20 to >50 m (Table 2; Fig. 5, 6). Vibracore samples show that the Tuncurry FRD consists of fine to medium grained, well sorted regressive barrier and shoreface sands dating back to isotope stage 3 (measured dates range from 44 to 59 ka; Roy et al. 1995, 1997). Transgressive barrier facies interfinger with fluvial-estuarine sediments along the landward margin of the Tuncurry FRD, which suggest that it represents a high-order transgressive-regressive cycle during isotope stage 3. Roy et al. (1995, 1997) have also used onshore vibracoring and ground penetrating radar surveys to identify an older regressive barrier at close to modern sea level that dates to the initial period of falling sea level in isotope stages 5a and 5b (measured dates range from 80 to 95 ka). This older regressive barrier feature steps down from a highstand barrier deposited 5 m above present sea level during the last interglacial (measured dates range from 131 to 147 ka), and may represent a stage 5b-5a FRD. Computer simulations by Roy et al. (1995) demonstrate that the Forster-Tuncurry late Pleistocene FRD could be completely accommodated and sourced by erosion of the inner shelf surface under falling sea-level conditions.

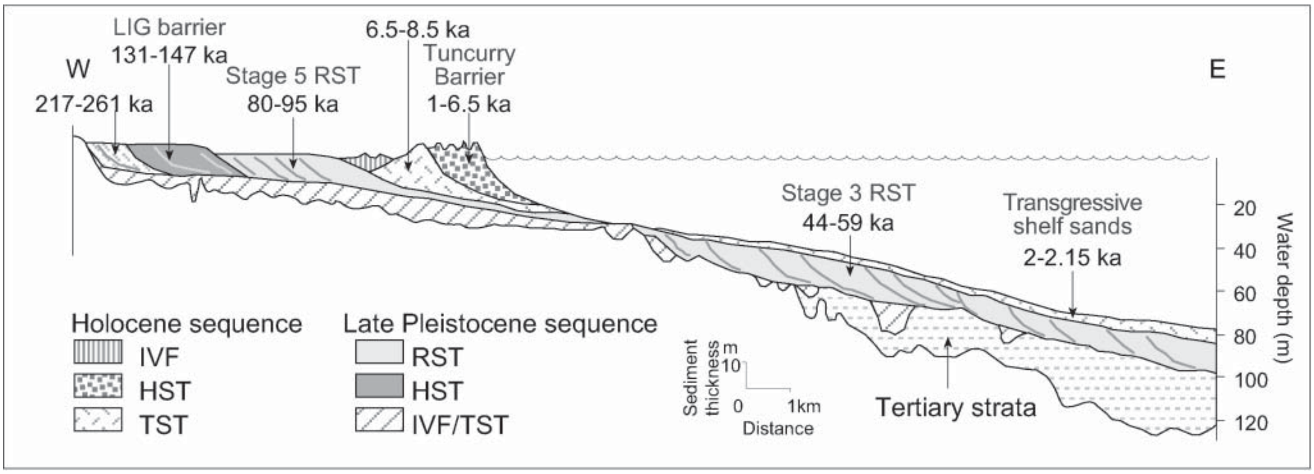


Fig. 7 Shore-normal profile summarising the late Pleistocene sequence stratigraphy and ages of sediment bodies on the Forster-Tuncurry coast and shelf, southeast Australia (adapted from Roy et al. 1997). As in the east Coromandel situation, the southeast Australian coastline is compartmentalised, wave dominated, and starved of fluvial sediment input, and there are many similarities in the shelf seismic units between the two areas. Given the absence of cores and absolute age dating for the subsurface Coromandel units, the southeast Australian ages have been used to help interpret the evolutionary history of the east Coromandel deposits (see Fig. 8). Note that the Forster-Tuncurry profile has FRDs dating to isotope stage 5 behind modern barrier deposits, and to isotope stage 3 across the inner and mid-shelf that have similar seismic geometry to the east Coromandel FRDs in seismic unit 4 (Fig. 5). TST, transgressive systems tract; HST, highstand systems tract; RST, regressive systems tract; IVF, incised-valley fill.

EVOLUTIONARY MODEL FOR THE EAST COROMANDEL SEISMIC UNITS

A conceptual model for the depositional history of the east Coromandel shelf off Waihi Beach has been developed in Fig. 8 to account for the juxtaposition of the different late Pleistocene seismic units 3–6 (Table 2), and to demonstrate in particular how FRDs (unit 4) may have developed in this moderate gradient, wave dominated, low sediment supply shelf setting over the past c. 140 000 yr. The model extends from the modern coastal plain to the mid shelf, and is supported by some of the stratigraphic interpretations already noted for the similar Forster-Tuncurry shelf seismic study in southeastern Australia (Fig. 7). Coromandel seismic data are used to constrain the model over the inner shelf. Mapping of onshore coastal deposits by Abrahamson (1987) and Brathwaite & Christie (1996) helps to constrain the model over the modern coastal plain. The late Pleistocene geology over the mid-shelf area is based on observations off Whiritoa, just north of Waihi Beach.

Last interglacial (isotope stage 5e)

The model begins during the last interglacial highstand when sea level was probably c. 5–6 m higher than present (Fig. 8A) (Marshall & Thom 1976). Highstand conditions are assumed to have prevailed from c. 125 to 112 ka, based on late Pleistocene sea-level curves (Fig. 1B). Barrier deposits from the last interglacial highstand have been identified behind several modern barrier systems on the east Coromandel coast (Abrahamson 1987), and we infer the former were constructed during isotope stage 5e as the shoreface profile steepened to adjust to stillstand conditions (Fig. 9C). Minor accretion of shoreface sands may have occurred late in the last interglacial once river valleys had infilled and sediments began to bypass estuary mouths. Offshore, a thin shelf sand sheet would have overlain incised-valley fill deposits formed during the earlier marine transgression (Fig. 8A). Seismic unit 3 probably represents remnants of these incised-valley fill and shelf deposits. It is difficult to model what most of the strata beneath the shelf surface were like due to extensive reworking by the subsequent forced regression. However, it is possible that an older FRD was present beneath much of the shelf given that similar prolonged falls in sea level also characterised earlier Pleistocene sea-level cycles (Fig. 1). Our model thus shows the last interglacial highstand ending with similar shelf geology to the present with a narrow highstand barrier system and a wide, relatively flat shelf surface underlain by a substantial thickness of unconsolidated sediments (Fig. 8A).

Last interstadial (isotope stages 5–2)

The next phase of sedimentation on the Waihi shelf is modelled as occurring during the slow fall in relative sea level from isotope stages 5–2 (Fig. 8B), based on correlations with established sea-level curves and dated FRDs from the Tuncurry shelf (Fig. 7). The first evidence for forced regressive deposition is apparent in the narrow, sharp-based prograding shoreface deposits from seismic unit 4a. The base of seismic unit 4b subsequently truncates clinoforms from unit 4a and steps down from this initial FRD. This is interpreted as the response to a short fall in sea level (c. 5 m). Sea-level curves show that episodic sea-level falls of this magnitude were common throughout isotope stages 5–3 (Fig. 1B). This fall in sea level is inferred to have triggered the erosion and onshore reworking of older shelf deposits into a forced regressive strandplain (Fig. 8B). Subsequent incremental falls in sea level continued to erode lower shoreface and inner shelf sediments and deposit a downstepping forced regressive shoreface across the Waihi inner and mid shelf. Some sediments in the FRDs may have been sourced from fluvial sediments bypassing Tauranga Harbour to the south. However, it is possible to entirely reconstruct the accommodation space generated and

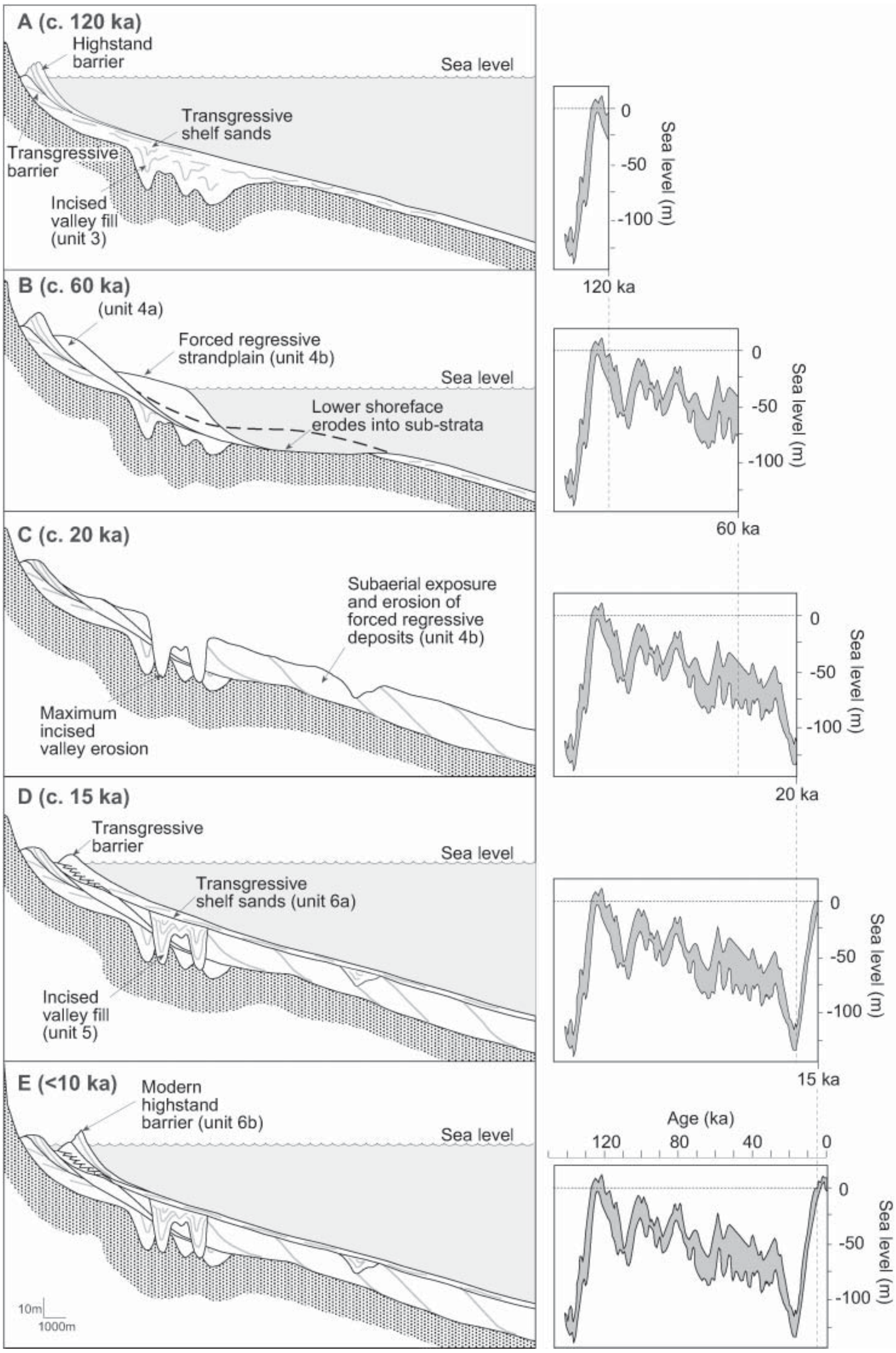


Fig. 8 Conceptual model for deposition of late Pleistocene and Holocene sediments on the east Coromandel shelf. **A**, Barrier deposition at the beginning of highstand conditions in the last interglacial c. 120 ka. **B**, Falling sea-level conditions during isotope stages 5, 4, and 3 result in erosion of underlying shelf sands that are reworked onshore into a forced regressive strandplain (seismic unit 4). **C**, Sea level reaches a maximum low of c. 120 m in the last glacial c. 18 ka, exposing the entire continental shelf and promoting the maximum development of incised valleys eroding into the underlying FRDs. **D**, Erosional shoreface retreat during the postglacial marine transgression reworks the upper 5 m of the FRDs into a shelf lag sand (seismic unit 6a) and transgressive barrier. **E**, Highstand conditions are established at c. 6.5 ka resulting in a steepening of the shoreface and onshore reworking of eroded shelf sands into a highstand barrier (seismic unit 6b). The progression of sea-level records at right is developed from Fig. 1B.

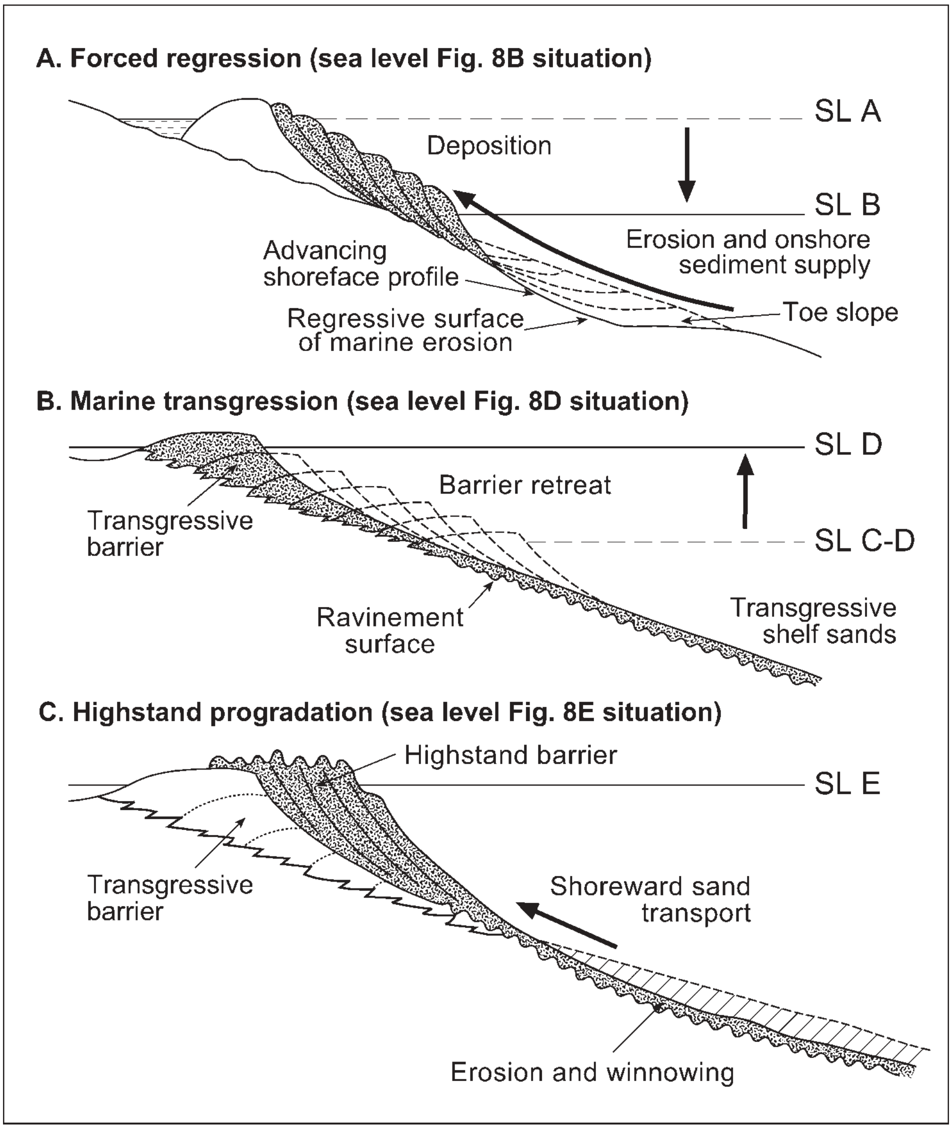
sediment supply for the Waihi FRDs using the same model of inner shelf erosional and onshore reworking of sediments as described by Roy et al. (1995) for the Forster-Tuncurry FRD (Fig. 9A).

Although the east Coromandel seismic coverage does not show the offshore limit of the FRDs, seismic data from Tuncurry show that FRDs continued in this location to at least the modern outer shelf (80 m depth; Fig. 7). FRDs should have similarly continued to be deposited throughout isotope stages 3 and 2 across the Waihi mid shelf, given that there are no major changes in shelf gradient and that there is a thick source of unconsolidated sediments beneath the shelf surface (seismic unit 2).

Last glacial (isotope stage 2)

The end of forced regressive deposition is modelled to occur at the last glacial lowstand during isotope stage 2 (c. 18 ka), when sea level fell to c. 120 m below present, placing the coastline at about the shelf break. Subaerial exposure of the entire forced regression strandplain occurred during this maximum lowstand event (Fig. 8C). The incised valleys interpreted to extend off northern Waihi Beach (Fig. 5C,D) may have been initiated earlier during smaller falls in sea level, but are inferred to have experienced their maximum erosion at the last glacial lowstand. Fluvial incision of this scale can occur during a sea-level fall in response to an increase in gradient for river systems flowing across the

Fig. 9 Response of moderate to low gradient, accommodation-dominated shelves to late Pleistocene sea-level oscillations, based on computer simulations by Roy et al. (1995). **A**, Slow fall in relative sea level results in erosion of underlying sediments on the lower shoreface and inner shelf to form a regressive surface of marine erosion. Sediments are reworked onshore to form a forced regression strandplain. **B**, Marine transgressions result in erosional shoreface retreat with underlying shelf sediments eroded to form a ravinement surface and reworked into a transgressive barrier. **C**, Highstand sea-level conditions immediately following a marine transgression result in a steepening of the shelf surface. Underlying shelf sediments are reworked onshore to form a regressive highstand barrier.



exposed continental shelf (Posamentier & Allen 1999). However, contemporary fluvial systems behind Waihi Beach are very small features that begin only up to c. 5 km from the modern shoreline (Fig. 3), and the modern shelf has a relatively consistent slope of 0.22°. A lower sea level would thus not result in either a significant increase or decrease in gradient for river systems flowing across the exposed shelf surface. The main factor that is inferred to have led to incision by these fluvial systems across the inner shelf is therefore an increase in fluvial discharge in response to development of a larger catchment area through increasing exposure of the continental shelf. The present steep rocky hinterland west and north of Waihi Beach would have formed a steep catchment drainage divide, focusing runoff into the flat sandy exposed shelf supporting a major late Pleistocene fluvial system. Eroded sediments from the forced regression strandplain were probably transported offshore to the shelf break to be reworked downslope by gravity flows.

Postglacial marine transgression (isotope stages 2 and 1)

Erosional shoreface retreat of the coastline during the rapid rise in sea level between 15 and 6.5 ka reworked the upper surface of the FRDs into a thin (c. 5 m) transgressive sand sheet (unit 6a; Fig. 9B). Incised valleys probably infilled with fluvial sands, estuarine muds, and back-barrier/tidal inlet deposits (unit 5) as transgressive barrier systems migrated progressively farther onshore. The ravinement surface imaged on seismic profiles above the incised-valley fills and FRDs marks the erosional retreat of the transgressive shoreline. By 6.5 ka, the transgressive barrier system was located at the modern Waihi Beach coastline (Fig. 8D).

Present highstand (isotope stage 1)

Radiocarbon dating of modern barrier deposits on the east Coromandel coast (Gibb & Aburn 1986) indicates that the bulk of highstand barrier deposition occurred early in the Holocene stillstand, between 6.5 and 4 ka (Fig. 8E, unit 6b). Similar observations have also been made in southeast Australia (Roy & Thom 1981; Roy et al. 1995). The initial rapid highstand progradation is attributed to the change from transgressive to stillstand conditions at 6.5 ka promoting the erosion and onshore mass transfer of relatively flat transgressive shoreface and shelf sands into a steeper progradational highstand shoreface (Fig. 9C) (Roy et al.

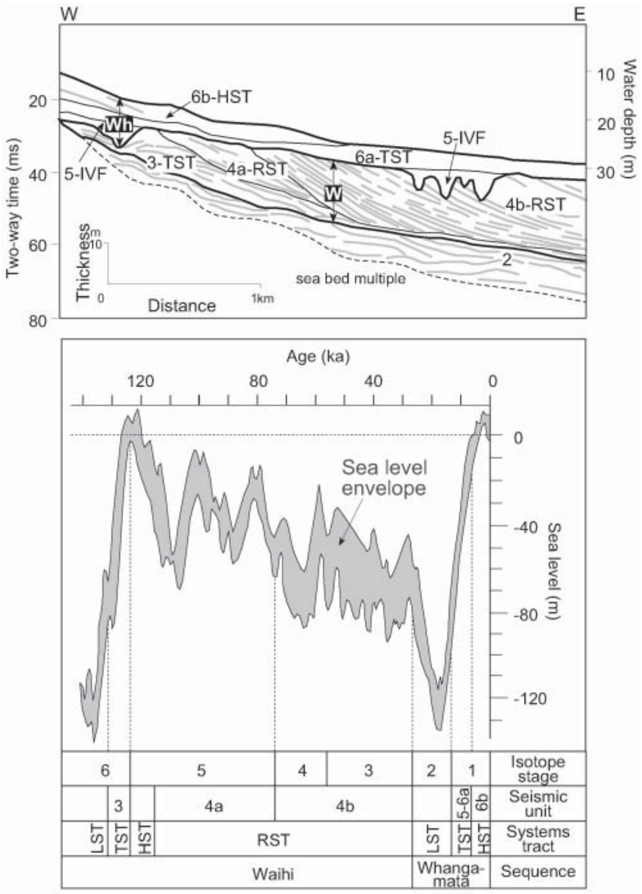


Fig. 10 Schematic summary diagram of the sequence stratigraphic architecture of seismic units beneath the east Coromandel inner shelf in relation to the late Pleistocene sea-level record (Fig. 1B). The late Pleistocene Waihi Sequence (W) is the only complete depositional sequence apparent in the high-resolution seismic data, and is dominated by the RST composed of FRDs from seismic unit 4. The mainly Holocene Whangamata Sequence (Wh) is only in the early stages of its development and is currently dominated by incised-valley fill sediments. Seismic units defined in Table 2. LST, lowstand systems tract; TST, transgressive systems tract; HST, highstand systems tract; RST, regressive systems tract; IVF, incised-valley fill.

1995). These autochthonous highstand barrier deposits are similar to the FRDs in that they are sourced by the erosion of lower shoreface and inner shelf sands associated with a change in relative sea-level conditions from transgression to highstand. The modern Waihi barrier system is a narrow depositional system that has not prograded since the initial onshore flux of sediments between 6.5 and 4 ka.

LATE PLEISTOCENE SEQUENCE STRATIGRAPHY OF THE EAST COROMANDEL INNER SHELF

The Waihi Sequence

Two late Pleistocene stratigraphic sequences are interpreted on the east Coromandel coast and shelf (Fig. 10). The oldest preserved sequence is correlated to a fifth-order (c. 100 000 yr) glacio-eustatic sea-level cycle that began with a maximum lowstand in sea level at c. 140 ka (isotope stage 6), and ended with the most recent maximum fall in sea level at c. 18 ka (isotope stage 2). This fifth-order sequence is best developed and preserved on the Waihi inner shelf and is therefore referred to as the "Waihi Sequence" (Fig. 10). The Waihi Sequence is bounded above and below by sequence boundaries generated during periods of maximum subaerial exposure, and subsequently modified by episodes of submarine erosion. The lower sequence boundary originated as a surface of maximum subaerial erosion, when the maximum sea-level lowstand was reached at c. 140 ka. Remnants of the incised valleys generated during the period of maximum subaerial exposure are evident in some locations at the base of seismic unit 3 (Fig. 4B). Elsewhere, the original maximum subaerial erosion surface was modified by erosional shoreface retreat during the subsequent marine transgression, and an ensuing period of regressive shoreface erosion during the late Pleistocene forced regression. Thus, the lower sequence boundary in places will have a maximum subaerial erosion surface, a transgressive surface of erosion, and a regressive surface of erosion (RSE) superposed. The upper sequence boundary is evident at the base of several well-preserved incised valleys (i.e., the base of seismic unit 5) generated during the maximum sea-level lowstand at c. 18 ka. This surface of maximum subaerial erosion was subsequently modified in places by a transgressive surface of erosion generated during the postglacial marine transgression between 15 and 6.5 ka.

Location of sequence boundaries

The placement of sequence boundaries in depositional sequences containing FRDs has been extensively debated over the past decade, with two divided schools of thought—one placing the boundary at the base, and the other at the top, of FRDs. Most workers agree that the sequence boundary should fit three key criteria: be chronostratigraphically significant; be aerially extensive and correlatable in different settings and facies; and be readily recognisable and have high preservation potential. Proponents of placing sequence boundaries at the base of FRDs argue that the sequence boundary underlies all sediments deposited during the downward and basinward trajectory of the shoreline, and is coincident with the base of fan deposition on the basin floor (Posamentier et al. 1992; Kolla et al. 1995; Morton & Suter 1996; Posamentier & Allen 1999; Posamentier & Morris 2000). Posamentier & Allen (1999) proposed that the base of FRDs correlates to a specific point in time (i.e., the onset of falling sea level), while the top of FRDs is a highly diachronous surface that represents a series of amalgamated higher frequency unconformities formed over a significant time interval. Proponents of placing sequence boundaries at the top of FRDs base their arguments on the easy recognition, widespread development, and chronostratigraphic significance of the surface of maximum subaerial erosion generated during the maximum lowstand (Van Wagoner 1995; Hunt & Tucker 1992, 1995; Mellere & Steel 1995; Naish & Kamp 1997; Chiocci 2000; Hernández-Molina et al. 2000; Kolla et al. 2000; Plint & Nummedal 2000). This is particularly important in basins where the base of FRDs is a gradational surface and lacks a RSE or any correlative unconformity, as occurs in the Pliocene–Pleistocene sequences of the Wanganui Basin, New Zealand (Naish & Kamp 1997)

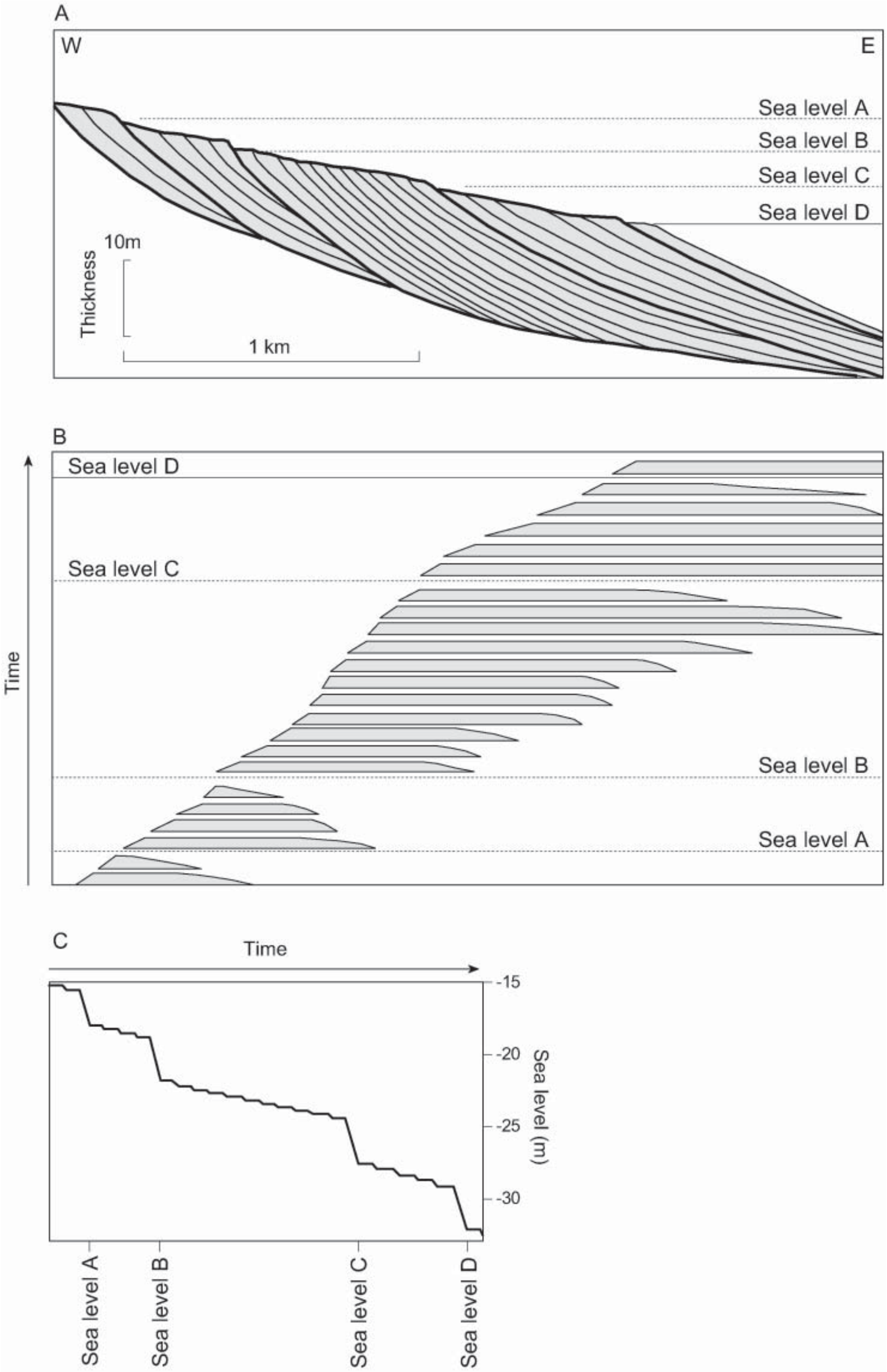


Fig. 11A–C High-resolution sequence stratigraphy of the RST from the Waihi Sequence highlighting the high-frequency phases of barrier-shoreface progradation punctuated by incremental falls in sea level that erode the seaward toe of previous deposits and initiate a new phase of forced regression deposition. The diagram emphasises the highly diachronous nature at both the base and top of the RST.

and late Pleistocene FRDs on the Canterbury shelf (Browne & Naish 2003). However, a prominent and easily identifiable erosion surface corresponding to the point of maximum lowstand in relative sea level is usually present at the top of FRDs that can be easily correlated within and between basins.

In the case of the east Coromandel coast, the base of the late Pleistocene FRD is a highly diachronous surface characterised by numerous RSE that become progressively younger farther offshore (Fig. 11). It is not possible from the available data to define a RSE and a correlative conformity that corresponds to the first fall in sea level at c. 112 ka. Thus, the base of the FRD cannot be used to define a chronostratigraphically significant surface. The top of the FRD is interpreted as incised valleys representing a maximum subaerial erosion surface generated during a maximum lowstand event. Although subaerial exposure and erosion may have commenced during earlier higher frequency sea-level falls, the final maximum lowstand event at c. 18 ka was the major fifth-order event that resulted in maximum subaerial exposure of the shelf and the final development of this erosional unconformity. This surface has also been modified in places by erosional shoreface retreat during the postglacial marine transgression. Both the RSE and surface of maximum subaerial erosion are thus diachronous surfaces. However, the surface of maximum subaerial erosion is considered the most chronostratigraphically significant surface as it comes closest to representing a point in time on the sea-level curve, and can be easily interpreted and correlated across the east Coromandel shelf, particularly where FRDs are absent.

Systems tracts

Lowstand systems tract (LST) deposits are not apparent in the imaged inner shelf section of the Waihi Sequence, but probably accumulated beyond the seismic coverage on the continental slope during the maximum lowstand. The Waihi Sequence has a preserved transgressive systems tract (TST) beneath the modern shoreface, as represented by seismic unit 3. TST deposition occurred during the short and rapid rise in sea level at the end of isotope stage 6. A highstand systems tract (HST) from the Waihi Sequence is represented by late Pleistocene barrier deposits mapped behind several of the modern barrier systems along the east Coromandel coast by Abrahamson (1987). HST barriers were deposited during the last interglacial (isotope stage 5e) when sea level was possibly slightly higher than present (Fig. 10). Any associated HST shelf deposits were subsequently cannibalised by the RSE during deposition of FRDs.

The volumetrically significant depositional systems tract from the Waihi Sequence is the regressive systems tract (RST) represented by seismic unit 4. The RST imaged in seismic profiles off the east Coromandel coast was probably deposited during the overall gradual fall in sea level from isotope stages 5–2 (c. 112–18 ka). The internal geometry of the RST indicates a series of downward and basinward shifting regressive phases of deposition, each associated with a RSE (Fig. 11). The most prominent RSE occurs between seismic units 4a and 4b. This RSE may represent a higher order sequence boundary, as is commonly observed in late Pleistocene RST from other continental margins (e.g., the Gulf of Mexico, Kolla et al. 2000; the Gulf of Cádiz, Hernández-Molina et al. 2000). If so, then the lack of associated LST, TST, and HST deposits could be attributed to either a lack of sediment supply or subsequent erosion by the next phase of FRDs. A less prominent RSE is also evident within seismic unit 4a, which is interpreted to represent a small, incremental fall in sea level with possibly a small hiatus in deposition between two prograding barrier-shoreface deposits (Fig. 11). The seismic data are too limited in offshore coverage to appreciate the full extent of major and minor RSE. However, we suspect that the RST extends across much of the Waihi shelf and is composed of a series of high-frequency pulses of lower shoreface erosion and associated barrier-shoreface progradation generated during high-frequency incremental falls in sea level, some possibly separated by minor transgressions.

The Whangamata Sequence

The second depositional sequence from the east Coromandel shelf is the Holocene sequence that began forming after the maximum lowstand at c. 18 ka. It is best developed and preserved on the Whangamata inner shelf and is therefore referred to as the “Whangamata Sequence” (Fig. 10). The Whangamata Sequence is bounded below by the sequence boundary generated during the last glacial maximum lowstand at c. 18 ka. This is a contemporary sequence in the very early stages of its development. The most volumetrically significant component of the Whangamata Sequence is the incised-valley fill (part of the TST) deposited during the postglacial marine transgression. The Whangamata Sequence is presently experiencing limited HST deposition, with highstand barriers forming subaerial deposits at the mouth of drowned river valleys. Significant coastal plain progradation is unlikely to occur under present sea-level conditions given the lack of sediment supplied to the east Coromandel coast.

CONCLUSIONS

1. Shelf sediments on the east Coromandel coast have been extensively reworked by wave- and wind-generated currents under all sea-level conditions. A lack of major rivers supplying significant amounts of new sediment directly to the coastline, coupled with slow subsidence rates (c. 4 cm/ka), have meant that depositional sequences in the late Pleistocene were mainly sourced from reworking of previous depositional sequences. Consequently, the depositional setting is an autochthonous one.

2. Seismic imaging suggests that only one complete fifth-order (c. 100 000 yr) depositional sequence, the late Pleistocene Waihi Sequence, has been preserved beneath the inner shelf since back-arc extension ceased at c. 1 Ma (Table 1; Fig. 10). Its stratigraphic position and internal architecture, as well as gross similarities to dated seismic sequences from the continental shelf off southeastern Australia, suggest that the Waihi Sequence is likely bounded below by the c. 140 ka lowstand at the end of isotope stage 6 and above by the c. 18 ka lowstand in isotope stage 2. TST sediments from the Waihi Sequence (seismic unit 3) are preserved above the lower sequence boundary as an incised-valley fill. HST deposits are limited to discontinuous barriers preserved behind some modern barrier systems in embayments along the otherwise predominantly rocky coastline. Forced regressive deposits (FRDs) interpreted as regressive barrier-shoreface sediments form the regressive systems tract (RST; seismic unit 4), and are the volumetrically dominant component of the Waihi Sequence.

3. The Holocene-age Whangamata Sequence is a contemporary sequence in its early stages of development, being bounded below by the c. 18 ka (isotope stage 2) lowstand surface (LST equivalent) and above by the modern seafloor. The early TST is represented by thick, localised incised-valley fill deposits (seismic unit 5) formed during postglacial sea-level rise over the isotope stage 2–1 transition, while subsequent TST deposits comprise a transgressive shelf lag (seismic unit 6a) generated by erosional shoreface retreat during that rise. The HST is represented by modern barrier systems and a nearshore, landward-thickening wedge building the modern accretionary shoreface (seismic unit 6b), associated with latest isotope stage 1 stillstand conditions.

4. A predominance of RST (and outer shelf/slope LST) deposits over HST and TST deposits is a feature of several late Pleistocene shelf sequences described elsewhere (e.g., Hunt & Gawthorpe 2000), but equally many shelves do not appear to have accumulated FRDs. While the development

of substantial FRDs during the RST is expected to have been encouraged by the asymmetrical nature of Pleistocene glacio-eustatic sea-level cycles, involving prolonged periods of gradual sea-level fall (Fig. 1), other factors must also be important. Following Roy et al. (1995), favourable factors probably also include low to moderate shelf gradients (not steep), and a significant sediment source from either onshore river systems or underlying unconsolidated sediment.

5. Where, as in the east Coromandel and southeast Australian examples, FRDs are sourced mainly from the reworking of underlying unconsolidated shelf sediments, the term autochthonous FRDs is appropriate. In contrast, FRDs formed on shelves associated with relatively high river-supplied sediment inputs (and subsidence rates), such as about the Mediterranean and northern Gulf of Mexico margins, are named allochthonous FRDs. The latter typically form much thicker and composite (outer) shelf-perched wedges involving several higher order sequences. In some instances, such as the Pliocene–Pleistocene sequences from the Wanganui Basin in New Zealand, subsidence and sediment supply rates were sufficiently high to produce gradationally based FRDs, with no evidence of underlying shelf erosion (Naish & Kamp 1997). Intuitively, allochthonous FRDs are likely to have a greater preservation potential than those from autochthonous depositional settings. Autochthonous FRDs are thus likely to be rarer features in ancient deposits. However, some indications of their presence might include relatively thin (15–20 m), sharp-based, tabular bodies of clean, reworked shoreface sandstones that progressively downlap basinward, and are bounded below by a RSE and above by an erosional unconformity.

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REFERENCES

Abrahamson, L. 1987: Aspects of late Quaternary stratigraphy and evolution on the Coromandel Peninsula, New Zealand. Unpublished MSc thesis, University of Waikato, Hamilton, New Zealand. 250 p.

Bard, E.; Hamelin, B.; Fairbanks, R. G. 1990: U-Th obtained by mass spectrometry in corals from Barbados: sea level during the past 130,000 years. *Nature 346*: 456–458.

Bard, E.; Fairbanks, R. G.; Hamelin, B. 1992: How accurate are the U-Th ages obtained by mass spectrometry on coral terraces? *In*: Kukla, G. J.; Went, E. *ed*. Start of a glacial. *NATO ASI Series I*: *Global Environmental Changes 3*: 15–21.

Bond, G.; Broecker, W.; Johnsen, J.; McManus, L.; Labeyrie, J.; Jouzel, J.; Bonani, G. 1993: Correlations between climate records from North Atlantic sediments and Greenland ice. *Nature 265*: 143–167.

Bradshaw, B. E. 1991: Nearshore and inner-shelf sedimentation on the east Coromandel coast, New Zealand. Unpublished PhD thesis, University of Waikato, Hamilton, New Zealand. 565 p.

Bradshaw, B. E.; Healy, T. R.; Dell, P. M.; Bolstad, W. M. 1991: Inner-shelf dynamics on a storm-dominated coast, east Coromandel, New Zealand. *Journal of Coastal Research 7*: 11–30.

Bradshaw, B. E.; Healy, T. R.; Nelson, C. S.; Dell, P. M.; de Lange, W. P. 1994: Holocene sediment lithofacies and dispersal systems on a storm-dominated, back-arc shelf margin: the east Coromandel coast, New Zealand. *Marine Geology 119*: 75–98.

Brathwaite, R. L.; Christie, A. B. 1996: Geology of the Waihi area 1:50 000. *Institute of Geological & Nuclear Sciences Geological Map 21*. 1 sheet + 64 p. Lower Hutt, New Zealand, Institute of Geological & Nuclear Sciences Limited.

Browne, G. H.; Naish, T. R. 2003: Facies development and sequence architecture of a late Quaternary fluvial-marine transition, Canterbury Plains and shelf, New Zealand: implications for forced regressive deposits. *Sedimentary Geology 158*: 57–86.

Chappell, J.; Shackleton, N. J. 1986: Oxygen isotopes and sea level. *Nature 234*: 137–140.

Chiocci, F. L. 2000: Depositional response to Quaternary fourth-order sea-level falls on the Latium margin (Tyrrhenian Sea, Italy). *In*: Hunt, D.; Gawthorpe, R. L. *ed*. Sedimentary responses to forced regression. *Geological Society, London, Special Publication 172*: 271–290.

Dansgaard, W.; Johnsen, S. J.; Clausen, H. B.; Dahl-Jensen, D.; Gundestrup, N. S.; Hammer, C. U.; Hvidberg, C. S.; Steffensen, J. P.; Sveinbjörnsdottir, J.; Jouzel, J.; Bond, G. 1993: Evidence for general instability of past climate from a 250-Kyr ice record. *Nature 364*: 218–220.

Davis, R. A. Jr; Healy, T. R. 1993: Holocene coastal depositional sequences on a tectonically active plate margin: southeastern Tauranga Harbour. *Sedimentary Geology 84*: 57–69.

Emery, D.; Myers, K. *ed*. 1996: Sequence stratigraphy. Oxford, Blackwell Science.

Gibb, J. G.; Aburn, J. H. 1986: Shoreline fluctuations and an assessment of a Coastal Hazard Zone along Pauanui Beach, eastern Coromandel Peninsula, New Zealand. *Water and Soil Technical Publication 27*. 48 p.

Harmsworth, G. R. 1983: Quaternary stratigraphy of the Tauranga Basin. Unpublished MSc thesis, University of Waikato, Hamilton, New Zealand. 342 p.

Hart, B. S.; Long, B. F. 1996: Forced regressions and lowstand deltas: Holocene Canadian examples. *Journal of Sedimentary Research A66*: 820–829.

Haywick, D. W. 2000: Recognition and distinction of normal and forced regressions in cyclothemic strata: a Plio-Pleistocene case study from eastern North Island, New Zealand. *In*: Hunt, D.; Gawthorpe, R. L. *ed*. Sedimentary responses to forced regression. *Geological Society, London, Special Publication 172*: 193–216.

Hernández-Molina, F. J.; Somoza, I.; Lobo, F. 2000: Seismic stratigraphy of the Gulf of Cádiz continental shelf: a model for late Quaternary very high-resolution sequence stratigraphy and response to sea-level fall. *In*: Hunt, D.; Gawthorpe, R. L. *ed*. Sedimentary responses to forced regression. *Geological Society, London, Special Publication 172*: 329–362.

Hunt, D.; Gawthorpe, R. L. *ed*. 2000: Sedimentary responses to forced regression. *Geological Society, London, Special Publication 172*. 381 p.

Hunt, D.; Tucker, M. E. 1992: Stranded parasequences and the forced regressive wedge systems tract: deposition during base-level fall. *Sedimentary Geology 81*: 1–9.

Hunt, D.; Tucker, M. E. 1995: Stranded parasequences and the forced regressive wedge systems tract: deposition during base-level fall—reply. *Sedimentary Geology 95*: 147–160.

Kitamura, A.; Matsui, H.; Oda, M. 2000: Constraints on the timing of systems tract development with respect to sixth-order (41 ka) sea-level changes: an example from the Pleistocene Omma Formation, Sea of Japan. *Sedimentary Geology 131*: 67–76.

Kolla, V.; Posamentier, H. W.; Eichenseer, H. 1995: Stranded parasequences and the forced regression wedge systems tract: deposition during base-level fall—discussion. *Sedimentary Geology 95*: 147–160.

Kolla, V.; Biondi, P.; Long, B.; Fillon, R. 2000: Sequence stratigraphy and architecture of the late Pleistocene Lagniappe delta complex, northeast Gulf of Mexico. *In*: Hunt, D.; Gawthorpe, R. L. *ed*. Sedimentary responses to forced regression. *Geological Society, London, Special Publication 172*: 291–328.

McQuillin, R. M.; Ardos, D. A. 1977: Exploring the geology of shelf seas. London, Graham and Trotman. 243 p.

Marks, G. P.; Nelson, C. S. 1979: Sedimentology and evolution of Omaro Spit, Coromandel Peninsula. *New Zealand Journal of Marine and Freshwater Research 13*: 347–372.

Marshall, J. F.; Thom, B. G. 1976: The sea level in the last interglacial. *Nature 263*: 120–121.

Martinson, D. G.; Pisias, N. G.; Hays, J. D.; Imbrie, J.; Moore, T. C.; Shackleton, N. J. 1987: Age dating and the orbital theory of ice ages: development of a high resolution 0 to 300,000-year chronostratigraphy. *Quaternary Research 27*: 1–29.

Mellere, D.; Steel, R. 1995: Variability of lowstand wedges and their distinction from the forced-regressive wedges in the Mesaverde Group, southeast Wyoming. *Geology 23*: 803–806.

Mitchum, R. M. Jr; Vail, P. R.; Sangree, J. B. 1977: Seismic stratigraphy and global changes of sea level, part 6: stratigraphic interpretation of seismic reflection patterns in depositional sequences. *In*: Payton, C. E. *ed*. Seismic stratigraphy—applications to hydrocarbon exploration. *American Association of Petroleum Geologists Memoir 26*: 117–133.

Morton, R. A.; Suter, J. R. 1996: Sequence stratigraphy and composition of late Quaternary shelf-margin deltas, northern Gulf of Mexico. *American Association of Petroleum Geologists Bulletin 80*: 505–530.

Naish, T.; Kamp, P. J. J. 1997: Sequence stratigraphy of sixth-order (41 k.y.) Pliocene-Pleistocene cyclothems, Wanganui basin, New Zealand: a case for the regressive systems tract. *Geological Society of America Bulletin 109*: 978–999.

Nummedal, D.; Riley, G. W.; Templet, P. L. 1993: High-resolution sequence architecture: a chronostratigraphic model based on equilibrium profile studies. *In*: Posamentier, H. W.; Summerhayes, C. P.; Haq, B. U.; Allen, G. P. *ed*. Sequence stratigraphy and facies associations. *International Association of Sedimentologists Special Publication 18*: 55–68.

Plint, A. G. 1988: Sharp-based shoreface sequences and "offshore bars" in the Cardium Formation of Alberta; their relationship to relative changes in sea level. *In*: Wilgus, C. K.; Hastings, B. S.; Kendall, C. G. St C.; Posamentier, H. W.; Ross, C. A.; Van Wagoner, J. C. *ed*. Sea level changes—an integrated approach. *SEPM Special Publication 42*: 357–370.

Plint, A. G. 1991: High frequency relative sea level oscillations in Upper Cretaceous shelf clastics of the Alberta foreland basin: possible evidence of a glacio-eustatic control? *In*: Macdonald, D. I. M. *ed*. Sedimentation, tectonics and eustacy. *Association of Sedimentologists Special Publication 12*: 409–428.

Plint, A. G.; Norris, B. 1991: Anatomy of a ramp margin sequence: facies successions, paleogeography and sediment dispersal patterns in the Muskiki and Marshybank formations, Alberta foreland basin. *Bulletin of Canadian Petroleum Geology 39*: 18–42.

Plint, A. G.; Nummedal, D. 2000: The falling stage systems tract: recognition and importance in sequence stratigraphic analysis. *In*: Hunt, D.; Gawthorpe, R. L. *ed*. Sedimentary responses to forced regression. *Geological Society, London, Special Publication 172*: 1–18.

Pomar, L.; Ward, W. C. 1995: Sea-level changes, carbonate production, and platform architecture: the Llucmajor platform, Mallorca, Spain. *In*: Haq, B. U. *ed*. Sequence stratigraphy and depositional response to eustatic, tectonic and climatic forcing. Dordrecht, Kluwer Academic Publishers. Pp. 87–112.

Posamentier, H. W.; Allen, G. P. 1999: Siliciclastic sequence stratigraphy—concepts and applications. *SEPM Concepts in Sedimentology and Paleontology 7*. 210 p.

Posamentier, H. W.; Morris, W. R. 2000: Aspects of the stratal architecture of forced regressive deposits. *In*: Hunt, D.; Gawthorpe, R. L. *ed*. Sedimentary responses to forced regression. *Geological Society, London, Special Publication 172*: 19–46.

Posamentier, H. W.; Allen, G. P.; James, D. P.; Tesson, M. 1992: Forced regressions in a sequence stratigraphic framework: concepts, examples, and exploration significance. *American Association of Petroleum Geologists Bulletin 76*: 1687–1709.

Roy, P. S.; Thom, B. G. 1981: Late Quaternary marine deposition in N.S.W. and southern Queensland—an evolutionary model. *Journal of the Geological Society of Australia 28*: 471–489.

Roy, P. S.; Cowell, P. J.; Ferland, M. A.; Thom, B. G. 1995: Chapter 4. Wave dominated coasts. *In*: Carter, R. W. G.; Woodroffe, C. D. *ed*. Coastal evolution. Cambridge University Press. Pp. 121–186.

Roy, P. S.; Zhuang, W-Y.; Birch, G. F.; Cowell, P. J.; Li, C. 1997: Quaternary geology of the Forster-Tuncurry coast and shelf, southeast Australia. *Geological Survey of New South Wales, Report GS 1992/201*. 405 p.

Saul, G.; Naish, T. R.; Abbott, S. T.; Carter, R. M. 1999: Sedimentary cyclicity in the marine Plio-Pleistocene sequence stratigraphic motif characteristics of the last 2.5 Ma. *Geological Society of America Bulletin 111*: 524–537.

Schofield, J. C. 1967: Sheet 3—Auckland. Geological map of New Zealand 1:250 000. Lower Hutt, New Zealand, Department of Scientific and Industrial Research.

Shackleton, N. J. 1987: Oxygen isotopes, ice volume and sea level. *Quaternary Science Review 6*: 183–190.

Tesson, M. R.; Allen, G. P.; Ravenne, C. 1993: Late Pleistocene shelf-perched lowstand wedges on the Rhône continental shelf. *In*: Posamentier, H. W.; Summerhayes, C. P.; Haq, B. U.; Allen, G. P. *ed*. Sequence stratigraphy and facies associations. *International Association of Sedimentologists Special Publication 18*: 183–197.

Thom, B. G.; Polach, H.; Bowman, G. 1978: Holocene age structure of coastal sand barriers in New South Wales, Australia. Department of Geography, University of New South Wales, report. Duntroon, A.C.T.

Thom, B. G.; Bowman, G. M.; Roy, P. S. 1981a: Late Quaternary evolution of coastal sand barriers, Port Stephens–Myall Lakes area, central New South Wales, Australia. *Quaternary Research 15*: 345–364.

Thom, B. G.; Bowman, G. M.; Gillespie, R.; Temple, R.; Barbetti, M. 1981b: Radiocarbon dating of Holocene beach-ridge sequences in southeastern Australia. *Geography Department, Faculty of Marine Studies, University of New South Wales, Monograph 11*.

Thrasher, G. P. 1986: Basement structure and sediment thickness beneath the continental shelf of the Hauraki Gulf and offshore Coromandel region, New Zealand. *New Zealand Journal of Geology and Geophysics 29*: 41–50.

Trincardi, F.; Field, M. E. 1991: Geometry, lateral variability, and preservation of downlapped regressive shelf deposits: eastern Tyrrhenian margin, Italy. *Journal of Sedimentary Petrology 61*: 75–90.

Vail, P. R. 1987: Seismic stratigraphy interpretation procedure. *In*: Bally, A. W. *ed*. Atlas of seismic stratigraphy. *American Association of Petroleum Geologists Studies in Geology 27*: 1–10.

Van Wagoner, J. C. 1995: Sequence stratigraphy and marine to non-marine facies architecture of foreland basin strata, Book Cliffs, Utah, U.S.A. *In*: Van Wagoner, J. C.; Bertram, G. T. *ed*. Sequence stratigraphy of foreland basin deposits. *American Association of Petroleum Geologists Memoir 64*: 137–223.

Van Wagoner, J. C.; Posamentier, H. W.; Vail, P. R. 1987: Seismic stratigraphy interpretation using sequence stratigraphy. Part II: Key definitions of sequence stratigraphy. *In*: Bally, A. W. *ed*. Atlas of seismic stratigraphy 1. *American Association of Petroleum Geologists Studies in Geology 27*: 11–14.

Wright, I. C. 1992: Shallow structure and active tectonism of an offshore continental back-arc spreading system: the Taupo Volcanic Zone, New Zealand. *Marine Geology 103*: 287–309.

Wright, I. C. 1993: Southern Havre Trough–Bay of Plenty (New Zealand): structure and seismic stratigraphy of an active back-arc basin complex. *In*: Ballance, P. F. *ed*. South Pacific sedimentary basins. Sedimentary basins of the world. Amsterdam, Elsevier. Pp. 195–211.