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Modern and ancient *Zygochlamys delicatula* shellbeds in New Zealand, and their sequence stratigraphic implications

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Abstract

The scallop *Zygochlamys delicatula* is an indicator species for a carbonate shellground facies which occurs on the sediment-starved outer shelf and upper slope around southern New Zealand. The modern distribution of *Z. delicatula* is restricted to areas where sea summer surface temperatures are less than ca. 15ºC. Its occurrence in Late Pliocene and Pleistocene strata in North Island has, therefore, been taken to indicate a northward-expanded range during former glacial intervals. We describe the sequence stratigraphic setting of examples of the *Z. delicatula* assemblage from the modern eastern South Island shelf, and from the Plio–Pleistocene Wanganui and Mangaopari Basins in North Island. We show that the *Z. delicatula* fauna occurs in both glacial and interglacial sediments, and that its development requires the concurrence of cold-water conditions and terrigenous sediment starvation. These conditions occur most commonly at the transition between the transgressive and highstand systems tracts (i.e. during rapid post-glacial sea-level rise, and probable warming temperature). However, for palaeo-locations below the contemporaneous lowstand shoreline, *Z. delicatula* can also occur at the transition between the highstand and lowstand systems tracts (i.e. during rapid post-interglacial sea-level fall, and probable cooling temperature).

Keywords: *Zygochlamys delicatula*; shellbed; sequence stratigraphy; sea-level change; cold water; New Zealand

1. Introduction

Late Quaternary sea-level has fluctuated in response to alternate periods of glaciation and interglaciation, driven primarily by Milankovitch variations in Earth's orbit (e.g. Hayes et al., 1976). The resulting transgressions and regressions of the shoreline across continental shelves are recorded in their stratigraphy (e.g. Carter et al., 1985; Nodder et al., 1995; Gillespie et al., 1998), and in some places by onland shelf cyclothems of Plio–Pleistocene age (Fleming, 1953; Vella, 1963; Ueda, 1973; Beu and Edwards, 1984; Clifton et al., 1988; Abbott and Carter, 1994; Naish and Kamp, 1997). More generally, sequence stratigraphy has been used to evaluate the architecture of continental margin successions in terms of relative changes in sea-level (e.g. Payton, 1977; Vail, 1987; Wilgus et al., 1988). This paper presents a sequence stratigraphic summary of the post-glacial (ca. 20 ka to present) biogenic gravels of the Otago continental shelf, with the aim of comparing their sequence stratigraphic setting with that of their ancient Plio–Pleistocene counterparts (Wan-

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ganui Basin: Abbott and Carter, 1994; Naish and Kamp, 1997; Mangaopari Basin: Gammon, 1997). The Otago shelf affords an excellent opportunity to study systems tract development during a period of known episodic sea-level rise because of the following factors: (a) the local sea-level history is known (Carter et al., 1985, 1986; Gibb, 1987); (b) the facies distribution and Holocene stratigraphy is well-described (Andrews, 1973, 1979; Carter and Ridgeway, 1974; Carter et al., 1985); and (c) the outer shelf carries extensive cold-temperate carbonate sediments, which are characterised by a distinctive *Zygochlamys delicatula*–bryozoan faunal assemblage.

We describe the development of the *transgressive systems tract* (TST) deposited during the isotope stage 2-1 transition (20 ka to 6.5 ka), and the contemporary *highstand systems tract* (HST) which was deposited during the late Holocene stillstand (6.5 ka to present). We document also a compound *mid-cycle shellbed* (MCS) 'in the making' which comprises sediment-starved, biogenic facies deposited on the middle and outer shelf during sea-level rise and the Holocene highstand. Finally, we compare these modern shelf sediments with their Plio–Pleistocene analogues from North Island, New Zealand, and show that fossil *Zygochlamys* shell concentrations most commonly, but not exclusively, represent deposition on the mid–outer shelf, seawards of the transgressing post-glacial shoreline sediment prism.

2. The Otago continental shelf

2.1. General setting

The coastline bordering the Otago shelf has undergone progressive uplift during the Pleistocene, caused by convergence across the Alpine Fault sector of the New Zealand–Australia Plate boundary, and is currently subject to gentle uplift (Wellman, 1979). Consequently a coastal escarpment has developed, and incised rivers emerge at the coast and deliver sandy terrigenous sediments to the inner shelf. Of the fluviatile sources, the Clutha River is overwhelmingly dominant and supplies 1.6 Mt of sediment per year. By comparison, the input from the Taieri River, the next biggest river on the coast, is only 0.53 t per year (Carter, 1986). The study area is contained between the Taieri and Karitane canyons (Fig. 1), where the adjacent Otago continental shelf is reduced in width from around 30 km to 10 km, and the outer margin is incised by four major submarine canyons. These canyons constitute the head of the Otago fan complex, and have acted as sediment

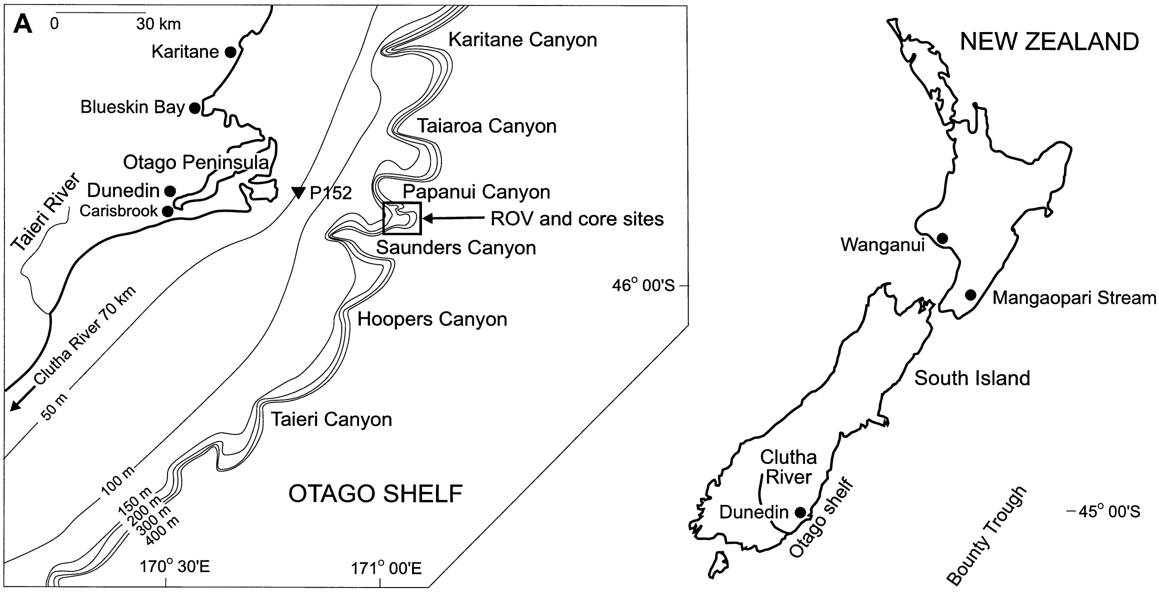


Fig. 1. Locality map of the Recent and Pleistocene occurrences of *Zygochlamys delicatula* discussed in this paper.

conduits to the head of the Bounty Trough since the Early Miocene (Carter and Carter, 1987). The shelf break at ca. −150 m coincides with the seaward edge of a terrace which has its inner edge at ca. −120 m, in the vicinity of Last Glacial Maximum shoreline (ca. 18 ka). A suite of carbonate chimneys described by Orpin (1997) is located on a deeper terrace between Saunders and Papanui canyons, at approximately 220 m water depth (Fig. 1). The terrace is approximately 1 km^2 in area, and some 50 m below the regional shelf break.

2.2. Hydrodynamic regime

Modern terrigenous sediment transport, and the geometry of the inner shelf terrigenous sediment prism, is strongly influenced by a combination of northeast longshore currents, tides, and the Southland Current. The Southland Current transports subtropical, high-salinity (>34.5‰) oceanic water northeast, parallel to the South Island coast (Brodie, 1960; Jillett, 1969; Heath, 1972, 1975). At the sea surface, Southland Current speeds over the shelf are estimated to be between 0.07 and 0.2 m s^{-1} (Heath, 1973; Carter and Hertzer, 1979; Robertson, 1980; Carter et al., 1985; Murdoch et al., 1990; Hawke, 1992), and near the bed range between 0.02 and 0.06 m s^{-1} (Carter et al., 1985). Tidal speeds off the Otago Peninsula are also enhanced by constriction of flow against the headland (Carter et al., 1985; Murdoch et al., 1990). Large swells induced by storms, internal waves, and up-canyon currents are probable mechanisms for sediment transport on the outer shelf and near the shelf edge (Carter et al., 1985). On the outer shelf and upper slope, Orpin (1997) has estimated a mid-water mean speed for the Southland Current of ca. 0.5 m s^{-1}, with peak velocities of up to 0.8 m s^{-1}, and a tidal oscillatory component of 0.1–0.25 m s^{-1}. It is unknown whether similar speeds exist near the bed, but remote operated vehicle (ROV) observations, discussed below, suggest that currents up to 0.2 m s^{-1} occur, i.e. above the movement threshold for sand-sized sediment.

2.3. Post-glacial sedimentation

Since the Last Glacial Maximum, the Otago shelf has evolved to its present state in a series of discrete steps, controlled by the post-glacial behaviour of sea level and by the evolution of the modern hydraulic regime (Carter et al., 1985). The available sea-level estimates indicate that the sea transgressed rapidly from the lowstand shoreline at ca. −110 m (ca. 18–20 ka), with stillstands at approximately −75 m (ca. 15 ka), −55 m (ca. 12 ka), −30 m (ca. 9 ka), and −12 m (ca. 7.5 ka) (Carter et al., 1986). Modern sea-level was attained approximately 6.5 ka BP, since when no major fluctuations have occurred (Gibb, 1979; Larcombe et al., 1995).

Carter et al. (1985) described four broadly shore-parallel belts of sediment from the Otago shelf, and attributed their origin to deposition during the episodic post-glacial transgression (Fig. 2A), viz.:

Shore-connected terrigenous sand	0–20 m	HST
Relict quartz gravel	20–55 m	TST
Relict/palimpsest sand	55–85 m	TST
Relict/palimpsest shell hash	85–200 m	TST–MCS

The inner shelf *terrigenous sand* facies is composed of fine sand derived mainly from the Haast Schist terrane via the Clutha River (Carter, 1986). The sand occurs as a narrow shore-connected belt, usually no more than a few metres thick, and with a gently tapered seaward toe which downlaps onto the inner edge of the relict gravel facies. The sand has been deposited since sea-level reached its modern height ca. 6.5 ka BP. The *relict gravel* facies comprises well-rounded clasts of iron-stained vein quartz in granules and pebbles up to 5 cm diameter, derived from the Clutha River and deposited as shore-parallel gravel ridges up to 5 m high. The gravels are underlain by estuarine deposits with relict molluscs which have been radiocarbon dated around 12 ka BP. A surficial veneer of palimpsest gravel is being created by unmixing of the upper part of the gravels by ocean swell, but the main gravel ridges are in situ and represent a drowned shoreline sediment body, which was deposited during a pause in sea-level rise. The relict gravels therefore represent a parasequence within the post-glacial transgressive systems tract, deposited when the palaeo-Clutha River was delivering copious coarse bedload sediment to the coast (Fig. 2B). Seaward of the belt of gravel, the low-gradient middle shelf is covered by a thin sheet of moderately well-sorted *palimpsest quartz sand*,

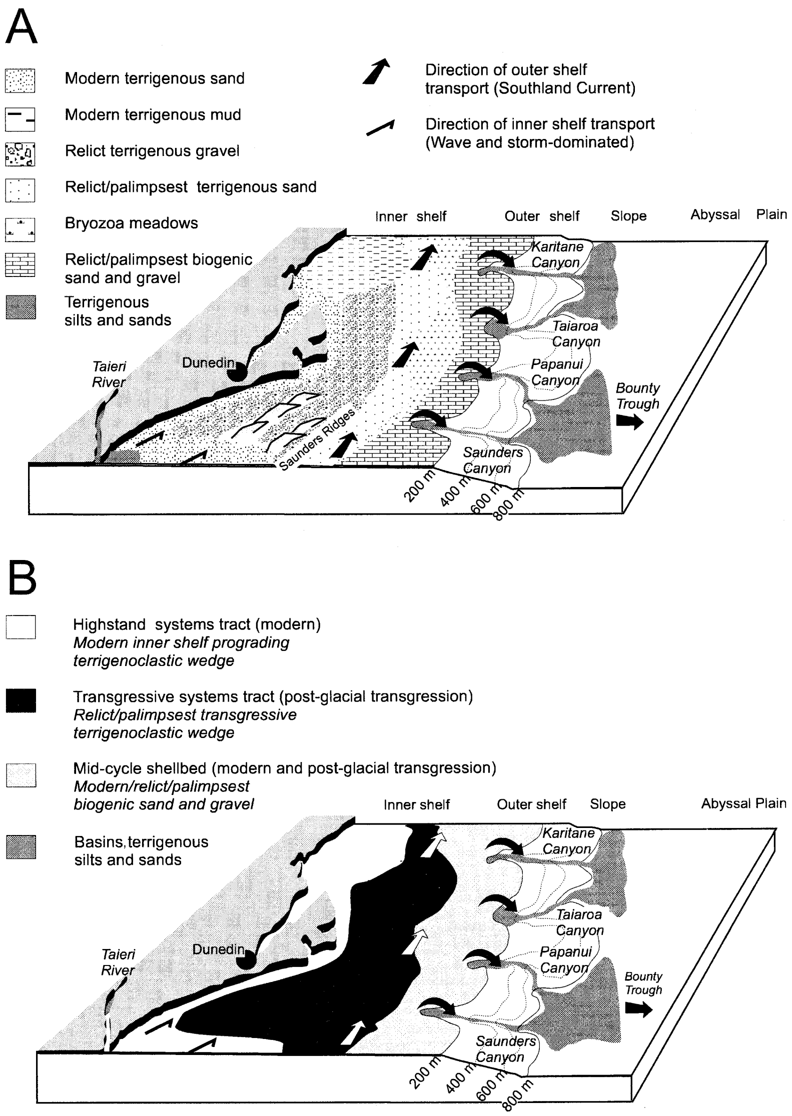


Fig. 2. (A) Summary of the main surficial sedimentary facies belts developed on the Otago shelf, with (B) their sequence stratigraphic interpretation.

locally shelly, and with diffuse seaward and landward edges. Compared to modern shoreline sand, the mid-shelf sand is coarser grained (fine to medium sand) and more poorly sorted, largely as a result of the presence of relict biogenic and terrigenous granular gravel. Relict taxa within the mid-shelf sand include common shoreface-shallow shelf forms such as *Struthiolaria, Zethalia* and *Antisolarium*. Carter et al. (1985) interpret the mid-shelf sands as a sandsheet produced by the reworking of transgressive sediments during the westward advance of the shoreline. Modern currents and biotic activity continue to modify the nature and distribution of the mid-shelf sand (Andrews, 1976).

Wide areas of the mid-outer shelf are covered by a thin veneer of *bryozoan meadows and palimpsest shell hash* up to a few tens of cm thick. The hash comprises abraded, bio-eroded, relict shells derived from a variety of shoreface and shelf environments (*Panopea, Zygochlamys, Zethalia, Anti-*

solarium, *Zeacolpus*, and *Tawera*), intimately intermixed with a living outer shelf shellground community dominated by *Zygochlamys delicatula* and bryozoa (Powell, 1950; Probert et al., 1979). The matrix of bryozoan–molluscan detritus is poorly sorted, because of the typical presence of 10–25% biogenic gravel. The occurrence of *Zethalia* and *Antisolarium* well below their normal depth range implies that these species are relict, together with the abraded foraminifera *Notorotalia* and *Elphidium*. Associated fresh benthic foraminifera include *Uvigerina, Hoeglundina, Hauslerella, Bolovinita* and *Nonionella*, species which are characteristic of mid–outer shelf and upper slope environments (Hayward, 1986). The shoreward edge of the biogenic gravels grades into the mid-shelf palimpsest sand facies, with a boundary located where the sediment carbonate content exceeds terrigenous content, usually at depths of 85–100 m. Carter et al. (1985) have shown that the biogenic gravel facies occurs in shelf-edge-parallel belts or ribbons only a few tens of metres across, indicating control by currents, particularly those developed during southerly storms. Cores show that the outer shelf shell hashes are underlain by a poorly sorted, bioturbated, muddy fine sand, with a well-preserved microfauna of middle–outer shelf origin (Orpin, 1992). A microfaunal assemblage collected from sediment piston core OU63265 recorded in Orpin (1992) constrains the age of the muddy fine sand as no older than latest Pleistocene (ca. 150 ka).

The outer shelf biogenic gravels are clearly palimpsest, in that they comprise a mixture of relict and modern shells and sediment. The modern fauna, first described by Powell (1950), is a characteristic cold-water assemblage: molluscs such as *Zygochlamys delicatula, Oxyperas elongata, Cominella* (*Eucominia*) *nassoides, Fusitriton laudandus, Argobuccinum tumidum, Stiracolpus symmetricus*; the crab *Jacquinotia edwardsii*; the echinoid *Goniocidaris umbraculum*; and brachiopods *Neothyris ovata, Magasella sanguinea* and *Waltonia inconspicua*. A similar faunal assemblage has been widely recognized in Plio–Pleistocene sediments in North Island, New Zealand, and has been interpreted to represent an influx of cold, southern waters during climatic cooling episodes (Fleming, 1944; Boreham, 1963; Beu, 1969; Beu et al., 1977). The restriction of the modern *Z. delicatula* fauna to the outermost Otago shelf and continental slope (to depths of ca. 600 m) probably reflects a water-mass control rather than a depth control, since the boundary between inshore water of subtropical origin (34.7‰ salinity, and no warmer than 15ºC in summer) and offshore subantarctic water (34.4‰ salinity, and no warmer than 13ºC in summer) lies along the path of the Southland Current over the outer shelf and upper slope (Heath, 1972, 1975).

2.4. ROV observations of the Zygochlamys delicatula beds

Orpin (1992) and Gray (1993) have reported on extensive ROV observations from the outer shelf and upper slope off Otago, including areas covered by the *Z. delicatula* beds. The *Zygochlamys* community in this area occurs in conjunction with carbonate-cemented chimneys described by Orpin (1997). Petrographic and geochemical data from the chimneys are consistent with cementation occurring just below the sediment–water interface. Encrustation, borings, and the abundance of chimneys and carbonate debris observed today on the uppermost slope (Fig. 3a, e), suggest that the chimneys have been exhumed and are relict features, and gave a maximum radiocarbon age of $33,000 \pm 550$ ka BP. Orpin (1997) suggested that they formed from aquifer-forced ground water of marine character, which was derived from beneath the exposed inner-middle shelf during glacially lowered sea level.

Fig. 3 shows typical scenes of the *Z. delicatula* shell hash facies, selected from the available ROV video footage, and shows chimney features surrounded by a mixture of relict and modern fauna. Noteworthy points include the following: (a) an abundance of *Z. delicatula* shells, including both relict (Fig. 3b (ii), d (ii), f (ii)) and living (Fig. 3a (i), b (i)) specimens; (b) encrustation and boring of the chimney outer surfaces, implying exhumation and erosion of the surrounding substrate (Fig. 3a (ii), e (i)); (c) dominantly convex up, but also some convex down, orientation of *Z. delicatula* valves, implying mild transportation (Fig. 3f (i), f (ii)); (d) an abundance of both living (Fig. 3c (i), f (iii)), and dead, broken bryozoa (Fig. 3c (ii), d (ii)); and (e) evidence of erosional current scours around the base of the chimneys (Fig. 3e (ii)).

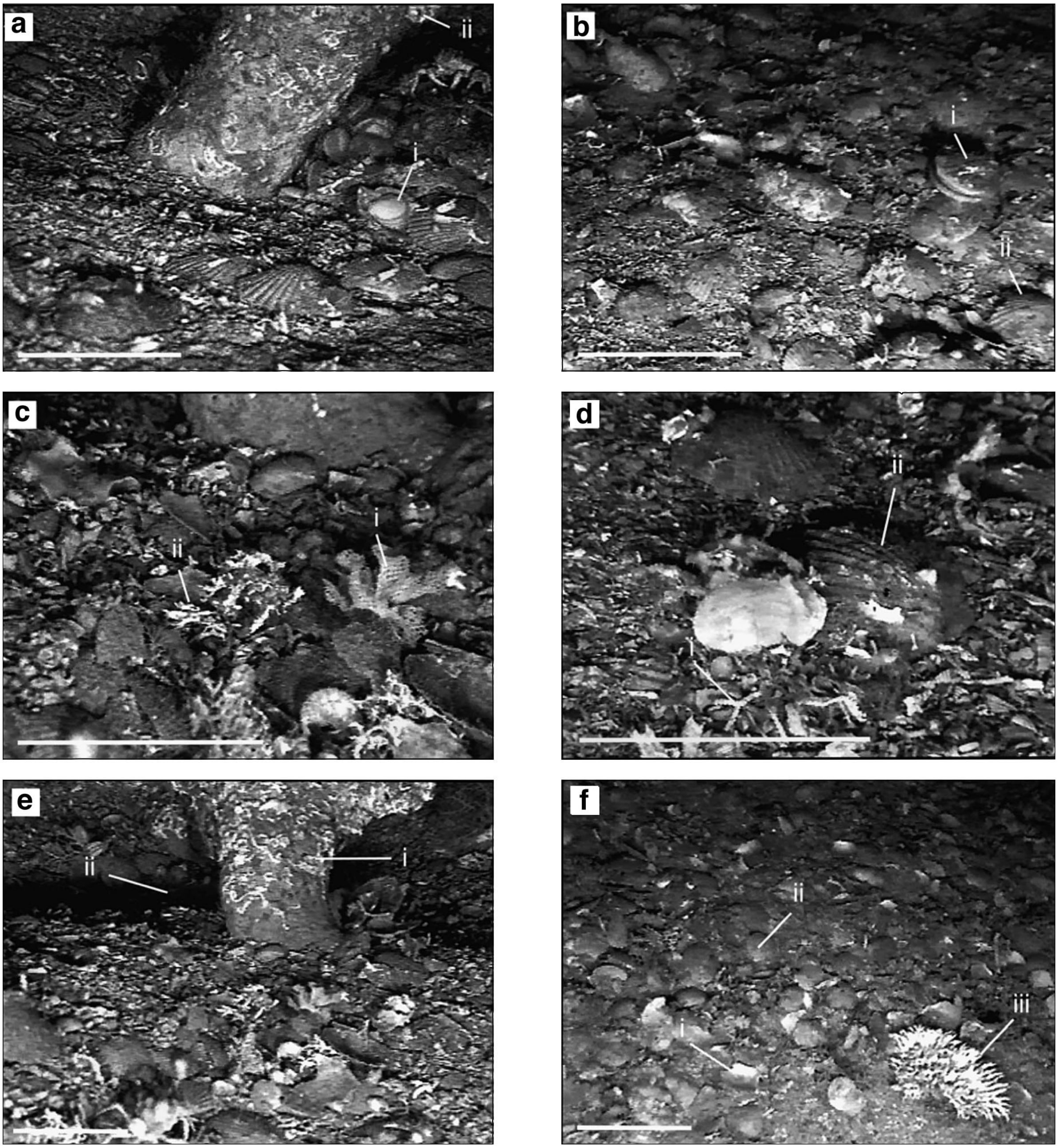


Fig. 3. Selected frames from ROV coverage of the *Zygochlamys delicatula* shellbeds, at 210–240 m water depth, on a terrace off the Otago shelf. The white scale bar in each case is 10 cm long. See text for detailed explanation.

Thin sections from surface samples from piston cores taken from the chimney site, and from mid-shelf box core P152 (Carter et al., 1985), show the presence of green-brown foraminiferal infills, protoglauconitic in appearance (Orpin, 1992, 1997). Microprobe analysis of these infillings was inconclusive regarding their precise mineralogy, but Ensor (1986) has recorded possible glauconitic foraminiferal in-

fills from shelf sediments off Blueskin Bay, 20 km north of Otago Peninsula. The presence of glauconitic minerals is consistent with slow rates of sediment deposition.

2.5. Sequence stratigraphic interpretation

During relative sea-level rise, the sequence stratigraphic model predicts that terrigenous deposition will shift landward, with a progressive reduction in grain size and amount of terrigenous sediment deposited offshore. Widespread carbonate sedimentation eventuates on the offshore shelf, due to the favourable conditions for suspension-feeding benthos, and is often accompanied by evidence for hiatus, such as precipitation of phosphate or glauconite. Eventually, towards the early highstand, slow hemipelagic sedimentation extends over much of the basin, and a condensed muddy shellbed forms diachronously across the shelf (Fig. 4A). This *mid-cycle shellbed*, first described from Pleistocene cyclothems by Abbott and Carter (1994), becomes younger towards the basin margin, as it overlaps shorewards across terrigenous parasequences which were deposited earlier in the transgressive cycle. In more offshore regions, the mid-cycle shellbed will continue to accumulate through the highstand and during the early relative fall of sea level until it is smothered by prograding sediments of the highstand and regressive systems tracts. Haq et al. (1987), Van Wagoner et al. (1988) and Baum and Vail (1988) have referred to this deposit, which encompasses the top of the TST and the base of the HST, as the *condensed section*. The mid-cycle shellbed (MCS) marks the major part of the condensed section in Pleistocene 5th- and 6th-order sequences in the Wanganui Basin, New Zealand (Abbott, 1997; Naish and Kamp, 1997), and is inferred to have accumulated during late rise (transgression), highstand and early fall (regression) of the contemporaneous sea-level cycle

Naish and Kamp (1997) have shown that the shelly parts of some condensed sections (or mid-cycle shellbeds) can be subdivided. These authors distinguish the following two discrete shellbed types within these condensed sections (Fig. 4B).

(1) *Lower shellbed*: a shell-rich horizon, containing transported molluscan shells of mixed shoreface and inner-mid shelf origin, which occurs at the base of a deepening-upward succession, often immediately above the sequence boundary or a flooding surface. This shellbed is inferred to form during rapid shoreline transgression, which cuts a ravinement surface and mantles it with a shell lag.

(2) *Upper shellbed*: a packed shellbed with an insitu offshore fauna, which occurs gradationally above the lower shellbed and represents deposition during the later stages of transgression and the early regression, seaward of the edge of the shoreface-connected sediment prism. The constituent taxa of these upper shellbeds commonly comprise an insitu or mildly transported mixed assemblage of offshore shellground molluscs (*Chlamys, Tiostrea, Tawera*), brachiopods and bryozoans, i.e. they are type B shellbeds sensu Abbott and Carter (1994). The top of the shellbed is overlain by massive HST siltstone, and corresponds to the downlap surface. In offshore settings, seaward of the shoreface sediment prism, the lower and upper shellbeds may become superposed and merge to form a single *compound shellbed*.

The outer shelf *Z. delicatula* beds off Otago are both relict and modern, i.e. the sediments have a polyphase development and are palimpsest. We infer that, initially, shelly shoreface sediments were reworked into a transgressive lag during rapid post-glacial sea-level rise across the outer shelf just after the last glacial maximum. Further migration of the shoreline landward caused the shelf to become progressively starved of terrigenous sediment, and the resulting firmground was colonised by a diverse epifauna, especially *Z. delicatula* and bryozoans. Continued sediment omission, and even erosion, is indicated by sediment scouring, the occurrence of intensely bored and altered shell fragments, the formation of glaucony, and by the intense encrustation observed on the outer surface of the carbonate chimneys (Orpin, 1992, 1997). Since 6.5 ka an insitu faunal assemblage has developed which is in equilibrium with the modern water depth (85–200 m) and oceanographic environment (current activity, low turbidity, maximum summer water temperature ca. 13ºC). The Otago *Z. delicatula* beds, therefore, provide a striking contemporary example of a compound mid-cycle shellbed in the process of formation (Fig. 4A, upper right). The relict elements of the fauna and sediment (and chimneys) represent the

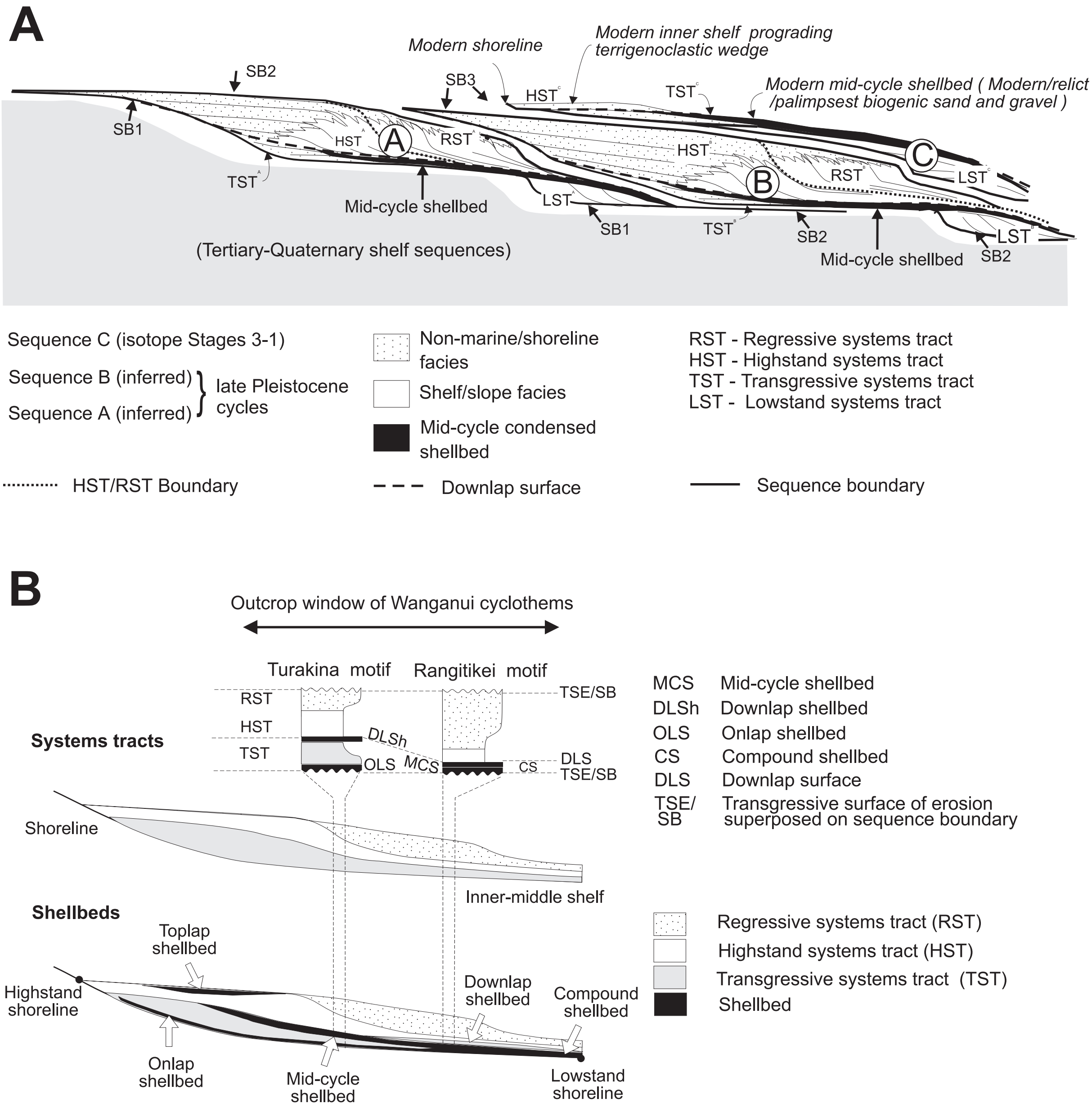


Fig. 4. (A) Sequence stratigraphic interpretation of the sedimentary prisms developed during three successive glacial–interglacial sea-level cycles. Cycles *A* and *B* based upon observed Pleistocene sequences of Wanganui Basin, and half-cycle *C* based upon the post-glacial history of the Otago shelf. (B) Two idealised cyclothem motifs, showing the disposition of the main shellbed facies with respect to systems tracts (based upon New Zealand Pleistocene and recent examples).

basal lag formed during the post-glacial transgression, i.e. comprise a transgressive shellbed, which is being modified by bioturbation, current erosion, in-situ carbonate production, and minor mud deposition, as the upper highstand part of the shellbed continues to form. The result after another few thousand years will be the development of a compound mid-cycle shellbed, with a transgressive lower part and an upper part characterised by in-situ clumps and individuals of the outer shelf epibenthos.

3. *Zygochlamys* shellbeds in Plio–Pleistocene strata

We have shown above that shell hashes with common *Z. delicatula* are characteristic of the post-glacial and modern outer shelf and upper slope environment in southern New Zealand, in depths of 75 to ca. 600 m. In terms of sequence stratigraphy, these sediments represent a transgressive lag, and an incipient mid-cycle shellbed (sensu Abbott and Carter, 1994; Abbott, 1994). *Z. delicatula,* which lives today only on the shelf of South Island, has long been known as a cold-water form, which at periods during the late Neogene occurred some 5º of latitude further north, at 40ºS in central North Island, (Fleming, 1944; Beu, 1969, 1977; Beu et al., 1977, 1981). In addition, fossil scallops, most often *Phialopecten, Towaipecten* or *Zygochlamys*, are particularly characteristic of Plio–Pleistocene coquina limestones and shellbeds throughout New Zealand (Beu, 1995). We therefore discuss below important aspects of the occurrence of fossil *Z. delicatula* shellbeds, and assess their palaeoecological and palaeoclimatic significance.

3.1. *Zygochlamys as an indicator of cold water*

Fleming (1944) was the first author to comment on the restriction of living *Z. delicatula* to cold southern waters, and to interpret the presence of *Zygochlamys* in North Island late Neogene sediments as a result of the incursion of pulses of cold water during late Neogene glaciations. Pantin (1963) demonstrated that sparse living individuals occurred at Cook Strait (latitude 42ºS, summer sea surface temperature ca. 15ºC), well north of the main breeding population. Beu (1985) summarised the distribution of *Z. delicatula* off southeastern Tasmania, and noted the significance of the eastward-flowing Antarctic circumpolar current to its larval dispersion history since the Early Pliocene. The larvae of *Z. delicatula* are planktotrophic, and the distribution of the species is therefore probably controlled by the presence of surface waters with a summer maximum temperature of less than 15ºC (Fleming, 1944; Beu, 1998). In the Wanganui Basin, the incoming (FAD) of *Zygochlamys* in the Hautawa Shellbed was taken as evidence for the first major climatic cooling, and therefore for the base of the Nukumaruan Stage and the start of the Pleistocene (Boreham, 1963; Te Punga, 1981). Recently, Beu (1998) has reported occurrences of *Zygochlamys* from inferred Late Pleistocene (glacial) sediments dredged from the seafloor up to 600 km north of the previously known limit of fossil distribution. Beu interprets these far northern occurrences as resulting from the enhanced upwelling of cold water during a glacial maximum.

Though later work has confirmed the FAD of *Zygochlamys* in the Hautawa Shellbed, it has also shown that the early interpretations oversimplified the significance of *Zygochlamys* occurrences. Boreham (1963), Beu (1969, 1977, 1998) and Te Punga (1981) have shown that the FAD of *Zygochlamys* occurs in different sections across New Zealand at different times, as indeed might be expected for a latitudinally controlled benthic organism which migrated south to north and back again in concert with glacial–interglacial rhythms. Recent work on the cyclostratigraphy of the New Zealand Plio–Pleistocene has confirmed that the FAD of *Zygochlamys* occurs in the Late Pliocene on both the east and west coasts of North Island, but at different horizons in different basins. For example, in the Wanganui Basin, the FAD of *Zygochlamys* in the Hautawa Shellbed is correlated with oxygen isotope stages 98/97 (2.47 Ma) (Naish and Kamp, 1997); in Mangaopari Stream the FAD in the main regressive part of the section occurs in a thin siltstone-matrix shellbed, which is correlated with the transition between isotope stages 87 and 86 (2.25 Ma) (cycle M9; Gammon, 1997); and, only a few km away, at Clay Creek and Bull Creek, the FAD is estimated to be slightly later, about isotope stage 87. Much older mid-Pliocene *Z. delicatula* occur also within the deep-water, mass-emplaced Bull Creek Limestone at Clay Creek (Beu, 1995), but these specimens have almost certainly been displaced from shallow-water environments at the edge of the basin, adjacent to rising greywacke highs (Vella and Briggs, 1971).

Zygochlamys occurs at only two stratigraphic levels in the Wanganui Basin: in the Hautawa Shellbed (stage 98/97) and the Tuha Shellbed (stage 96/95) in two adjacent cyclothems. As detailed further below, these shellbeds are interpreted to be of early interglacial origin. In contrast, at Mangaopari Stream,

Zygochlamys shellbeds occur repeatedly throughout the Late Pliocene and Early Pleistocene section, in shellbeds and coquina limestones of both glacial and interglacial origin. It is quite clear from the modern distribution data that *Zygochlamys* favours cold, clear water. It is equally clear, from the fossil distribution at Mangaopari Stream, that *Zygochlamys* does not occur uniquely in glacial lowstand strata. We conclude that pulses of cold water of southern origin moved northwards along the eastern side of New Zealand during interglacial as well as glacial times.

Thus, the first appearance of *Zygochlamys* is not isochronous, and does not mark either the base of the New Zealand Nukumaruan Stage (except, by traditional definition, at its type locality; Fleming, 1956), or the modern Plio–Pleistocene boundary (1.81 Ma, Aguirre and Pasini, 1985), or the onset of major Northern Hemisphere ice accumulation (2.54 Ma; Raymo, 1994) (cf. Kennett et al., 1971). Rather, the first occurrence of *Zygochlamys* at a particular location is controlled closely by local palaeoceanographic and sedimentological factors.

4. Discussion

4.1. *Zygochlamys as an indicator of sequence stratigraphic position*

We have shown earlier in this paper that the modern *Zygochlamys* shellbeds on the Otago shelf represent a mid-cycle shellbed, and were deposited during the transgressive and highstand phases of the post-glacial sea-level cycle. We now analyse the sequence stratigraphic significance of ancient *Zygochlamys* accumulations.

4.1.1. Wanganui Basin

The Wanganui Basin *Zygochlamys* shellbeds occur within a repetitive sequence of cyclothems which can be correlated with individual Late Pliocene oxygen isotope stages (Naish and Kamp, 1997). Saul et al. (1997), following Beu and Edwards (1984) and Abbott and Carter (1994), have shown that most Wanganui cyclothems represent deposition during the interglacial part of each climatic cycle, i.e. correspond to odd-numbered isotope stages; even-numbered stages (glacials) are missing at the unconformities which separate successive cyclothems, and which were created by subaerial erosion during sea-level lowstands. The Hautawa and Tuha shellbeds occur near the base of the Rangitikei River section, which marks the Pliocene basin depocentre, and therefore, accumulated in relatively deep, middle to outer shelf waters during interglacial highstands. The shellbeds occur immediately above the base of Wanganui cyclothems 2 and 3 (Fig. 5), mark the transgressive and mid-cycle part of their respective cycles, and are overlain by highstand siltstone and highstand and regressive sandy siltstone and sandstone of shoreface origin (Naish and Kamp, 1997).

The Hautawa and Tuha shellbeds are compound shellbeds (sensu Naish and Kamp, 1997). Their lower part encompasses a transgressive lag of reworked, mainly shallow-water shells in a muddy sand matrix, which passes up rapidly into an in-situ assemblage of molluscs, brachiopods and bryozoans of mid-outer shelf origin (Figs. 5 and 6a). The upper part of each shellbed is also a mid-cycle shellbed (sensu Abbott and Carter, 1994), which represents the ‘middle’ part of each cyclothem, separating the basal ravinement surface and its transgressive lag below from the highstand and regressive terrigenoclastic sediments above. At most localities, reworked, single shells of *Zygochlamys* occur within the basal part of the Hautawa and Tuha shellbeds, though at Hautawa Road individuals are scattered throughout the shellbed. We conclude that *Zygochlamys* lived mainly during the early part of each cycle, i.e. in climatic conditions which represented the transition between glacial and interglacial time, when the sea-level was rising rapidly and the shelf substrate was being rapidly transgressed by an advancing shoreline (transgressive systems tract). The Wanganui Basin occurrences of *Zygochlamys* represent, therefore, cold-water (waning glacial) conditions, and deposition on a shelf which was starved of terrigenous sediment because of the rapid landward advance of the contemporary shoreline. The absence of *Zygochlamys* from all higher cyclothems at Wanganui indicates the presence of an unfavourable combination of palaeo-hydrography, including depth, water temperature and turbidity. It is also possible that *delicatula* larvae were unable to penetrate into the Wanganui Basin from eastern New Zealand, because

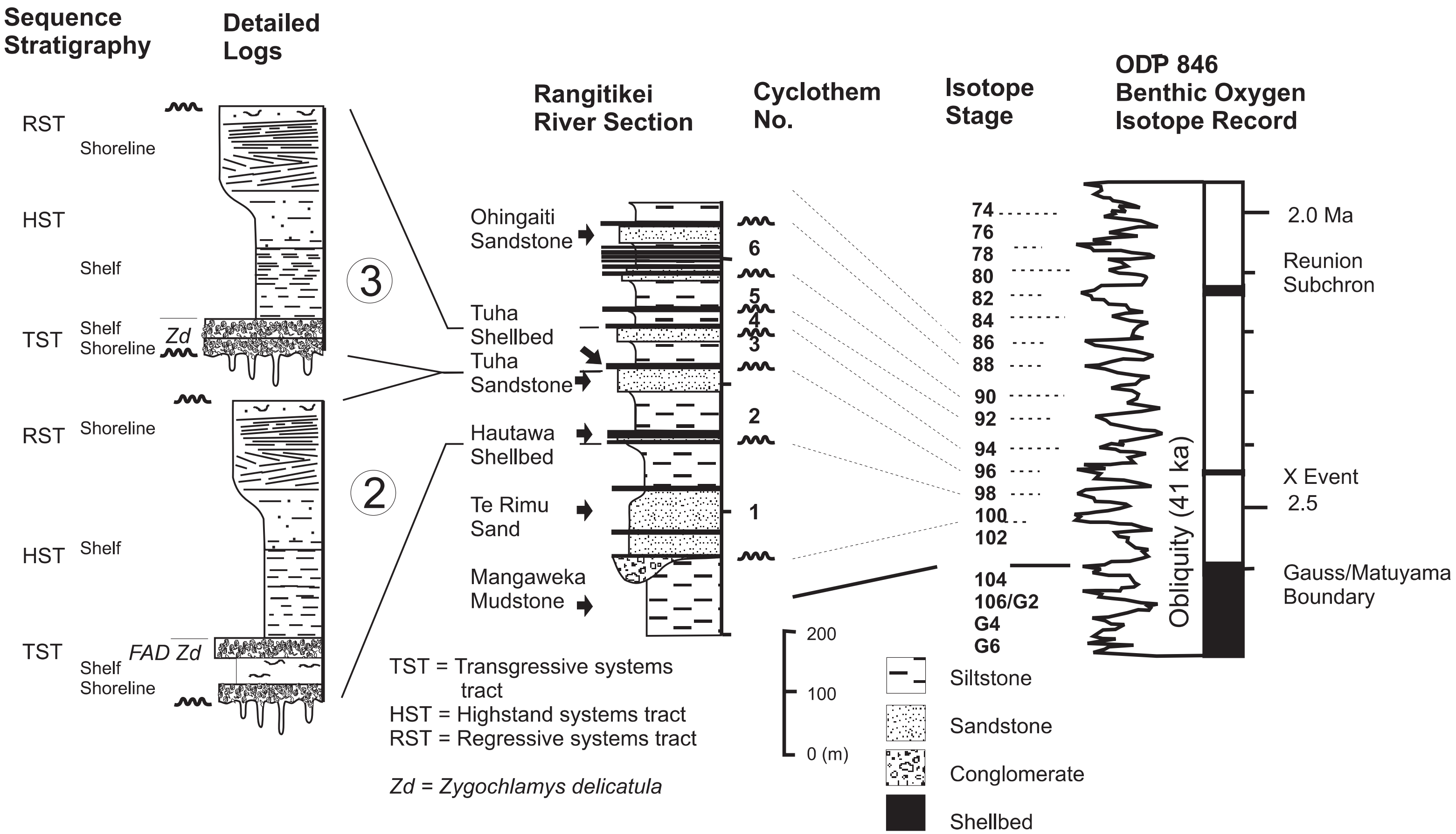
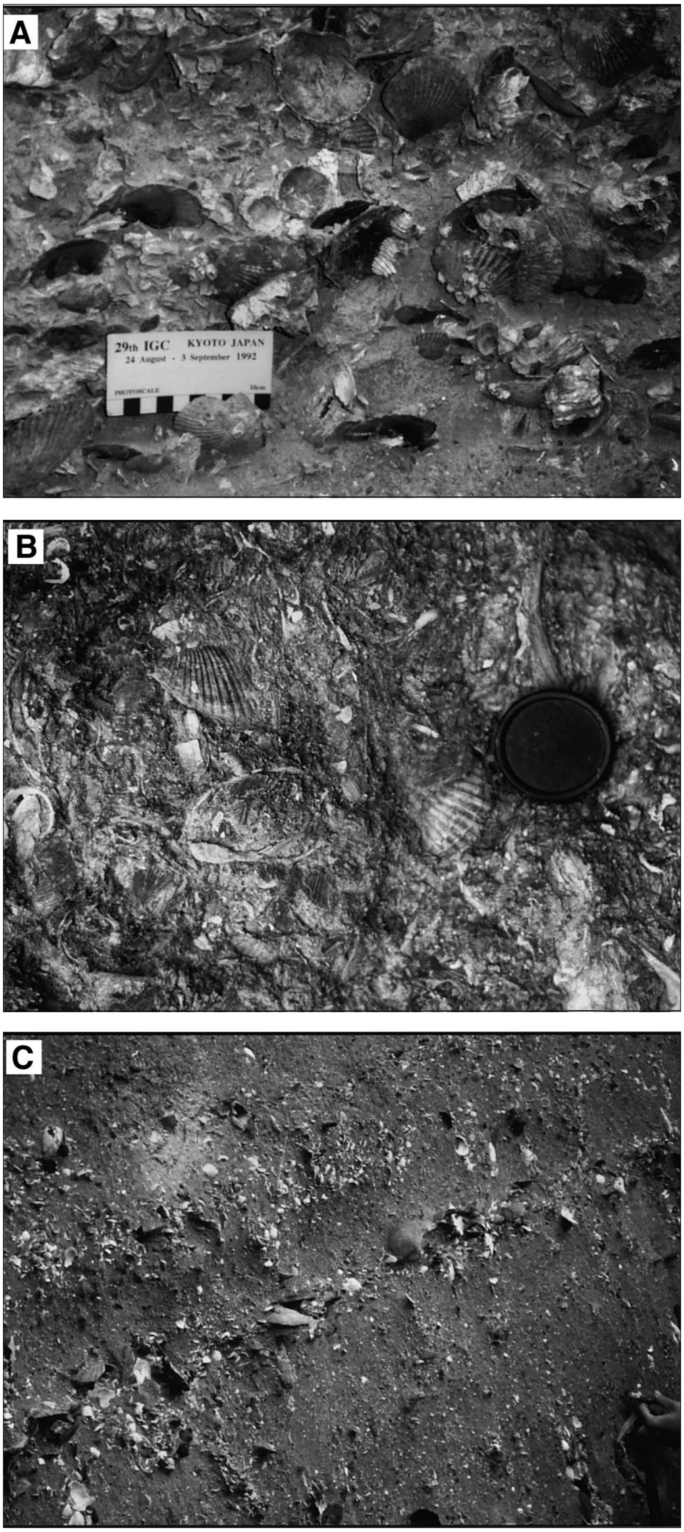


Fig. 5. Details of cyclothems *2* (including the Hautawa Shellbed) and *3* (including the Tuha Shellbed), Rangitikei River section, Wanganui Basin, showing occurrence of *Zygochlamys delicatula* (after Naish, 1996).


A
29th IGC KYOTO JAPAN
24 August - 3 September 1992
B
C

of the closure of the Manawatu palaeo-strait at about this time (Alan Beu, pers. commun.)

4.1.2. Mangaopari Basin, Wairarapa

The Mangaopari Stream section (Fig. 1) differs from that of the Wanganui Basin in that it comprises a single regressive tectonostratigraphic succession, deposited during progressive shallowing between 3.5 and 1.4 Ma (Fig. 7). The basal mid-Late Pliocene part of the succession comprises monotonous deep-water siltstone of slope origin (depositional depths ca. 150–500 m). The upper part of the succession comprises unconformity-bound sequences which include entirely non-marine facies, indicating that the basin was emergent by the middle Pleistocene. It follows that the lower parts of the succession accumulated entirely below the lowstand shoreline, and includes sediment deposited during both glacials and interglacials. In contrast, and as for the Wanganui cyclothems, the unconformity-bound cyclothems in the upper section represent largely interglacial deposits. In between, the middle part of the succession comprises rhythmic alternations of siltstone and sandstone/coquina limestone of upper slope and shelf origin, within which most cycles were deposited below their contemporary lowstand shoreline, and which therefore, contain both glacial (lowstand systems tract) and interglacial (highstand systems tract) parts.

Z. delicatula is a common fossil throughout the middle Mangaopari section (Vella, 1963; Kennett et al., 1971; Gammon, 1997). Its occurrence is always stratigraphically restricted to individual narrow zones within siltstone/sandstone (generally 1–10 cm thick), or as discrete thicker coquina shellbeds (10–80 cm thick). In only two cases does *Zygochlamys* occur scattered throughout massive offshore siltstone, a fact in keeping with its known modern preference for a sediment-starved substrate. There are two main modes of occurrence of *Z. delicatula* within the Mangaopari Basin: Type 1 and Type 2, which represent terrigenous and bioclastic settings, respectively, and are discussed below in turn.

Type 1 (terrigenous setting) occurrences consist

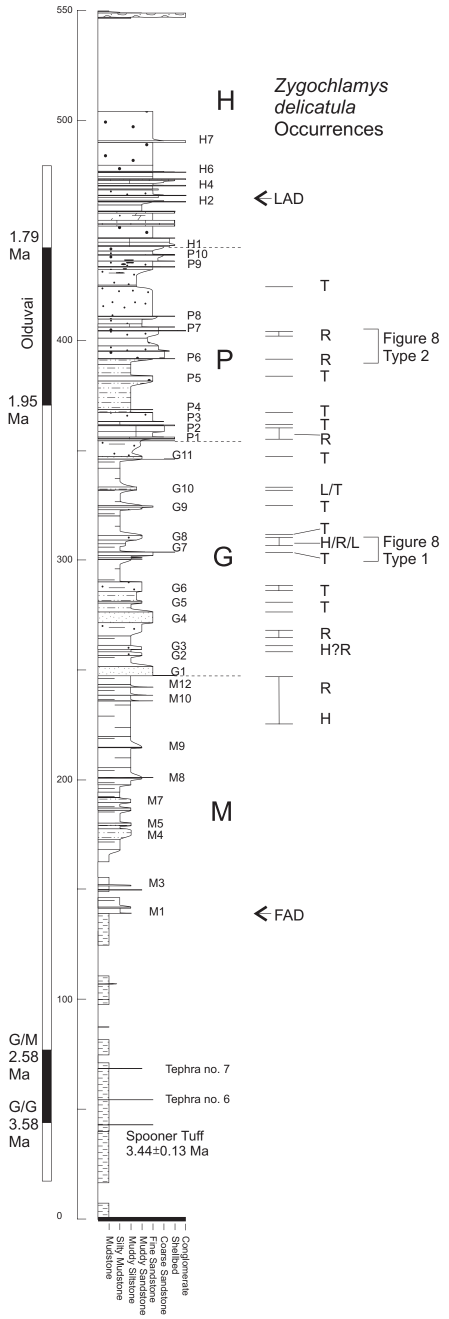


Fig. 7. Mangaopari Stream section, showing glacio-eustatic cycles of the Mangaopari (*M*), Greycliffs (*G*), Pukenui (*P*) and Hautotara (*H*) Formations.

Fig. 6. *Zygochlamys delicatula* in (a) Hautawa Shellbed, Wanganui Basin, (b) HST/RST transition, cycle P4, Mangaopari Stream, (c) TST/HST transition, cycle G3, Mangaopari Stream.

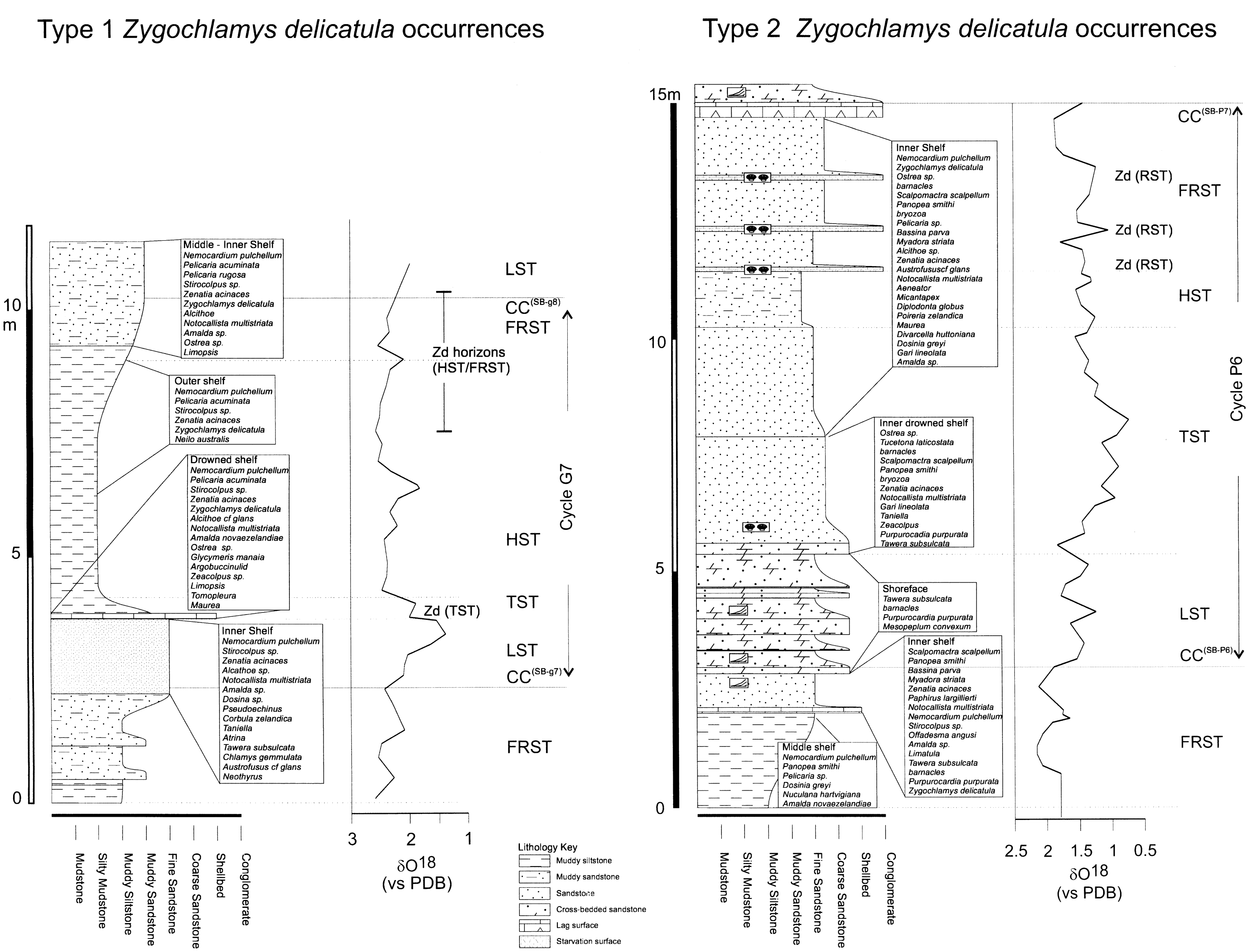


Fig. 8. Details of cycles P6 and G7 showing typical occurrence of Type 2 and Type 1 *Zygochlamys delicatula* shell accumulations, respectively (after Gammon, 1997).

of double and single valved individuals of *Zygochlamys*, concentrated along a thin zone within massive siltstone, either (a) at deepening TST transitions between LST inner shelf sands and outer shelf HST muds, or (b) at shallowing transitions between HST silts and LST sands (less common). Associated macrofossils include encrustations of *Austromegabalanus* on *Zygochlamys* shells, and *Kereia greyi*, *Nemocardium, Stiracolpus* and *Pelicaria acuminata* which occur scattered in the enclosing shelf siltstones.

Type 1 *Zygochlamys* shell accumulations mark either surfaces of drowning, deposited during sea-level rise, at the transition between glacial and interglacial periods, or occur at surfaces of rapid basinward shoreline movement during interglacial to glacial regressions. Eighteen cycles in the Late Pliocene part of the succession contain drowning *Zygochlamys* beds, and five of these cycles also contain *Zygochlamys* shellbeds at the HST–LST shallowing transition (Figs. 6 and 7). For cycles above G7 (i.e. younger than ca. 2.10 Ma), the changing oxygen isotope ratios are consistent with the palaeoclimate inferred from lithostratigraphy, and become more negative across the *Zygochlamys* beds located at drowning (warming) junctions, and more positive across shallowing (cooling) junctions. Below cycle G7, a similar oxygen isotope cyclicity exists, but possesses an inverse relationship with the climate change inferred from lithostratigraphy, i.e. the isotope signature becomes more *positive* across drowning (warming) junctions. Gammon (1997) has argued that these older and out-of-phase isotope cycles result from local palaeoceanographic factors, which resulted in relatively warmer glacial sea temperatures and relatively colder interglacial temperatures. Specifically, a warming of 3–6ºC during glacials with respect to interglacials can be attributed to an enhanced influence of the warm water D'Urville Current at the expense of the cold-water Southland Current (Gammon, 1997). *Zygochlamys* still occurs at TST transitions in these out-of-phase cycles (as inferred from the lithostratigraphy), but in a situation where the isotope measurements indicate a concomitant change from warmer glacial to colder interglacial water. These inferences notwithstanding, the overall evidence is consistent with the presence of *Zygochlamys* being controlled primarily by sediment starvation in both in-phase and out-of-phase oxygen isotope cycles.

Type 2 (bioclastic setting) occurrences consist of lose-packed, convex-upwards shells of *Zygochlamys* in the basal cycle of the Ruakokopatuna Limestone and in the Birch Hill Limestone (Fig. 8) (Gammon, 1997; cycles P1 and P6, previously informally termed the 'A' and 'B' limestones, respectively). The *Zygochlamys* beds comprise packed shell hashes, with worn or broken single shells set in a matrix of moderately sorted fine terrigenous sand and comminuted shell fragments. *Zygochlamys* shells are often bored by epibionts and encrusted with epifauna on both sides, including '*Balanus*' and *Austromegabalanus*. Bryozoans and *Stiracolpus* are common accessory fossils.

Type 2 *Zygochlamys* shellbeds are discrete units which lie at the change from regressive shelf silts and muddy sands of the HST–RST to shore face, trough cross-bedded calcarenites and calcirudites of the LST (Fig. 7). As for some Type 1 shellbeds, Type 2 shellbeds lie at a shallowing, interglacial to glacial transition, and the oxygen isotope ratio shows a concomitant shift towards more positive values across the shellbeds. Type 2 *Zygochlamys* beds therefore represent strong terrigenous sediment starvation, and strongly agitated and cooler waters.

5. Conclusions

We have described five different occurrences of *Z. delicatula* shellbeds, enclosed in terrigenous and carbonate sediments. All are associated with climatically controlled late Neogene sedimentary cycles, which are as follows: (a) at the TST–HST transition on the modern Otago shelf (carbonate); (b) at the TST–HST transition in Wanganui cyclothems (terrigenoclastic); (c) at the TST–HST transition in Mangaopari cyclothems (Type 1, terrigenoclastic); (d) at the HST–(RST)–LST transition in Mangaopari cyclothems (Type 1, terrigenoclastic); and (e) at the HST–(RST)–LST transition in Mangaopari cyclothems (Type 2, mixed-carbonate).

In all these cases, the presence of *Zygochlamys* required the coincidence of relatively cold water temperatures and a reduction or cessation in the supply of terrigenous sediment. Such conditions

are not associated with one unique level within a glacio-eustatic cyclothem (sequence). However, sediment starvation or omission is nearly always associated with the rapid movement of the shoreline across the shelf, and *Zygochlamys* shellbeds, therefore, occur most commonly at either the TST–HST transition (where they may form part of a mid-cycle shellbed), or, for cyclothems deposited below the lowstand shoreline, at the HST–(RST)–LST transition. Whether particular shellbeds are enclosed by dominantly carbonate or terrigenoclastic sediments depends upon the location and magnitude of contemporary sediment sources, the width of the shelf, and the prevailing hydraulic regime.

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References

Abbott, S.T., 1994. Sequence stratigraphy, sedimentology and paleoecology of Mid-Pleistocene cyclothems in the Castlecliff Section, Wanganui Basin, New Zealand. Ph.D. Thesis, James Cook University of North Queensland, Townsville.

Abbott, S.T., 1997. Mid-cycle condensed shellbeds from mid-Pleistocene cyclothems, New Zealand: implications for sequence architecture. Sedimentology 44, 805–824.

Abbott, S.T., Carter, R.M., 1994. The sequence architecture of mid-Pleistocene (ca. 1.1–0.4 Ma) cyclothems from New Zealand: facies development during a period of orbital control on sea-level cyclicity. Int. Assoc. Sedimentol. Spec. Publ. 19, 367–394.

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

Andrews, P.B., 1973. Late Quaternary continental shelf sediments off Otago Peninsula, New Zealand. N.Z. J. Geol. Geophys. 16, 793–830.

Andrews, P.B., 1976. Sediment transport on the continental shelf east of Otago — a reinterpretation of so-called relict features. Comment. N.Z. J. Geol. Geophys. 19, 527–531.

Andrews, P.B., 1979. Notes on a sediment map for the South Otago continental shelf. N.Z. J. Mar. Freshwater Res. 13, 309–313.

Baum, G.R., Vail, P.R., 1988. Sequence stratigraphy concepts applied to Paleogene outcrops, Gulf and Atlantic basins. In: Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A., Van Wagoner, J.C. (Eds.), Sea-Level Changes: An Integrated Approach. Soc. Econ. Paleontol. Mineral., Spec. Publ. 42, 309–328.

Beu, A.G., 1969. Index macrofossils and New Zealand Pliocene and Lower Pleistocene time-stratigraphy. N.Z. J. Geol. Geophys. 12, 643–658.

Beu, A.G., 1977. Ages of some *Chlamys delicatula* localities in North Canterbury (note). N.Z. J. Geol. Geophys. 20, 199–203.

Beu, A.G., 1985. *Pleistocene Chlamys* patagonica delicatula (Bivalvia: Pectinidae) off southeastern Tasmania, and history of its species group in the Southern Ocean. S. Aust. Dept. Min. Energy 5, 1–11.

Beu, A.G., 1995. Pliocene limestones and their scallops. Lithostratigraphy, pectinid biostratigraphy and paleogeography of eastern North Island late Neogene limestone. N.Z. Inst. Geol. Nucl. Sci., Monogr. 10, 1–243.

Beu, A.G., 1998. Fossil records of the cold-water scallop *Zygochlamys delicatula* (Mollusca: Bivalvia) off northernmost New Zealand. N.Z. J. Geol. Geophys. (in press).

Beu, A.G., Edwards, A.R., 1984. New Zealand Pleistocene and Late Pliocene glacio-eustatic cycles. Palaeogeogr., Palaeoclimatol., Palaeoecol. 46, 119–142.

Beu, A.G., Grant-Taylor, T.L., Hornibrook, N. deB., 1977. Nukumaruan records of the subantarctic scallop *Chlamys delicatula* (Hutton) and crab *Jacquinotia edwardsii* (Jacquinot) in central Hawkes Bay. N.Z. J. Geol. Geophys. 20, 21–248.

Beu, A.G., Browne, G.H., Grant-Taylor, T.L., 1981. New *Chlamys delicatula* localities in the central North Island and uplift of the Ruahine Range. N.Z. J. Geol. Geophys. 24, 127–132.

Boreham, A.U.E., 1963. Some problems concerning the application of the Lower Nukumaruan (Hautawan) Substage (Lower Pleistocene, New Zealand). N.Z. J. Geol. Geophys. 6, 3–27.

Brodie, J.W., 1960. Coastal surface currents around New Zealand. N.Z. J. Geol. Geophys. 3, 235–252.

Carter, L., 1986. A budget for modern–Holocene sediment on the South Otago continental shelf. N.Z. J. Mar. Freshwater Res. 20, 665–676.

Carter, L., Hertzer, R.H., 1979. The hydraulic regime and its potential to transport sediment sediment on the Canterbury continental shelf. N.Z. Oceanogr. Mem. 83.

Carter, R.M., Carter, L., 1987. The Bounty Channel system: a 55-million-year-old sediment conduit to the deep sea, south west Pacific Ocean. Geo-Mar. Lett. 7, 183–190.

Carter, L., Ridgeway, N.M., 1974. Hydrology and marine sedimentation off the Clutha River. N.Z. Oceanogr. Inst., Oceanogr. Summary 2.

Carter, R.M., Carter, L., Williams, J.J., Landis, C.A., 1985. Modern and relict sedimentation on the South Otago continental shelf, New Zealand. N.Z. Oceanogr. Inst. Mem. 93.

Carter, R.M., Carter, L., Johnson, D.P., 1986. Submergent shorelines in the SW Pacific: evidence for an episodic post-glacial transgression. Sedimentology 33, 629–649.

Clifton, H.E., Hunter, R.E., Gardner, J.V., 1988. Analysis of eustatic, tectonic and sedimentologic influences on transgressive and regressive cycles in the Upper Cenozoic Merced Forma-

tion, San Francisco, California. In: Kleinspehn, K.L., Paola, C. (Eds.), New Perspectives in Basin Analysis. Springer-Verlag, New York, pp. 109–128.

Ensor, M.J., 1986. Sedimentology of Blueskin Bay. Unpubl. MSc. thesis, Otago University, Dunedin.

Fleming, C.A., 1944. Molluscan evidence of Pliocene climatic change in New Zealand. R. Soc. N.Z. Trans. 74, 207–220.

Fleming, C.A., 1953. The geology of the Wanganui Subdivision, Waverley and Wanganui sheet districts (N137 and N138). N.Z. Geol. Surv. Bull. 52, 1–362.

Fleming, C.A., 1956. Quaternary geochronology in New Zealand. Acta IV Congr. Int. Quat. 1953, pp. 925–930.

Gammon, P.R., 1997. Sequence Stratigraphy of the Mangaopari Basin. Unpubl. PhD. dissertation, James Cook University of North Queensland, Townsville.

Gibb, J.B., 1979. Late Quaternary Shoreline Movement in New Zealand. Thesis, Victoria University of Wellington, 217 pp.

Gibb, J.G., 1987. A New Zealand regional Holocene eustatic sea-level curve and its application to determination of vertical tectonic movements. R. Soc. N.Z. Bull. 24, 377–393.

Gillespie, J.L., Nelson, C.S., Nodder, S.D., 1998. Post-glacial sea-level control and sequence stratigraphy of carbonate–terrigenous sediments, Wanganui shelf, New Zealand. Sediment. Geol. 122, 245–266 (this volume).

Gray, F.L., 1993. The Karitane Canyon: A Submarine Valley Cut into the Otago Continental Shelf. Unpubl. MSc. thesis, University of Otago, 150 pp.

Haq, B.U., Hardenbol, J., Vail, P.R., 1987. Chronology of fluctuating sea levels since the Triassic. Science 235, 1156–1167.

Hawke, D.J., 1992. Salinity variability in the shelf waters near Otago Peninsula, New Zealand, on a time scale of hours. N.Z. J. Mar. Freshwater Res. 26, 167–173.

Hayes, J.D., Imbrie, J., Shackleton, N.J., 1976. Variations in the earth's orbit: pacemaker of the ice ages. Science 194, 1121–1132.

Hayward, B.W., 1986. A guide to paleoenvironmental assessment using New Zealand Cenozoic foraminiferal faunas. N.Z. Geol. Surv. Rep. PAL 109.

Heath, R.A., 1972. The Southland Current. N.Z. J. Mar. Freshwater Res. 6, 497–533.

Heath, R.A., 1973. Direct measurements of coastal currents around southern New Zealand. N.Z. J. Mar. Freshwater Res. 7, 331–367.

Heath, R.A., 1975. Oceanic circulation and hydrology off the southern half of the South Island, New Zealand. N. Z. Oceanogr. Mem. 72.

Jillett, J.B., 1969. Seasonal hydrology of the waters off the Otago Peninsula, south-eastern New Zealand. N.Z. J. Mar. Freshwater Res. 3, 349–375.

Kennett, J.P., Watkins, N.D., Vella, P., 1971. Paleomagnetic chronology of Pliocene–Early Pleistocene climates and the Plio–Pleistocene boundary in New Zealand. Science 171, 276–279.

Larcombe, P., Carter, R.M., Dye, J., Gagan, M.K., Johnson, D.P., 1995. The nature of the post-glacial sea-level rise, central Great Barrier Reef, Australia: new evidence for episodic rise. Mar. Geol. 127, 1–44.

Murdoch, R.C., Procter, R., Jillett, J.B., Zeldis, J.R., 1990. Evidence for an eddy over the continental shelf in the downstream lee of Otago Peninsula. Estuarine Coastal Shelf Sci. 30, 489–507.

Naish, T.R., 1996. High-Resolution Sequence Stratigraphy, Sedimentology, Paleoecology, and Chronology of the Pliocene–Pleistocene (ca. 2.6–1.7 Ma) Rangitikei Group, Wanganui Basin, New Zealand. Unpubl. PhD. thesis, University of Waikato, Hamilton, 300 pp.

Naish, T.R., Kamp, P.J.J., 1997. Sequence stratigraphy of 6th order (41 k.y.) Pliocene–Pleistocene cyclothems, Wanganui Basin, New Zealand: a case for the regressive systems tract. Geol. Soc. Am. Bull. 109, 978–999.

Nodder, S.D., 1995. Late Quaternary transgressive/regressive sequences from Taranaki continental shelf, western New Zealand. Mar. Geol. 123, 187–214.

Orpin, A.R., 1992. Authigenic Carbonate Chimneys as Possible Conduits for Fluid Expulsion on the Outer Otago Shelf. Unpubl. MSc. thesis, University of Otago, 175 pp.

Orpin, A.R., 1997. Dolomite chimneys as possible evidence of coastal fluid expulsion, uppermost Otago continental slope, southern New Zealand. Mar. Geol. 138, 51–67.

Pantin, H.M., 1963. The significance of living Chlamys delicatula (Mollusca: Bivalvia) from Cook Strait. N.Z. J. Sci. 6, 507–512.

Payton, C.E. (Ed.), 1977. Seismic Stratigraphy — Applications to Hydrocarbon Exploration. Am. Assoc. Pet. Geol. Mem. 26, 516 pp.

Powell, A.W.B., 1950. Mollusca from the Continental Shelf, Eastern Otago. Rec. Auckland Inst. Mus. 4, 73–81.

Probert, P.K., Batham, E.J., Wilson, J.B., 1979. Epibenthic macrofauna off southeastern New Zealand and mid-shelf bryozoan dominance. N.Z. J. Mar. Freshwater Res. 13, 379–392.

Raymo, M.E., 1994. The initiation of northern hemisphere glaciation. Annu. Rev. Earth Planet. Sci. 22, 353–383.

Robertson, D.A., 1980. Hydrology and the quantitative distribution of planktonic eggs of some marine fishes of the Otago coast, south-eastern New Zealand. N.Z. Min. Agric. Fish., Fish. Res. Bull. 21, 69.

Saul, G., Naish, T.R., Abbott, S.T., Carter, R.M., 1998. Sedimentary cyclicity in the marine Plio–Pleistocene: sequence stratigraphic motifs characteristic of the last 2.5 Ma. Geol. Soc. Am. Bull., in press.

Te Punga, M.T., 1981. The Pliocene/Pleistocene boundary and the Nukumaruan stage. N.Z. Geol. Surv. Rept. 96-1-19.

Ueda, F., 1973. Geology of the northern part of Boso Peninsula, Japan — a cyclothemic study of sedimentation, Part 2. Tokyo Univ. J. Gen. Educ. 16, 57–107.

Vail, P., 1987. Seismic stratigraphy interpretation using sequence stratigraphy, part 1. Seismic stratigraphy interpretation procedure. In: Bally, A.W. (Ed.), Atlas of Seismic Stratigraphy. Am. Assoc. Pet. Geol. 27, 1–10.

Van Wagoner, J.C., Posamentier, H.W., Mitchum, R.M., Vail, P.R., Sarg, J.F., Loutit, T.S., Hardenbol, J., 1988. An overview of the fundamentals of sequence stratigraphy and key definitions. In: Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A., Van Wagoner, J.C. (Eds.), Sea-

Level Changes: An Integrated Approach. Soc. Econ. Paleontol. Mineral., Spec. Publ. 42, 39–45.

Vella, P., 1963. Pliocene–Pleistocene cyclothems, Wairarapa, New Zealand. Trans. R. Soc. N.Z., Geol. 2, 15–50.

Vella, P., Briggs, W.M., 1971. Lithostratigraphic names, upper Miocene to lower Pleistocene, northern Aorangi range, Wairarapa. N.Z. J. Geol. Geophys. 14, 253–274.

Wellman, H.W., 1979. An uplift map for the South Island of New Zealand, and a model for the uplift of the Southern Alps. In: Walcott, R.I., Cresswell, M.M. (Eds.), The Origin of the Southern Alps. R. Soc. N.Z., Bull. 18, 13–20.

Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A., Van Wagoner, J.C. (Eds.), 1988. Sea-Level Changes: An Integrated Approach. Soc. Econ. Paleontol. Mineral., Spec. Publ. 42, 407 pp.