

Exposed coasts vs sheltered bays: contrast between New Zealand and Japan in the molluscan record of temperature change in Plio–Pleistocene cyclothem

Alan Beu ^{a,*}, Akihisa Kitamura ^b

^a Institute of Geological and Nuclear Sciences, P.O. Box 30-368, Lower Hutt, New Zealand

^b Institute of Geosciences, Faculty of Science, Shizuoka University, Shizuoka 422, Japan

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Abstract

Cyclothem in the Omma Formation, on the Japan Sea coast of central Honshu, each contains two ecostratigraphic datums: the appearance and disappearance datums of warm-water molluscs. Cold-water molluscs occur both below (in early TST) and above (in late HST and possibly RST) warm-water ones (which occur in late TST and early HST). In contrast, no New Zealand cyclothem in the main Plio–Pleistocene basins contain both cold- and warm-water faunas in one cycle. Cyclothem in the Petane Group, central Hawke's Bay and in the Castlecliff section, Wanganui Basin, contain entirely eurythermal and warm-water molluscs throughout. Cyclothem in South Wairarapa have entirely eurythermal and cold-water molluscs throughout (the subantarctic *Zygochlamys delicatula* fauna), even in HSTs of some cycles. This contrast demonstrates the importance of exposure of the deposition site to strong coastal currents for the maximum faunal expression of temperature change. The Omma Formation was deposited in an open site on the Japan Sea coast, where currents transported larvae of a wide variety of molluscs northwards and southwards in response to temperature oscillations. The main New Zealand cyclothem successions were deposited in large embayments, sheltered from the influence of coastal currents. The maximum faunal expression within one cyclothem of Plio–Pleistocene temperature change can be expected in only those few deposition sites that satisfy the optimum requirements: deposition of reasonably complete sequences (at least TSTs, HSTs and RSTs preserved) in an exposed coastal site influenced by strong currents from both the north and south, on the inner shelf, in the temperate regions (between ca. 30° and 60°, north and south), near the north–south oriented coast of a large continent. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

Most examples of Plio–Pleistocene marine cyclothem preserved on land and described in this volume are found in either Japan or New Zealand.

This is hardly surprising, as these are the main areas of the world (together with California, Italy and some other Mediterranean margins) that bear thick Plio–Pleistocene successions that have been uplifted above present sea-level because they are close to active plate boundaries. The thick shallow-marine cyclothem sequences in Japan and New Zealand are similar in containing many shellbeds rich in mol-

* Corresponding author. Tel.: +64-4-5704847; Fax: +64-4-5704600; E-mail: a.beu@gns.cri.nz

luses, which have provided a fertile field for palaeontologists for more than a century. Many aspects of the faunas of cyclothemic successions can be of use in the interpretation of depositional environments in sequence stratigraphy, particularly water depth, site of deposition (shoreface, enclosed bay, open inner shelf, etc.) and sea temperature.

As the cyclothem studied here were deposited as a result of sea-level change during Plio–Pleistocene temperature oscillations, some sort of response by shallow-marine faunas to the temperature change would be expected. Although New Zealand and Japan lie in similar latitudes and have similar, highly

diverse molluscan faunas at present, some aspects of their faunas, geography and ecology suggest that temperature palaeoecology might be recorded differently in their Plio–Pleistocene rocks. These aspects are: (a) a higher degree of endemism (particularly at the generic and family levels) in New Zealand than in Japanese molluscan faunas; (b) Japan's coastal position, separated from Asia by straits no more than 130 m deep at present (Fig. 1), and still shallower or even subaerially exposed during Late Pliocene–Pleistocene glacial maxima, compared with New Zealand's isolated oceanic position, separated by a minimum of 1200 km from Australia and with sev-

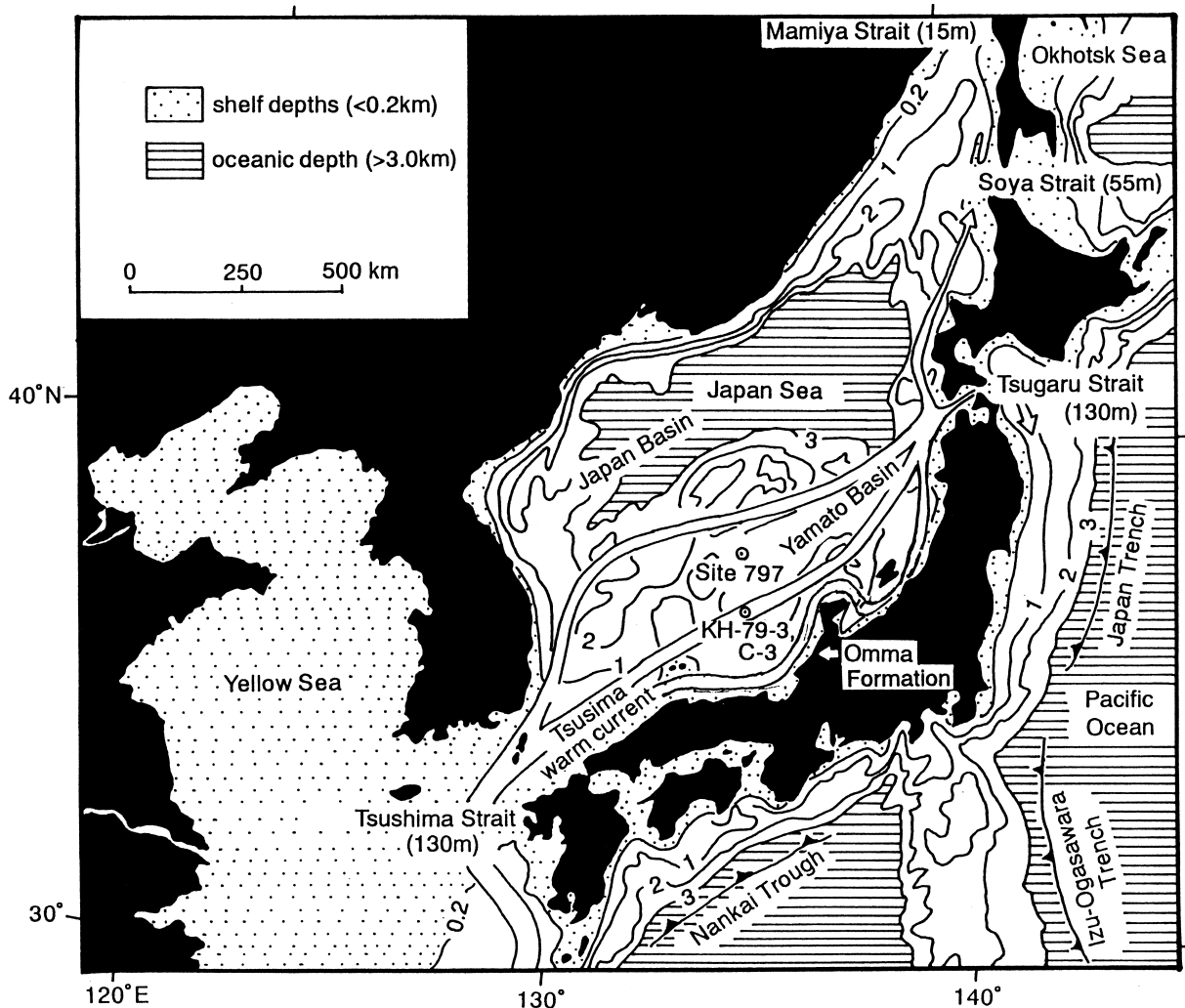


Fig. 1. Map of the Japan sea and surrounding region, showing the location of the Omma Formation. Modified from Tada et al. (1992).

eral small island groups to the south but few to the north; and (c) Japan's being influenced by several strong coastal currents, branches of the cold Oyashio current flowing along the coast of Asia from the north and the warm Kuroshio current from the south, compared with New Zealand's few, relatively weak coastal currents; only one strong, fauna-transporting current occurs around New Zealand, the Southland current, which flows northwards up the east coast of the South Island.

This paper compares the faunal response to temperature change within a single cyclothem in sequences exposed on land in Japan and New Zealand. We discuss how differing exposure of the deposition site to coastal currents explains the differences in the faunal record of temperature change between the two countries. This leads to a consideration of the criteria that would allow a deposition site to record the maximum faunal expression of temperature change during sea-level oscillations at the Milankovitch time-scale.

2. Pleistocene cyclothem of the Omma Formation

The Omma Formation is exposed around Kanazawa City on the Japan Sea coast of central Honshu, Japan (Fig. 1). Eleven cyclothem are recognised in the middle part of the Omma Formation. They are described in detail elsewhere (Kitamura et al., 1994; Kitamura, 1998) and the description is not repeated here. The Omma Formation is ideal for the purpose of this paper, because the eleven cyclothem correspond to 6th-order cycles equivalent to oxygen isotope stages 50 to 28 (Fig. 2; Kitamura and Kondo, 1990; Kitamura et al., 1994; Kitamura, 1998), i.e., it was deposited between about 1.5 and 1.0 Ma, during a period for which the pattern of glacio-eustatic sea-level change is known (Shackleton and Opdyke, 1973). Also, each cyclothem in the Omma Formation contains two time planes, identified by the appearance and disappearance datums of warm-water molluscs (Kitamura, 1995, 1998). Because these datums are based on frequency variations of climatically controlled molluscan associations, their recognition is independent of sequence stratigraphic concepts.

The appearance and disappearance datums of warm-water molluscs within cyclothem in the

Omma Formation constitute an internal cyclicality in the vertical distribution of in situ molluscan fossil associations (Fig. 3). The term 'association' is defined as the recurrent autochthonous relicts of former communities (Fürsich, 1984). The molluscan association changes within an individual cyclothem indicate that sea temperatures changed from cold water, through to warm water, followed again by cold water during the deposition of one cyclothem.

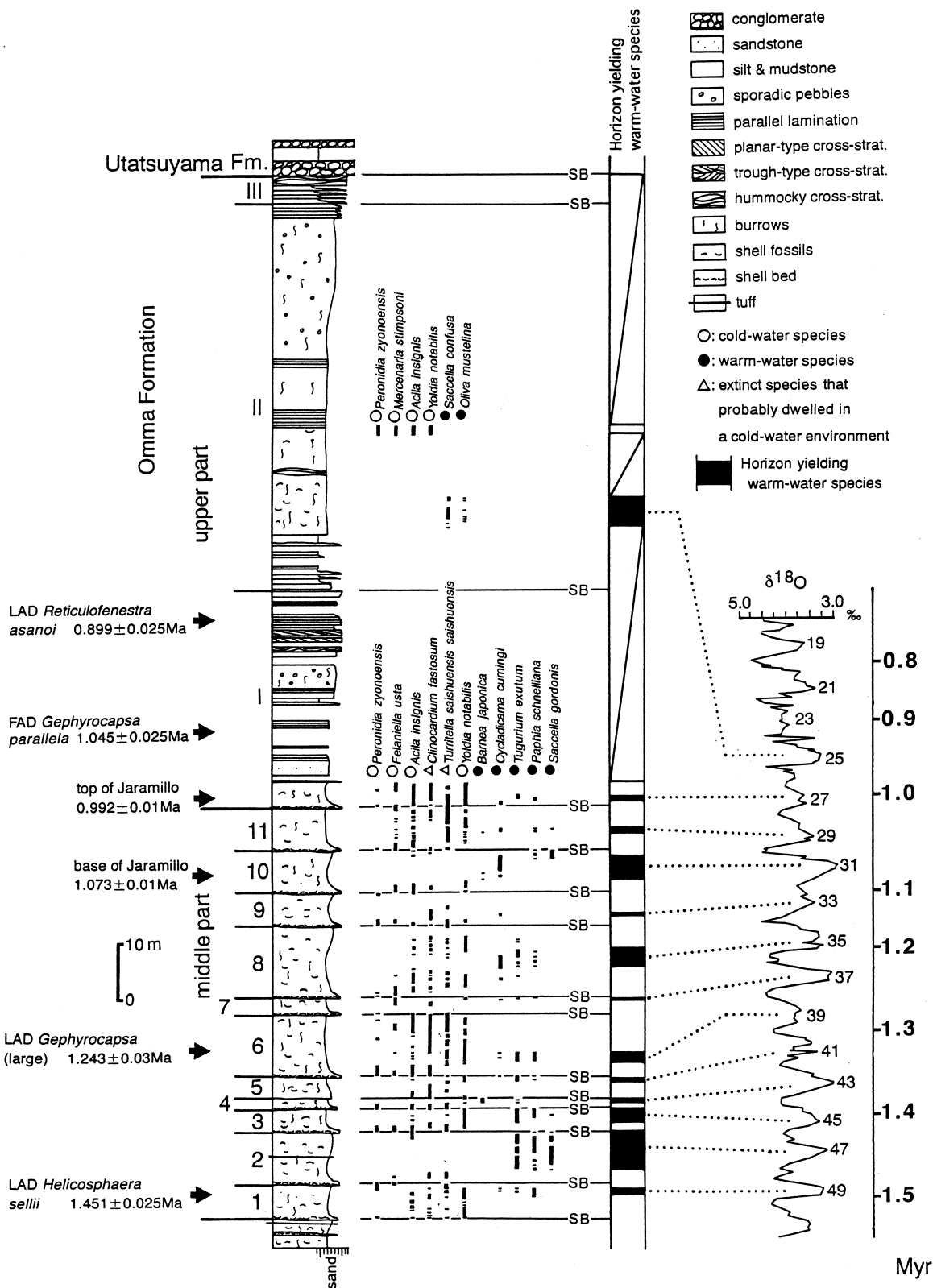
2.1. Warm- and cold-water molluscs in the Omma Formation

The occurrence and the significance for palaeotemperature interpretation of molluscs within cyclothem in the Omma Formation have been described by Kitamura and Kondo (1990) and Kitamura (1991a, 1998), and the molluscs within each cyclothem were listed in detail by Kitamura (1991b).

Kitamura (1991b) defined 'cold-water species' as those living in the area north of 35°N, 'warm-water species' as those living south of 35°N, and 'intermediate species' as those living throughout the area both north and south of 35°N, as defined in the fauna now living on the Pacific coast of Japan. The distributional limit of cold- and warm-water molluscs is influenced strongly by the warm Kuroshio current, which diverges from the coast of the Japanese Islands at 35°N. Judged from their present-day depth and temperature ranges, molluscs occurring in the Omma Formation were classified into the following associations.

(1) *Peronidea* Association: cold-water molluscs living from the low-tide mark down to 20–30 m, and occurring in the basal TST shellbeds of cyclothem; common species are *Peronidea zyonensis* (Hatai and Nishiyama), *Glycymeris yessoensis* (Sowerby), *Mercenaria stimpsoni* (Gould), *Pseudamiantis tauyensis* (Yokoyama), *Felaniella usta* (Gould), *Acila insignis* (Gould), *Turritella saishuensis saishuensis* Yokoyama and *Mizuhopecten yessoensis yokoyamae* (Masuda).

(2) *Macoma sector* Association: cold-water molluscs living from low-tide mark to 20–30 m, in a unique association confined to the basal shellbed of Cycle 10. This association lacks representative species of the *Peronidea* Association (e.g., *P. zyonensis*, *G. yessoensis* and *M. stimpsoni*) and is dominated by *Macoma sector*. Associated species are



Acila insignis, *Yoldia notabilis* Yokoyama, *Clinocardium fastosum* (Yokoyama) and *Panopea japonica* A. Adams.

(3) *Felaniella* Association: cold-water molluscs occurring in well sorted fine sandstone deposited from the low-tide mark to depths of 50 to 60 m; common species are *Felaniella usta*, *Acila insignis*, *Peronidea zyonoensis* and *Turritella saishuensis*.

(4) *Clinocardium–Turritella* Association: cold-water molluscs occurring in muddy, fine to very fine sandstone deposited from the low-tide mark down to ca. 50–60 m; common species are *Clinocardium fastosum*, *Turritella saishuensis*, *Yoldia notabilis*, *Acila insignis*, *Cryptomya busoensis* (Yokoyama), *Ennucula tenuis* (Montagu), *Liocyma fluctuosa* (Gould) and *Cryptonatica janthostomoides* (Kuroda and Habe).

(5) *Macoma tokyoensis–Felaniella* Association: cold-water molluscs occurring in muddy, fine to very fine sandstone deposited in depths of ca. 20–40 m; common species are *Macoma tokyoensis* Makiyama, *Felaniella usta* and *Yoldia notabilis*.

(6) *Yoldia* Association: cold-water molluscs occurring in muddy, fine to very fine sandstone deposited in depths of ca. 40–60 m; common species are *Yoldia notabilis*, *Felaniella usta*, *Acila insignis* and *Dosinia japonica* (Reeve).

(7) Transitional Association: intermediate-water molluscs occurring in muddy, fine to very fine sandstone deposited in ca. 30–60 m; common species are *Clinocardium fastosum*, *Turritella saishuensis*, *Ennucula tenuis* and *Cryptonatica janthostomoides*.

(8) *Barnea* Association: warm-water molluscs occurring in muddy, fine to very fine sandstone deposited from the low-tide mark down to ca. 30 m; common species are *Barnea dilatata* (Souleyet) and *Tugurium exutum* (Reeve).

(9) *Cycladicama* Association: warm-water molluscs occurring in muddy, fine to very fine sandstone deposited from the low-tide mark to ca. 60 m; common species are *Cycladicama cumingi* (Hanley),

Barnea dilatata and *Paphia schnelliana* (Dunker).

(10) *Tugurium–Paphia* I Association: warm-water molluscs occurring in muddy, fine to very fine sandstone deposited in ca. 30–60 m; common species are *Tugurium exutum*, *Paphia schnelliana*, *Nassarius caelatus* (A. Adams) and *Yoldia notabilis*.

(11) *Tugurium–Paphia* II Association: warm-water molluscs occurring in muddy, fine to very fine sandstone deposited in ca. 60–120 m; common species are *Tugurium exutum*, *Paphia schnelliana*, *Glycymeris rotunda* (Dunker), *Saccella gordonis* (Yokoyama), *Limopsis crenata* A. Adams, *Nemocardium samarangae* Makiyama and *Acila divaricata* (Hinds).

As shown clearly in Figs. 2–5, these molluscan associations have a consistent, cyclical relationship with systems tracts in each cyclothem in the Omma Formation. Figs. 3 and 5 and the detailed faunal lists for individual cyclothem given by Kitamura (1991b, 1998) demonstrate that the *Peronidea* and *Macoma sector* Associations are always found in basal shellbeds, the *Felaniella*, *Clinocardium–Turritella*, *Macoma tokyoensis–Felaniella* and *Yoldia* Associations are always found in the lower parts of TSTs, and the *Barnea*, *Cycladicama*, *Tugurium–Paphia* I and *Tugurium–Paphia* II and transitional Associations are always found in the upper parts of TSTs and lower parts of HSTs. In most cyclothem, the uppermost preserved part (high in the HST, or perhaps in part RST) shows a return to the *Clinocardium–Turritella* Association and, in a few cyclothem (e.g., Fig. 3) the uppermost preserved part contains the *Felaniella* Association. In a few other cyclothem the uppermost preserved part falls within one of the warm-water associations, but this merely implies that the uppermost part of the HST has been eroded before the deposition of the TST shellbed of the succeeding cyclothem.

It is clear, then, that molluscan associations within cyclothem in the Omma Formation not only display the expected changes in depth of deposition through one cyclothem, deepening upwards from the basal

Fig. 2. Comparison of stratigraphic distribution of warm-water species in the Omma Formation (Kitamura, 1995; Kitamura et al., 1994) with the oxygen isotope record from DSDP Site 607 (Ruddiman et al., 1989). Biostratigraphic datums after Takayama et al. (1988) and Sato and Takayama (1992); magnetostratigraphic data from Ohmura et al. (1988) and Kitamura et al. (1993); time scale of oxygen isotope record of DSDP Site 607 and ages of biostratigraphic datums and magnetic polarity changes from Berger et al. (1994). SB = sequence boundary. I–11, I–III cyclothem numbers.

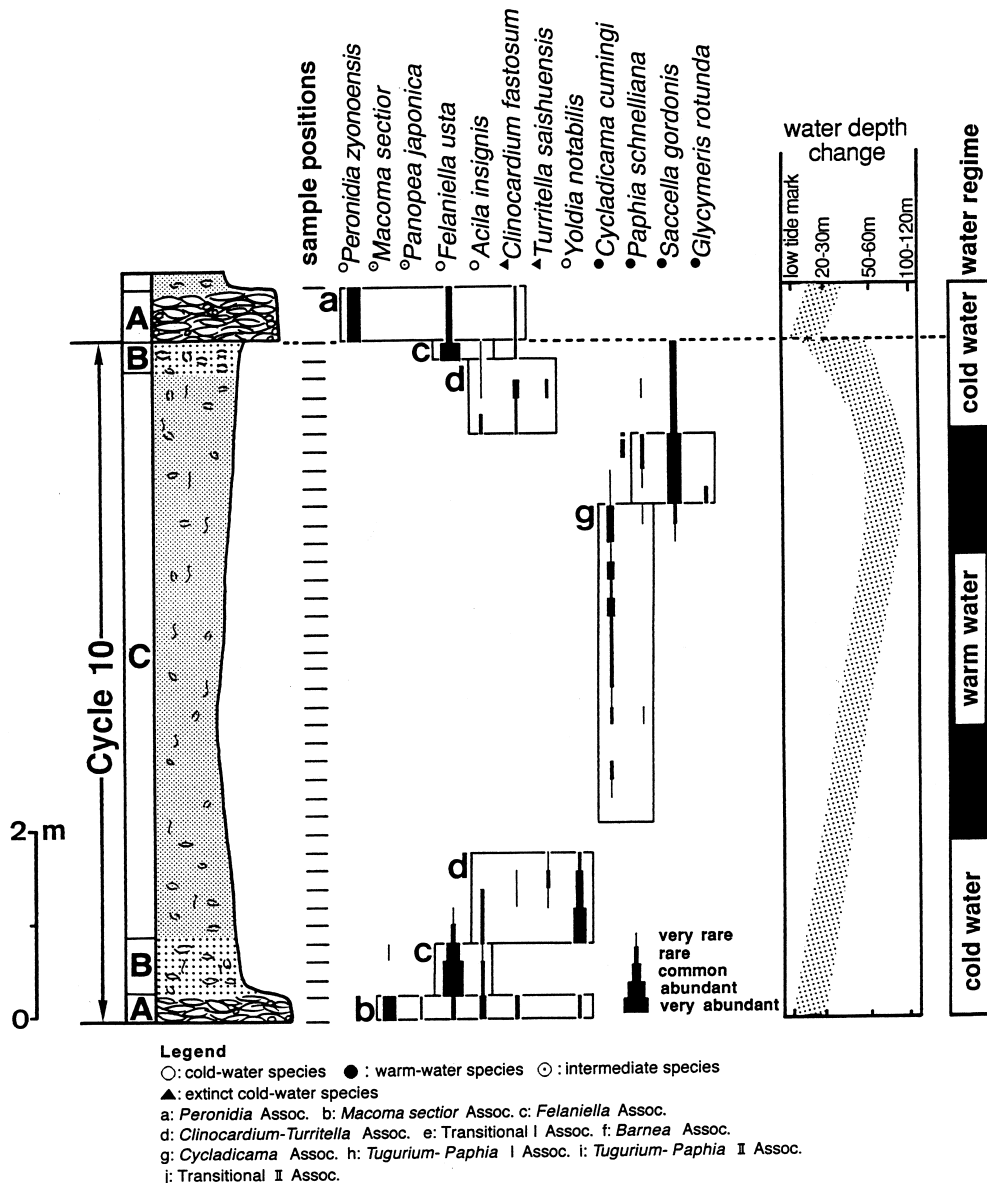


Fig. 3. Stratigraphy of Omma Formation cyclothem 10, showing the distribution of molluscan fossil associations, and inferred changes in oceanic conditions and water depth. Specimen numbers on abundance bars: very rare, 1 specimen; rare, 2–4 specimens; common, 5–9 specimens; abundant, 10–19 specimens; very abundant, >19 specimens.

TST shellbed into the uppermost TST (many cycles showing also a shallowing at the top of the HST — perhaps in part RST), but also demonstrate changes in sea temperature through one cyclothem. Cold-water molluscs are present in the lower part of the TST of all cycles and in the uppermost HST (or RST) of most cycles, and a transitional association

and warm-water molluscs are present in the upper part of the TST to lower part of the HST of all reasonably complete cycles. As noted by Kitamura (1995, 1998), these consistent appearance and disappearance datums of warm-water molluscs provide consistent ecostratigraphic datums that are helpful in the interpretation of sequence stratigraphy. Kondo

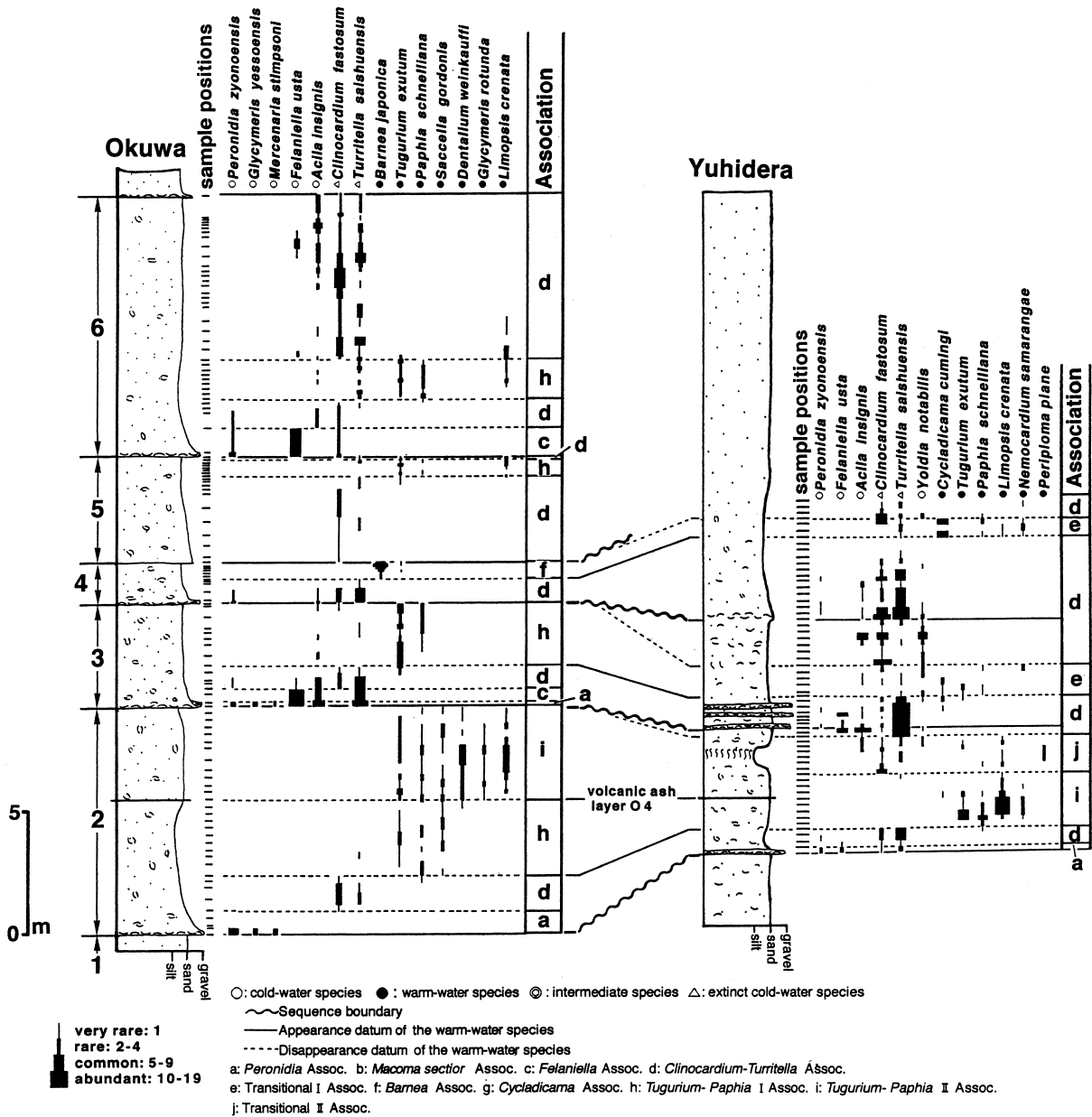


Fig. 4. Correlation of cyclothem 1 to 6 of the middle part of the Omma Formation between the Okuwa and Yuhidera sections by ecostratigraphic datums and volcanic ash layer O4.

(1994) previously has pointed out that temperature changes within one cyclothem can be recognised in both the Omma Formation (Japan Sea coast) and the Boso Peninsula (Pacific coast) in Japan, and this seems to be a consistent character of Plio–Pleistocene cyclothem in Japan.

3. Nukumaruan (Plio–Pleistocene) cyclothem of the Petane Group

The present land area and coastal currents of New Zealand are shown in Fig. 6. Nukumaruan (2.5 to ca. 1.63 Ma) cyclothem are widespread in New Zealand

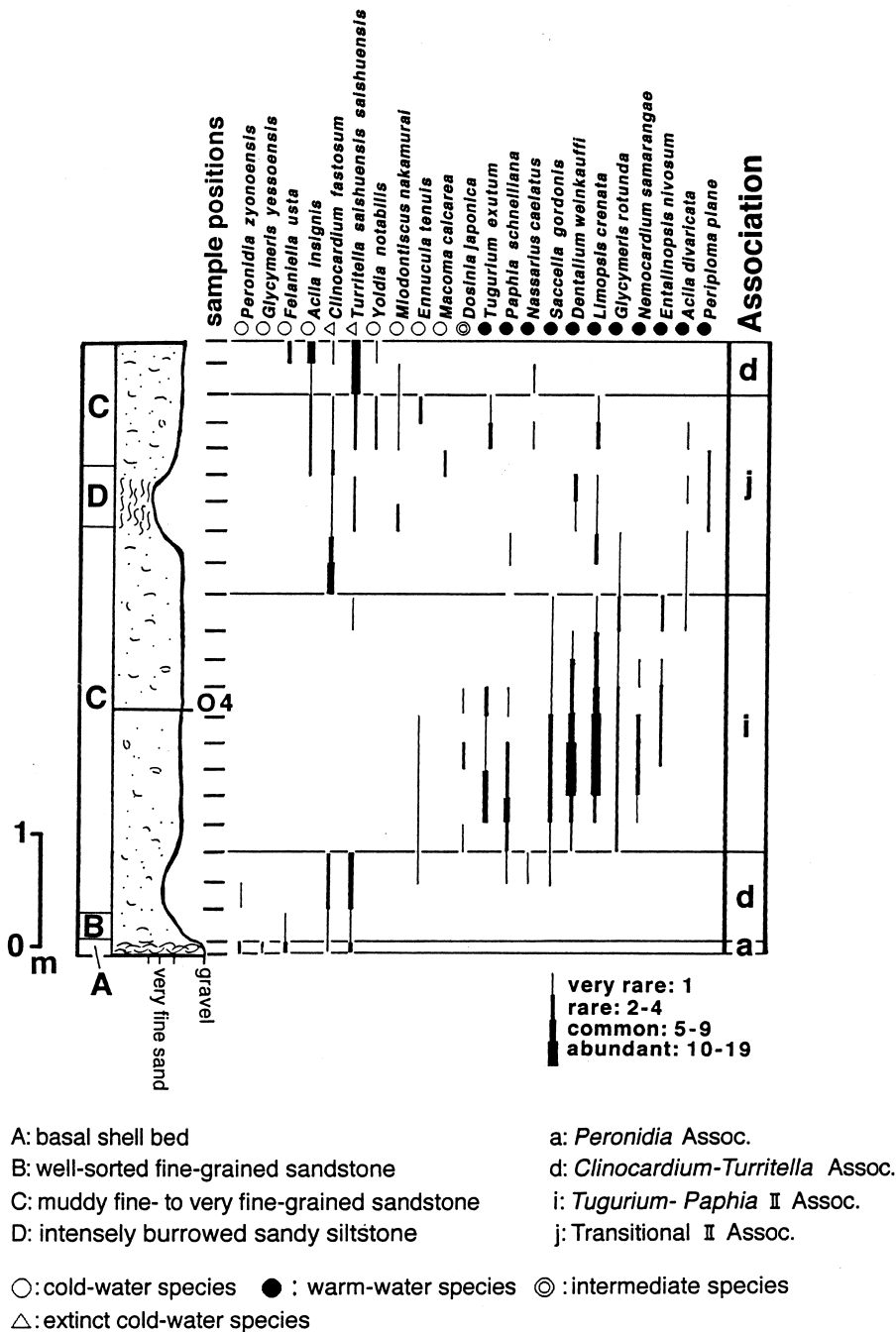


Fig. 5. Stratigraphy of cyclotem 2 at Yuhidera, showing stratigraphic distribution of molluscan fossil associations. See legend to Figs. 2 and 4 for explanation of symbols.

on-shore, shallow-water successions (Fig. 7). Those in South Wairarapa (Gammon, 1994, 1995; Orpin et al., 1998) and in the Wanganui Basin (Saul, 1994;

Naish and Kamp, 1995, 1997) and the excellently exposed Castlecliffian (middle to Late Pleistocene) cyclotems of the Castlecliff section, Wanganui coast

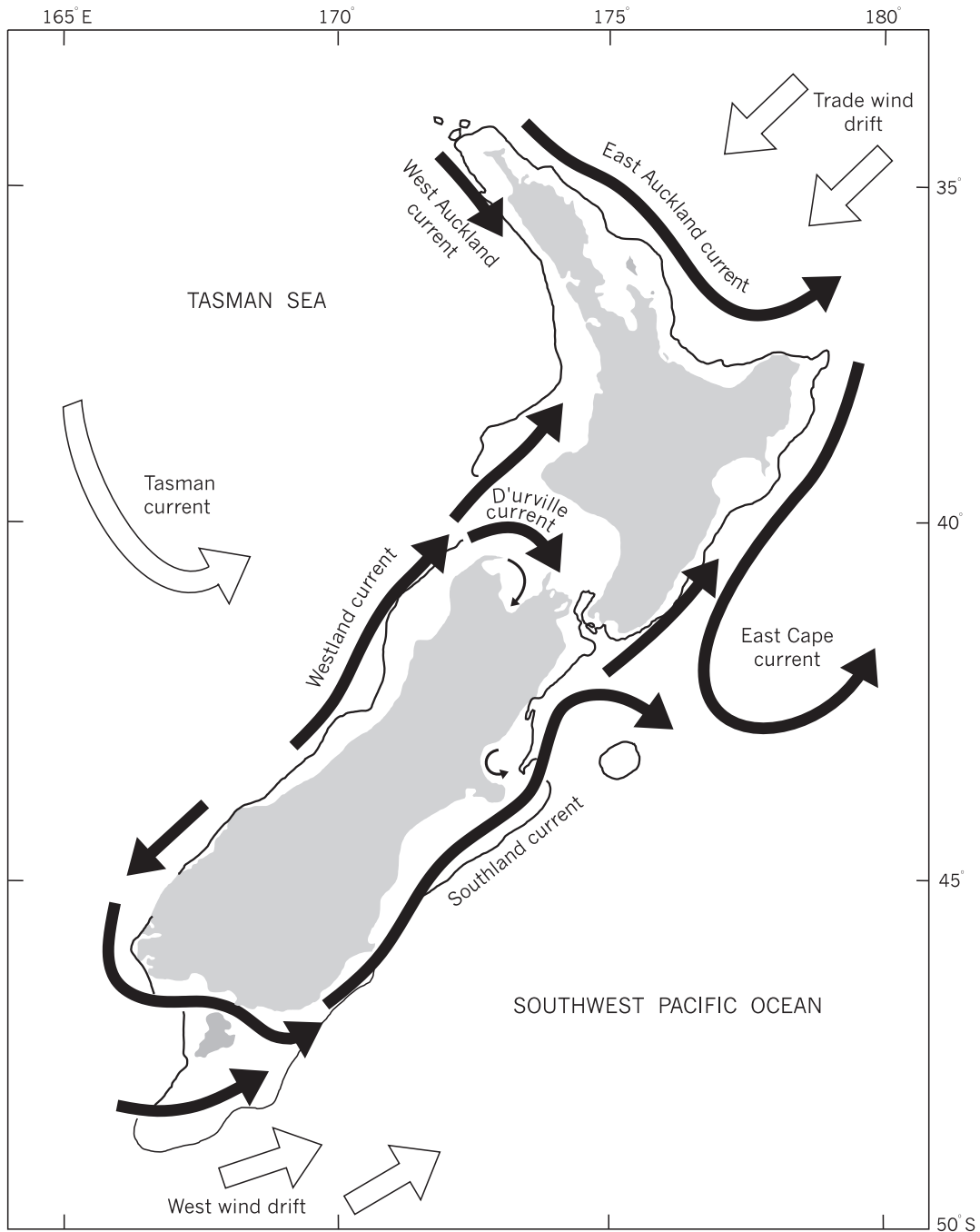


Fig. 6. The present New Zealand land area (in grey), showing approximate edge of the continental shelf (thin line), and the main ocean currents (hollow arrows) and coastal currents (solid arrows) affecting New Zealand (from Carter, 1975, fig. 3).

(Carter et al., 1991; Abbott and Carter, 1994; Abbott, 1998) have been described in detail by previous authors, with sequence stratigraphic interpretations.

The most obviously cyclothem of all New Zealand Plio–Pleistocene successions, the Petane Group of central Hawke’s Bay (Haywick et al., 1991; Beu,

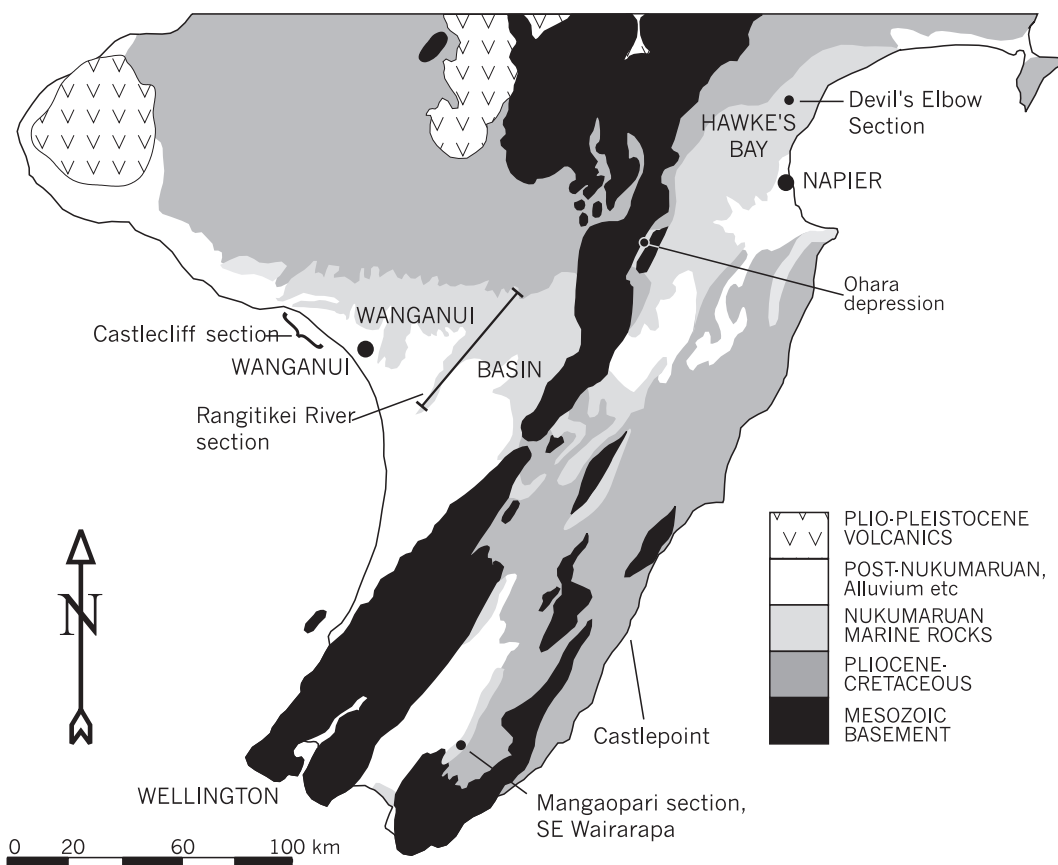


Fig. 7. Map of southern North Island, New Zealand, showing generalised geology, and localities and sections described in the text.

1995, pp. 117–135) has had a regional lithostratigraphy described, but only recently has its sequence stratigraphy been interpreted (Beu, 1995, pp. 178–180; but principally by Haywick et al., 1998). This contribution has space only for a brief description of the two uppermost cyclothem of the Petane Group in the Tangoio block outcrop area, in the Devil's Elbow hill section on the Napier–Wairoa highway, 30 km north of Napier.

A sequence stratigraphic interpretation and detailed lithostratigraphy of the uppermost two cycles at Devil's Elbow are shown in Fig. 8. In this succession, formation boundaries were originally positioned by Haywick et al. (1991, 1992) at the *top* of the limestone beds. For example, the unnamed sandstone unit between Te Ngaru Mudstone and Waipatiki Limestone (Fig. 8) previously was included in Waipatiki Limestone. This had the effect of masking the sequence boundary between what are

here concluded to be two distinct cyclothem and of producing the concept of a gradational contact between the two named formations. Reexamination of the freshly exposed section during road realignment in 1994 showed the obvious, sharp sequence boundary at the *base* of Kaiwaka Limestone, leading to reexamination of the underlying units and recognition of a sharp break, interpreted as a sequence boundary, at the base of the cemented coquina of Waipatiki Limestone (Beu, 1994). This makes it clear that the shallow-water, sparsely fossiliferous sandstone unit overlying Te Ngaru Mudstone, previously identified as the lower part of the Waipatiki Formation by Haywick et al. (1991) does, indeed, intergrade with Te Ngaru Mudstone, and represents the thick, upper, shallowing RST part of the cyclothem that includes Te Ngaru Mudstone; i.e., the basal unit of sequence 5 of Haywick et al. (1998, fig. 2) is actually the RST of their sequence 4. Conceptually as well as physically,

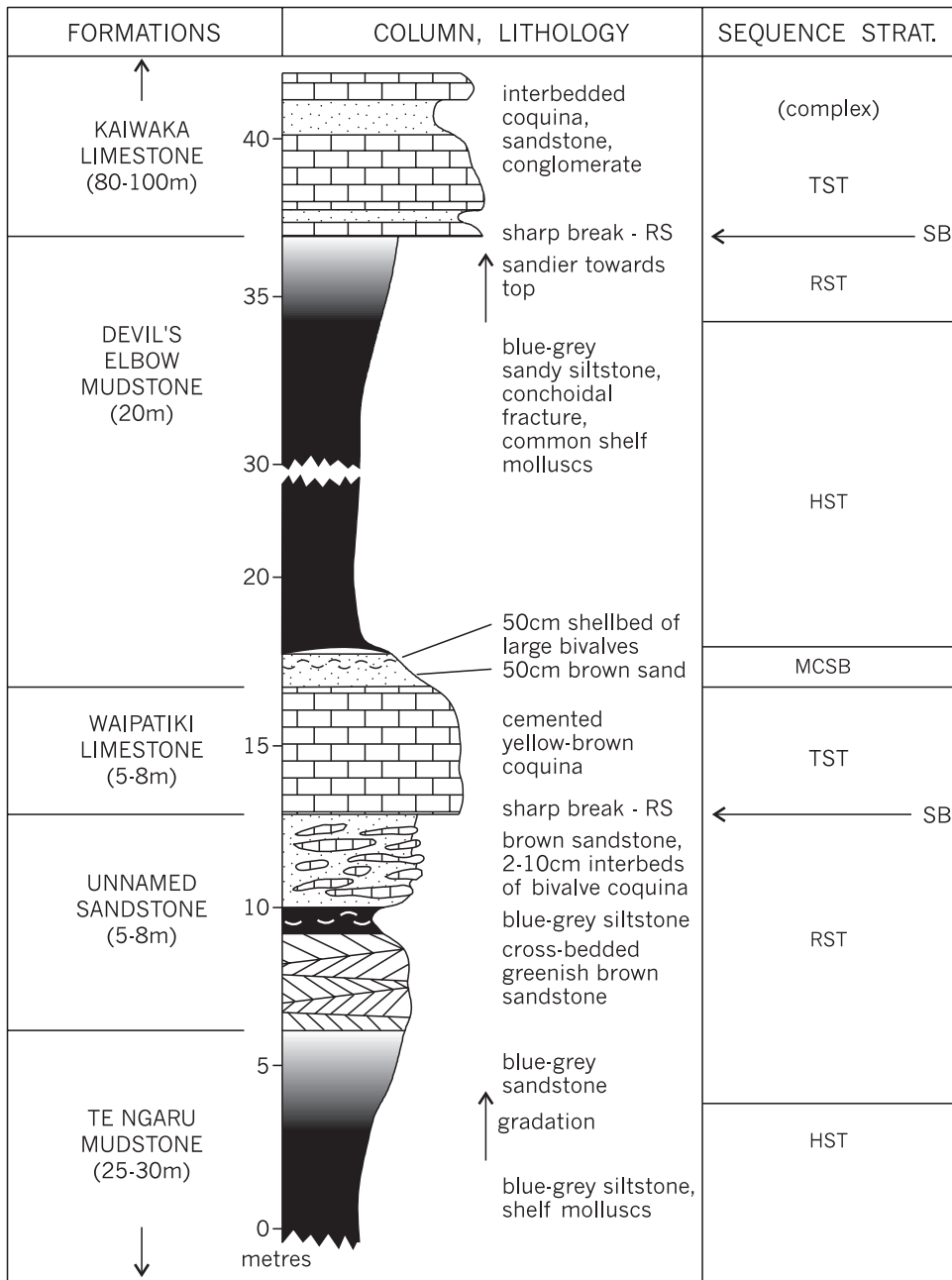


Fig. 8. Column of parts of the uppermost three cyclothem in the Devil's Elbow hill section on State Highway 3, with sequence stratigraphic interpretation (new). Lithological names from Beu (1995), with addition of an unnamed unit.

the sandstone unit is distinct from Waipatiki Limestone, and is distinguished as an unnamed member of Te Ngaru Mudstone (Fig. 8). Although the concept of the RST has been used little in sequence stratigraphy,

Naish and Kamp (1997) have shown that it is a useful and realistic systems tract that can be recognised in several New Zealand successions, and the thick, upper, regressive sandstone units at the top

of several Petane Group cyclothems are interpreted here as RSTs.

This explains the lack of recognition of diastems (sequence boundaries) in the Petane Group previously: (a) the contact, although abrupt, is not at first sight obvious from lithology, as in most cases it lies between firm or cemented yellow–brown coquina and firm or cemented yellow–brown to greenish brown, coarse, cross-bedded sandstone; and (b) it has been confused conceptually because of the inclusion of the RST of the underlying cycle within the basal formation (TST) of the overlying cycle.

Cyclothems in the Petane Group therefore conform to a similar model to cyclothems in the Omma Formation; the base of each basal shellbed (a coquina limestone bed, in the studied cyclothems) is interpreted as a sequence boundary, coinciding with a ravinement surface formed by shoreface erosion during a transgression. The basal shellbeds (most are now cemented coquina) are TSTs, and no LSTs are present, at least in this part of the basin. The rapid gradation, over ca. 0.5 m, from shellbeds to sandy mudstone with matrix-supported fossils is interpreted as the change to the HST. However, the coarse sandstone RST present in most cyclothems of the Petane Group is not present in the Omma Formation. Conceptually at least, Petane Group cyclothems are also similar to the Castlecliff sequence motif described by Abbott and Carter (1994) in having: (1) a basal TST shellbed (a muddy or sandy, cemented, aragonitic bivalve coquina, compositionally dominated by the shallow-water to eurybathyal venerid *Tawera*, in most Petane cyclothems), overlain by (2) a siliclastic unit corresponding to the upper TST (a thin, brown-weathering, weakly consolidated sandstone bed in Petane cyclothems), overlain in turn by (3) a mid-cycle shellbed (a 50 cm- to 1 m-thick bed of robust bivalves such as *Ostrea*, *Dosina*, *Purpurocardia*, and *Patro*, and a few gastropods such as the turritellid *Maoricolpus*) present in most but by no means all cyclothems, grading rapidly up into (4) a relatively thick, mudstone HST with common, scattered (matrix-supported), diverse shelf molluscs (dominantly inner shelf gastropods, such as *Pellicaria* and *Austrofusius*), deposited in about 40–100 m of water, grading up in turn into (5) a thin to relatively thick, cross-bedded, shallow-water sandstone RST.

Some lithological exceptions are the replacement of coquina by roundstone, clast-supported conglomerate in a few early cyclothems, particularly in the western (landward) part of the Tangoio outcrop area, and the uppermost limestone unit, Kaiwaka Limestone, an 80–100 m-thick, highly varied formation of interbedded coquina, sand and silt interbeds, and conglomerate, suggesting the possibility of a still finer scale of cyclicity.

The most obvious differences from the Castlecliff motif are: (a) the much thinner and less obvious Type B shellbeds (MCSBs), not present in all cycles; (b) the presence of a thick, upper, sandstone RST in most cyclothems of the Petane Group; and (c) diagenetic alteration of TST shellbeds to coquina.

These differences seem to have resulted from the greater age of the rocks (allowing diagenesis), and a markedly greater rate of basinal down-dropping in central Hawke's Bay than at Castlecliff, producing greater accommodation to allow the preservation of RSTs in central Hawke's Bay that are not present at Castlecliff. The similarity is therefore still greater to the Turakina cyclothem motif (Haywick et al., 1998) than to the Castlecliff motif, but once again there is a significant difference. The difference in this case is that the thick, sandy, upper TST of the Turakina motif is absent from most Petane Group cyclothems, in which a thin MCSB shellbed is separated by only ca. 0.5–1 m from what is here interpreted as the TST shellbed. The recognition of the Petane Group cyclothem motif as a distinct one, the Tangoio motif, by Haywick et al. (1998, fig. 4) is therefore amply justified, but the sequence stratigraphic interpretation of this motif presented here differs sharply from that of Haywick et al. (1998).

The sequence stratigraphic interpretation of Tangoio cyclothems that does not agree with either outcrop lithostratigraphy or temperature palaeoecology based on molluscs applies only to sequences 4, 5 and the upper part of 3 (Haywick et al., 1998, figs. 2 and 4). Differences in interpretation in the diagram presented here (Fig. 8) from that by Haywick et al. (1998) are as given below.

(1) Despite the previous description by Haywick et al. (1991) of *gradational* contacts between siltstone units and the overlying sandstone units in sequences 3 and 4 in the Tangoio block, these contacts are interpreted by Haywick et al. (1998) as the

sequence boundaries at the base of sequences 4 and 5. In outcrop, these contacts clearly are gradational over ca. 2–3 m, as shown here (Fig. 8), and it seems an unnecessary complication in the model to place sequence boundaries at this position. A simpler interpretation, preferred here, is that these sandstone units grading up from the underlying siltstone are RSTs, as recognised recently in Mangapanian and Nukumaruan (Late Pliocene and earliest Pleistocene) sequences in the Rangitikei River section, Wanganui Basin (Naish and Kamp, 1997).

(2) In contrast, the bases of coquina limestone units are abrupt wherever we have examined them and, at least in the more western exposures in the Tangoio block, these abrupt bases are likely to identify ravinement surfaces, and therefore are the most likely positions of sequence boundaries (Fig. 8). Even if, in more eastern exposures, the bases of coquina units are gradational as described by Haywick et al. (1998), by their own arguments there is no reason why this should not be the position of the sequence boundaries; but even Haywick et al. (1998) note that “it is true that some of the coquinas, and particularly the top coquina bed in sequences 4 and 5, have sharp, erosive bases which could be taken as marking a sequence boundary.” It seems illogical to ignore this potential boundary position, and then to state that there is *no* lithological break at the alternative position adopted.

(3) The most important point, crucial to the interpretation of sea temperature in the present paper, is the molluscan evidence for a cool temperature, and therefore for the coquina units being LSTs, in the interpretation by Haywick et al. (1998). The statement by Haywick et al. (1998) that is critical to the present paper is: “the presence of two species of bivalve mollusc which dominate the Tangoio coquinas and which evidently flourished in cold, shallow waters, namely *Tawera subsulcata* (a coarsely ribbed form similar to the modern subantarctic *Tawera bollonsi*) and *Eumarcia plana* (whose nearest living relative, *E. hedleyi*, is an estuarine form).”

This statement contains a number of misinterpretations, which deserve refutation here. The following points are important for the temperature interpretation of the coquina beds.

(a) *Tawera*. The *Tawera* species that is so abundant in many Petane Group coquina beds is either

T. assimilis (Hutton) or *T. subsulcata* (Suter). In most beds *T. assimilis* is the common species. This elongate, weakly inflated, relatively weakly sculptured species is limited to Nukumaruan rocks in Hawke’s Bay, and therefore its temperature significance is unclear (in the sense that it cannot be based on the uniformitarian adoption of a Recent range); but as it is more nearly similar to the living, widespread species *T. spissa* (Deshayes) than to any other species, and as it also occurs in mudstone with warm-water molluscs, intervening between the limestone beds, there is no reason to assume a cold-water preference. *T. subsulcata*, with greater inflation than *T. assimilis* and with relatively few, prominent commarginal ridges separated by flat interspaces, occurs most commonly in Nukumaruan Brown Sand at Wanganui, along with such warm-water taxa as *Lutrarina*, *Panis*, *Glycymeris shrimptoni*, and *Patro*, as well as *Eumarcia*, which we contend is also a warm-water group. In any case, *Tawera* is a very poorly understood group, taxonomically, with a huge range of variation in all species, and any possible similarity to the living subantarctic species *T. bollonsi* Powell is likely to be (i) taxonomically superficial, and (ii) meaningless for temperature palaeoecology.

(b) *Eumarcia*. The reference by Marwick (1927) of the large, smooth New Zealand Cenozoic fossil tapetine venerids to *Eumarcia* has always been one of convenience, indicating the most nearly related group rather than necessarily an accurate generic position. The New Zealand species, particularly the Waipipian to Nukumaruan *E. plana*, are much larger than the South African, Indian Ocean and Australian typical species of *Eumarcia* (up to 125 mm long, cf. 40 mm in living species), and the phylogenetic relationship between these two groups may not be close. *Atamarcia*, with moderately to very strong commarginal ridges, is probably another, endemic New Zealand genus, and appears to be more closely related phylogenetically to *Hemitapes* Roemer, 1864 than to *Eumarcia* (see Lamprell and Whitehead, 1992, plates 75 and 76). In any case, the taxonomic position may not be critical, as the New Zealand species referred to these genera (or genus and subgenus) occur in Oligocene to earliest Pleistocene (late Nukumaruan) rocks, i.e., they are among the many apparently warm-water but at least locally extinct genera that disappeared from New Zealand at the end of Nukumaruan time, and

they most certainly do not have any connotation of cool sea temperatures. Indeed, they rather confer the opposite connotation; *Eumarcia* (sensu lato) appears to be one of the *warm-water* groups that became extinct at the end of Nukumaruan time because of falling sea temperatures, along with *Glycymeris*, *Patro*, *Paninis*, *Lutraria*, *Chama*, *Zeacuminia*, *Zeatoma*, and numerous other genera among 13% of the total generic composition of the molluscan fauna (Beu, 1990; Beu and Maxwell, 1990, fig. 5). The New Zealand species assigned to *Eumarcia* (sensu lato) also are fully marine, shallow-water taxa, without the connotation of an estuarine environment that was assigned to them by Haywick et al. (1998).

(c) *Faunal composition of coquina*. Beu (1995) discussed the faunal composition of the Petane Group coquina beds, showing that most have a markedly more diverse fauna than the uppermost two units in the Tangoio block. Park Island Limestone (Beu, 1995, pp. 126–127) contains moulds of a diverse, shallow-water fauna, including the bivalves *Tiostrea chilensis*, *Tucetona laticostata*, *Dosinia*, *Eumarcia plana*, *Dosina zelandica*, *Tawera assimilis*, *Purpurocardia purpurata*, *Lutraria solida*, and the gastropods *Zethalia zelandica* and *Trochus tiaratus*. Large blocks of cemented Tangoio Limestone in the huge quarry behind Tangoio Beach display bedding planes closely covered with beautifully preserved moulds of bivalves, including common *Glycymeris shrimpstoni*, *Purpurocardia purpurata*, *Dosina zelandica*, *Eumarcia plana* and *E. (Atamarcia) benhami*, *Lutraria* and *Panopea*, as well as rare struthiolariids and *Zethalia*. So the dominance of *Tawera* and the presence of only markedly less common *Tiostrea*, *Eumarcia*, *Purpurocardia* and *Dosina* in Tangoio Limestone and Waipatiki Limestone in the northern and eastern Tangoio block are the exception rather than the rule, and need indicate little other than deposition in a shallow, weakly current-scoured environment favouring the dominance of *Tawera* over other faunal elements.

In summary, the faunal evidence advanced by Haywick et al. (1998) as support for a glacial period of deposition and for the interpretation of coquina units in the Tangoio block as LSTs is actually denied, emphatically, by the molluscan fauna. The fauna actually consists of eurythermal or warm-water taxa, indicating that deposition occurred during a period

when sea temperatures were, if anything, slightly warmer than in Hawke's Bay at present. This also implies that the coquina beds are more likely to be TSTs than LSTs.

Beu (1995, pp. 117–135) identified Petane Group cyclothem units over a large area of central Hawke's Bay, 40 km wide (i.e., in an east–west direction) and 60 km from north to south. Individual cyclothem units can be identified throughout this area, despite minor variations in thickness and lithology, and there seems to be no reason to doubt that the individual limestone units correlated throughout this large area by Beu (1995, fig. 66) truly are laterally continuous.

3.1. Molluscan fauna of the Petane Group cyclothem units

The abundant, well preserved, diverse molluscan fauna of the Petane Group has been studied by many palaeontologists. Taxa that are wide-ranging, eurythermal components of the present-day New Zealand inner shelf, such as *Ostrea*, *Talochlamys gemmulata*, *Purpurocardia*, *Dosina*, *Tawera*, *Panopea*, *Pellicaria*, *Stiracolpus*, *Austrofusus* and *Alcithoe* are common in most lithologies. Coquinas are dominated compositionally by aragonitic bivalves, particularly shallow-water Veneridae such as *Tawera* and *Eumarcia*. Some taxa present live only further north than Hawke's Bay today, either in the northern North Island (such as *Trivia*; and *Prototyphis* aff. *angasi*, a form larger than the living North Auckland–SE Australian species) or further north, in Australia (*Arca* s.s., *Patro*, *Lutraria* and, as noted above, *Eumarcia* and *Atamarcia*). Others are extinct genera with warm-water affinities, judged to have been stenothermal warm-water taxa that became extinct at the end of Nukumaruan time (such as the bakevelliid bivalve *Paninis*). Although most of these warm-water molluscs are limited to HST mudstone units of the Petane Group, some (such as *Patro* and *Eumarcia*) occur abundantly also in TST and MCSB shellbeds. This distribution demonstrates that the occurrence of most stenothermal warm-water taxa in HST mudstone beds is *not* an indication of higher temperatures during HST than during TST–MCSB deposition but, rather, reflects palaeoecology, particularly sedimentary facies and water depth, at the deposition site. A taphonomic bias is also likely, such as the bet-

ter preservation of fragile shells in matrix-supported mudstone than in clast-supported shellbeds. TST and MCSB shellbeds are low-diversity concentrations of moderately to very robust taxa, such as calcitic (*Ostrea*, *Patro*) and aragonitic bivalves (carditids and venerids), with only a few gastropods such as the ubiquitous turritellids and the shoreface umboniine *Zethalia*. It is clear that most taxa in the mudstone units lived out beyond the coarse substrates and high-energy, shoreface and nearby environments represented by the shellbeds.

The main point to make clear is that no stenothermal cold-water molluscs have ever been recognised in the Petane Group, despite the statement to the contrary by Haywick et al. (1998). Undoubted cold-water fossils of the New Zealand region, such as the subantarctic scallop *Zygochlamys delicatula* (Hutton) and crab *Jacquiniotis edwardsi* (Jacquinot), have never been collected from the Petane Group, but would be expected to occur in coquina of the Tangoio block if it truly were deposited during a glacial period. Beu (1998) has recognised Last Glacial Maximum fossils of *Z. delicatula* in deep water (ca. 600 m), a short distance to the north of the Three Kings Islands, off northernmost New Zealand, so there is no reason why this species would not have occurred in Hawke's Bay during glacial maxima.

3.2. Contrasting faunas in South Wairarapa

Cyclothem in the Onoke Group, in the Mangaopari Stream section (Fig. 7), southeast of Martinborough, in the southeastern North Island 200–250 km south of the outcrop area of the Petane Group cyclothem, are documented by Gammon (1994, 1995) and Orpin et al. (1998). Stenothermal warm-water molluscs, as in the Petane Group, are unknown in South Wairarapa. Instead, the subantarctic crab *Jacquiniotis edwardsii* and scallop *Zygochlamys delicatula* are moderately common to abundant in TST and some MCSB shellbeds, and a few other cold-water taxa such as *Cominella nassoides* (Reeve) (now living in shallow water at Stewart Island, tracking the isotherms northwards to live on the outer shelf off Otago) occur in small numbers in some shellbeds. In some places, concentrated banks of *Z. delicatula* up to ca. 2 m thick are conspicuous features of TST shellbeds. The relationships and the

present and past ranges of *Z. delicatula* have been summarised most recently by Beu (1995, pp. 15–17). This is a markedly cold-water element, which appeared abruptly in North Canterbury and southern to central North Island at ca. 2.5 Ma (beginning of the Nukumaruan Stage, approximately coeval with base Gelasian Stage and the first marked onset of Northern Hemisphere glaciation). It occurs today in large numbers well beyond the shelf-edge (in ca. 400–600 m) in the Pegasus Canyon, north of Christchurch (material in Museum of New Zealand) and from the Otago Peninsula southwards and, around the subantarctic islands to the south of New Zealand, in markedly shallow water, up to the inner shelf. As a fossil, it intuitively would be expected to occur most commonly in LST shellbeds, with some possible reworking into TST shellbeds, but to be absent from MCSBs and, in particular, from HSTs. The presence of this cold-water element in some MCSBs and even HSTs in South Wairarapa (Carter et al., 1995; Orpin et al., 1998) indicates that sea temperatures were very cold indeed at the deposition site, perhaps comparable with temperatures around the subantarctic Auckland Islands at present. Such a low temperature presumably resulted in part from deposition in relatively deep water, and in part from South Wairarapa lying in a widely open, moderately shallow sea exposed to the south (Beu, 1995, fig. 85), at a time when the cold Southland current was greatly enhanced compared with its present flow, and bathed the deposition site with cold water containing larvae of taxa now restricted to southeastern South Island and further south. These conditions of enhanced Southland current flow might also have enhanced coastal upwelling of cold subantarctic water to the north of its present locus, off Kaikoura.

The contrast is dramatic with cyclothem in the Petane Group. The contrast in occurrences of stenothermal molluscs in these two areas of eastern North Island presumably results from: (a) the 200–250 km separating the deposition sites; and (b) the lack of a connection (seaway) between the deposition sites in inland eastern North Island, because of blocking of the former Ruataniwha seaway very early in Nukumaruan time by uplift of the Mt Bruce basement block in northern Wairarapa (Beu, 1995). The wide, shallow, deeply embayed Hawke's Bay in

which Petane cyclothem was deposited was, therefore, presumably exposed to warm currents from northern New Zealand (such as the present East Cape current) but separated by the elevated northern East Coast highlands from the cold Southland current.

3.3. Castlecliff section, Wanganui

Fleming (1953) and Abbott and Carter (1994, 1997) have listed the molluscan faunas and described the lithostratigraphy, sequence stratigraphy and molluscan faunal associations from the Castlecliff section, and from other sections through Castlecliffian rocks in the Wanganui Basin. A number of warm-water species have been recorded over the years from these sections (e.g., *Capulus uncinatus* (Hutton) and *Eunaticina cincta* (Hutton) [= *E. linneana* Récluz; Beu and Maxwell, 1990] have been recorded from Landguard Sand; Fleming, 1953). However, it is a remarkable fact that, despite all these studies and a huge amount of fossil collecting by many other palaeontologists, no changes in molluscan faunas indicating palaeotemperature differences within one cyclothem have ever been recognised from this basin (Kondo, 1994). Many faunal differences occur within cyclothem, and a wide variety of faunal associations from within single cyclothem have been described by Abbott and Carter (1997), but all are attributable to differences in the water depth and other aspects of the deposition site (wave energy, proportion of mud, etc.) resulting from differences in position within the sea-level cycle. None can be attributed to temperature change.

4. Contrasts between New Zealand and Japan

The main difference of interest for this paper between cyclothem in the Omma Formation and in the main New Zealand basins is in the faunal record of temperature change. The faunas of cyclothem in the Omma Formation reveal a marked temperature change from cold water to warm water and back to cold water within a single cyclothem, whereas such a change has not been observed in any cyclothem within the main New Zealand basins. At first sight it seems possible that one of the reasons for such

a difference is the widely differing geographical situations of the two areas. The Omma Formation was deposited close to the Asian mainland, separated from it only by a continuous shallow, relatively narrow strait that would have been markedly shallower and narrower or even subaerially exposed during Early Pleistocene glaciations, whereas New Zealand is isolated in a deep ocean. However, consideration of molluscan dispersal capabilities (see below) leads us to conclude that relative isolation is irrelevant to this question. Kondo (1994) previously has pointed out that climatic palaeoecological changes within one cyclothem can be recognised in both the Omma Formation (Japan Sea coast) and the Shimosa Group (Boso Peninsula, on the Pacific coast) in Japan, in contrast to the Wanganui Basin in New Zealand, where the absence of strong coastal currents prevented the transport of stenothermal molluscs within one cyclothem. During Plio–Pleistocene glacial–interglacial oscillations, only stenothermal cold-water taxa from southern New Zealand were able to reappear in central New Zealand repeatedly. Warm-water taxa from Australia (separated from New Zealand by a minimum of 1200 km of open ocean) or even from closer southwest Pacific islands to the north of New Zealand (such as the Kermadec Islands) were not able to be transported to the main Pleistocene cyclothem succession, in the Wanganui Basin, but at best acted as rare, brief ‘warm guests’ during one or a few interglacial periods, mostly during the high-amplitude sea-level cycles of the middle Pleistocene (A. Beu, unpubl.).

4.1. Larval development and dispersal of molluscs

Our initial assumption was that the faunal differences between Japanese and New Zealand cyclothem resulted from the greater geographical isolation of New Zealand, and fewer molluscan larvae consequently being dispersed to deposition sites than in Japan. During the last 25 years, much emphasis in biogeography has been placed on an expected contrast in dispersal capability between planktotrophic and non-planktotrophic molluscan larvae. The enormously wide distributions achieved through passive larval dispersal by some tonnoideans (e.g., the almost cosmopolitan *Cymatium parthenopeum*) and architectonicids had long been assumed to imply an

unusually long larval life. This expectation was amply satisfied by the excellent work of Scheltema (e.g., Scheltema, 1971, 1986, 1989) on planktotrophic larvae in plankton tows. The wide dispersal capabilities of planktotrophic larvae were seized upon as a means of explanation of wide distributions and of relative species longevities and macroevolution (e.g., Shuto, 1974; Hansen, 1980; Jablonski and Lutz, 1983). More recently, though, Hadfield and Strathmann (1990) and Hickman (1992, pp. 267–268) have pointed out that some trochoidean gastropods, although lacking planktotrophy and having small, cap-shaped larval shells, have achieved very wide dispersal simply because their larvae are so small, and float easily in currents. It is obvious that many trochids and turbinids are just as widely distributed throughout the tropical Indo-West Pacific as are the planktotrophic tonnoideans and architectonicids. The lack of planktotrophy clearly has not hindered these trochoideans from being dispersed, and the notion that planktotrophic larvae have any higher dispersal capability than many small, non-planktotrophic larvae is now largely discredited. The critical factors for good larval dispersal capability would appear to be weight and flotation ability; small, light larvae, regardless of developmental type, and specialised planktotrophic larvae are all capable of being dispersed widely in currents.

There are still many molluscs that cannot have participated in rapid range expansions during Plio–Pleistocene temperature oscillations, because they have no means of dispersal, particularly the direct developers with a large hatching stage. Perhaps the most obvious example is the great majority of Volutidae, in which a single relatively enormous, benthic, small replica of the adult hatches from each egg case. But even in *Pellicaria vermis*, a New Zealand gastropod with direct development, the empirical record suggests that dispersal has occurred over 100–200 km, as early Castlecliffian fossils in the Wanganui Basin most closely resemble the form now living along eastern New Zealand. The relatively small benthic juvenile was illustrated by Morton (1950, p. 456, fig. 6).

A New Zealand example demonstrating abundant molluscan dispersal serves to show, also, that a general lack of dispersal around New Zealand is *not* the explanation for the difference between the Omma

Formation and the New Zealand cyclothemms compared here. The diverse *interglacial* molluscan fauna of late-middle Pleistocene (stage 5c) uplifted marine terraces at the Kaikoura Peninsula and Haumuri Bluff, Marlborough, was listed by Beu in Ota et al. (1996, pp. 60–62). This fauna of ca. 160 species (most of them non-planktotrophic; many with adults under 10 mm high) includes ca. 35 species limited to the southernmost South Island and areas further south at present, in a background fauna of eurythermal central and southern New Zealand taxa. This is the coldest-water fauna yet recorded from New Zealand Cenozoic rocks, and was interpreted as resulting from larval transport in a strengthened Southland current flow compared with that of today, and consequent enhancement of the intense upwelling of cold water off Kaikoura. The effect during the preceding cold stage 5d was presumably still more intense. This example shows that, without doubt, currents operating along exposed New Zealand coasts disperse a wide variety of molluscan larvae, and no difference in dispersal exists between New Zealand and Japan to explain the difference in the faunal record of temperature change.

4.2. *Deposition in large embayments*

Consideration of the deposition sites of the main New Zealand successions of cyclothemmic Plio–Pleistocene rocks shows that they all were deposited in large sheltered embayments, protected from the influence of coastal currents. The central Hawke's Bay site of the Petane Group deposition was a wide, shallow bay, ca. 40 km wide and 60 km long, and Nukumaruan rocks displaying obvious sedimentary cycles were deposited in this site only *after* closure of the Ruataniwha seaway stopped the flow of water to and from the Wairarapa Basin (Beu, 1995). The Wanganui Basin is a larger and still more deeply enclosed embayment formed on the western side of the rising axial Mesozoic greywacke ranges (the main locus of dextral offset at the plate boundary in North Island), and had a particularly constricted entrance during middle Pleistocene glaciations, when the Cape Farewell–Cape Egmont ridge was exposed above sea-level. Cook Strait was the only remaining exit. The Late Pliocene–Early Pleistocene Wairarapa Basin was interpreted by Beu (1995, fig. 85) as

widely open to the south, which explains its receipt of cold-water taxa in the strengthened Southland current; but even here, planktonic foraminiferal faunas of mudstone units are impoverished, limestone was deposited in shallow water on the rising sills of the Tararua–Ruahine ranges to the west and the East Coast highlands to the east, and the deposition site was protected from coastal currents by shoals, even if not by dry land.

It therefore appears that the critical factor causing almost no faunal record of Plio–Pleistocene temperature change within each New Zealand cyclothem is deposition within an embayment sheltered from coastal currents. The exposed Omma Formation deposition site, on the Japan Sea coast, therefore seems to offer such a dramatic contrast with New Zealand cyclothem because it was influenced by strong coastal currents, transporting abundant molluscan larvae.

A final New Zealand case shows that there possibly are sites deserving investigation as examples of more marked faunal change in an exposed coastal situation. The very areally limited Castlepoint Formation, of early Nukumaruan age, crops out on the exposed mid-east Wairarapa coast (Fig. 7). Its fauna includes units containing stenothermal warm-water molluscs, such as *Trivia* and *Chama* (the sole New Zealand Neogene locality with common *Chama*) alternating with units containing common *Zygochlamys delicatula* and other, less common, stenothermal cold-water taxa such as *Cominella nasoides*. Although cyclic sedimentological differences are clear in outcrop, the site has not yet been studied from a sequence stratigraphy viewpoint because it does not display visually distinct systems tracts as in Wanganui, Hawke's Bay and Mangaopari Stream cyclothem. Both differences — faunal and sedimentary — therefore suggest that this is possibly a New Zealand example of a succession deposited under the influence of coastal currents, as in the Omma Formation. However, the deep-water species present in small numbers in some lithologies and the chaotic debris-flow lithologies of the Castlepoint Formation suggest a more complex origin, such as canyon-head debris flows in response to cyclic sea-level changes on the adjacent shelf.

5. Requirements for the faunal expression of rapid temperature change

The differences between the Japanese and New Zealand examples of the faunal record of temperature change lead to consideration of the theoretical requirements for the maximum expression of rapid temperature change by fossil faunas during Plio–Pleistocene sea-level oscillations. The main requirements seem to be the following.

(a) Deposition in a sedimentary and tectonic regime that allows the preservation of TSTs, HSTs and RSTs, but not necessarily distinguishable visibly in outcrop. For the maximum expression of faunal change LSTs should be available as well, but these cannot be expected to lie close to TST–HST sequences in most shallow-marine sites (they will generally lie out over the shelf edge). Clearly, the more complete the cyclothem, the fuller the possible record of faunal change.

(b) Deposition on the inner (preferably) to middle shelf. This is needed to preserve the most strongly stenothermal faunas. Bathyal and, to a lesser degree, outer shelf faunas live in a uniform temperature range over very wide areas, and so will be much less sensitive indices of temperature change than inner to middle shelf taxa. Intertidal faunas are at least as sensitive as inner shelf ones, but have a much lower preservation potential.

(c) Deposition within the temperate regions, preferably near a coast oriented in a north–south direction. The consideration here is a deposition site where faunal change in response to temperature oscillations will have the maximum expression. Deposition within the central tropics or near the poles would have (at best) limited expression of climate change, as surrounding faunas are all similar to those at the deposition site. Deposition near a north–south oriented coast would allow transport of larvae to introduce stenothermal taxa with the least transport distance; a coast strongly oblique to the isotherms would require further transport (greater temperature change) for the same result. Deposition probably needs to occur within ca. 30° and 60° north and south, near a coast oriented north–south, to record the maximum faunal change.

(d) Deposition on an exposed oceanic coast, where currents are strong enough in both northward

and southward directions to transport molluscan larvae to the deposition site when temperature change occurs. The main requirement here is for deposition *not* to occur in a sheltered embayment, as the New Zealand examples demonstrate that coastal currents do not transport molluscan larvae into a sheltered deposition site in response to temperature change.

(e) Deposition in a site with a continuous shallow-marine connection to a large continent. This will allow the largest possible number of larvae to be transported to the deposition site. Also, currents to transport larvae are an inevitable property of continental coasts, given the motion of wind and the rotation of the earth, but need not occur around all oceanic islands.

The differences in the faunal record of temperature change between Japanese and New Zealand examples of Plio–Pleistocene cyclothem examined in this paper, despite their similarity of cycle motif and a similar availability of diverse molluscan faunas, result from the Omma Formation being deposited in one of the *best* possible sites to preserve a record of temperature change. In contrast, the main New Zealand cyclothem successions were all deposited in large embayments sheltered from coastal currents, the *worst* possible deposition site to preserve a faunal record of temperature change. No doubt the real world displays fossil records of all sorts between these extremes, depending principally on the degree of influence of strong coastal currents on the deposition site.

6. Conclusions

(1) Cyclothem in the Omma Formation each contain basal and uppermost cold-water molluscan faunas, separated by a central warm-water molluscan fauna. The two ecostratigraphic datums provided by the appearance and disappearance of warm-water molluscs are time planes independent of sequence stratigraphic interpretations, and help the assessment of sequence stratigraphy.

(2) In contrast, none of the main New Zealand cyclothem successions contain both cold- and warm-water stenothermal molluscs in one cyclothem. Instead, Nukumaruian cyclothem in Hawke's Bay and Castlecliffian cyclothem in the Wanganui Basin con-

tain mixed stenothermal warm-water and eurythermal molluscs throughout each cycle, and cyclothem in South Wairarapa contain mixed stenothermal cold-water and eurythermal molluscs throughout each cycle. Of New Zealand examples, only the Castlepoint Formation seems likely to preserve warm- and cold-water molluscs in different parts of one cycle.

(3) The maximum faunal expression of Plio–Pleistocene temperature change within one cyclothem can be expected only in those few deposition sites that satisfy all the requirements of deposition of reasonably complete sequences (at least TSTs, HSTs and RSTs preserved), in an exposed coastal site affected by currents from both the north and south, on the inner shelf, in the temperate regions (between ca. 30° and 60° north and south), near the north–south oriented coast of a large continent. Obviously, to have preserved and exposed the cyclothem, deposition must also have occurred in a gradually and regularly subsiding site that has since been elevated above sea-level.

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