New Zealand Journal of Geology & Geophysics, 2004, Vol. 47: 719–730
0028–8306/04/4704–0719

Strontium isotope dating of the New Zealand Oligocene

CAMPBELL S. NELSON[1]
DAPHNE LEE[2]
PHILLIP MAXWELL[3]
ROLAND MAAS[4]
PETER J. J. KAMP[1]
STEVE COOKE[5, 1]

[1]Department of Earth Sciences
University of Waikato
Private Bag 3105
Hamilton, New Zealand
email: c.nelson@waikato.ac.nz

[2]Department of Geology
University of Otago
P.O. Box 56
Dunedin, New Zealand

[3]Bathgates Road
RD 10
Waimate, New Zealand

[4]School of Earth Sciences
University of Melbourne
Victoria 3010, Australia

[5]School of Ocean and Earth Sciences
Southampton Oceanography Centre
Southampton SO14 3ZH, UK

Abstract One of the least well resolved portions of the New Zealand Cenozoic time-scale is that centred on and about the Oligocene Epoch, internationally regarded as spanning c. 10 m.y. from 33.7 to 23.8 Ma. We have determined the $^{87}Sr/^{86}Sr$ ratios and derived absolute ages for 77 macrofossil samples collected from several biostratigraphically dated mid-Tertiary sections in the South Auckland (North Island) and North Otago/South Canterbury (South Island) regions. While the site-specific stratigraphic significance of our ages remains to be assessed, we present them here to foster wider consideration and discussion in relation to evolving absolute age schemes for the New Zealand Oligocene biostratigraphic stages. Initial results suggest:

(1) The approximate boundary ages for the mid-Tertiary Stages are: Runangan/Whaingaroan, 34.8 Ma; early Whaingaroan/late Whaingaroan, 31.0 Ma; Whaingaroan/Duntroonian, 28.5 Ma; Duntroonian/Waitakian, 25.5 Ma; Waitakian/Otaian, 22.2 Ma. These values are mainly older than ages assigned over the past decade.

(2) The early Whaingaroan Stage, traditionally held to be entirely within the Oligocene, and to define its base, extends back across the Eocene/Oligocene boundary at 33.7 Ma into the late Eocene by up to 1.1 m.y., as previously suspected by Morgans et al. (1996) on biostratigraphic grounds.

(3) There has been considerable uncertainty about placement of the Waitakian Stage over the past two decades, whether entirely in the Miocene, entirely in the Oligocene, or straddling both epochs. Our Sr dating shows that the Oligocene/Miocene boundary (23.8 Ma) lies about midway through the Waitakian Stage, in agreement with Graham et al. (2000).

(4) The Whaingaroan/Duntroonian boundary approximates the international early–late Oligocene one (28.5 Ma).

Comparisons with recently published Oligocene stable oxygen isotope records suggest that $\delta^{18}O$ maxima and attendant sea-level lowering, with possibly significant unconformity development, may be anticipated on three occasions in the early Whaingaroan, two or three in the late Whaingaroan, two in the Duntroonian, and at least two in the Waitakian. The unconformities bounding formations and members in the Oligocene successions may relate to these sea-level changes, and so be regionally correlatable, including the well publicised Marshall Paraconformity of latest Whaingaroan (c. 29 Ma) age.

Keywords New Zealand; Oligocene; Whaingaroan Stage; Duntroonian Stage; Waitakian Stage; absolute age; strontium isotope dating; fossils

INTRODUCTION

Interpretation of Earth history from the sedimentary rock record is necessarily dependent on having good age control. The mid-Tertiary Oligocene Epoch is presently internationally regarded as spanning a time interval of c. 10 m.y., from 33.7 to 23.8 Ma (Berggren et al. 1995). Paleoenvironmentally, the Oligocene is extremely important because it heralded several major global paleoclimatic and paleoceanographic changes associated with rapid build-up of ice sheets on Antarctica (Zachos et al. 1994), effectively marking the Cenozoic transition from a greenhouse to the present icehouse world (Fig. 1).

Some examples of these paleoenvironmental changes include significant cooling of the waters of the Southern Ocean (Wei 1991) and the establishment of strong latitudinal temperature gradients between polar and equatorial regions (Miller et al. 1991; Nelson & Cooke 2001). There was an associated development of much stronger ocean circulation patterns in both surface and bottom waters, and fluctuating ice volumes drove some major shifts in sea level by possibly up to

G03055; Online publication date 1 December 2004
Received 29 May 2003; accepted 1 October 2003

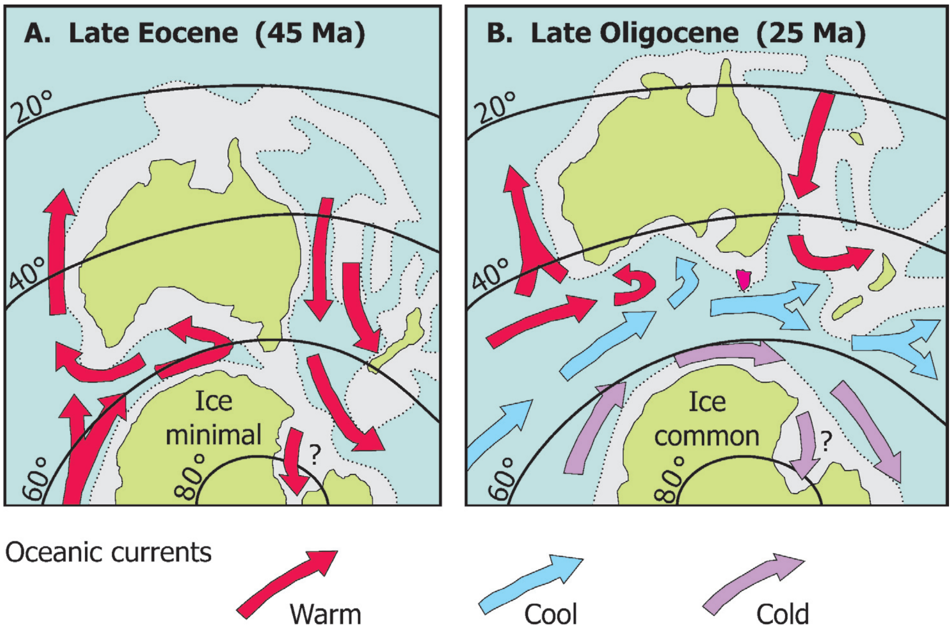

Fig. 1 Transition from late Eocene greenhouse to Oligocene icehouse conditions in the South–west Pacific sector of the Southern Ocean. Note the evolution of a decoupled circum-Antarctic current system in the Oligocene as a result of plate separations and build-up of a permanent ice sheet on East Antarctica (modified from Kamp et al. 1990). The question marked arrows are possible circulation routes through the West Antarctic seaway at these times (Nelson & Cooke 2001).

100 m or more (Fulthorpe et al. 1996). In the early Oligocene there was rapid faunal turnover in the world oceans (Diester-Haass & Zahn 1996). And towards the end of the period in the Southwest Pacific region, the propagation of a new plate boundary through the New Zealand subcontinent marked the birth of its present geologically dynamic setting characterised by earthquakes, volcanism, and mountain building (Kamp 1992; King 2000).

Such globally significant events are to varying degrees recorded by distinctive stratal features developed in New Zealand Oligocene to earliest Miocene deposits, but in general the absolute ages of the expression of these events in the Southwest Pacific region remain poorly constrained. To better constrain these ages would be an important advance, and provide not only a basis for attempting meaningful regional and global correlation of the mid-Tertiary deposits and events, but also for establishing a far tighter absolute chronology for the New Zealand biostratigraphic stages across this time interval.

ABSOLUTE AGES FROM STRONTIUM ISOTOPES

The technique of strontium isotope stratigraphy and its use for correlation and dating of marine sediments is firmly established (e.g., Elderfield 1986; McArthur 1994; Veizer et al. 1999). Measurement on a mass spectrometer of the strontium (Sr) isotope ratio $^{87}Sr/^{86}Sr$ in marine fossil shells can provide absolute ages for those shells (e.g., Oslick et al. 1994). The Sr substitutes in trace amounts for Ca in the calcareous shells, and the $^{87}Sr/^{86}Sr$ ratio reflects the value in the sea water during growth of the shells. This ratio is preserved in the rock record provided that diagenetic alteration has not occurred. Consequently, it is important to use fossils whose original mineralogy was stable low-Mg calcite, such as foraminifera, brachiopods, pectinids, and oysters.

The $^{87}Sr/^{86}Sr$ ratio in marine carbonates has increased and decreased throughout geological history in response to shifts in source fluxes (e.g., submarine volcanism, submarine and continental weathering), but has increased almost continuously over the past 40 m.y. (Fig. 2A). The rate of change was highest during the Oligocene to early Miocene, enabling determination of absolute ages to within c. 0.5 Ma resolution or better during this time interval (Fig. 2B). Recently, Howarth & McArthur (1997) and McArthur et al. (2001) have discussed in some detail the statistics for strontium isotope stratigraphy, and devised look-up tables including 95% confidence limits for predicting the absolute age from measured $^{87}Sr/^{86}Sr$ values.

NEW ZEALAND OLIGOCENE STAGES

The Cenozoic sedimentary record in New Zealand developed in response to a major transgressive-regressive cycle which was primarily tectonically driven (e.g., Kamp 1986, 1992; Carter 1988; King et al. 1999). The transgressive portion culminated in widespread temperate-latitude (cool-water) carbonate deposition in the Oligocene to earliest Miocene when subsidence accompanying thermal relaxation was at a maximum (Nelson 1978; Dodd & Nelson 1998). These mid-Tertiary facies are remarkably similar throughout New Zealand, involving condensed sections of highly calcareous, often glauconitic mudstone, sandstone, and skeletal limestone. Hood & Nelson (1996) used the informal name Te Kuiti limestone megafacies for these regionally distinctive calcareous deposits of mainly Oligocene age.

The Oligocene in New Zealand is one of the least well resolved portions of our Cenozoic time-scale. This is because the Oligocene, essentially encompassing the New Zealand Landon Series (L), includes only three biostratigraphic stages for the c. 10 m.y. interval: a long Whaingaroan (Lwh) Stage (informally subdivided into lower and upper); a much shorter Duntroonian (Ld) Stage; and a comparatively short Waitakian (Lw) Stage whose position has historically fluctuated from being entirely within, to partly within, to wholly younger than, the Oligocene. The problem has been compounded by the very wide variations in suggested ages and durations of these stages by different workers over time (Fig. 3).

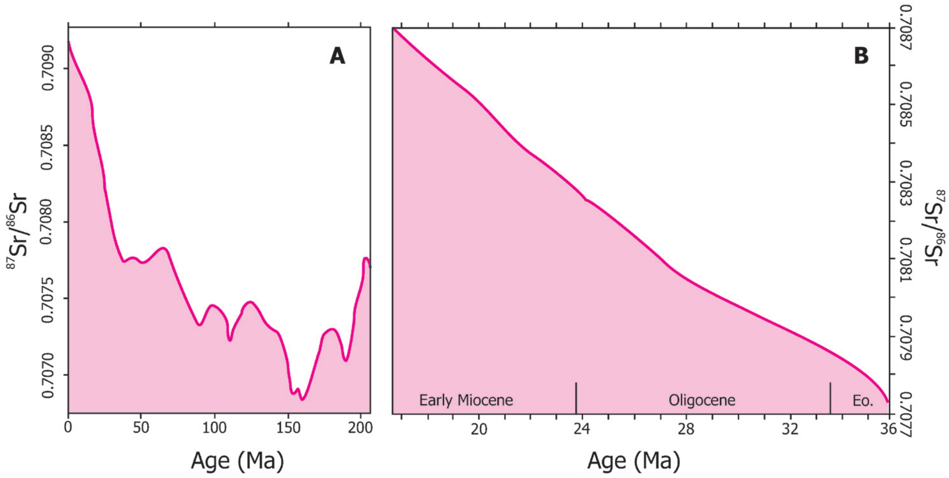

Fig. 2 **A**, $^{87}Sr/^{86}Sr$ fossil shell record versus age for the past 200 m.y. (after Howarth & McArthur 1997). **B**, Calibration curve relating $^{87}Sr/^{86}Sr$ ratio in marine fossil shells to absolute age for the late Eocene to early Miocene (after Oslick et al. 1994).

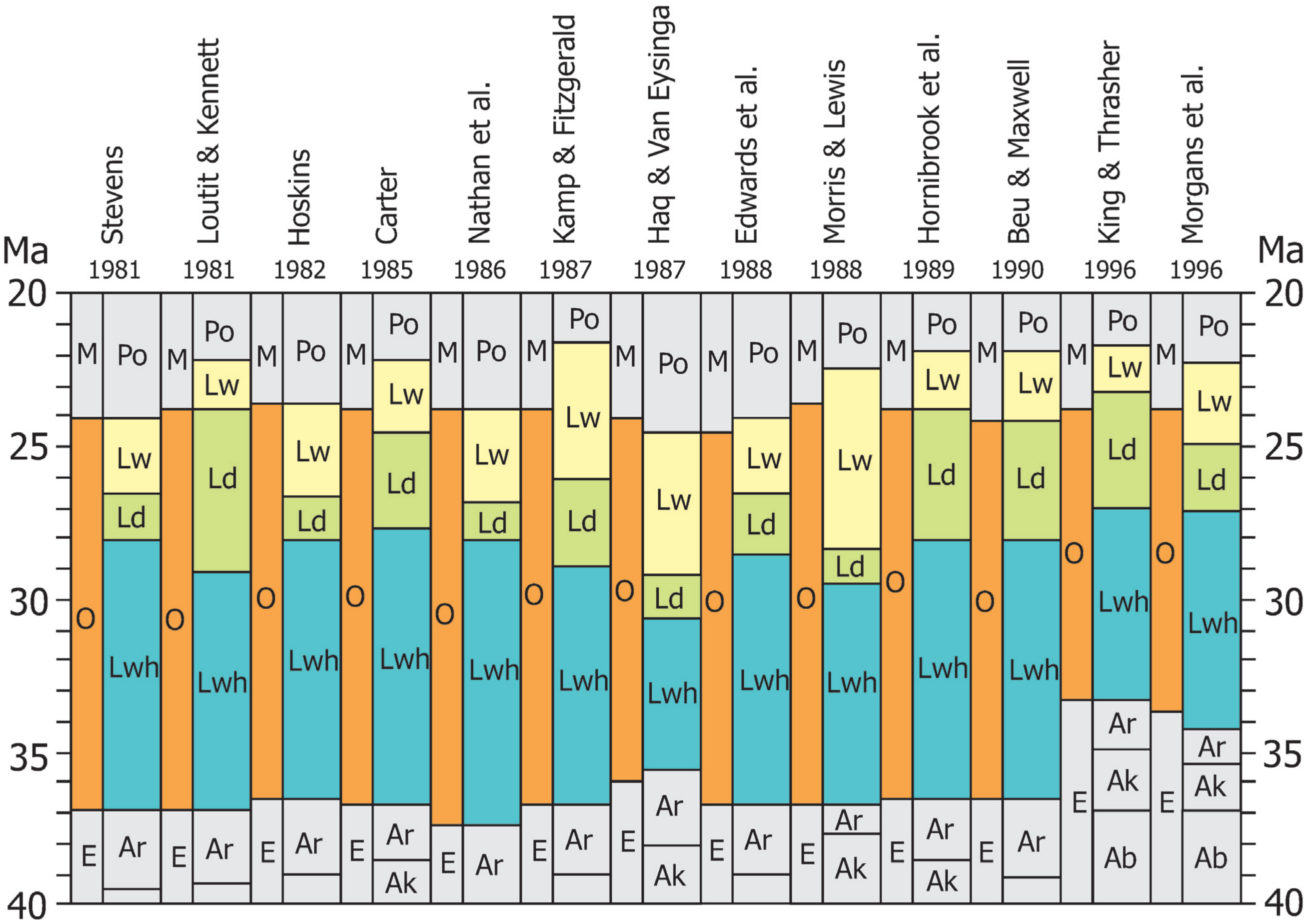

Fig. 3 Examples of historical variations in the placement and duration of mid-Tertiary New Zealand biostratigraphic stages. E, Eocene; O, Oligocene; M, Miocene; Ab, Bortonian; Ak, Kaiatan; Ar, Runangan; Lwh, Whaingaroan; Ld, Duntroonian; Lw, Waitakian; Po, Otaian.

The biostratigraphic basis for the stages is summarised by Hornibrook et al. (1989) and Morgans et al. (1996), and is not elaborated upon here. Type and reference sections for these stages and their deposits are in North Otago/South Canterbury and South Auckland (Hoskins 1982), within rocks of the Alma/Otiake Groups (Gage 1957; Carter 1988; Edwards 1991) and Te Kuiti Group (Kear & Schofield 1959; Nelson 1978; White & Waterhouse 1993), respectively (Fig. 4).

METHODS

Fossil collections

About 160 samples of fresh macrofossil shell material, mainly pectinids, brachiopods, and oysters, were collected from several previously well documented latest Eocene/Oligocene/earliest Miocene sections within the Alma/Otiake Groups and Te Kuiti Group, or from archived samples associated

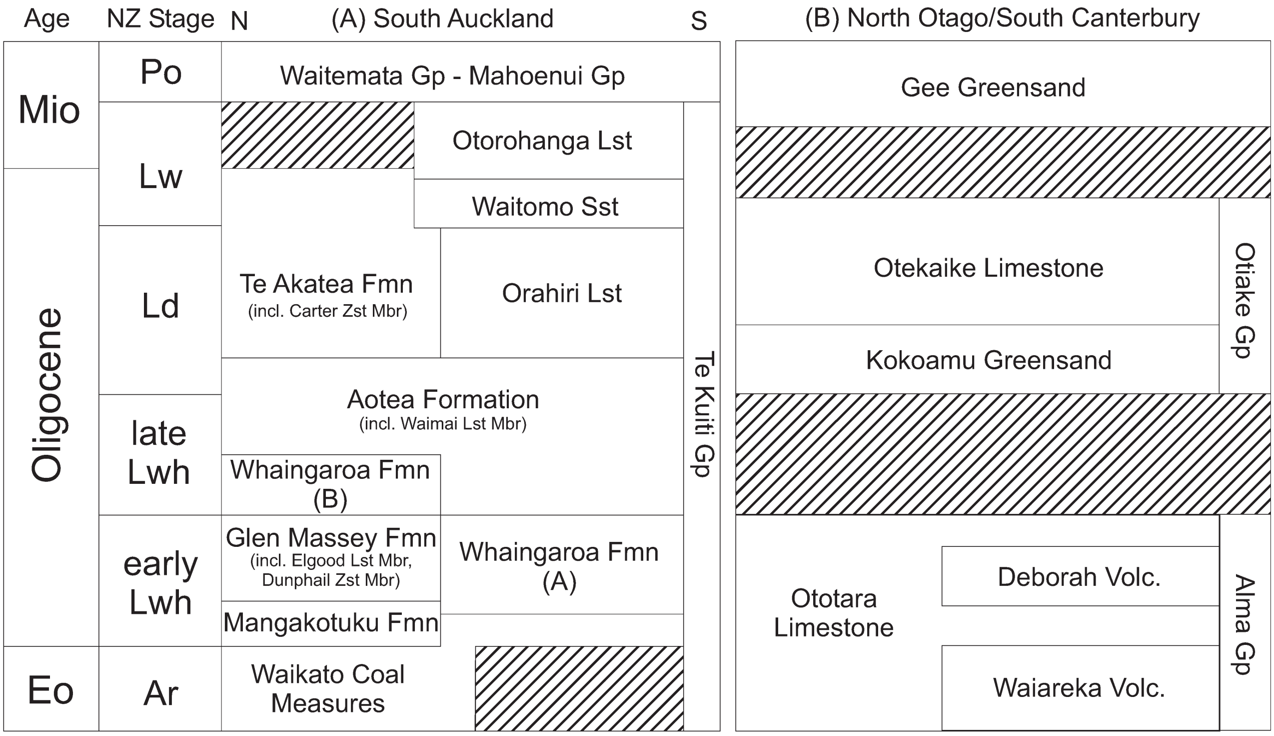

Fig. 4 **A**, Schematic and simplified stratigraphic relationships among the Te Kuiti Group formations in a north (N) to south (S) profile through the South Auckland region (modified from White & Waterhouse 1993). Fossil material was analysed from all formations except the Waikato Coal Measures and the Whaingaroa Formation that is here labelled B. Note that the lithostratigraphic nomenclature for the Whaingaroan (Lwh) age deposits in the Te Kuiti Group is currently under review because of past duplication of names for strictly non-correlatable units (e.g., Carter & Nelson 2002). **B**, Generalised stratigraphy for formations within parts of the Alma/Otiake Groups in the North Otago/South Canterbury region (Gage 1957; Edwards 1991). Fossil material was analysed from all formations except the Deborah Volcanic Formation. New Zealand (NZ) stage symbols are defined in caption to Fig. 3. Eo, Eocene; Mio, Miocene; Gp, Group; Fmn, Formation; Mbr, Member; incl., includes; Lst, Limestone; Sst, Sandstone; Zst, Siltstone; Volc., Volcanics. Diagonal hatching indicates especially prominent hiatuses in the local stratigraphy.

with an earlier South Auckland study by Nelson (1973). In all cases the associated lithostratigraphic unit (formation or member) bearing the fossils had previously been assigned to a New Zealand biostratigraphic stage, either Runangan, Whaingaroan, Duntroonian, Waitakian, or Otaian, but sometimes more broadly and expressing indefiniteness, such as Whaingaroan–Duntroonian or Duntroonian–Waitakian (e.g., Gage 1957; Kear & Schofield 1959; Nelson 1978; Carter 1988; Hornibrook et al. 1989) (Fig. 4). In the North Otago/South Canterbury case, it was often possible to collect similar fossil material in stratigraphic order from the one section, but in the South Auckland occurrences the fossils represent mainly isolated specimens from separate localities.

Stratigraphic information for the analysed fossil collections is summarised in Appendix 1. A spreadsheet including more specific locality data is available on request, and other information is recorded for those samples classified within the New Zealand Fossil Record Data File.

Strontium isotope dating

From the original suite of fossil samples, 77 were selected for Sr isotope analysis, 34 from North Otago/South Canterbury sites and 43 from South Auckland localities. After careful cleaning to remove surficial impurities or rock matrix, the shells were powdered and small (30–50 mg) aliquots were leached in cold 1*M* acetic acid (Bailey et al. 2000). Sr was extracted from the leachates using a single pass over small (0.1 ml) beds of EICHROM^{TM} Sr resin. $^{87}Sr/^{86}Sr$ ratios were determined in multi-dynamic double collection mode on an automated Finnegan MAT262 mass spectrometer at La Trobe University, Melbourne. Samples were run with ^{88}Sr signals near 3×10^{-11}A and mass bias was corrected by normalising to $^{86}Sr/^{88}Sr = 0.1194$. Typical in-run precision was ±0.000020 (2 SD). Twenty-three runs of the SRM987 Sr standard made during this study varied from 0.710196 to 0.710257. The population is near gaussian, with a mean of 0.710232 ± 32 (2 SD). Repeat runs of the same sample Sr fraction differ by ±0.000004 to ±0.000041, equivalent to ≤ ±1 Ma and usually ≤ ±0.5 Ma age uncertainty during the Oligocene. Modern sea-water Sr (Hmc) measured on the same instrument yields a ratio of 0.709164 ± 30 (2 SD). Age assignment (see below) was made after adjusting our $^{87}Sr/^{86}Sr$ ratios by +0.000016 to be consistent with the SRM987 value of 0.710248 (Hmc = 0.709175) used in the Howarth & McArthur (1997) calibration.

Stable oxygen and carbon isotopes

As well as strontium isotope values, the oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotope compositions of the fossil shells were analysed, mainly to ascertain that we were dealing with specimens typical of temperate shallow marine waters, and that these had been unaffected by any significant diagenetic

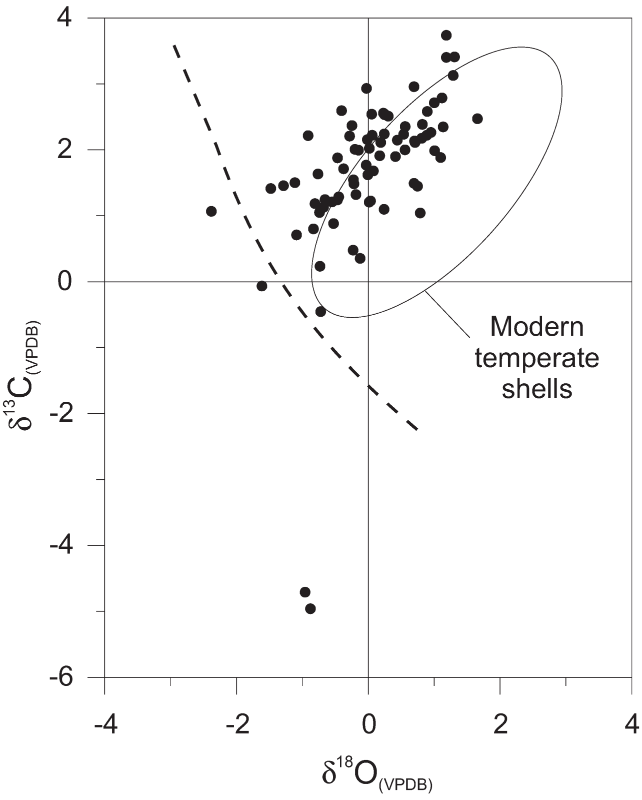

Fig. 5 Stable oxygen versus carbon isotope cross-plot of Oligocene fossil shells used for Sr isotope dating. The small displacement of plots from the oval field typical of modern cool-water shelf skeletons to slightly more negative $\delta^{18}O$ values is consistent with compositions anticipated from unaltered Oligocene calcite shells because of less ice volume in the mid-Tertiary (Nelson & Smith 1996). According to Nelson & Smith (1996), fossil shells plotting well to the left of the dashed line may be diagenetically altered. The more negative $\delta^{13}C$ values of two oyster samples (nos 35 and 36) from the Mangakotuku Siltstone in the South Auckland region indicate their marginal marine depositional setting (Nelson et al. 1983).

change, especially meteoric alteration (Nelson & Smith 1996). Stable isotope analyses were performed on a PDZ Europa Geo 20–20 mass spectrometer at Southampton Oceanography Centre, using an individual acid-bath carbonate preparation device, within which the dry powder samples were reacted with orthophosphoric acid at 70°C. The isotope ratios are expressed relative to Vienna PeeDee Belemnite (VPDB) and have an external precision better than 0.06‰ for both $\delta^{18}O$ and $\delta^{13}C$.

ANALYTICAL RESULTS

All isotope results are presented in Appendix 1. The $\delta^{18}O$ and $\delta^{13}C$ values of the Oligocene shells range between c. −1 and +1.5‰ and c. 0 and 3‰, respectively, consistent with good quality preservation of the original low-Mg calcite mineralogy of the shells (Fig. 5). The $^{87}Sr/^{86}Sr$ ages in Appendix 1 were calculated initially using the method of Oslick et al. (1994), and subsequently refined using the detailed look-up tables available from Howarth & McArthur (1997). Some modifications to their look-up table ages appeared in McArthur et al. (2001), but these did not affect the mid-Tertiary portion of their compilation (J. McArthur pers. comm. 2002).

The absolute ages of the New Zealand fossils are summarised in Fig. 6 in relation to the previously reported biostratigraphic stages for their contained strata. As anticipated, there exists a broad overall trend of decreasing absolute age from the oldest (Runangan) to youngest (Otaian) stages.

The few apparently discrepant ages could result from any of several causes, including undetected shell alteration, a paleoenvironmental setting that was not fully marine, or an originally incorrect biostratigraphic stage assignment of the associated strata because of limited or poor (micro)paleontological control. The last reason is probably particularly important in some of the South Auckland limestone formations where paleontological ages can be poorly constrained and have been inferred mainly from regional stratigraphic grounds (Nelson 1978). Thus, for example, it appears from the Sr ages that several of the South Auckland samples originally assigned Whaingaroan–Duntroonian ages lie mainly within the Whaingaroan Stage. It is also notable that the few fossils yielding extreme, and clearly wrong, ages for particular stages mainly come from deposits sitting directly upon Mesozoic basement rocks within basal facies, suggesting they probably incorporated a variable degree of inheritance of "old strontium" into their shells.

ABSOLUTE AGES OF NEW ZEALAND MID-TERTIARY STAGES

The first matter to emphasise is that relatively few absolute age determinations exist for any of the Cenozoic sedimentary successions in New Zealand. Thus, the absolute ages shown against the various Cenozoic time-scales presented in the past, including the most recent compilation by Morgans et al. (1996), have depended heavily on attempts to first correlate local or regional biostratigraphic events to possible international biostratigraphic events, and then in turn to relate these to the increasingly better chronostratigraphically constrained global polarity time-scale (GPTS), for example as synthesised by Berggren et al. (1995). So most of the absolute ages have been "imported" into the New Zealand Cenozoic Stage scheme, rather than being based on direct absolute dating of the strata or their contained components.

In light of this paucity of independent absolute age control for the New Zealand time-scale, Morgans et al. (1999) and Graham et al. (2000) recently reported on $^{87}Sr/^{86}Sr$ dating of foraminiferal concentrates and some macrofossils in two mid-Tertiary sections (Bluecliffs and Trig Z) from North Otago. These important studies are directly relevant to the present one, and provided ages of c. 21.7 and 25.2 Ma for the Waitakian/Otaian and Duntroonian/Waitakian Stage boundaries, respectively, both a little younger than the ages suggested here.

The best estimates of the numeric ages of the New Zealand stage boundaries from the Runangan to Otaian Stages based on our $^{87}Sr/^{86}Sr$ ratio data are shown in Fig. 7 against the relevant portions of the international time-scale of Berggren et al. (1995) and the most recent New Zealand time-scale compiled by Morgans et al. (1996). Some particular points to note about the new $^{87}Sr/^{86}Sr$ dates reported here (Fig. 6, 7) include:

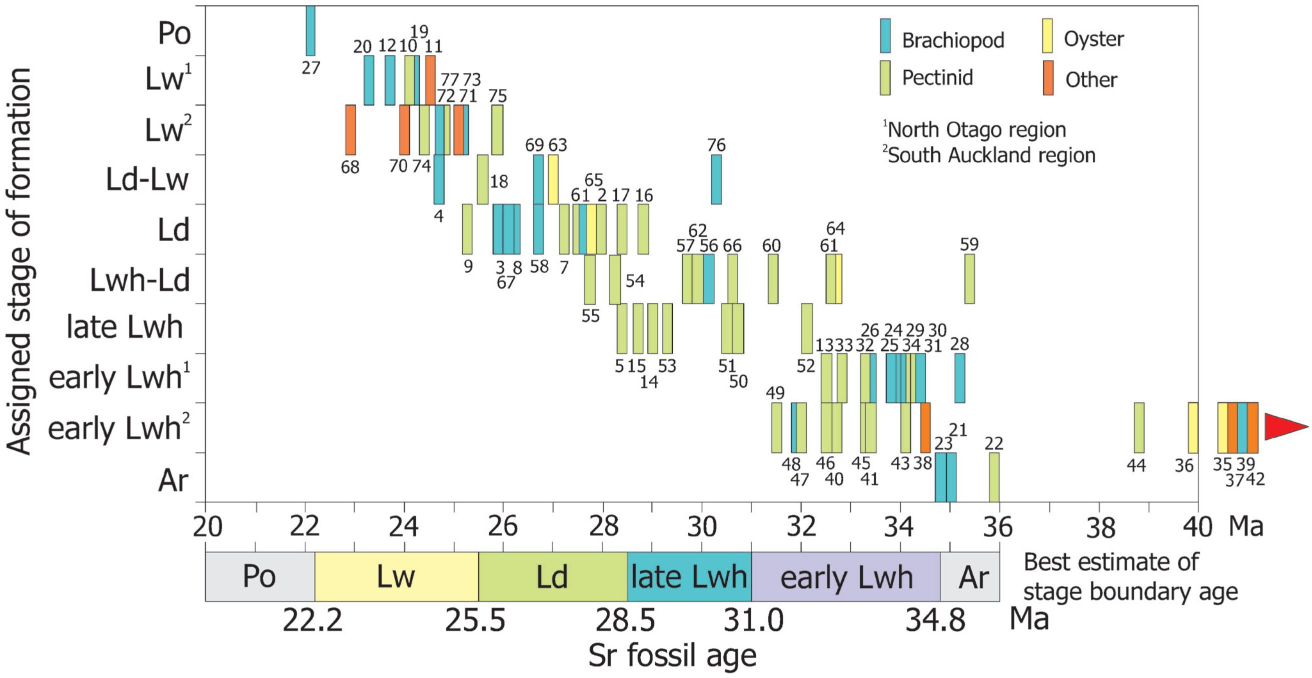

Fig. 6 Absolute ages of the 77 mid-Tertiary fossil shell samples analysed for their $^{87}Sr/^{86}Sr$ ratio. Samples are plotted against the previously published New Zealand biostratigraphic stage assigned their enclosing formation. The absolute ages, determined from the look-up tables in Howarth & McArthur (1997), are suggested to be theoretically resolvable to ±200–300 k.a. for the steep mid-Tertiary segment of the Sr sea-water curve (Fig. 2). The best age estimate from our data for the New Zealand stage boundaries is shown along the bottom of the diagram.

(1) The boundary ages of the biostratigraphic stages appear mainly to be a little older than currently assigned ages, namely Runangan/Whaingaroan c. 34.8 Ma; early Whaingaroan/late Whaingaroan c. 31.0 Ma; Whaingaroan/Duntroonian c. 28.5 Ma; Duntroonian/Waitakian c. 25.5 Ma; and Waitakian/Otaian c. 22.2 Ma.
(2) The durations of these biostages differ considerably (Runangan, probably c. 1.2 m.y.; Whaingaroan, c. 6.3 m.y.; Duntroonian, c. 3 m.y.; Waitakian, c. 3.3 m.y.).
(3) The Runangan/Whaingaroan boundary does not appear to coincide with the international Eocene/Oligocene boundary (33.7 Ma), the Whaingaroan Stage extending down into the Eocene by up to 1.1 m.y. This supports the placement suggested by Morgans et al. (1996) on the basis of biostratigraphic evidence.
(4) The Waitakian Stage, which has over time fluctuated in and out of the Oligocene (Fig. 3), begins in the Oligocene, and the international Oligocene/Miocene boundary at 23.8 Ma occurs about mid-way through the stage.
(5) The Whaingaroan/Duntroonian boundary closely approximates the international early/late Oligocene (Rupelian/Chattian) one at 28.5 Ma.

DATING OLIGOCENE GLOBAL EVENTS IN NEW ZEALAND

We conclude with brief comment about the relevance of our suggested new ages in hunting for the expression of some of the kinds of mid-Tertiary global paleoenvironmental events mentioned in the introduction to this paper. For example, the supposed dramatic sea-level fall of up to 200 m postulated by Haq et al. (1987) in the mid Oligocene (c. 29–30 Ma), be it real or not, would, depending on the publication consulted, be anticipated to occur in any of the late Whaingaroan, Duntroonian, or even earliest Waitakian age sections in New Zealand (Fig. 3). Our revised age scheme suggests it should be developed in deposits of late Whaingaroan age in New Zealand (Fig. 7, 8), variably truncating them and possibly older strata. This agrees with the findings of Fulthorpe et al. (1996) who suggested the Haq et al. sea-level fall coincided with development in the South Island of the so-called Marshall Paraconformity, with bracketing Sr dates of c. 32.4 and 29.0 Ma, and effective removal in many localities of deposits of late Whaingaroan or even older age.

Based on recent moderately high resolution Oligocene stable isotope records (Abreu & Anderson 1998; Kominz & Pekar 2001), one might anticipate the major $\delta^{18}O$ maxima events, otherwise proxies for periods of maximum lowered sea level, to be represented in the records of New Zealand paleoshelf sections as follows: three in the early Whaingaroan; two or three in the late Whaingaroan; two in the Duntroonian; and at least two in the Waitakian (Fig. 8). The possibility exists that the bounding unconformities of some of the members and formations within the Alma/Otiake and Te Kuiti Groups (Fig. 4) are associated with these sea-level events (e.g., Vella 1967; Nelson 1978), a matter currently under investigation. Nelson & James (2000) recorded marine cements at the discontinuities separating stratigraphic units in several of these mid-Tertiary mixed siliciclastic-carbonate temperate deposits, and related their development to energetic sea-water pumping during times of lowered sea level.

Finally, the Marshall Paraconformity, mentioned above, defined originally by Carter & Landis (1972), marks the base

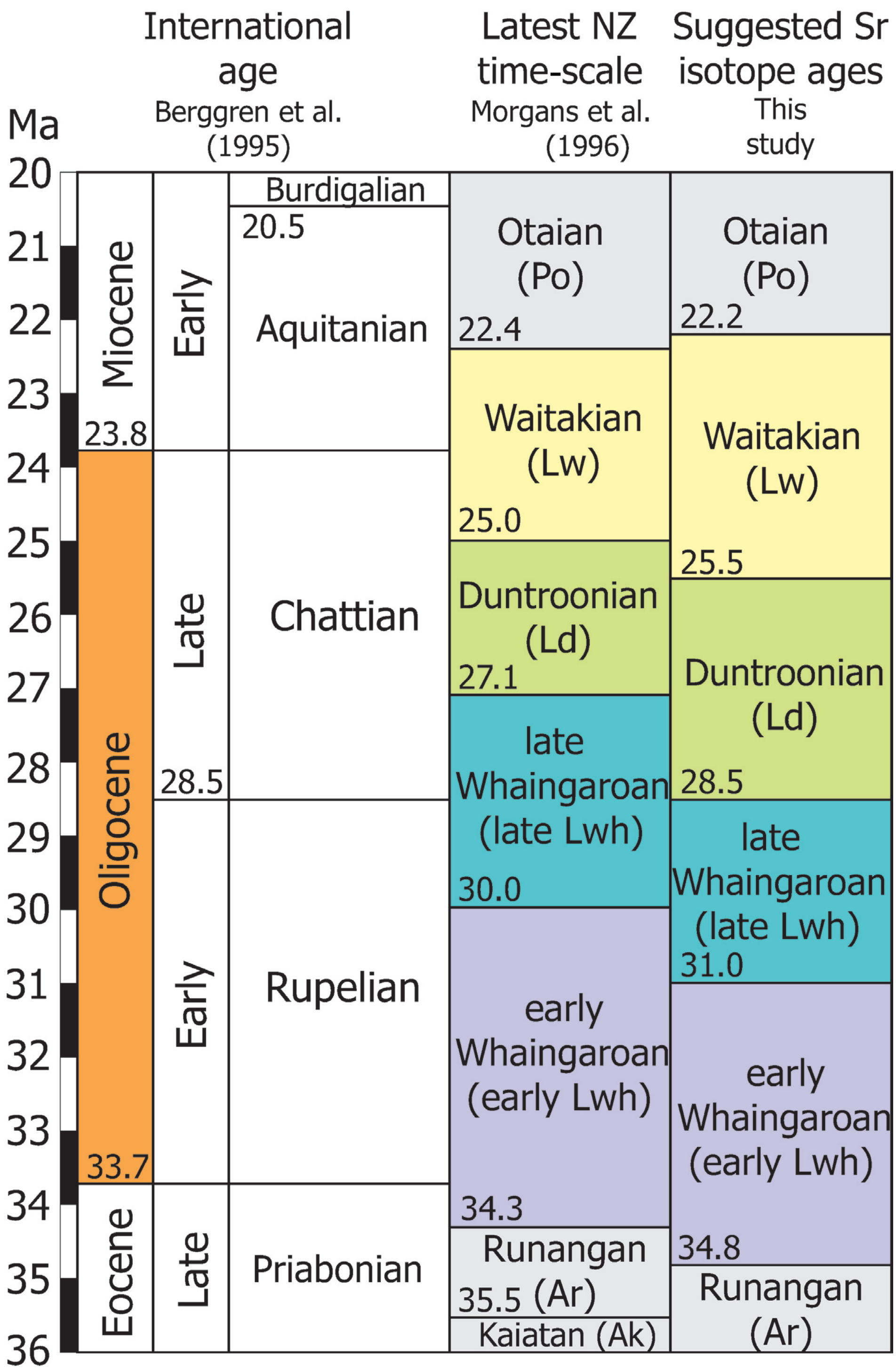

Fig. 7 Comparison of international and New Zealand mid-Tertiary time-scales, incorporating the Sr isotope ages obtained in this study.

of the Otiake Group in South Island and has been promoted as a mid-Oligocene (c. 30 Ma) unconformity of international extent (Carter 1985). However, considerable debate exists concerning the nature, age, correlation, and significance of the mid-Tertiary unconformities in South Island sections (e.g., Lewis & Bellis 1984; Hornibrook 1987; Gage 1988; Lewis 1989, 1992), and it is possible that the Marshall Paraconformity has little more paleoceanographic significance than several of the other unconformities developed in the condensed Oligocene sections in New Zealand (Findlay 1980). This whole period was a time of transition from a greenhouse to an icehouse world (Fig. 1), and the evolution of cold and vigorous Southern Ocean circulation patterns that directly affected the wider New Zealand region, in concert with sea-level changes, undoubtedly became potentially important agents of erosion, non-deposition, and condensation on several occasions (e.g., Fulthorpe et al. 1996; Nelson & Cooke 2001).

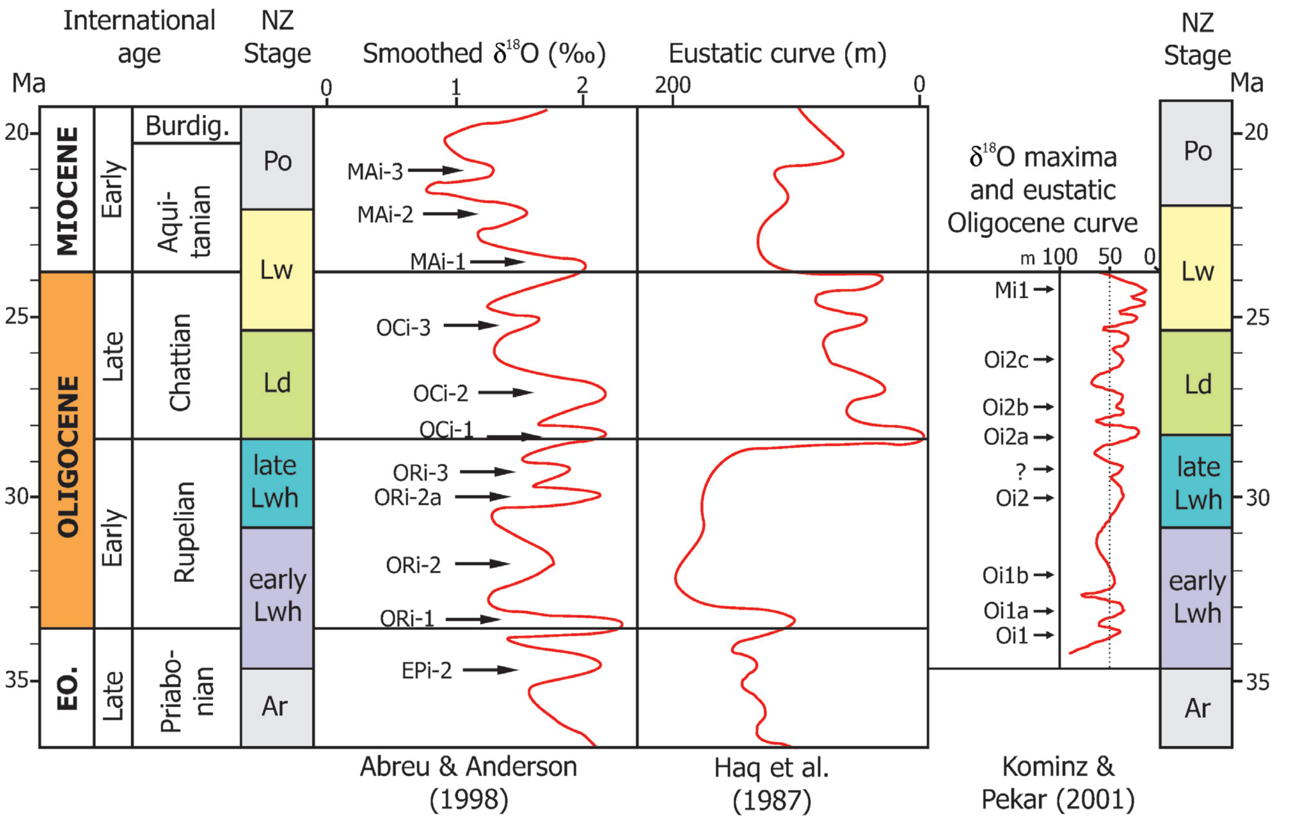

Fig. 8 Some recent stable oxygen isotope and sea-level records centred on the Oligocene in relation to the New Zealand mid-Tertiary stages (defined in Fig. 7) and their suggested Sr isotope ages. Black arrows highlight the approximate position of oxygen isotope ($\delta^{18}O$) maxima events in the late Eocene (EPi-2), Oligocene (ORi-1 to OCi-3 in the Abreu & Anderson (1998) curve; Oi1 to Mi1 in the Kominz & Pekar (2001) curve), and early Miocene (MAi-1 to MAi-3), which correspond to times of relatively lowered sea level and potential unconformity development in shelf sequences. Note that the Oligocene eustatic amplitudes determined by Kominz & Pekar (2001) are mainly much less than those originally suggested by Haq et al. (1987). Also note that Kominz & Pekar (2001) placed the Mi1 event, defined originally by Miller et al. (1991) to lie just inside the Miocene (c. 23.5 Ma), within the topmost Oligocene because of subsequent small time-scale adjustments (e.g., Berggren et al. 1995).

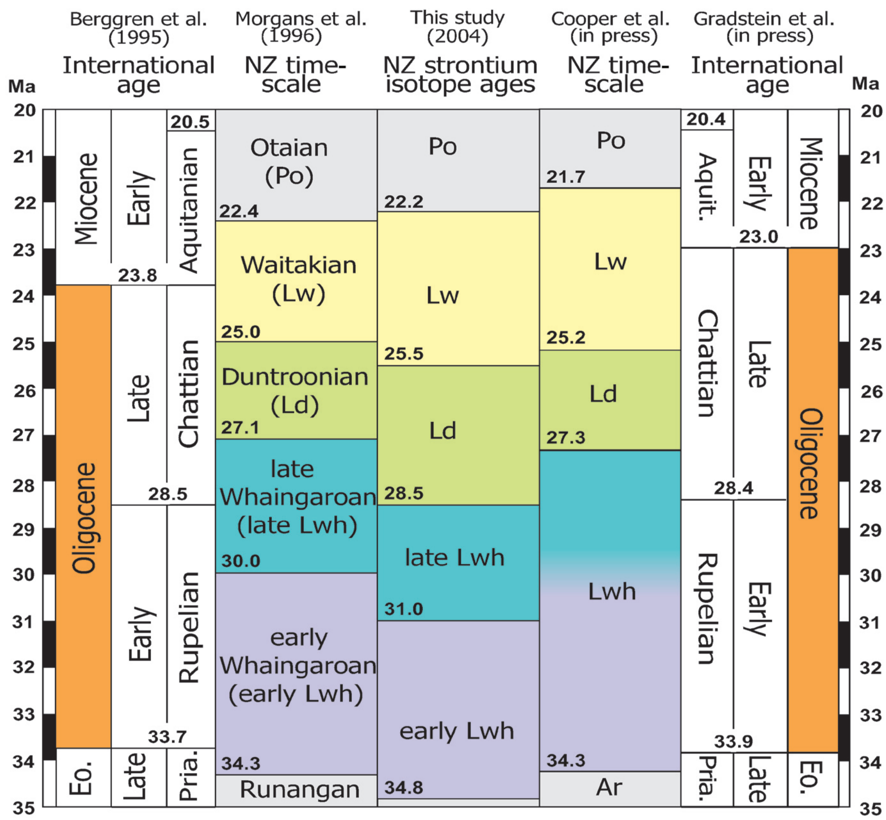

Fig. 9 This figure extends Fig. 7 by showing the revised New Zealand geological time-scale by Cooper et al. (in press), and the revision of the Oligocene part of the international time-scale by Gradstein et al. (in press). See NOTE ADDED IN PROOF for brief discussion and some implications of these new time-scales.

ACKNOWLEDGMENTS

Many thanks to the Geology Department, University of Auckland, for access to fossil specimens in their Paleontological Store; to Austin Hendy for fieldwork assistance; to Dale Arbury for the cleaning and preparation of fossil shells for analysis; and to Arne Pallentin for assistance with the computer generation of diagrams. The project could not have been undertaken without the funding support for the acquisition of strontium isotope dates provided to Cam Nelson by the New Zealand Lottery Grants Board (Client No. SR 38345; Application No. AP: 59462). An additional funding contribution from the Geology Department, University of Otago, to Daphne Lee towards analytical costs is also kindly acknowledged. The paper benefited from the perceptive review comments of Penelope Cooke (University of Waikato) and Hugh Morgans (GNS, Lower Hutt).

NOTE ADDED IN PROOF: Following final acceptance of this paper, two in press articles very relevant to the Phanerozoic geological time-scale have come to our attention. The first is a review and new compilation of the New Zealand geological time-scale by Cooper et al. (in press), an early version of which is the Morgans et al. (1996) time-scale that has been used for comparison of the new strontium ages for the New Zealand Oligocene stages suggested in this study (Fig. 7). Changes in the Cooper et al. (in press) scheme compared with the Morgans et al. (1996) one for the Oligocene interval include a small shift in the base of the Duntroonian Stage from 27.1 to 27.3 Ma, likewise for the base of the Waitakian Stage from 25.0 to 25.2 Ma, and a more significant shift from 22.4 to 21.7 Ma for the base of the Otaian Stage. However, these changes do not alter the conclusions made in our strontium isotope age study of the New Zealand Oligocene.

The second relevant article is a pending revision of absolute ages for the international time-scale to appear in Gradstein et al. (in press), and drawn to our notice during a recent New Zealand visit by Dr Frits Agterberg from the Geological Survey of Canada who has contributed a chapter in the Gradstein et al. volume. Unfortunately, the compilation of the Cooper et al. (in press) scheme for New Zealand predates this new synthesis, and may necessitate subsequent amendments to many of their suggested New Zealand stage boundary ages and their duration. For the Oligocene being considered here, the Gradstein et al. (in press) international scale amends the former base and top ages (Berggren et al. 1995) from 33.7 to 33.9 Ma and from 23.8 to 23.0 Ma, respectively, so increasing the duration of the Oligocene from c. 9.9 to 10.9 m.y. On the basis of the strontium ages presented here (Fig. 7), this means that the early Whaingaroan Stage extends back beyond the Oligocene into the Eocene by c. 0.9 m.y. instead of the suggested 1.1 m.y., while the international Oligocene/Miocene boundary would lie closer to three-quarters the way up through the Waitakian Stage instead of about mid-way. The international early/late Oligocene boundary, corresponding to the Rupelian/Chattian boundary, changes only from 28.5 to 28.4 Ma, and remains near-coincident with the boundary strontium age being proposed between the early and late Whaingaroan Stages in New Zealand (Fig. 7). A summary of the above age shifts is shown in Fig. 9.

REFERENCES

Abreu, V. S.; Anderson, J. B. 1998: Glacial eustasy during the Cenozoic: sequence stratigraphic implications. *American Association of Petroleum Geologists Bulletin 82*: 1385–1400.

Bailey, T. R.; McArthur, J. M.; Prince, H.; Thirlwall, M. F. 2000: Dissolution methods for strontium isotope stratigraphy: whole rock analysis. *Chemical Geology 167*: 313–319.

Berggren, W. A.; Kent, D. V.; Swisher, C. C.; Aubry, M-P. 1995: A revised Cenozoic geochronology and chronostratigraphy. *In*: Berggren, W. A.; Kent, D. V.; Aubry, M-P.; Hardenbol, J. *ed*. Geochronology, time-scales and global stratigraphic correlation. *SEPM Special Publication 54*: 129–212.

Beu, A. G.; Maxwell, P. A. 1990: Cenozoic Mollusca of New Zealand. *New Zealand Geological Survey Paleontological Bulletin 58*.

Carter, M.; Nelson, C. S. 2002: The mid-Tertiary Te Kuiti Group in the vicinity of Aotea Harbour: unravelling lithostratigraphic relationships. Abstracts and Programme, GSNZ Annual Conference "Northland 2002". *Geological Society of New Zealand Miscellaneous Publication 112A*: 12.

Carter, R. M. 1985: The mid-Oligocene Marshall Paraconformity, New Zealand: coincidence with global eustatic sea-level fall or rise? *Journal of Geology 93*: 359–371.

Carter, R. M. 1988: Post-breakup stratigraphy of the Kaikoura Synthem (Cretaceous–Cenozoic), continental margin, southeastern New Zealand. *New Zealand Journal of Geology and Geophysics 31*: 405–429.

Carter, R. M.; Landis, C. A. 1972: Correlative unconformities in southern Australasia. *Nature 237*: 12–13.

Cooper, R. A. et al. in press: The New Zealand geological timescale. *Institute of Geological & Nuclear Sciences Monograph 22*. Lower Hutt, New Zealand, Institute of Geological & Nuclear Sciences.

Diester-Haass, L.; Zahn, R. 1996: Eocene–Oligocene transition in the Southern Ocean: history of water mass circulation and biological productivity. *Geology 24*: 163–166.

Dodd, J. R.; Nelson, C. S. 1998: Diagenetic comparisons between cool-water Cenozoic limestones of New Zealand and tropical Mississippian limestones from Indiana, USA: is the cool-water model better than the tropical model? *Sedimentary Geology 121*: 1–21.

Edwards, A. R. *comp*. 1991: The Oamaru diatomite. *New Zealand Geological Survey Paleontological Bulletin 64*.

Edwards, A. R.; Hornibrook, N. de B.; Raine, J. I.; Scott, G. R.; Stevens, G. R.; Strong, C. P.; Wilson, G. J. 1988: A New Zealand Cretaceous–Cenozoic geological time scale. *New Zealand Geological Survey Record 35*: 135–149.

Elderfield, H. 1986: Strontium isotope stratigraphy. *Palaeogeography, Palaeoclimatology, Palaeoecology 57*: 71–90.

Findlay, R. H. 1980: The Marshall Paraconformity (Note). *New Zealand Journal of Geology and Geophysics 23*: 125–133.

Fulthorpe, C. S.; Carter, R. M.; Miller, K. G.; Wilson, J. 1996: Marshall Paraconformity: a mid-Oligocene record of inception of the Antarctic Circumpolar Current and coeval glacio-eustatic lowstand? *Marine and Petroleum Geology 13*: 61–77.

Gage, M. 1957: The geology of the Waitaki Subdivision. *New Zealand Geological Survey Bulletin 55*.

Gage, M. 1988: Mid-Tertiary unconformities in north Otago—a review and assessment. *Journal of the Royal Society of New Zealand 18*: 119–125.

Gradstein, F. M.; Ogg, J. G.; Smith, A. G. *ed*. in press: A geological time scale 2004. Cambridge University Press.

Graham, I. J.; Morgans, H. E. G.; Waghorn, D. B.; Trotter, J. A.; Whitford, D. J. 2000: Strontium isotope stratigraphy of the Oligocene–Miocene Otekaike Limestone (Trig Z section) in southern New Zealand: age of the Duntroonian/Waitakian Stage boundary. *New Zealand Journal of Geology and Geophysics 43*: 335–347.

Haq, B. U.; Van Eysinga, F. 1987: Geological timetable. Wall Chart. Amsterdam, Elsevier.

Haq, B. U.; Hardenbol, J.; Vail, P. R. 1987: The chronology of fluctuating sea level since the Triassic. *Science 235*: 1156–1167.

Hood, S. D.; Nelson, C. S. 1996: Cementation scenarios for New Zealand Cenozoic nontropical limestones. *New Zealand Journal of Geology and Geophysics 39*: 109–122.

Hornibrook, N. de B. 1987: Mid-Tertiary unconformities in the Waitaki Subdivision, North Otago—a comment. *Journal of the Royal Society of New Zealand 17*: 181–184.

Hornibrook, N. de B.; Brazier, R. C.; Strong, C. P. 1989: Manual of New Zealand Permian to Pleistocene foraminiferal biostratigraphy. *New Zealand Geological Survey Paleontological Bulletin 56*.

Hoskins, R. H. *ed*. 1982: Stages of the New Zealand marine Cenozoic: a synopsis. *New Zealand Geological Survey Report 107*. 74 p.

Howarth, R. J.; McArthur, J. M. 1997: Statistics for strontium isotope stratigraphy: a robust LOWESS fit to the marine Sr-isotope curve for 0 to 206 Ma, with look-up table for derivation of numeric age. *Journal of Geology 105*: 441–456.

Kamp, P. J. J. 1986: The mid-Cenozoic Challenger Rift System of western New Zealand and its implications for the age of Alpine Fault inception. *Geological Society of America Bulletin 97*: 255–281.

Kamp, P. J. J. 1992: Tectonic architecture of New Zealand. *In*: Soons, J. M.; Selby, M. J. *ed*. Landforms of New Zealand. 2nd ed. Auckland, Longman Paul. Pp. 1–30.

Kamp, P. J. J.; Fitzgerald, P. F. 1987: Geologic constraints on the Cenozoic Antarctic-Australia-Pacific relative plate motion circuit. *Geology 15*: 694–697.

Kamp, P. J. J.; Waghorn, D. B.; Nelson, C. S. 1990: Late Eocene–early Oligocene integrated isotope stratigraphy and bio–stratigraphy for paleoshelf sequences in southern Australia: paleoceanographic implications. *Palaeoceanography, Palaeoclimatology, Palaeoecology 80*: 311–323.

Kear, D.; Schofield, J. C. 1959: Te Kuiti Group. *New Zealand Journal of Geology and Geophysics 2*: 685–717.

King, P. R. 2000: Tectonic reconstructions of New Zealand: 40 Ma to the Present. *New Zealand Journal of Geology and Geophysics 43*: 611–638.

King, P. R.; Thrasher, G. P. 1996: Cretaceous–Cenozoic geology and petroleum systems of the Taranaki Basin, New Zealand. *Institute of Geological & Nuclear Sciences Monograph 13*.

King, P. R.; Naish, T. R.; Browne, G. H.; Field, B. D.; Edbrooke, S. W. *comp*. 1999: Cretaceous to Recent sedimentary patterns in New Zealand. *Institute of Geological & Nuclear Sciences Folio Series 1, version 1999*. 1 folder with 35 p., 1 encl. Lower Hutt, New Zealand, Institute of Geological & Nuclear Sciences Ltd.

Kominz, M. A.; Pekar, S. F. 2001: Oligocene eustasy from two-dimensional sequence stratigraphic backstripping. *Geological Society of America Bulletin 113*: 291–304.

Lewis, D. W. 1989: Mid-Tertiary unconformities in North Otago revisited. *Journal of the Royal Society of New Zealand 19*: 113–116.

Lewis, D. W. 1992: Anatomy of an unconformity on mid-Oligocene Amuri Limestone, Canterbury, New Zealand. *New Zealand Journal of Geology and Geophysics 35*: 463–475.

Lewis, D. W.; Belliss, S. E. 1984: Mid-Tertiary unconformities in the Waitaki Subdivision, north Otago. *Journal of the Royal Society of New Zealand 14*: 251–276.

Loutit, T. S.; Kennett, J. P. 1981: Australasian Cenozoic sedimentary cycles, global sea level changes and the deep sea sedimentary record. *Oceanologica Acta 26*: 45–63.

McArthur, J. M. 1994: Recent trends in strontium isotope stratigraphy. *Terra Nova 6*: 331–358.

McArthur, J. M.; Howarth, R. J.; Bailey, T. R. 2001: Strontium isotope stratigraphy: LOWESS version 3. Best-fit to the marine Sr-isotope curve for 0 to 509 Ma and accompanying look-up table for deriving numerical age. *Journal of Geology 109*: 155–169.

Miller, K. G.; Wright, J. D.; Fairbanks, R. G. 1991: Unlocking the icehouse: Oligocene–Miocene oxygen isotopes, eustasy, and margin erosion. *Journal of Geophysical Research 96*: 6829–6848.

Morgans, H. E. G.; Scott, G. H.; Beu, A. G.; Graham, I. J.; Mumme, T. C.; St George, W.; Strong, C. P. 1996: New Zealand time scale (1996). *Institute of Geological & Nuclear Sciences Science Report 96/38*.

Morgans, H. E. G.; Edwards, A. R.; Scott, G. H.; Graham, I. J.; Kamp, P. J. J.; Mumme, T. C.; Wilson, G. J.; Wilson, G. S. 1999: Integrated stratigraphy of the Waitakian–Otaian Stage boundary stratotype, early Miocene, New Zealand. *New Zealand Journal of Geology and Geophysics 42*: 581–614.

Morris, J. C.; Lewis, D. W. 1988: Revised Paleogene time stratigraphic scale. *Geological Society of New Zealand Newsletter 80*: 45–49.

Nathan, S.; Anderson, H. J.; Cook, R. A.; Herzer, R. H.; Hoskins, R. H.; Raine, J. I.; Smale, D. 1986: Cretaceous and Cenozoic sedimentary basins of the West Coast region, South Island, New Zealand. *New Zealand Geological Survey Basin Studies 1*.

Nelson, C. S. 1973: Stratigraphy and sedimentology of the Te Kuiti Group in Waitomo County, South Auckland. Unpublished PhD thesis, lodged in the Library, University of Auckland, Auckland, New Zealand. 877 p.

Nelson, C. S. 1978: Stratigraphy and paleontology of the Oligocene Te Kuiti Group, Waitomo County, South Auckland, New Zealand. *New Zealand Journal of Geology and Geophysics 21*: 553–594.

Nelson, C. S.; Cooke, P. J. 2001: History of oceanic front development in the New Zealand sector of the Southern Ocean during the Cenozoic—a synthesis. *New Zealand Journal of Geology and Geophysics 44*: 535–553.

Nelson, C. S.; James, N. P. 2000: Marine cements in mid-Tertiary cool-water shelf limestones of New Zealand and southern Australia. *Sedimentology 47*: 609–629.

Nelson, C. S.; Smith, A. M. 1996: Stable oxygen and carbon isotope compositional fields for skeletal and diagenetic components in New Zealand Cenozoic nontropical carbonate sediments and limestones: a synthesis and review. *New Zealand Journal of Geology and Geophysics 39*: 93–107.

Nelson, C. S.; Burns, D. A.; Rodgers, K. A. 1983: The taxonomic status, and isotopic evidence for paleoenvironments, of giant oysters from the Oligocene Te Kuiti Group, South Auckland, New Zealand. *New Zealand Journal of Geology and Geophysics 26*: 289–299.

Oslick, J. S.; Miller, K. G.; Feigenson, M. D.; Wright, J. D. 1994: Oligocene–Miocene strontium isotopes: stratigraphic revisions and correlations to an inferred glacioeustatic record. *Paleoceanography 9*: 427–443.

Stevens, G. R. *comp*. 1981: Geological time scale. Geological Society of New Zealand Wall Chart.

Veizer, J. et al. 1999: $^{87}Sr/^{86}Sr$, $\delta^{13}C$ and $\delta^{18}O$ evolution of Phanerozoic seawater. *Chemical Geology 161*: 59–88.

Vella, P. 1967: Eocene and Oligocene sedimentary cycles in New Zealand. *New Zealand Journal of Geology and Geophysics 10*: 119–145.

Wei, W. 1991: Evidence for an earliest Oligocene abrupt cooling in the surface waters of the Southern Ocean. *Geology 19*: 780–783.

White, P. J.; Waterhouse, B. C. 1993: Lithostratigraphy of the Te Kuiti Group: a revision. *New Zealand Journal of Geology and Geophysics 36*: 255–266.

Zachos, J. C.; Stott, L. D.; Lohmann, K. C. 1994: Evolution of early Cenozoic marine temperatures. *Paleoceanography 9*: 353–387.

Appendix 1 New Zealand Oligocene fossil C, O, and Sr isotope data.

No.	Sample	Locality	Formation	NZ stage	Shell type	Strat. order	$\delta^{13}C$	$\delta^{18}O$	$^{87/86}Sr$	$^{87/86}Sr$ adj	Age (Ma)
North Otago/South Canterbury samples (Total 34)											
1	SQ1	Squires Farm	Kokoamu Gsd	Ld	Brach	Bottom	2.263	0.952	0.708058	0.708074	27.72
2	SQ2	Squires Farm	Kokoamu Gsd	Ld	Pecten		–0.454	–0.723	0.708047	0.708063	27.99
3	SQ3	Squires Farm	Kokoamu Gsd	Ld	Brach		2.582	0.896	0.708130	0.708146	25.87
4	SQ4	Squires Farm	Otekaike Lst	Ld–Lw	Brach	Top	2.221	0.887	0.708199	0.708215	24.66
5	HA1	Haugh's Qu.	Kokoamu Gsd	?Up. Lwh	Pecten	Bottom	1.448	0.749	0.708030	0.708046	28.43
6	HA2a	Haugh's Qu.	Kokoamu Gsd	Ld	Pecten		1.492	0.694	0.708063	0.708079	27.58
7	HA3a	Haugh's Qu.	Kokoamu Gsd	Ld	Pecten		1.988	1.008	0.708076	0.708092	27.2
8	HA4	Haugh's Qu.	Basal Otekaike	Ld	Brach		1.898	0.412	0.708121	0.708137	26.06
9	HA6a	Haugh's Qu.	Mid Otekaike	Ld	Pecten		1.206	0.014	0.708158	0.708174	25.32
10	HA7a	Haugh's Qu.	Top Otekaike	?Lw	Pecten		2.958	0.695	0.708234	0.708250	24.12
11	HA8a	Haugh's Qu.	Topmost Otekai	Lw	Bivalve		2.174	0.813	0.708213	0.708229	24.45
12	HA8b	Haugh's Qu.	Topmost Otekai	Lw	Brach	Top	2.221	0.060	0.708259	0.708275	23.69
13	WH1	Wharekuri	Wharekuri Gsd	Low Lwh	Pecten (Lenti)	Bottom	1.321	–0.186	0.707865	0.707881	32.48
14	WH2	Wharekuri	Kekenodon Beds	Up Lwh–?Ld	Pecten (Lenti)		2.021	0.017	0.708008	0.708024	28.99
15	WH3	Wharekuri	Kekenodon Beds	Up Lwh–?Ld	Pecten (Lenti)		2.135	0.702	0.708020	0.708036	28.68
16	WH4	Wharekuri	Kekenodon Beds	?Ld	Pecten (Lenti)		2.000	0.558	0.708014	0.708030	28.84
17	WH5	Wharekuri	Kekenodon Beds	Ld	Pecten (Lenti)		1.679	0.079	0.708033	0.708049	28.35
18	WH6	Wharekuri	Otekaike Lst	Up Ld–Lw	Pecten (Lenti)	Top	2.351	0.561	0.708143	0.708159	25.61
19	TZ2	Trig Z	Otekaike Lst	Lw	Brach	Bottom	2.534	0.248	0.708231	0.708247	24.17
20	TZ5	Trig Z	Otekaike Lst	Lw	Brach	Top	2.557	0.229	0.708276	0.708292	23.36
21	WE1	Weston Qu.	Ototara Lst	Ar	Brach	Bottom	2.208	–0.282	0.707764	0.707780	34.9
22	WE2a	Weston Qu.	Intra-tuff	Ar	Pecten		2.241	0.242	0.707748	0.707764	35.92
23	WE2b	Weston Qu.	Intra-tuff	Ar	Brach	Top	2.540	0.053	0.707782	0.707798	34.79
24	MC1	McDonald Qu.	Ototara (McD) Lst	Basal Lwh	Brach	Bottom	3.402	1.185	0.707791	0.707807	33.94
25	MC2	McDonald Qu.	Ototara (McD) Lst	Basal Lwh	Brach	(Bottom =)	3.126	1.289	0.707797	0.707813	33.79
26	MC3	McDonald Qu.	Ototara (McD) Lst	Basal Lwh	Brach	Top	3.409	1.311	0.707816	0.707832	33.39
27	GP3	Gees Pt	Gee Gsd	Po	Brach		2.146	0.442	0.708324	0.708340	22.14
28	KA1	Kakanui R.	Ototara Lst	Lwh	Brach	Bottom	2.154	–0.015	0.707759	0.707775	35.18
29	KA2a	Kakanui R.	Ototara (McD) Lst	Lwh	Pecten		2.112	0.710	0.707799	0.707815	34.16
30	KA2b	Kakanui R.	Ototara (McD) Lst	Lwh	Brach		3.737	1.186	0.707777	0.707793	34.35
31	KA3	Kakanui R.	Ototara (McD) Lst	Lwh	Pecten		2.714	1.003	0.707780	0.707796	34.25
32	KA4	Kakanui R.	Ototara (McD) Lst	Lwh	Pecten		2.347	1.136	0.707819	0.707835	33.33
33	KA5a	Kakanui R.	Ototara (McD) Lst	Lwh	Pecten		2.471	1.658	0.707846	0.707862	32.81
34	KA5b	Kakanui R.	Ototara (McD) Lst	Lwh	Brach	Top	2.788	1.118	0.707784	0.707800	34.13
Te Kuiti Group samples (Total 43)											
35	AU2438	Pt Waikato	Mangakotuku Zst	Lwh	Oyster	Bottom	–4.707	–0.960	0.707597	0.707613	
36	AU12890	S12/Q08 (0)	Mangakotuku Zst	Lwh	Oyster		–4.961	–0.876	0.707706	0.707722	39.85
37	AU6472	R13 (3)	Mangakotuku Zst	Lwh	Eumarcia		0.234	–0.733	0.707578	0.707594	

(continued)

Appendix 1 *(continued)*

No.	Sample	Locality	Formation	NZ stage	Shell type	Strat. order	$\delta^{13}C$	$\delta^{18}O$	$^{87/86}Sr$	$^{87/86}Sr$ adj	Age (Ma)
38	AU7842b	S15 (19)	Mangakotuku Zst	Lwh	Eumarcia		1.244	–0.656	0.707772	0.707788	34.52
39	AU2045	N73/803	Whaingaroa Zst	Lwh	Brachiopod		1.545	–0.224	0.707693	0.707709	53.36
40	AU2000	N82/689	Whaingaroa Zst	Lwh	Pecten		1.210	–0.549	0.707851	0.707867	32.72
41	AU1090	N91/745	Whaingaroa Zst	Lwh	Pecten		1.994	–0.148	0.707814	0.707830	33.43
42	AU1092	N91/747	Whaingaroa Zst	Lwh	Bivalve		2.111	0.190	0.707660	0.707676	
43	AU4173	R13 (10)	Sub Elgood Lst	Lwh	Pecten		1.240	–0.469	0.707784	0.707800	34.13
44	AU9529	R13 (7)	Elgood Lst	Lwh	Pecten		0.799	–0.832	0.707719	0.707735	38.77
45	AU2468	R13 (13)	Elgood Lst	Lwh	Pecten		1.456	–1.286	0.707824	0.707840	33.23
46	AU8998	N51/675	Dunphail Zst	Lwh	Pecten		1.877	–0.465	0.707865	0.707881	32.48
47	AU2460	S14 (17)	Dunphail Zst	Lwh	Pecten		1.226	0.035	0.707890	0.707906	31.96
48	AU1331	R13 (7)	Glen Massey Sst	Lwh	Brachiopod		2.237	0.538	0.707893	0.707909	31.89
49	AU8003	S15 (19b)	Glen Massey	Lwh	Pecten		0.881	–0.527	0.707912	0.707928	31.46
50	AU1330	R13 (6)	Waimai Lst	Lwh	Pecten		2.385	0.822	0.707943	0.707959	30.65
51	AU3037	N64/558	Aotea Sst	Lwh	Pecten		1.285	–0.447	0.707949	0.707965	30.49
52	AU1974(a)	N73/936	Aotea Sst	Lwh–(?)	Pecten		2.931	–0.025	0.707885	0.707901	32.07
53	AU1978	N74/609	Aotea Sst (Ao-2)	Lwh	Pecten		1.712	–0.374	0.707995	0.708011	29.32
54	AU1979	N74/610	Aotea Sst	Lwh+	Pecten		1.621	–0.005	0.708038	0.708054	28.22
55	AU1991	N74/613	Aotea Sst	Lwh	Pecten		1.129	–0.680	0.708058	0.708074	27.72
56	AU1087	N91/741	Aotea Sst	Ld	Brachiopod		2.007	–0.202	0.707969	0.707985	29.96
57	AU1536	R13 (4)	Aotea Sst	Ld	Pecten		0.710	–1.088	0.707978	0.707994	29.74
58	AU2441	R15 (6)	TeAk-Waimai bdy	Ld	Brachiopod		1.769	–0.031	0.708094	0.708110	26.67
59	M8	Mangaotaki	Aotea Sst	Lwh–Ld	Pecten		1.634	–0.764	0.707755	0.707771	35.4
60	M7	Mangaotaki	Orahiri Lst	Ld	Pecten		1.184	–0.809	0.707916	0.707932	31.37
61	M5	Mangaotaki	Orahiri Lst	Ld	Pecten		1.413	–1.478	0.707858	0.707874	32.61
62	M1	Mangaotaki	Orahiri Lst	Ld	Pecten		1.501	–1.114	0.707979	0.707995	29.71
63	AU2053	N74/566	Orahiri Lst	Ld–w	Oyster		1.099	0.239	0.708083	0.708099	26.99
64	AU2007	N82/708	Orahiri Lst	Ld	Oyster		1.882	1.099	0.707862	0.707878	32.54
65	AU2008	N82/709	Orahiri Lst	Ld	Oyster		1.042	0.790	0.708054	0.708070	27.82
66	AU2014	N82/715	Orahiri Lst	Ld	Pecten		1.067	–2.380	0.707946	0.707962	30.57
67	AU1088	N91/743	Orahiri Lst	Ld	Brachiopod		1.049	–0.740	0.708120	0.708136	26.08
68	AU1298a	R14 (5)	Carter Zst	Ld	Oyster		1.484	–0.218	0.708298	0.708314	22.86
69	AU4184	N51/678	Te Akatea Zst	Ld-Lw	Brachiopod		1.911	0.173	0.708093	0.708109	26.7
70	AU4179	N51/1096	Te Akatea Zst	Lw	Echinoderm		0.478	–0.230	0.708238	0.708254	24.05
71	AU6387	R13 (2)	Te Akatea Zst	Lw	Echinoderm		0.354	–0.123	0.708170	0.708186	25.1
72	AU7995	R15 (6)	Waitomo Sst	Lw	Brachiopod		2.594	–0.404	0.708197	0.708213	24.68
73	AU2050	N74/563	Otorohanga Lst	Lw	Brachiopod		2.511	0.304	0.708172	0.708188	25.06
74	AU2028	N83/557	Otorohanga Lst	Lw	Pecten		2.541	0.252	0.708218	0.708234	24.38
75	AU2029	N83/558	Otorohanga Lst	Lw	Pecten		2.216	–0.913	0.708128	0.708144	25.91
76	AU2026	N83/555	Otorohanga Lst	Ld–w	Brachiopod		–0.067	–1.613	0.707957	0.707973	30.27
77	AU2039	N91/807	Otorohanga Lst	Lw	Pecten	Top	2.368	–0.247	0.708189	0.708205	24.8