New Zealand Quaternary Stratigraphy : Integrating marine and terrestrial records of environmental changes

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Abstract

Correlation and dating of widespread rhyolite tephra erupted from Taupo Volcanic Zone, North Island, New Zealand, provides remarkable opportunities for correlating marine and terrestrial records of Quaternary environmental changes. Tephrostratigraphy, magnetostratigraphy and biostratigraphy of emergent marine sediments in Wanganui Basin allows correlation of strata to the isotope record of deep sea cores, with a precision of better than one isotope stage. Radiometric ages for several tephras are consistent with the astronomically calibrated isotope stage chronology of Shackleton *et al.* (1990). Pollen assemblages and oxygen isotope analyses from marine cores indicate that terrestrial vegetation changes in New Zealand were closely linked with global climatic changes. Major glaciations in the South Island were also closely synchronous with glaciations in the Northern Hemisphere, as evidenced by the isotope and sediment records of DSDP Site 594. Stratigraphic relationships between loess and marine terraces near Wanganui, provide a framework for linking terrestrial and marine records over the past 500 ka. Plant phytoliths in the loess indicate two major periods of climatically induced deforestation during the last 150 ka, one from 20–50 ka and one from 130–150 ka.

I. Introduction

Partly because of concerns about future global warming, there is currently much interest in the causes of Quaternary climatic changes, and their environmental responses. This interest has led to an increasing demand for precisely dated Quaternary records, so that theories of climatic change can be quantitatively tested against independently dated geological sequences. The Milankovitch (astronomical) theory is considered by many to provide an accurate chronology for Quaternary climatic changes, based on variations in the earth's orbital

parameters (obliquity, precession and eccentricity.). As a consequence there is a tendency to apply the astronomical chronology to isotope records in deep sea sediments, and to "tune" the isotope stratigraphy to orbital variations (*e. g.* Hays *et al.*, 1976; Imbrie *et al.*, 1984; Shackleton *et al.*, 1990). Such tuning requires careful verification by precise dating techniques. Since few dating methods are suitable for dating deep sea sediments directly, it is important to develop correlations between deep sea sediments and on-land strata which can be dated. In addition, it is important to examine leads and lags between ter-

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Fig. 1 Locations of Wanganui Basin, major volcanic centres, and other sites mentioned in the text. Inset shows locations of deep sea cores. [Recently active volcanoes] W : White Island, T : Tarawera, To : Tongariro, N : Ngaruhoe, E : Egmont/Taranaki. (after Pillans, 1994)

restrial and marine environmental changes. New Zealand Quaternary stratigraphy offers substantial opportunities for establishing links between marine and terrestrial records of environmental changes through correlation and dating of widespread rhyolite tephtras erupted from Taupo Volcanic Zone (Fig. 1).

The two main islands of New Zealand span

latitudes 34–47 °S and reach elevations over 3,500 m, rather similar in geographic position and size to the four main islands of Japan. In New Zealand, as in Japan, there are marked climatic gradients extending from sub-tropical to sub-alpine in a small geographic area. Consequently the Quaternary records of both countries are sensitive recorders of past environ-

mental changes. The relative geographic isolation of New Zealand has meant that human impact on the Quaternary record is restricted to only the last 1,000 years, which simplifies analysis of past environmental changes.

In this paper I will show how correlations can be made between on-land marine and terrestrial deposits in New Zealand (particularly in the North Island), and deep sea sediments in surrounding ocean basins.

II. DSDP Site 594 as a Record of Glacial History

Glaciers occur in the South Island today, and during the Last Glacial Maximum some 30 % of the South Island was covered by ice. In the North Island, glaciers (both past and present) have a very restricted distribution. Although glacial deposits have played an important role in New Zealand Quaternary stratigraphy, in general they are poorly dated and lack continuity (Suggate, 1990). High uplift rates in conjunction with high erosion rates in the Southern Alps (the main glaciated area of the South Island) have apparently allowed only a fragmentary glacial record to be preserved.

A more complete record of New Zealand glaciations than that provided by on-land sequences is inferred from deep sea sediments cored at DSDP Site 594 (Fig. 1), some 300 km east of the South Island (Nelson *et al.*, 1985)—see Fig. 2. The core contains an alternation of pelagic and hemipelagic sediments, with the former comprising dominantly foraminifera and nannofossil ooze, and the latter enriched in silt-sized terrigenous minerals. Each hemipelagic unit is interpreted to represent a major period of increased erosion and outwash aggradation associated with expanded glaciation in the Southern Alps. Oxygen isotope analyses of both benthonic and planktonic forams show

that each hemipelagic unit corresponds with a period of significant $\delta^{18}\text{O}$ enrichment, principally reflecting increased size of Northern Hemisphere ice sheets. Nelson *et al.* (1985) therefore concluded that alpine glaciations in the South Island of New Zealand are closely synchronous (± 3 ka) with global climate changes. Pollen assemblages (Heusser, 1985) broadly follow the oxygen isotope record, with cool temperate (*Nothofagus* rich) assemblages in even numbered (glacial) stages and warm temperate (podocarp rich) assemblages in odd numbered (interglacial) stages. The absence of herb and grass dominated pollen assemblages is consistent with the persistence of significant areas of forest in favourable sites in the eastern South Island even during glaciations.

III. On-land Marine Sequences Containing Tephra, Wanganui Basin

Pliocene and Pleistocene marine strata are widely preserved in uplifted basins of the North Island, but are rare in the South Island. Wanganui Basin in the southwestern North Island, is a back-arc basin containing up to 4 km of Plio-Pleistocene shallow marine sediments. The basin contains the type sections for the New Zealand Pleistocene and Upper Pliocene stages and substages (Pillans, 1991), and a coastal section at Wanganui has been proposed as a possible international type section for the Lower/Middle Pleistocene boundary at the level of the 780 ka Brunhes/Matuyama paleomagnetic reversal (Pillans *et al.*, 1991). An extensive flight of 12 marine terraces occurs near the western margin of the basin (Pillans, 1983). The stratigraphy of loess deposits overlying the terraces provides an important link between marine and terrestrial events over the past 500 ka (see below). Offshore marine deposits, now emergent, unconformably underlie

Fig. 2 Colour (a), texture (b), calcium carbonate (c), quartz content (d) and planktonic foraminiferal oxygen isotope (e) data for DSDP Site 594 (modified after Nelson *et al.*, 1985)

White and black intervals (a) are pelagic and hemipelagic sediment respectively. Numbers in the carbonate record (c) are oxygen isotope stages. The Brunhes/Matuyama boundary (0.78 Ma) is tentatively placed at 88.5 m sub-bottom in (a).

the marine terraces (Fig. 3). The detailed interfingering sequence of marine and terrestrial sediments, spanning the entire Quaternary, makes Wanganui Basin one of the most complete Quaternary stratigraphic records in the world. Tephrostratigraphy, magnetostratigraphy and coccolith biostratigraphy are used for correlations from Wanganui Basin to deep sea cores in the New Zealand region (Fig. 3).

Several widespread rhyolite tephra, erupted from Taupo Volcanic Zone, occur within the basin. One of these, Rangitawa Tephra (tep-

hra A in Fig. 3), is interbedded within loess on the oldest five marine terraces, and is also interbedded within marine strata underlying the younger marine terraces (Fig. 3). Rangitawa Tephra is dated on-land at 333 ± 7 ka (weighted mean of 17 reliable radiometric age determinations—Pillans *et al.*, in review). At Site 594 and in core SO-36-31 to the northwest of New Zealand (Fig. 1) Rangitawa Tephra occurs close to the isotope stage 9/10 boundary, and has an astronomically calibrated age of 340 ± 7 ka (Pillans *et al.*, in review).

Generalised cross-section Wanganui, New Zealand

Fig. 3 Generalised cross-section at Wanganui, showing stratigraphic relationships between marine terraces (numbers beneath terrace names are isotope stages), and older marine strata containing rhyolite tephras

A: Rangitawa tephra (Kohn *et al.*, 1992), 0.34 ± 0.03 Ma, B: Kupe tephra (Pillans *et al.*, 1994), 0.61 ± 0.8 Ma, C: Kaukatea ash (Seward, 1976), 0.87 ± 0.05 Ma, D: Potaka pumice (Seward, 1976), 1.05 ± 0.05 Ma, E: Rewa pumice (Seward, 1976), 1.20 ± 0.18 Ma, F: Pakihikura pumice (Seward, 1976), 1.63 ± 0.15 Ma, G: Waipuru ash (Seward, 1976), 1.87 ± 0.15 Ma, H: Ohingaiti Ash (Seward, 1976). Tephra ages from Alloway *et al.* (1993) and Alloway pers. comm. (1994).

[Coccolith datums] Eh: FAD *Emiliana huxleyi*, Pl: LAD *Pseudoemiliana lacunosa*, Ra: LAD *Reticulofenestra asanoi*, Hs: LAD *Helicosphaera sellii*, Go: FAD *Geophyrocapsa oceanica*, Gs: FAD *Geophyrocapsa sinuosa*. (Beu and Edwards 1984; A. Edwards pers. comm., 1994)

Isotopic record from ODP Site 677 after Shackleton *et al.* (1990). Polarity timescale after Shackleton *et al.* (1990) and Hilgen (1991). Stippled area between tephras E and F shows strata missing at coastal type section, but present elsewhere in the basin (Pillans, 1991).

Thus, within error limits, the radiometric and astronomical age estimates are in excellent agreement.

IV. Linking Loess Deposits with Sea Level Changes

Alluvial terraces are associated with major

Fig. 4 Rangitatau East loess section (Pillans and Wright 1992), Wanganui Basin, showing marine terraces and ages (Pillans, 1983), thermoluminescence ages (Berger *et al.*, 1992), plant phytolith data (Kondo *et al.*, 1994), quartz content (A. Palmer pers. comm., 1993), and correlations with oxygen isotope record of deep sea cores (Imbrie *et al.*, 1984)

ivers in both islands, particularly in areas of rapid uplift. In the South Island many are glacial outwash terraces, and have clear paleoclimatic significance. Even in areas not directly affected by glaciation, the terraces are interpreted as representing climatically controlled periods of river aggradation, interspersed with periods of downcutting to keep pace with uplift. In these non-glaciated areas, major phases of aggradation resulted from increased sediment production in headwater regions accompanying glacial and stadial changes in vegetation patterns. Aggrading river flood plains were major sources of loess during these times, as were unconsolidated tephra deposits in the central North Island. During intervening periods of river downcutting, little or no loess

appears to have been produced on a regional scale, and soil development occurred.

A 15 m thick, 500 ka record of loess accumulation near Wanganui in the North Island is the longest such record yet documented in the Southern Hemisphere (Pillans and Wright, 1990). The site occurs immediately inland of a broad flight of marine terraces, at an elevation of 400 m above present sea level (see Fig. 3). Eleven loess layers, labelled from youngest to oldest L1 to L11, are recognised (Fig. 4). Stratigraphic relationships between loess and dated marine terraces near Wanganui are summarised in Fig. 4. Here, as elsewhere in the North Island, the loess is non-calcareous quartzose feldspathic loess with a high volcanic content (often referred to as tephric loess).

Two rhyolite tephtras erupted from Taupo Volcanic Zone are present as discrete layers: Kawakawa Tephra, within loess L 1, which has a radiocarbon age 22.6 ka (Wilson *et al.*, 1988) and Rangitawa Tephra, within loess L 10, which has a fission track age 350 ± 40 ka at the site (Kohn *et al.*, 1992). Two other rhyolite tephtras are present as microscopic glass concentrations: Rotoehu Ash in the base of L 2 which is K/Ar dated in the Bay of Plenty area at 64 ± 4 ka (Wilson *et al.*, 1992), and an unnamed tephra in the base of L 7. Although several andesitic tephtras are recognised as discrete layers, most individual andesitic eruptions are too small to be preserved as discrete layers. Rather, numerous small andesitic eruptions from Taranaki Volcanic Centre have provided a continuous background input, which tends to be diluted during times of rapid loess accumulation, and concentrated in paleosols during times when loess accumulation slowed. Quartz content of the loess (Fig. 4) is interpreted to be a measure of the rate of non-andesitic sediment accumulation at the site—generally high during glacial and stadial periods and low during interstadial and interglacial periods. The quartz curve and loess-marine terrace relationships, in conjunction with the dated tephtras and thermoluminescence dates on the loess (Berger *et al.*, 1992) allow correlation of the loess record with the isotopic record of deep sea cores (Fig. 4).

Plant phytoliths extracted from the loess are being studied to provide a detailed vegetation record (Kondo *et al.*, 1994). The present elevation of the site (400 m) is some 1,000 m below the modern regional treeline. Thus, only during the coldest glacial periods would trees have been excluded from the site. The ratio of grass/tree phytoliths in the upper 8 m of the loess section indicates two major periods when

the vegetation at the site was dominated by non-forest taxa: one from *c.* 50–20 ka, and one prior to *c.* 130 ka, corresponding to the last two major glacial periods (Fig. 4). The phytolith data therefore provide confirmation of the correlations made independently between the loess stratigraphy and the isotopic record of deep sea cores.

V. Pollen and Tephtras in Marine Cores S 803 and S 794, Bay of Plenty

Pollen analyses of organic-rich sediments have been carried out at many Quaternary sites in New Zealand. Although such sites are very important in paleoclimatic reconstructions, few records span time intervals of more than 10–20 ka. Long lake records are not available, largely because most major New Zealand lakes were either occupied by ice (South Island lakes) or have been affected by intermittent volcanic activity (North Island lakes). In fact, the longest, continuous pollen records in the New Zealand region are from deep sea cores (cf. DSDP Site 594 pollen results of Heusser (1985) discussed above).

Pillans and Wright (1992) described the tepthrostratigraphy of three marine cores located between 50 and 100 km offshore from Coromandel Peninsula in western Bay of Plenty (Fig. 1). Several rhyolitic tephtras from TVZ occur in the cores (Fig. 5), which allow a *c.* 60 ka chronostratigraphy to be established. The tephtra layers, in conjunction with other lithological changes (*e. g.* alternations between pelagic and hemipelagic sediment), permit excellent intercore correlation (Fig. 5). Oxygen isotope analyses from core S 794 and pollen analyses from core S 803 show terrestrial vegetation changes in broad correspondence with global ice volume changes during isotope stages 1, 2 and 3. Most of the pollen is assum-

Fig. 5 Oxygen isotope record and lithostratigraphy, core S794 (Pillans and Wright, 1992; C. S. Nelsion pers. comm., 1993). Pollen data and lithostratigraphy for core S803 (Pillans and Wright, 1992; M. S. McGlone pers. comm. 1993)

Pollen data are percentages of a pollen sum that includes all woody plants and non-wetland herbs, and excludes wetland and aquatic plants and all fern spores except *Pteridium esculentum*. [Tephra] Ka: Kaharoa, Tp: Taupo, Ma: Mamaku, Wh: Waiohau, Kk: Kawakawa, Om: Omataroa, Hu: Hauparu, Ta: Tahuna, Re: Rotoehu.

ed to have been transported to the site from areas north of Coromandel Peninsula (Fig. 1), by surface ocean currents, with minor aeolian input. Thus the implied vegetation changes apply to the northernmost (warmest) part of New Zealand, where extensive deforestation probably did not occur during glacial periods as it did elsewhere in New Zealand. The pollen data from Core S803 show that during isotope stage 2, there was a decrease in *Agathis*, and *Dacrydium* (warm temperate trees) and an increase in *Nothofagus* (cool temperate tree) pollen. Swamp taxa such as *Empodisma* show an increase during stage 2, probably reflecting the abundance of swamps on coastal plains exposed by lower sea level. The rapid

increase in bracken fern spores in the uppermost part of the core reflects a marked human impact associated with clearing and burning of forest by Polynesian immigrants in the last 1 ka (cf. McGlone, 1983).

VI. Towards more precise correlation of marine and terrestrial records

Quaternary stratigraphy in New Zealand offers a way of testing the astronomically calibrated timescale developed for deep sea cores by Shackleton *et al.*, (1990). This involves establishing direct links between marine and terrestrial records using, as precise stratigraphic markers, the widespread rhyolitic tephra erupted from Taupo Volcanic Zone (TVZ). There

have been nearly 40 rhyolitic eruptions documented from TVZ over the past 50 ka (Froggatt and Lowe 1990), and there is no reason to suppose that the frequency of eruptions over this time interval is atypical of the TVZ throughout the Quaternary. The potential for wide-ranging precise correlation between onshore and offshore strata is therefore great. Where such tephras can be dated at on-land sites, the resultant ages can then be transferred by tephra correlation to deep sea cores for which an isotope stratigraphy is available. At the same time, dated tephras can provide a chronostratigraphic framework for on-land paleoclimate records (*e. g.* pollen and loess).

The most voluminous New Zealand eruptions (typically those exceeding 500 km³) occur in deep sea cores more than 1,000 km from source, particularly east of New Zealand. These largest eruptions include Kawakawa Tephra (22.6 ka), Rangitawa Tephra (340 ka) and Potaka Tephra (1.0 Ma), each of which allows precise correlations with isotope stratigraphy in deep sea cores (isotope stages 2, 10 and 28 respectively). Fission track (Alloway *et al.*, 1993) and ⁴⁰Ar/³⁹Ar ages (Shane, 1994) for Potaka Tephra, and its occurrence at the top of Jaramillo Subchron in Wanganui Basin and marine cores such as DSDP Site 593 (Pillans *et al.*, 1994), RC 12-215 and RC 13-113 (Pillans, 1994), lend support to the astronomically calibrated timescale of Shackleton *et al.* (1990). Extensive dating of Rangitawa Tephra (see above) at onland sites is also consistent with the astronomical timescale. Kawakawa Tephra, erupted near the peak of the last glaciation, provides an important chronostratigraphic marker at many pollen sites in New Zealand (*cf.* Pillans *et al.*, 1993).

While tephras allow precise dating of paleoclimatic records on land (independent of deep

sea cores), and their comparison with the astronomical timescale, there are other terrestrial deposits which can yield high precision dates. For example, combined mass-spectrometric U/Th dating and stable isotope analyses of speleothems (*e. g.* Winograd *et al.*, 1992) has yet to be undertaken in New Zealand, but there is clearly much potential in deep cave systems such as Nettlebed Cave in the northern South Island (Fig. 1) and elsewhere in New Zealand (*cf.* Hendy and Wilson, 1968). Nettlebed Cave, the deepest known cave in the Southern Hemisphere, contains speleothems of reverse polarity (Williams, 1991) and could yield a paleoclimate record longer than the 500 ka Devils Hole record (Winograd *et al.*, 1992) from Nevada, western USA. Unlike Devils Hole, groundwater moving through the Nettlebed system is of local origin, and not subject to lag times of thousands of years between the time the water arrives at the surface as rainfall and the time when calcite is precipitated in the cave. Such short travel times simplify temporal comparisons with other dated paleoclimate records.

References

- Alloway, B. V., Pillans, B. J., Sandhu, A. S. and Westgate, J. A. (1993): Revision of the marine chronology in the Wanganui Basin, New Zealand, based on the isothermal plateau fission-track dating of tephra horizons. *Sedimentary Geology*, **82**, 299-310.
- Berger, G. W., Pillans, B. and Palmer, A. S. (1992): Dating loess up to 800 ka by thermoluminescence. *Geology*, **20**, 403-406.
- Beu, A. G. and Edwards, A. R. (1984): New Zealand Pleistocene and Late Pliocene glacio-eustatic cycles. *Palaeogeogr., Palaeoclimat., Palaeoecol.*, **46**, 119-142.
- Froggatt, P. C. and Lowe, D. J. (1990): A review of late Quaternary silicic and some other tephra formations from New Zealand: Their stratigraphy, nomenclature, distribution, volume and age. *New Zealand J. Geol. Geophys.*, **33**, 89-109.
- Hays, J. D., Imbrie, J. and Shackleton, N. J. (1976):

- Variations in the earth's orbit: Pacemaker of the ice ages. *Science*, **194**, 1121-1132.
- Hendy, C. H. and Wilson, A. T. (1968): Paleoclimatic data from speleothems. *Nature*, **219**, 48-51.
- Heusser, L. E. (1985): Palynology of selected Neogene samples from holes 594 and 594 A, Chatham Rise. In Kennett, J. C. and von der Borch, C. C. eds.: *Initial Reports of the Deep Sea Drilling Project, Volume 90*. U. S. Government Printing Office, Washington, D. C., 1085-1092.
- Hilgen, F. J. (1991): Astronomical calibration of Gauss to Matuyama sapropels in the Mediterranean and implication for the geomagnetic polarity time-scale. *Earth & Planetary Sci. Lett.*, **104**, 226-244.
- Imbrie, J., Hays, J. D., Martinson, D. G., McIntyre, A., Mix, A. C., Morley, J. J., Pisias, N. G., Prell, W. L. and Shackleton, N. J. (1984): The orbital theory of Pleistocene climate: Support from a revised chronology of the marine $\delta^{18}\text{O}$ record. In Berger, A. L. et al. eds.: *Milankovitch and climate Part 1*. D. Reidel, 269-305.
- Kohn, B. P., Pillans, B. and McGlone, M. S. (1992): Zircon fission track age for middle Pleistocene Rangitawa Tephra, New Zealand: Stratigraphic and paleoclimatic significance. *Palaeogeogr., Palaeoclim., Palaeoecol.*, **95**, 73-94.
- Kondo, R., Childs, C. and Atkinson, I. (1994): *Opal phytoliths of New Zealand*. Manaaki Whenua Press, Lincoln, Canterbury, New Zealand, 85 p.
- McGlone, M. S. (1983): Polynesian deforestation of New Zealand: A preliminary synthesis. *Archaeology in Oceania*, **18**, 11-25.
- Nelson, C. S., Hendy, C. H., Jarrett, G. R. and Cuthbertson, A. M. (1985): Near-synchronicity of New Zealand alpine glaciations and Northern Hemisphere continental glaciations during the past 750 kyr. *Nature*, **318**, 361-363.
- Pillans, B. (1983): Upper Quaternary marine terrace chronology and deformation, South Taranaki, New Zealand. *Geology*, **11**, 292-297.
- Pillans, B. (1991): New Zealand Quaternary stratigraphy: An overview. *Quat. Sci. Rev.*, **10**, 405-418.
- Pillans, B. (1994): Direct marine-terrestrial correlations, Wanganui Basin, New Zealand: The last 1 million years. *Quat. Sci. Rev.*, **13**.
- Pillans, B., Abbott, S. T., Beu, A. G. and Carter, R. M. (1991): A possible Lower/Middle Pleistocene boundary stratotype in Wanganui Basin, New Zealand. *Abstracts International Union for Quaternary Research, XIII International Congress, August 2-9, 1991, Beijing China*.
- Pillans, B., McGlone, M., Palmer, A., Mildenhall, D., Alloway, B. and Berger, G. (1993): The Last Glacial Maximum in central and southern North Island, New Zealand: A paleoenvironmental reconstruction using the Kawakawa Tephra Formation as a chronostratigraphic marker. *Palaeogeogr., Palaeoclim., Palaeoecol.*, **101**, 283-304.
- Pillans, B. J., Roberts, A. P., Wilson, G. S., Abbott, S. T. and Alloway, B. V. (1994): Magnetostratigraphic, lithostratigraphic and tephrostratigraphic constraints on Lower and Middle Pleistocene sea-level changes, Wanganui Basin, New Zealand. *Earth & Planetary Sci. Lett.*, **121**, 81-98.
- Pillans, B. and Wright, I. (1990): 500,000-year paleomagnetic record from New Zealand loess. *Quat. Res.*, **33**, 178-187.
- Pillans, B. and Wright, I. (1992): Late Quaternary tephrostratigraphy from the southern Havre Trough—Bay of Plenty, northeast New Zealand. *New Zealand J. Geol. Geophys.*, **35**, 129-143.
- Seward, D. (1976): Tephrostratigraphy of the marine sediments in the Wanganui Basin, New Zealand. *New Zealand J. Geol. Geophys.*, **19**, 9-20.
- Shackleton, N. J., Berger, A. and Peltier, W. R. (1990): An alternative astronomical calibration of the Lower Pleistocene timescale based on ODP Site 677. *Trans. the Royal Society of Edinburgh: Earth Sciences*, **81**, 251-261.
- Shane, P. A. R. (1994): A widespread, early Pleistocene tephra (Potaka tephra, 1 Ma) in New Zealand: Character, distribution, and implications. *New Zealand J. Geol. Geophys.*, **37**, 25-36.
- Suggate, R. P. (1990): Late Pliocene and Quaternary glaciations of New Zealand. *Quat. Sci. Rev.*, **9**, 175-197.
- Williams, P. W. (1991): Tectonic geomorphology, uplift rates and geomorphic response in New Zealand. *Catena*, **18**, 439-452.
- Wilson, C. J. N., Houghton, B. F., Lanphere, M. A. and Weaver, S. D. (1992): A new radiometric age estimate for the Rotoehu Ash from Mayor Island, New Zealand. *New Zealand J. Geol. Geophys.*, **35**, 371-374.
- Wilson, C. J. N., Switsur, V. R. and Ward, A. P. (1988): A new ^{14}C age for the Oruanui (Wairakei) eruption, New Zealand. *Geol. Mag.*, **125**, 297-300.
- Winograd, I. J., Coplen, T. B., Landwehr, J. M., Riggs, A. C., Ludwig, K. R., Szabo, B. J., Kolesar, P. T. and Revesz, K. M. (1992): Continuous 500,000-year climate record from vein calcite in Devils Hole, Nevada. *Science*, **258**, 255-260.

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