

# Climate and vegetation in southeastern Australia respond to Southern Hemisphere insolation forcing in the late Pliocene–early Pleistocene

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## ABSTRACT

**Terrestrial climate responses to orbital forcing during the late Pliocene–early Pleistocene are poorly understood, particularly in the Southern Hemisphere, but are important for determination of the timing of regional climate evolution early in the history of the glaciated Quaternary world. We present a pollen record from southeastern Australia that shows marked cyclic change over some 280,000 yr straddling the Pliocene–Pleistocene boundary. Rainforest communities responded to climate forcing primarily within the precession and eccentricity bands, suggesting that major vegetation changes were driven directly by summer insolation, rather than by obliquity-dominated glacial cycles.**

**Keywords:** paleoecology, paleoclimate, Australia, insolation, Pliocene–Pleistocene.

## INTRODUCTION

The late Pliocene to early Pleistocene (ca. 2.6–0.78 Ma) is a critical interval for understanding the development of modern climate (Ruddiman et al., 1989) and terrestrial vegetation (Traverse, 1982). Extensive Northern Hemisphere glaciation commenced abruptly at ca. 2.7 Ma (Haug et al., 2005), while, at the same time, the cyclicity of ice sheets, as measured by the marine  $\delta^{18}\text{O}$  record from both hemispheres, became strongly dominated by the obliquity period, ushering in the “41 k.y. world” (Raymo and Nisancioglu, 2003).

However, very few sequences are available in which it is possible to evaluate the response of terrestrial climate and vegetation during the late Pliocene–early Pleistocene. Power spectra of late Pliocene pollen records from the Mediterranean (Klotz et al., 2006) and northwest Africa (Dupont and Leroy, 1995) suggest variable responses in which some plant groups were sensitive to forcing by obliquity, while others responded primarily to a precession-dominated signal, such as summer insolation. In the Southern Hemisphere, the situation is even less certain. A pollen record from Ocean Drilling Program (ODP) 1082, offshore southwest Africa at 21°S (Dupont, 2006), shows high-frequency vegetation changes during the late Pliocene, but it is unclear whether these are primarily precession or obliquity responses. Between 0.78 and 1.18 Ma, a pollen record from ODP 1123 suggests that vegetation changes in New Zealand were dominated by a 41 k.y. rhythm (Mildenhall et al., 2004), but pollen transport to this site,

~800 km offshore, was likely to be highly influenced by oceanographic processes.

In Australia, it is clear that rainforest (fire-sensitive, typically evergreen forest), which dominated the plant fossil record through most of the Cenozoic Era (Macphail et al., 1994), but which had been in slow decline during the late Neogene, contrasted dramatically within the late Pliocene–early Pleistocene to be almost completely replaced by drought- and fire-tolerant sclerophyllous vegetation (Kershaw et al., 1994). The stark ecophysiological contrasts between these two vegetation formations suggest that this replacement was a response to a major climate transition, but detailed information about the nature and timing of the transition has been elusive (Kershaw et al., 1994, 2000; Macphail, 1997).

Here we present a high-resolution record of vegetation and climate change from upland southeastern Australia, which shows the orbital scale climate response, over some ~280 k.y. straddling the Pliocene–Pleistocene boundary, of both “Tertiary” rainforest and “Quaternary” sclerophyll floristic elements. Stony Creek Basin, a small (~10 ha) paleolake of probable maar origin (144.13°E, 37.35°S, 550 m above sea level), preserves ~40 m of black, organic-rich, partly microlaminated silty clays. These sediments were cored in 2000 with hollow auger drilling equipment. Fission-track dating of zircons, recovered from an ~10-cm-thick pyroclastic horizon at 29.9 m depth and from basal fine sands at 39.8 m yielded ages of  $1.93 \pm 0.18$  Ma and  $1.99 \pm 0.43$  Ma, respectively (GSA Data Repository<sup>1</sup>). Paleomagnetic analyses indicate that the sediments in the upper ~25 m of the

core are of reversed polarity, and must predate the Brunhes–Matuyama polarity transition at 0.78 Ma. A zone of normal polarity below 25–28 m is attributed to the Olduvai subchron, consistent with the  $1\sigma$  error of fission-track ages, the upper boundary of which has an age of 1.781 Ma (Lisiecki and Raymo, 2005).

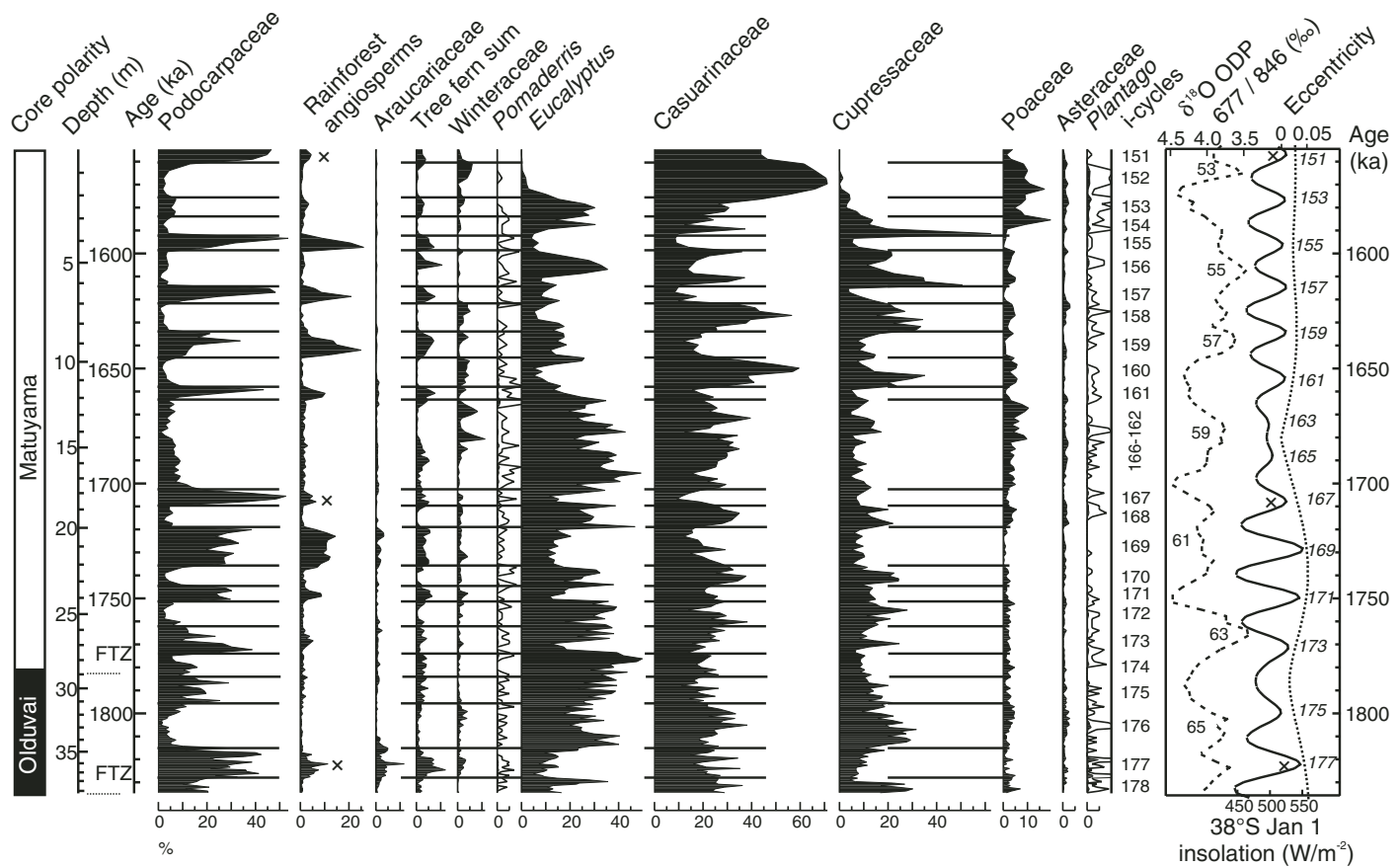
## STONY CREEK BASIN POLLEN RECORD

Pollen was analyzed from 208 samples at ~20 cm intervals. An average of 400–500 dry land pollen grains was counted per sample. Pollen preservation was generally excellent, and concentration was high, usually >100,000 grains  $\text{cm}^{-3}$ . Rainforest gymnosperms (Podocarpaceae and Araucariaceae), rainforest angiosperms, tree ferns, major open-forest dominants (*Eucalyptus* [Myrtaceae], Casuarinaceae, and *Callitris* [Cupressaceae]), and relatively moist (woody *Pomaderris* [Rhamnaceae] and Winteraceae) and dry (shrubby/herbaceous Poaceae, *Plantago*, and Asteraceae) open-forest understory taxa are plotted as percentages of total dry land pollen in Figure 1.

The pollen record reveals high-amplitude cyclic fluctuations of vegetation in upland southeastern Australia during the latest Pliocene and early Pleistocene. Many of the rainforest types represent taxa that were important compo-

<sup>1</sup>GSA Data Repository item 2007027, zircon fission-track and paleomagnetism methods, varve chronology, and pollen data, is available online at [www.geosociety.org/pubs/ft2007.htm](http://www.geosociety.org/pubs/ft2007.htm), or on request from [editing@geosociety.org](mailto:editing@geosociety.org) or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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**Figure 1.** Summary pollen percentage diagram of selected dry land taxa from Stony Creek Basin core, tuned to January 1 insolation, 38°S (Paillard et al., 1996). Ages of three tuning points are indicated by crosses. Rainforest cycles are correlated with Southern Hemisphere insolation maxima (= odd numbered i-cycles). Orbital eccentricity and composite  $\delta^{18}\text{O}$  data of Ocean Drilling Program (ODP) Sites 677/846 are shown for comparison. FTZ—location of fission-track zircon ages. *Pomaderris* and *Plantago* are exaggerated  $\times 10$ .

nents of Australian vegetation throughout much of the Cenozoic (Macphail et al., 1994), but are now highly restricted or extinct in Australia. Their Pleistocene histories are largely unknown. These types include: *Dacrydium*, *Dacrycarpus*, and extinct *Podosporites* cf. *microsaccatus* (Podocarpaceae); *Dilwynites* cf. *granulatus*, (cf. Wollemi Pine) (Araucariaceae); *Beauprea* (Proteaceae), *Ilex* (Aquifoliaceae), and the fern *Lophosoria* (Lophosoriaceae). Conversely, the open-forest vegetation includes *Pomaderris* and *Plantago*, which are today characteristic of eastern Australian open-canopied forests, but which are unknown prior to the early Pleistocene and late Pliocene, respectively (Macphail et al., 1995).

#### CHRONOLOGY DEVELOPMENT AND TIME SERIES ANALYSIS

Rhythmically alternating light/dark-colored couplets, ~40–400  $\mu\text{m}$  thick, occur in approximately half of the core. Laminated sediment samples were resin impregnated, polished, and observed with backscattered electron imagery, which translates the average atomic mass of a target into varying image brightness, revealing composition and porosity (Pike and Kemp,

1996). Couplets are composed of an ungraded, matrix-supported silty clay lamina, and a silt-poor, organic- and in places diatom-rich lamina. Each couplet is inferred to represent one year, based on its petrographic resemblance to annually generated clastic laminae fabrics typical of small, enclosed lakes (Dean et al., 1999) and because the seasonal climatic pulse is normally the dominant control on sediment production and deposition (Anderson and Dean, 1988; Anderson, 1996). These couplets are therefore interpreted as annual varves. They are unlikely to represent event deposits from episodic turbidity currents, because the silty clay laminae are consistently ungraded (Dean et al., 1999). Twenty-five stratigraphically representative laminated sediment samples were photographed under optical dissecting microscopy, and the thicknesses of 1653 couplets were measured with image analysis software. Varve thicknesses generally increase with depth, and indicate accumulation rates of 0.3–0.2  $\text{mm yr}^{-1}$  in the lower 15 m, and 0.2–0.1  $\text{mm yr}^{-1}$  in the upper 25 m of the sequence. An initial, 265.3-k.y.-long floating chronology (Data Repository; see footnote 1) was derived from an exponential function predicting varve thickness from depth, based on the

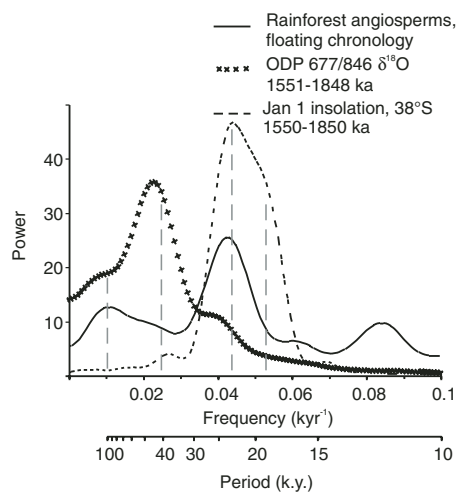
significant correlation (Pearson's  $r = 0.619$ ,  $p = 0.001$ ,  $n = 25$ ) between these two attributes.

When plotted in the time domain with this floating chronology (not illustrated), the rainforest angiosperms series shows distinct ~20–25 k.y. cycles that appear to be amplitude modulated by a much lower frequency cycle. In both the duration and fluctuating amplitude of its cycles, the rainforest angiosperms series resembles Earth's orbital precession, the amplitude of which is modulated by its envelope eccentricity. This similarity suggests that the rainforest angiosperms series represents a "clean" response (Shackleton, 2000) to a precession-dominated climate signal, such as mid-latitude summer insolation (Fig. 1), and this provides a basis for choosing an astronomical tuning target in order to place the Stony Creek Basin sequence precisely within the geological time scale.

In order to locate the stratigraphic position of an appropriate time window with which to compare the record, we provisionally located the floating chronology within the Matuyama chron by anchoring the core polarity change at the upper Olduvai boundary. We then compared the power spectrum of the floating chronology with power spectra of two likely forcing signals,

the composite benthic oxygen isotope stratigraphy from ODP 677/846 (Shackleton et al., 1990, 1995a), reflecting global ice volume, and of precession-dominated local summer insolation (Laskar, 1990) (January 1 insolation at 38°S, the approximate paleolatitude of the site at 1.5 Ma), both within 300 k.y. windows spanning between 1550 ka and 1850 ka, similar to the length and position of the provisionally anchored floating chronology.

Blackman-Tukey spectral analysis (Jenkins and Watts, 1968) (Fig. 2) shows that the marine oxygen isotope record is strongly dominated by variance near the 41 k.y. obliquity period, while the insolation series is dominated by a broad peak combining contributions from 19 k.y. and 23 k.y. precession components, which are not individually resolved in this short time window. The floating rainforest angiosperms spectrum is dominated by variance centered at 23 k.y., with side peaks at ~100 k.y. and ~12 k.y. This confirms the impression gained in the time domain, that rainforest angiosperms cycles are similar in duration to insolation cycles. Although the insolation and oxygen isotope series also include some power in the obliquity and precession bands, respectively, the log-linear plot of Figure 2 allows direct comparison of the proportion of variance in each band (Muller and MacDonald, 2000) and shows that the power of these secondary contributions is small. On this basis, the insolation series was chosen as a tuning target. Rainforest angiosperm peaks were correlated with Southern Hemisphere insolation peaks, on the simple first-order assumption that rainforest would expand at times of higher rainfall, driven by regionally higher tropical sea-surface temperatures asso-

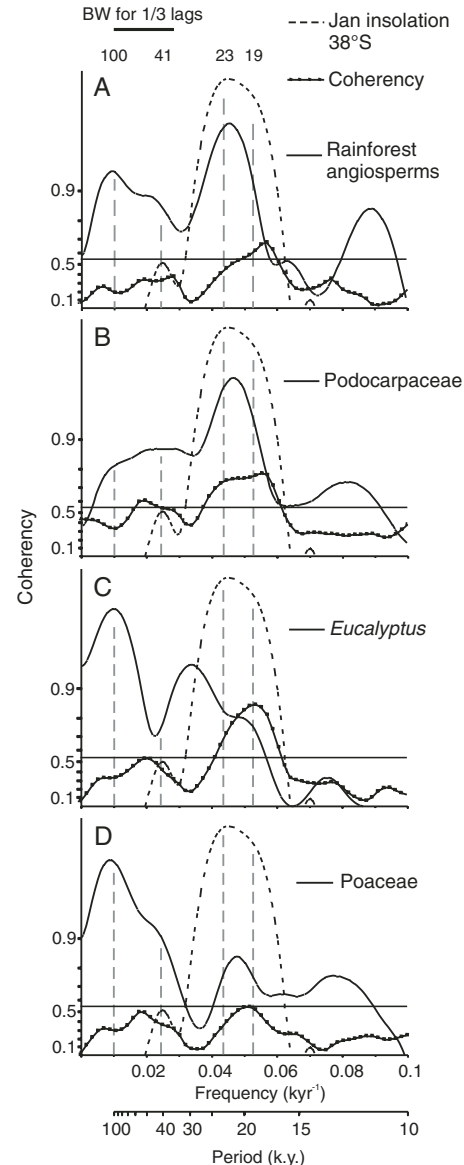


**Figure 2. Comparison of floating chronology with likely forcing functions representing global ice volume and local summer insolation. Also shown are linear power spectra of rainforest angiosperms, 38° S January 1 insolation between 1550 and 1850 ka, and Ocean Drilling Program (ODP) Sites 677/846  $\delta^{18}\text{O}$ , between 1551 and 1848 ka. Blackman-Tukey spectral analyses are shown with 1/3 lags.**

ciated with summer insolation maxima. This is consistent with patterns in regional terrestrial and marine paleoenvironmental records from the mid-late Quaternary that are dominated by the precessional signal (Hope et al., 2004; Holbourn et al., 2005).

The record was tuned by matching the amplitude-modulated pattern of rainforest angiosperm cycles with those of the insolation series. Three rainforest peaks were tied to correlative insolation peaks (*i*151 at 1557 ka, *i*167 at 1708 ka, and *i*177 at 1822 ka, using the *i*-cycle codification of Lourens et al., 1996), while the partial-cycle portions of the record above 1557 ka and below 1822 ka were left untuned. Following tuning, the record extends between 1554.7 and 1834.5 ka, a duration of 279.8 k.y., representing an ~5.5% “stretch” of the 265.3 k.y. floating chronology. While imperfections remain in the match of individual cycles to the insolation series, the use of only three widely spaced tuning points ensures that the tuning remains minimal (sensu Muller and MacDonald, 2000) with respect to insolation, thus limiting the importance of assumptions about the nature of climate forcing. Moreover, both before and after tuning, the amplitude modulation of the insolation target, which is a distinctive feature of the orbital imprint on climate proxy records (Shackleton et al., 1995b), is replicated by rainforest angiosperms, and to a lesser extent by Podocarpaceae.

Cross-spectral analyses of 38°S January 1 insolation with the tuned record confirm that cyclic fluctuations of rainforest angiosperms and Podocarpaceae (Fig. 3) primarily represent a response to insolation forcing. Nonzero coherency with insolation, at the 95% confidence level, is present for both rainforest types in the precession band and, for Podocarpaceae, in the obliquity band. The rainforest angiosperm spectrum also varies at ~100 k.y. and at ~12 k.y., periods which are not present in calculated insolation. Because the direct influence of eccentricity on insolation changes is very small (<0.1%) (Clemens and Tiedemann, 1997), these features are difficult to attribute directly to eccentricity. Instead, they probably reflect the transfer of variance that occurs when an amplitude-modulated climate proxy, such as the rainforest angiosperms series, is truncated at one end of its response spectrum (i.e., it drops close to zero at times of low-amplitude insolation) (Clemens and Tiedemann, 1997). Cross-spectral analyses of *Eucalyptus* and *Poaceae* indicate a different pattern in which variance is concentrated predominantly in the eccentricity band, although these taxa are also coherent with insolation in the precession band at 95% confidence. Since these open-forest indicators are essentially out of phase with rainforest within the 100 k.y. band, this appears to reflect the pacing by eccentricity of low-amplitude insolation cycles (Ridgwell et al., 1999), during which these taxa are best represented.



**Figure 3. Cross-spectral comparison of selected pollen types representing rainforest and open forest with calculated summer insolation. Bandwidth (BW) at 1/3 lags shown. Insolation was calculated for 38° S 1 January, 1550–1850 ka. Insolation changes account for increases in (A) rainforest angiosperms, (B) Podocarpaceae, (C) *Eucalyptus*, and (D) *Poaceae*. Cross-spectral comparisons with insolation indicate significant (nonzero coherency at 95% confidence limit) coherencies for all four pollen types in precession band, and for Podocarpaceae in obliquity band. Spectral power is plotted on log scales. Coherency spectra (solid line with crosses) are plotted on hyperbolic arc-tangent scales. Solid horizontal line indicates nonzero coherency at 95% confidence level. Dashed vertical lines denote primary orbital bands.**

## CONCLUSIONS

The changing amplitude of the seasonal cycle exerted the primary influence on the distribution of rainforest in southeastern Australia during the late Pliocene–early Pleistocene. The obliquity period, which strongly dominates the marine

oxygen isotope record during this interval, is difficult to discern in the Stony Creek Basin vegetation record, where instead, diverse rainforests alternated at precessional time scales with sclerophyllous forests. Such bimodal vegetation dynamics resemble dramatic glacial-interglacial vegetation changes familiar later in the Quaternary, but, because they were paced directly by effects of fluctuating seasonality, cannot accurately be described in terms of globally synchronized, glacial-interglacial cyclicality.

Such precessional dominance of climate responses was not universal in the Southern Hemisphere, since Pacific Ocean sea-surface temperature records from the late Pliocene near New Zealand (Saba et al., 2004) and from the early Pleistocene in the equatorial Pacific (Medina-Elizalde and Lea, 2005) were paced by obliquity. However, Raymo et al. (2006) suggested that the 41 k.y. world arose by cancellation of the precession component of high-latitude insolation, as ice growth and ablation were antiphased between Antarctic and Northern Hemisphere terrestrial ice sheets. If true, the 41 k.y. world may have been a predominantly oceanographic phenomenon that did not necessarily influence the climate of mid-latitude continents.

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#### REFERENCES CITED

- Anderson, R.Y., 1996, Seasonal sedimentation: A framework for reconstructing climatic and environmental change, *in* Kemp, A.E.S., ed., *Palaeoclimatology and Palaeoceanography from Laminated Sediments*: Geological Society of London Special Publication 116, p. 1–15.
- Anderson, R.Y., and Dean, W.E., 1988, Lacustrine varve formation through time: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 62, p. 215–235, doi: 10.1016/0031-0182(88)90055-7.
- Clemens, S.C., and Tiedemann, R., 1997, Eccentricity forcing of Pliocene early Pleistocene climate revealed in a marine oxygen-isotope record: *Nature*, v. 385, p. 801–804, doi: 10.1038/385801a0.
- Dean, J.M., Kemp, A.E.S., Bull, D., Pike, J., Patterson, G., and Zolitschka, B., 1999, Taking varves to bits: Scanning electron microscopy in the study of laminated sediments and varves: *Journal of Paleolimnology*, v. 22, p. 121–136, doi: 10.1023/A:1008069514445.
- Dupont, L.M., 2006, Late Pliocene vegetation and climate in Namibia (southern Africa) derived from palynology of ODP Site 1082: *Geochemistry, Geophysics, Geosystems*, v. 7, p. Q05007, doi: 10.1029/2005GC001208.
- Dupont, L.M., and Leroy, S.A.G., 1995, Steps toward drier climatic conditions in northwestern Africa during the Upper Pliocene, *in* Vrba, E.S., Denton, G.H., Burckle, L.H., and Partridge, T.C., eds., *Paleoclimate and Evolution with Emphasis on Human Origins*: New Haven and London, Yale University Press, p. 289–298.
- Haug, G.H., Ganopolski, A., Sigman, D.M., Rosell-Mele, A., Swann, G.E.A., Tiedemann, R., Jaccard, S.L., Bollmann, J., Maslin, M.A., Leng, M.J., and Eglinton, G., 2005, North Pacific seasonality and the glaciation of North America 2.7 million years ago: *Nature*, v. 433, p. 821–825, doi: 10.1038/nature03332.
- Holbourn, A., Kuhnt, W., Kawamura, H., Jian, Z.M., Grootes, P., Erlenkeuser, H., and Xu, J., 2005, Orbitally paced paleoproductivity variations in the Timor Sea and Indonesian throughflow variability during the last 460 kyr: *Paleoceanography*, v. 20, p. PA3002, doi: 10.1029/2004PA001094.
- Hope, G., Kershaw, A.P., van der Kaars, S., Xiangjun, S., Liew, P.M., Heusser, L.E., Takahara, H., McGlone, M., Miyoshi, N., and Moss, P.T., 2004, History of vegetation and habitat change in the Austral-Asian region: *Quaternary International*, v. 118–119, p. 103–126, doi: 10.1016/S1040-6182(03)00133-2.
- Jenkins, G.M., and Watts, D.G., 1968, *Spectral Analysis and its Applications*: Boca-Raton, Florida, Holden Day, 525 p.
- Kershaw, A.P., Martin, H.A., and McEwan Mason, J.R.C., 1994, The Neogene: A period of transition, *in* Hill, R.S., ed., *History of the Australian Vegetation: Cretaceous to Recent*: Cambridge, Cambridge University Press, p. 299–327.
- Kershaw, A.P., Quilty, P.G., David, B., Van Huet, S., and McMin, A., 2000, *Palaeobiogeography of the Quaternary of Australasia*: Association of Australasian Palaeontologists Memoirs, v. 23, p. 471–516.
- Klotz, S., Fauquette, S., Combourieu-Nebout, N., Uhl, D., Suc, J.P., and Mosbrugger, V., 2006, Seasonality intensification and long-term winter cooling as a part of the late Pliocene climate development: *Earth and Planetary Science Letters*, v. 241, p. 174–187, doi: 10.1016/j.epsl.2005.10.005.
- Laskar, J., 1990, The chaotic motion of the solar system: A numerical estimate of the chaotic zones: *Icarus*, v. 88, p. 266–291, doi: 10.1016/0019-1035(90)90084-M.
- Lisiecki, L.E., and Raymo, M.E., 2005, A Pliocene-Pleistocene stack of 57 globally distributed benthic  $\delta^{18}\text{O}$  records: *Paleoceanography*, v. 20, p. PA1003, doi: 10.1029/2004PA001071.
- Lourens, L.J., Antonarakou, A., Hilgen, F.J., Van Hoof, A.A.M., Vergnaud-Grazzini, C., and Zachariase, W.J., 1996, Evaluation of the Plio-Pleistocene astronomical timescale: *Paleoceanography*, v. 11, p. 391–413, doi: 10.1029/96PA01125.
- Macphail, M.K., 1997, Late Neogene early Pleistocene climates in Australia: Fossil pollen- and spore-based estimates in retrospect and prospect: *Australian Journal of Botany*, v. 45, p. 425–464, doi: 10.1071/BT96052.
- Macphail, M.K., Alley, N.F., Truswell, E.M., and Sluiter, I.R.K., 1994, Early Tertiary vegetation: Evidence from spores and pollen, *in* Hill, R.S., ed., *History of the Australian Vegetation: Cretaceous to Recent*: Cambridge, Cambridge University Press, p. 189–261.
- Macphail, M.K., Colhoun, E.A., and Fitzsimons, S.J., 1995, Key periods in the evolution of the Cenozoic vegetation and flora in western Tasmania: The late Pliocene: *Australian Journal of Botany*, v. 43, p. 505–526, doi: 10.1071/BT950505.
- Medina-Elizalde, M., and Lea, D.W., 2005, The mid-Pleistocene transition in the tropical Pacific: *Science*, v. 310, p. 1009–1012, doi: 10.1126/science.1115933.
- Mildenhall, D.C., Hollis, C.J., and Naish, T.R., 2004, Orbitally-influenced vegetation record of the mid-Pleistocene climate transition, offshore eastern New Zealand (ODP Leg 181, Site 1123): *Marine Geology*, v. 205, p. 87–111, doi: 10.1016/S0025-3227(04)00019-2.
- Muller, R.A., and MacDonald, G.J., 2000, *Ice ages and astronomical causes: Data, spectral analysis and mechanisms*: Chichester, UK, Springer-Praxis, 318 p.
- Paillard, D., Labeyrie, L., and Yiou, P., 1996, Macintosh program performs time-series analysis: *Eos (Transactions, American Geophysical Union)*, v. 77, p. 379.
- Pike, J., and Kemp, A.E.S., 1996, Preparation and analysis techniques for studies of laminated sediments, *in* Kemp, A.E.S., ed., *Palaeoclimatology and Palaeoceanography from Laminated Sediments*: Geological Society of London Special Publication 116, p. 157–169.
- Raymo, M.E., and Nisancioglu, K., 2003, The 41 kyr world: Milankovitch's other unsolved mystery: *Paleoceanography*, v. 18, p. 1011, doi: 10.1029/2002PA000791.
- Raymo, M.E., Lisiecki, L.E., and Nisancioglu, K.H., 2006, Plio-Pleistocene ice volume, Antarctic climate, and the global  $\delta^{18}\text{O}$  record: *Science*, v. 313, p. 492–495.
- Ridgwell, A.J., Watson, A.J., and Raymo, M.E., 1999, Is the spectral signature of the 100 kyr glacial cycle consistent with a Milankovitch origin?: *Paleoceanography*, v. 14, p. 437–440, doi: 10.1029/1999PA900018.
- Ruddiman, W.F., Raymo, M.E., Martinson, D.G., Clement, B.M., and Backman, J., 1989, Pleistocene evolution: Northern Hemisphere ice sheets and North Atlantic Ocean: *Paleoceanography*, v. 4, p. 353–412.
- Saba, A.T., Sikes, E.L., Hayward, B.W., and Howard, W.R., 2004, Pliocene sea surface temperature changes in ODP Site 1125, Chatham Rise, east of New Zealand: *Marine Geology*, v. 205, p. 113–125.
- Shackleton, N.J., 2000, The 100,000 year ice-age cycle identified and found to lag temperature, carbon dioxide, and orbital forcing: *Science*, v. 289, p. 1897–1902, doi: 10.1126/science.289.5486.1897.
- Shackleton, N.J., Berger, A., and Peltier, W.R., 1990, An alternative astronomical calibration of the Lower Pleistocene timescale based on ODP Site 677: *Transactions of the Royal Society of Edinburgh*, v. 81, p. 251–261.
- Shackleton, N.J., Crowhurst, S., Hagelberg, T., Pisias, N., and Schneider, D.A., 1995a, A new late Neogene timescale: Application to Leg 138 sites, *in* Pisias, N.G., Mayer, L.A., Janacek, T.R., Palmer-Julson, A. and van Andel, T.H., eds., *Proceedings of the Ocean Drilling Program, Scientific Results, Volume 138*: College Station, Texas, Ocean Drilling Program, p. 73–101.
- Shackleton, N.J., Hagelberg, T.K., and Crowhurst, S.J., 1995b, Evaluating the success of astronomical tuning: Pitfalls of using coherence as a criterion for assessing pre-Pleistocene timescales: *Paleoceanography*, v. 10, p. 693–697, doi: 10.1029/95PA01454.
- Traverse, A., 1982, Response of world vegetation to Neogene tectonic and climatic events: *Alcheringa*, v. 6, p. 197–209.

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