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Plio-Pleistocene cyclothems from Wanganui Basin, New Zealand: type locality for an astrochronologic time-scale, or template for recognizing ancient glacio-eustacy?

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Phil. Trans. R. Soc. Lond. A 1999 **357**, 1861-1872
doi: 10.1098/rsta.1999.0404

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Plio-Pleistocene cyclothems from Wanganui Basin, New Zealand: type locality for an astrochronologic time-scale, or template for recognizing ancient glacio-eustasy?

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Wanganui Basin is a 200×200 km^2 ovoid sedimentary basin of Plio-Pleistocene age situated in a back-arc position in western North Island, New Zealand. The eastern edge of the basin has been subjected to smooth tectonic uplift since about 350 000 years BP, resulting in the exposure onland of young sediments which elsewhere are more usually located beneath the modern continental shelf. The fill of the basin comprises several kilometres of markedly cyclothemic sediment of Plio-Pleistocene age. Accurate environmental interpretation of the succession is greatly enhanced by the presence of abundant sedimentary structures, and fossil invertebrates whose conspecific descendants live in modern New Zealand seas. The maximum water depth attained during the deposition of most cyclothems is less than 100 m, i.e. less than the known 100–130 m magnitude of most Late Pleistocene sea-level fluctuations. The magnetostratigraphic boundaries and abundant tephra which occur within the section allow accurate international correlation. The 47 Wanganui cyclothems which correspond to the last 2.4 Ma (oxygen isotope stages 100–1) each correlate with the highstand part only of each glacial-interglacial isotope stage couplet, i.e. with odd-numbered isotope stages. Even-numbered glacial stages are represented by the unconformities which separate stratigraphically adjacent cyclothems, and which mark sea-level withdrawal and subaerial exposure of the inner part of the basin. Therefore, only about half of elapsed geological time is represented by sediment within shallow-water basin fills deposited during times of high-amplitude glacio-eustatic sea-level fluctuation. Such strata, including those at Wanganui, are unsuitable for use as type sections for time-scale intervals. Nonetheless, the cyclothemic sedimentary motifs described from Wanganui, and especially the known relationships there between shellbed type and systems tracts, provide invaluable insights for the interpretation of other Phanerozoic glacio-eustatic successions such as those of Permo-Carboniferous and Ordovician age.

Keywords: sequence; sea-level change; eustasy; cyclic sediments; cyclothem; Wanganui Basin

1. Introduction

For the last 2.5 Ma, Earth's climatic history has been controlled by Milankovitch variations in the planetary orbit, and comprised alternate periods of glaciation and

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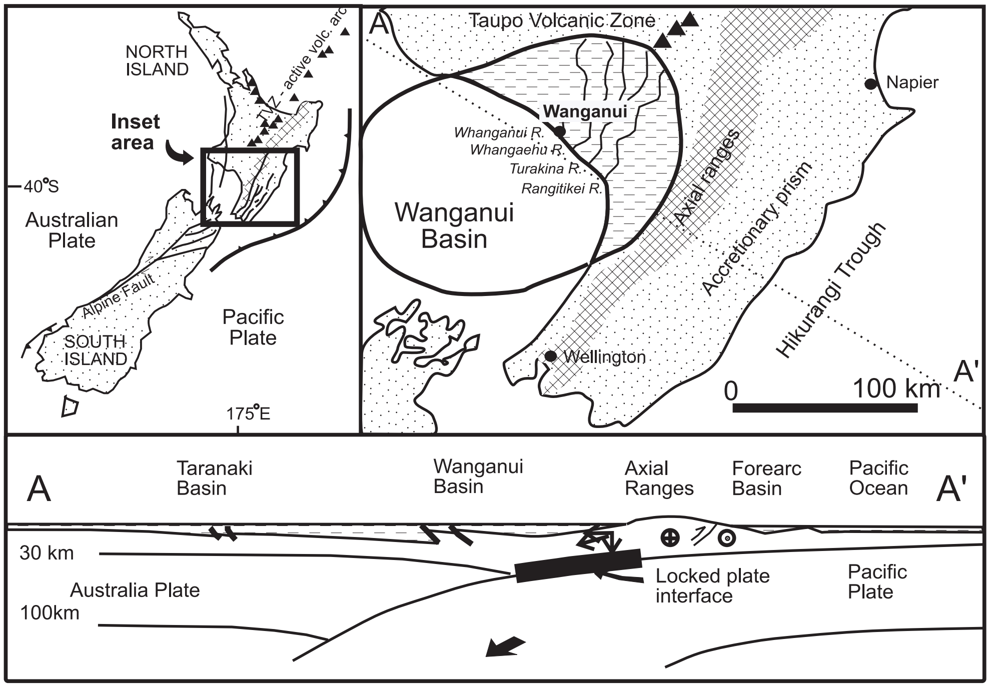

Figure 1. Locality map and geological setting of Wanganui Basin. Regional tectonic interpretation after Stern & Davey (1989) and Stern *et al.* (1992, 1993).

interglaciation with a dominant frequency of 41 000 years per cycle (Tiedemann *et al.* 1994; Shackleton *et al.* 1995*a*, *b*). Concomitantly, eustatic sea-level has fluctuated with a magnitude of 70–130 m, and caused rapid transgressions and regressions of the shoreline across the world's continental margins. The resulting shallow marine sedimentary record is cyclothemic, with each cyclothem corresponding to a single climatic and sea-level cycle. Neotectonic uplift at rates up to *ca.* 0.5 m ka^{-1} (Pillans 1986) has resulted in three onland New Zealand sedimentary basins containing excellent cyclothemic records of Plio-Pleistocene sea-level change, namely, the Hawke's Bay, Mangaopari and Wanganui Basins (Fleming 1953; Beu & Edwards 1984; Carter *et al.* 1991). Young cyclothemic sediments are also known from California (Clifton *et al.* 1988), Japan (Tokuhashi & Kondo 1989) and Italy (Rio *et al.* 1996).

The Wanganui Basin (figure 1) contains one of the most complete shallow water Plio-Pleistocene stratigraphic records in the world. As summarized in a recent review by Carter & Naish (1998*a*), the *ca.* 3 km thick basin-fill for the last 3.6 Ma comprises 47 superposed 5th- and 6th-order shallow marine cyclothems (figure 2) which correspond to individual 41 ka and 100 ka sea-level cycles since oxygen isotope stage MG6 (figure 3). Stages MG6–5 are represented by marine cyclothems (Saul *et al.* 1999), whereas stages 17–4 are represented by a suite of partly coeval and partly younger uplifted marine terrace deposits (Pillans 1983, 1990). In addition, a predominantly glacial loess stratigraphy exists for isotope stages 12–2 (Pillans 1988).

Each marine cyclothem (figure 2) corresponds to an unconformity-bound stratigraphic sequence (e.g. Vail *et al.* 1991), and contains a transgressive systems tract, often a mid-cycle shellbed, a highstand systems tract (Abbott *et al.* 1989; Abbott &

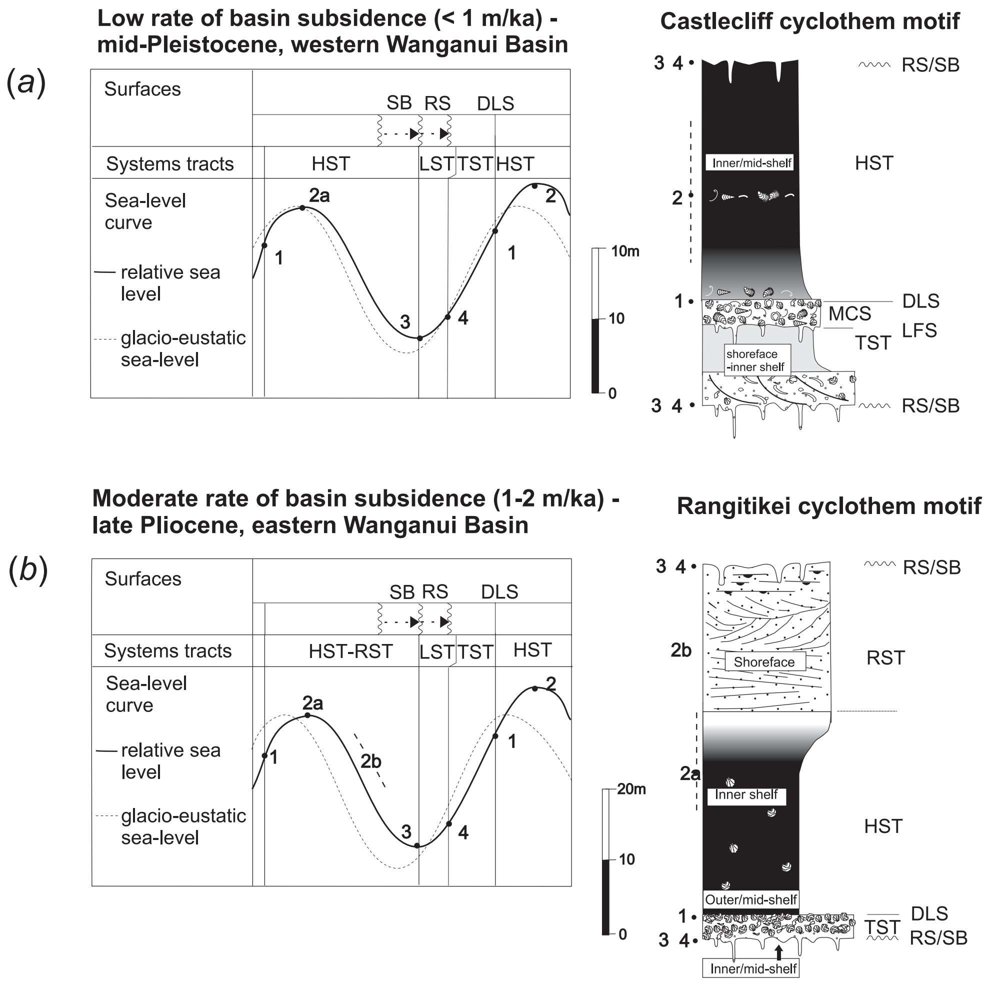

Figure 2. Idealized Castlecliff and Rangitikei cyclothem motifs from Wanganui Basin, and the inferred sea-level curves which forced their sedimentary architecture (after Naish & Kamp 1997*a*).

Carter 1994; Abbott 1997*a*, 1998), and sometimes a regressive systems tract (Naish & Kamp 1997*a*). Each sequence also contains up to four stratal discontinuities; in ascending order, the sequence boundary, ravinement surface, local flooding surface and downlap surface (Carter *et al*. 1998). In onland Wanganui Basin, all cylothems younger than isotope stage 100 represent shelf sediments deposited during interglacial sea-level highs (Beu & Edwards 1984; Abbott 1997*b*; Abbott & Carter 1997; Naish & Kamp 1997*b*) (figure 4). Marine lowstand systems tracts do not occur, and the stratigraphic record therefore comprises stacked interglacial cyclothems within which glacial periods are represented only by the sequence-bounding unconformities. The rare intervals of lowstand systems tract which do occur are represented by non-marine sediment or soil located immediately beneath a sequence boundary (Abbott 1992). In contrast, some Late Pliocene cyclothems from Hawkes Bay (Haywick *et al*. 1991, 1992) and Mangaopari Stream (Gammon 1997) include sediments which

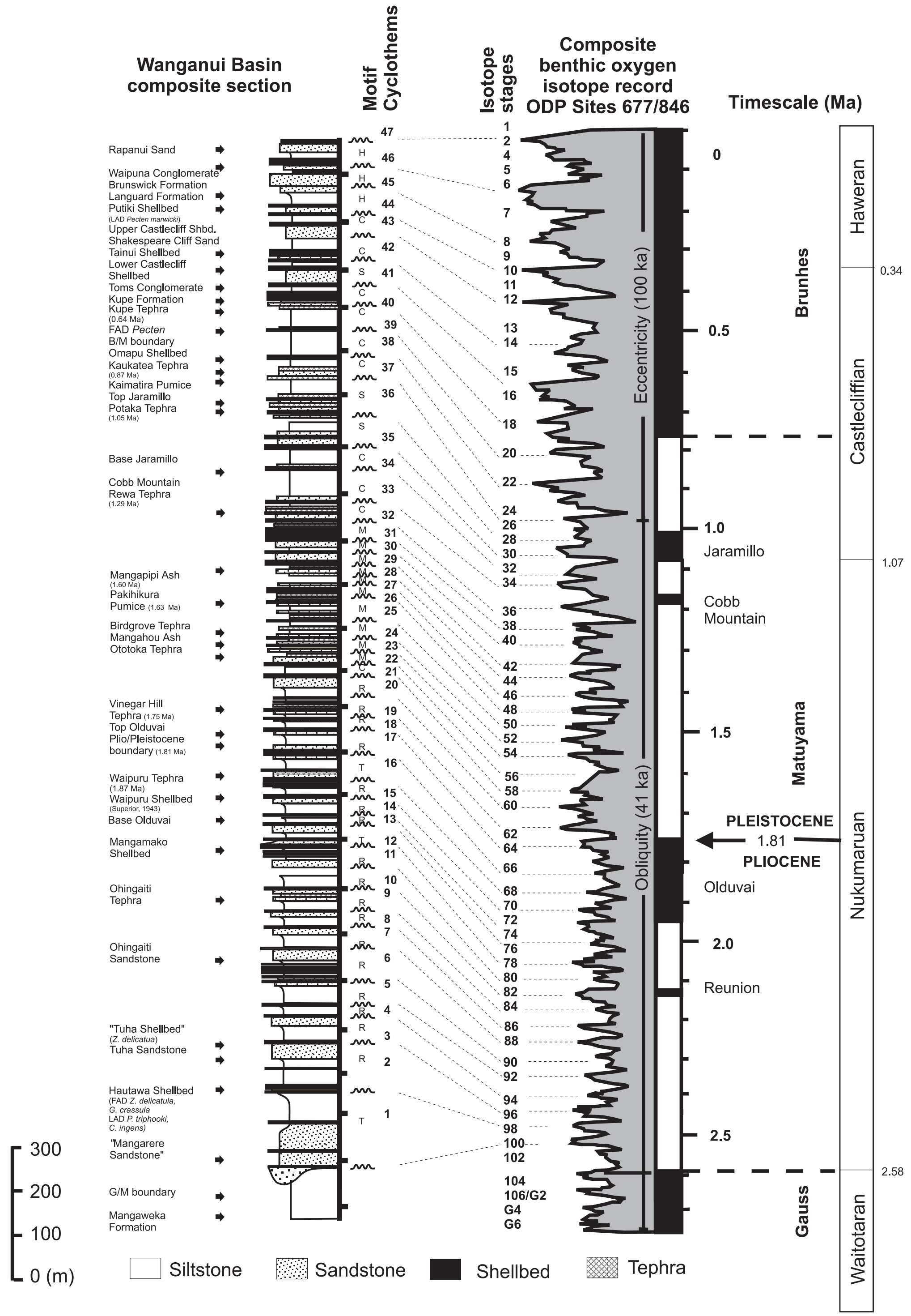

Figure 3. Composite stratigraphy for Wanganui Basin, showing the 47 cyclothems which occur and their correlation to the orbitally tuned isotope scale (after Naish *et al.* 1998).

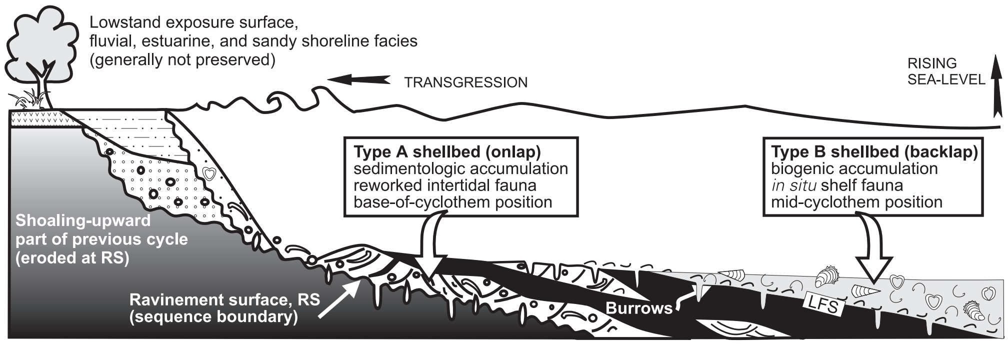

Figure 4. Summary cross-section of the main depositional facies and inferred environments for the lower and middle parts of a typical mid-Pleistocene cyclothem from Castlecliff, Wanganui (after Abbott 1997*a*).

were deposited below their contemporary lowstand shoreline, resulting in sedimentary motifs which contain a marine record of both glacial and interglacial stages, and are bounded by correlative conformities.

2. The definition of the geological time-scale

The traditional method of recognizing the Periods (and Systems) of the geological time-scale has been by biostratigraphy, based largely on fossil taxa from the historical type area for each Period. With the development of non-biostratigraphic means of dating strata, it has become evident that this loose system fails to recognize the critical distinction between the definition of a time-scale unit, and the separate issue of its correlation (Campbell 1959; Hughes *et al*. 1967; Carter 1974). Accordingly, in the 1970s, the International Subcommission for Stratigraphic Classification commenced a series of studies to redefine the intervals of the time-scale by placing internationally agreed stratotype markers at the base, and only the base, of each appropriate unit (e.g. Bassett 1985). These 'golden pegs' (or, global stratotype sections and points (GSSPs)) may be designated in sections other than the original type section. Satisfyingly, the first, which represents the base-Devonian boundary, was hammered in onomatopoetically at Klonk, Czechoslovakia (Martinsson 1977).

No stratigraphic horizon has been subject to more controversy than the definition of the Pliocene–Pleistocene Epoch/Series boundary. Indeed, in one sense this boundary was the first 'golden peg' to be driven in, when a Temporary Commission of the International Geological Congress recommended that the boundary should be located at the first sign of climatic deterioration in the Italian marine Neogene succession, which in the view of the Commission was marked by the base of the Calabrian Stage (King & Oakley 1950). A lengthy controversy then arose as to whether the Plio-Pleistocene boundary was climatic or stratigraphic in nature, where its type locality should be (for there was also ambiguity as to the location of the type locality for the Calabrian Stage), and whether macrofossils, microfossils, nannofossils, magnetostratigraphy, isotope stratigraphy, or even hominid evolution, should be central to its definition (see the historical summary in, for example, Berggren & Van Couvering 1979). The matter was finally put to rest by designation of an international boundary stratotype (GSSP) at the base of marine claystones conformably overlying sapropel bed e in the Vrica Section, southern Italy (Aguirre &

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Pasini 1985; Van Couvering 1997*a*), with an estimated age of 1.81 Ma. That some stratigraphers now wish to relocate the base-Pleistocene GSSP on the grounds that 'a Pliocene–Pleistocene Boundary at 1.8 Ma … is not marked by any distinctive litho- or biostratigraphic discontinuity accompanying a substantial global change in climate' (Morrison & Kukla 1998) shows that at the turn of the millennium the ghost of catastrophism stalks us still. The history of development of the geological time-scale surely teaches us that the scale is not necessarily, or even best, based on 'natural' global breaks in the rock record (e.g. Van Couvering 1997*b*). Those who do not recognize this reality will be doomed to an infinite regress of GSSP redefinitions into the distant future.

Recent developments in the astronomical calibration of sedimentary cycles provide an alternative method of assigning an absolute age to the base-Pleistocene GSSP and adjacent strata (Shackleton *et al*. 1990; Hilgen 1991*a*, *b*; Tiedemann *et al*. 1994; Lourens *et al*. 1996, 1997). In such studies, proxy climatic records are tuned to the astronomical solutions of the variations of the Earth's orbital parameters: eccentricity, obliquity, and precession (e.g. Berger & Loutre 1991; Laskar 1990; Quinn *et al*. 1991). The tuned time-scales which result have proved to be of higher resolution and accuracy than conventional time-scales based on linear interpolation between radiometrically dated calibration points in sea-floor magnetic anomaly sequences (Berggren *et al*. 1995; Cande & Kent 1995), and show that these radiometric ages are consistently too young by 5–7%. Thus the base-Pleistocene GSSP is now firmly based on physical stratigraphy, is located a little below the top of the Olduvai Subchron, and has an estimated age of 1.81 Ma based on astrochronologic correlation (Lourens *et al*. 1996, 1997).

The ISSC guidelines for designating a GSSP (Remane *et al*. 1996) do not require that a boundary stratotype section should exhibit an orbital climatic signature, and nor did the recognition of orbital cyclicity play any role in the designation of the base-Pleistocene GSSP. This is not an oversight, but results from the fact that modern outcrop-based astrostratigraphic studies only started to appear relatively recently (e.g. House 1985; Weedon 1985; Hilgen 1987). It was therefore to some degree a happenstance that the chosen type locality for the base-Pleistocene at Vrica comprises upper bathyal sediments deposited in water 500–800 m deep (Pasini & Colalongo 1996, p. 18), and therefore probably represents a complete interglacial and glacial record (Lourens *et al*. 1997).

The use of astrochronologic tuning for Plio-Pleistocene sediments has resulted in unprecedented stratigraphic resolution, and also yielded a highly accurate worldwide method of age estimation for sediments which exhibit suitable cyclicity. We therefore need to address how such astrochronologies might be extended further back in time, and how they would then be integrated with the conventional geological time-scale.

3. Integration of astrostratigraphy with the geological time-scale

The astrochronologic tuning of young Cenozoic sediments is based firmly upon physical calculations of the changing pattern of Earth's orbital parameters over the last several million years. Furthermore, these retrodictions start with a description of Earth's current position, and the resulting orbital time-series therefore extends back in time from an anchor point at 0.00 Ma. This astronomical target curve has now been integrated with outcrop records back to the 5.3 Ma Miocene–Pliocene boundary, and current research is likely to result in an outcrop-based astrostratigraphic time-scale that extends back into the Middle Miocene (Laskar, this issue).

The idea that Solar System dynamics might play a role in controlling sediment cyclicity has a long history, including the classic studies of Gilbert (1895) on Cretaceous chalks from Colorado, and Bradley (1929) on the Eocene Green River Formation from the western United States. More recently, increasing numbers of cyclostratigraphic or astrostratigraphic studies have become available for pre-Miocene strata (cf. Schwarzacher 1993), including Oligocene–Miocene oceanic sediments from ODP Leg 154 on the Ceara Rise (Weedon *et al*. 1997), Mid-Cretaceous black shales from Italy (Herbert & Fischer 1986), Early Jurassic marine sediments from England (Weedon 1985; Weedon & Jenkyns 1990), and Triassic rift-fill sediments from the eastern USA (Olsen & Kent 1996, and this issue). Unfortunately, orbital target curves against which to assess these older successions cannot be provided for periods before *ca.* 35 Ma (latest Eocene), because instabilities in the required numerical analysis result in chaotic solutions (Laskar, this issue). There is therefore no target curve available to which successions older than *ca.* 35 Ma can be tuned. Nonetheless—and as shown by their authors, who use a judicious combination of sedimentologic (facies analysis, and likely sedimentation rates), stratigraphic (continuous coring or outcrop exposure) and statistical (power spectrum analysis) techniques—the published studies of older successions have almost certainly captured accurate and internally continuous snapshots of parts of Earth's pre-35 Ma orbital history. For the moment these astrostratigraphic snapshots 'float' in time, in the sense that they are unable to be tied to an astrochronologic target curve, and instead are only loosely assigned to component intervals of the standard geological time-scale using conventional correlation criteria. In principle, however, there is nothing to prevent the eventual extension of similar studies throughout the Phanerozoic sedimentary record. The exciting prospect therefore exists of a complete Phanerozoic astrostratigraphy, which would extend the unprecedented accuracy and precision of correlation already available for the Late Cenozoic to earlier parts of the time-scale. Towards this end, we have now reached the point at which the ISSC should incorporate astrostratigraphic considerations into the criteria used by its GSSP working parties.

4. Quo vadis Wanganui and other shallow-water successions?

The shallow marine cyclostratigraphy of Wanganui Basin can be correlated with current astronomically calibrated Plio-Pleistocene time-scales. Correlations, and the resultant integrated chronology for the basin, are based on radiometric ages of interbedded rhyolitic tephra, biostatigraphic datums, palaeomagnetic polarity measurements, and cycle correlations with the oxygen isotope time-scale (figure 3) (Naish *et al*. 1996, 1997, 1998). Numeric ages on the tephra are consistent with the interpreted magnetostratigraphy and cyclostratigraphy, and fit well with the astronomically calibrated time-scale. The historic subdivision of the New Zealand marine Plio-Pleistocene is based on the biostratigraphy of shallow marine strata in both Wanganui and East Coast Basins, North Island (e.g. Fleming 1944; Beu 1969, 1995; Boreham 1963), but the ready availability of new correlation techniques raises the possibility of defining stage boundaries using criteria such as magnetic reversal boundaries (Carter & Naish 1998*b*). In any event, cyclostratigraphic correlations now provide age estimates for 116 stratigraphic horizons in Wanganui Basin that are not otherwise

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able to be dated, and thereby help to establish an astronomical chronostratigraphy for the New Zealand Plio-Pleistocene, including the accurate location of the Plio-Pleistocene boundary (Naish *et al*. 1996, 1997).

The shallow marine record of Wanganui Basin clearly contains a strong astrostratigraphic signature. However, up to half the sedimentary record is missing at unconformities between successive interglacial cyclothems, and any interpretation of the Wanganui succession must therefore lean heavily on cyclostratigraphies which were developed elsewhere; first, in the guise of the proxy ice-volume curve indicated from oxygen isotope studies (e.g. Shackleton & Opdyke 1973), and, second, in tuned astrochronologies (e.g. Lourens *et al*. 1996). Whatever their traditional historic or biostratigraphic importance (and Wanganui Basin is the type area for the Waitotaran, Nukumaruan and Castlecliffian Stages in New Zealand; cf. figure 3), shallow marine sections are by their very nature not suited to act as type localities for international GSSPs (cf. Pillans *et al*. 1991). Rather, GSSPs should be chosen in sections which meet the current ISSC criteria, and which where possible also contain a continuous astrostratigraphic signature in pelagic sedimentary facies, i.e. are of deeper-water origin.

Despite not being suitable for GSSP purposes, shallow marine successions are widely represented on continental margins, and remain important. For instance, their richly fossiliferous nature aids assessment of both the environment of deposition and their age. And understanding the shallow-water sedimentary motifs deposited during times of glacio-eustasy, such as those drawn from the sediments of the Wanganui Basin, provides powerful templates for the interpretation of more ancient glacio-eustatic strata such as those of Permo-Carboniferous, Ordovician, or Precambrian age. Indeed, where suitable pelagic successions do not exist, shallow marine successions may provide the only available astrostratigraphy for some Periods of Earth history.

5. Conclusions

1. Marine successions deposited during times of glacio-eustatic sea-level variation, such as those of the Plio-Pleistocene, are markedly cyclothemic. In terms of sequence stratigraphy, each cyclothem corresponds also to a stratigraphic sequence. Individual cyclothems deposited in highstand water depths less than *ca.* 130 m are punctuated by sequence boundary unconformities, each of which represents subaerial exposure of the immediately preceding seabed during a time of glacial lowstand.

2. An accurate astronomical age model is available for the Milankovitch-scale climatic and sea-level fluctuations which occurred during the Plio-Pleistocene. Consequently, refined correlations using astrochronologic cycle-matching can be made into shallow-water cyclothemic facies of that age, as exemplified by studies of the Wanganui Basin, New Zealand, and the Boso Peninsula, Japan. However, up to half of elapsed geological time (lowstands) is unrepresented by strata in such shallow-water successions, which are therefore not suitable for designation as stratotypes for intervals of geological time despite the very clear astrostratigraphy that they exemplify.

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3. Nonetheless, sedimentary models built upon Plio-Pleistocene successions provide excellent templates for the interpretation of older glacio-eustatic (cyclothemic) successions. Astronomical age models are not able to be computed for strata older than *ca.* 35 Ma. Older sediments which contain an undoubted record of Milankovitch-scale cyclicity therefore 'float' uncertainly alongside the geological time-scale. Extending astrostratigraphic studies throughout the Phanerozoic record, demonstrating their internal continuity, and eventually anchoring them to an accurate numeric time-scale, should be accorded high priority. Correlating an astrostratigraphy from oceanic into shallow-water strata requires a close understanding of sedimentary depositional models, including especially those drawn from Plio-Pleistocene studies.

This research was supported by Australian Research Council grant A-39805139. R.M.C. thanks organizers Nick Shackleton, Nick McCave and Graham Weedon for their kind invitation to participate in the Royal Society Discussion Meeting.

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