Cyclostratigraphic record of the Triassic: a critical examination

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Abstract: High frequency (fourth- and fifth-order) cyclicity is a common feature of sedimentary sequences in all depositional settings. While tectonism and autocyclic processes are clearly responsible for this cyclicity in some instances, many cases are interpreted as resulting from orbitally forced variations in solar insolation at the Milankovitch frequencies, that is, the precession and short and long eccentricity cycles at scales of tens of thousands to hundreds of thousands of years. This forcing is presumed to have controlled sedimentation through periodic changes in climate or sea-level. Examples of interpreted Milankovitch-frequency cyclicity occur throughout the Triassic record, and include much of the German Triassic, the Alpine Triassic and the Newark Supergroup of North America. The cyclostratigraphy of these sections has been used as a tool for intrabasinal and interbasinal correlation, and for chronostratigraphy. These interpretations are not always without controversy, however, as conceptual arguments and radio–isotopic age data have called some of these conclusions into question.

The stratigraphic record is inherently cyclical, but the scale of this cyclicity varies in scale from the outcrop to the continental. The largest scale, or first-order cycles are those that are truly continental in scope, as they are thought to record changes in sea-level caused by the operation of the Wilson cycle at a scale of hundreds of millions of years (Prothero 1990; Jacquin & Graciansky 1998). Second-order cycles, corresponding to the sedimentary sequences of Sloss (1963), last from tens of millions up to one hundred million years, and are generally considered the result of long-term trends in eustasy, potentially in direct proportion to the activity of the mid-ocean ridges. The cause of the third-order sea-level cycles, of millions of years duration, is not well understood; these cycles are often apparent at the basin scale and may be related to short-term tectonic activity. Higher frequency fourth- and fifth-order cycles frequently are evident at the outcrop scale. Fourth-order cycles include the classic cyclothems of the Carboniferous (e.g. Heckel 1986) and have periods in the range of hundreds of thousands of years, while fifth-order cycles operate at frequencies of tens of thousands of years. These high-frequency (fourth- and fifth-order) cycles are often referred to as Milankovitch cycles due to the match of their interpreted periods with the calculated Milankovitch orbital frequences. It is these high-frequency cycles that are the focus of much modern cyclostratigraphy, and the record and application of these cycles in the Triassic system is the focus of this chapter.

Orbital forcing

The Milankovitch hypothesis has become a conceptual paradigm in sedimentary geology because it appears to not only explain the rhythmicity of the Pleistocene glaciations, but also provides a model of stratigraphic succession that can be recognized, seemingly ubiquitously, in the rock record. Since the 1980s, an enormous volume of literature has been generated that is dedicated to the hypothesis that the cyclicity of sedimentary sequences has been controlled by the orbital forcing of climate on scales of 10^4 to 10^5 years. The concept is certainly not a recent one. Herschel (1832) suggested that changes in the amount of solar radiation reaching the Earth, caused by the eccentricity and precession cycles, could significantly affect climate and geological processes; Croll (1864), for example, specifically hypothesized orbital control for the cyclicity of Pleistocene glaciation. G. K. Gilbert (1895) pioneered the use of presumed climatic cycles in pre-Pleistocene stratigraphy by interpreting sequences of Cretaceous limestone-shale couplets as resulting from the precession cycle, but it was Bradley's (1929) analysis of varves in the Green River Formation that provided the first solid evidence linking orbital periods and sedimentary cycles.

Milutin Milankovitch (1941) is justly famous for calculating the changes in insolation that resulted in the past from the variation of the three key orbital parameters, citing these variations as cause for the Pleistocene glaciations. Corroborating evidence for the hypothesis appeared in the stable-isotope record of deep-sea sediments (Emiliani 1955; Emiliani & Geiss 1958), but did not achieve rigor until the ages of the deep-sea sediments were constrained by magnetostratigraphy (Hays *et al.* 1976). Even though the evidence for regular periodicities of sedimentary cycles in the pre-Pleistocene

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generally lacks the strength demonstrated for the Pleistocene, convincing arguments have been made for orbitally forced climate control of many cyclic sedimentary sequences.

The theoretical aspects of the Milankovitch hypothesis are well-summarized by Schwarzacher (1993, 2000) and Hinnov (2004). The various gravitational forces to which the Earth is subjected create a series of perturbations of the Earth's orbit that affect both the Earth–Sun distance and the angle of incidence of the Sun's rays and, consequently, the amount of solar insolation. Three primary orbital cycles are recognized: (1) The eccentricity of the Earth's orbit varies from nearly 0 (almost circular) to 0.06 (slightly elliptical) and back with an average period of 100 ka (Berger 1984). Superimposed fluctuations on the degree of variation have been detected at intervals of 400 ka, 1300 ka, and 2 Ma (Berger *et al.* 1992); (2) The inclination of the Earth's axis of rotation relative to the plane of the ecliptic, that is, obliquity, is presently about 23.5°, but varies from 22° to 24.5° and back over an average period of 41 ka; and (3) The precession or wobble of the Earth's axis of rotation, caused by the gravitational pull of the Sun and Moon on the equatorial bulge, results in a periodic change in the relationship of the seasons to Earth's perihelion. The precession cycle is also modified by the gradual rotation of the elliptical orbit, resulting in average periods of the precession index at 19 and 23 ka (Berger 1988; Hinnov 2004). These three parameters combine to produce predictable fluctuations in the amount of solar energy reaching the atmosphere. The eccentricity cycle by itself has little effect on insolation but does control the amplitude of the precession effect. The obliquity cycle produces variations in the degree of seasonality and is most pronounced at high latitudes (Weedon 1993, 2003). The precession index, conversely, determines the direction of inclination when the Earth is at perihelion and aphelion and, consequently, controls the amount of radiation received during each season. The effect of this cycle is strongest at low latitudes and results in latitudinal shifts in the caloric equator and shifting of the boundaries between climate zones (Berger 1978).

The interpretation of a sedimentary response to the orbital elements described above assumes regular changes in Earth's climate systems in response to changes in insolation. However, the resulting changes in climate are not nearly so predictable as the causal insolation changes. For example, the influence of the eccentricity cycle interpreted from many sedimentary sequences is significantly stronger than the precession index, the opposite of what would be predicted from insolation alone (De Boer & Smith 1994). Various feedback systems, such as variations in ice volume or atmospheric CO_2, may be responsible for creating a resonating or oscillating climate system with a frequency matched to the eccentricity cycle. General-circulation-type climate models have only limited ability to predict specific climate paramaters for the distant geological past, due to uncertainties of land-mass position, elevation and atmospheric composition (Kutzbach 1994; Sellwood & Valdes 2006). Nevertheless, various models suggest pronounced climatic effects of orbital changes in insolation on global climate (Kutzbach 1994; Morrill *et al.* 2001). Implicit in the interpretation of orbital control of sedimentation is the assumption that patterns of sedimentation are more sensitive to small-scale changes in sea-level or changes in climate than to tectonic influences or autocyclic controls.

Recognition of orbitally forced cyclicity in the stratigraphic record depends on being able to match the period of sedimentary cycles with frequencies in the Milankovitch band. Simply dividing the time represented within a stratigraphic section by the number of cycles present to yield an average time per cycle should not be considered sufficient to demonstrate Milankovitch periodicity conclusively. The standard method of analyzing the cyclicity of a stratigraphic sequence is spectral analysis, which determines the strength (relative frequency of repetition) of cycles of various periods, although thickness is an imperfect proxy for time in stratigraphic successions. Power spectra are generated by plotting the frequencies of the number of cycles per unit thickness in the strata; the most commonly recurring frequencies will form peaks corresponding to the cycle thickness (Fig. 1). Several methods exist for testing the significance of the identified peaks, for example matching the frequency of cycle repetition to a combination of sine and cosine waves by Fourier transform (see reviews of several methods in Schwarzacher 1993).

Bundling patterns of the cycles, caused by the imprint of the eccentricity cycle on the precession cycle, are sometimes cited as evidence of Milankovitch control; that is, a 5:1 bundling ratio may be indicative of cycles with both precessional (with mean 20 ka) and short eccentricity (100 ka) frequencies. One method of identifying this bundling is plotting the cumulative departure of the cycle thickness from the mean against the position of the cycle in the section (Fig. 2). These plots, called Fischer plots, record changes in sedimentation rate, and represent in graphic form the change in accommodation space through time (Fischer 1964); increasing thickness of the cycles up-section, for example, recorded as a positive departure from the mean, presumably resulted from some combination of sea-level rise or increased rate of subsidence.

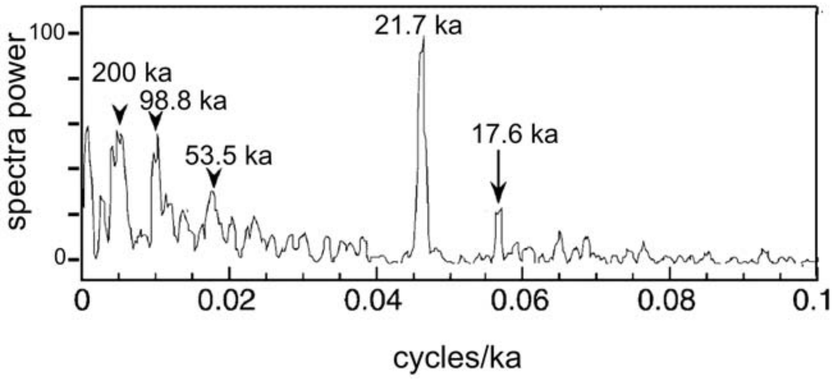

Fig. 1. Power spectrum based on depth-rank analysis data from shallow marine carbonates in the Middle Triassic Latemar Massif in the Dolomites, northern Italy (adapted from Preto *et al.* 2001). Peak intervals were converted to time by assuming precessional forcing. The peak at 21.7 ka was produced by combining a frequency doublet that is predicted for the Triassic.

Triassic sea-level

In one of the pioneering works of twentieth-century stratigraphy, Sloss (1963) described six major sedimentary sequences, or cycles, on the North American continent, defined by major episodes of transgression and bounding unconformities. These major cycles of eustasy, lasting from tens of millions to well over a hundred million years, are now commonly referred to as super-sequences because they are at least an order of magnitude greater in scale than stratigraphic sequences (i.e. an unconformity bounded succession of conformable strata), as they were later defined by sequence stratigraphers (e.g. Vail *et al.* 1977). These super-sequences, also called first-order sub-cycles (Jacquin & Graciansky 1998), are thought to be equivalent to the second-order sea-level cycles that are controlled by the rates of ocean crust formation (Plint *et al.* 1992). Within the framework of Sloss, the entirety of the Triassic falls within the upper part of the Absaroka sequence.

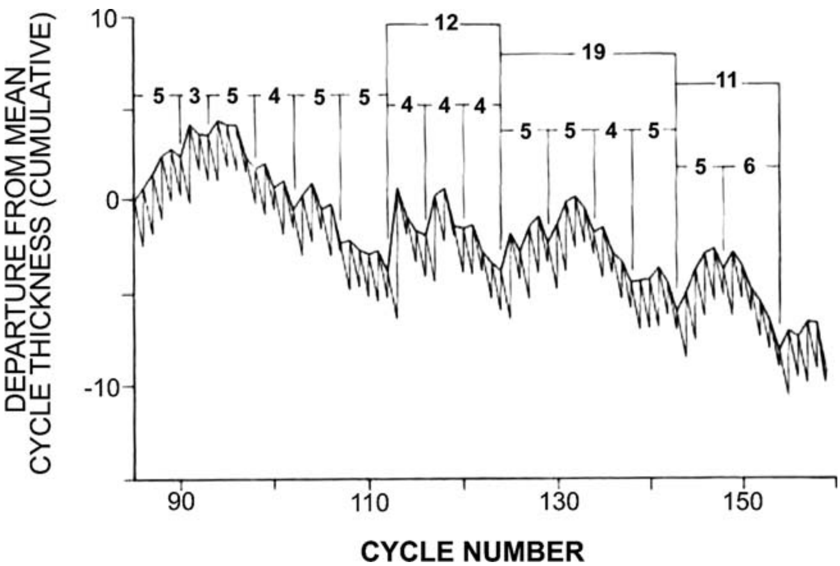

Fig. 2. This example of a Fischer plot is for a portion of a core of the Dachstein Limestone from the Transdanubian Range, Hungary (adapted from Balog *et al.* 1997). Identification of the bundling patterns of the cycles (i.e. bundling ratios) ideally permits correlation with Milankovitch frequencies at multiple orders.

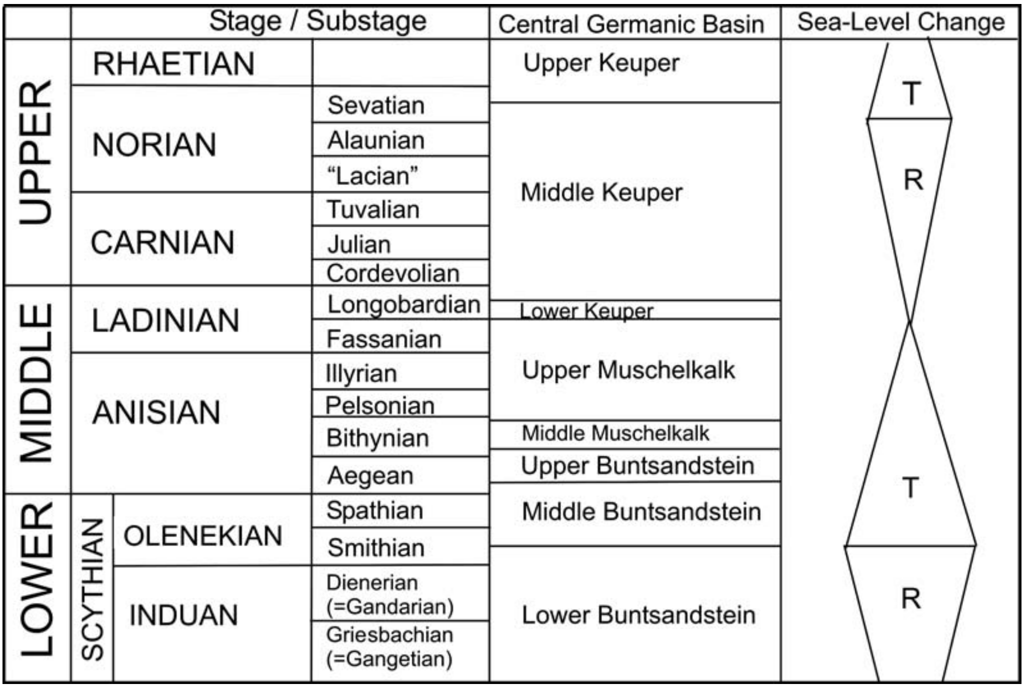

Fig. 3. Stratigraphy of the central Germanic basin, adapted from Bachmann & Kozur (2004), with general sea-level cycles of Aigner & Bachmann (1992).

In a now-classic paper, Haq *et al.* (1987) compiled relative sea-level data from both outcrop and the subsurface to establish a curve of global sea-level changes since the start of the Triassic. Based on these data, Haq *et al.* (1987, 1988) concluded that the area of continental emergence at the start of the Triassic was at the maximum level for the entire Phanerozoic. From this minimum, sea-level increased overall through most of the Triassic Period, before falling again in the latest Triassic (see also Hardenbol *et al.* 1998; Golonka & Ford 2000). This overall trend of Triassic eustasy is well illustrated by the German Triassic. As described by Aigner & Bachmann (1992), the entirety of the German Triassic can be described as a single transgressive–regressive super-sequence (i.e. second-order cycle), best exemplified by the classic succession of the Lower Triassic Buntsandstein, Middle Triassic Muschelkalk and Upper Triassic Keuper (Fig. 3). On this overall trend, according to Haq *et al.* (1987, 1988), are superimposed four super-cycles, the boundaries of which approximately coincide with the boundaries of the Scythian–Anisian, Ladinian–Carnian, Carnian–Norian and Norian–Rhaetian stages. Haq *et al.* (1987) included the uppermost Rhaetian with the Hettangian in the succeeding super-cycle. The super-cycles are, in turn, divided into eleven third-order cycles – five in the Lower Triassic, two in the middle Triassic, and four in the Upper Triassic – each lasting one to several million years. Superimposed on these third-order cycles are the higher-frequency fourth and fifth-order cycles that have been interpreted from essentially every stage of the Triassic, from the system base to the Triassic–Jurassic boundary, and from every conceivable depositional environment, from deep marine to desert.

Case studies

South China

Many of the best-known and most-studied stratigraphic sections of the basal Triassic occur in South China. For example, the shelfal, mixed carbonate-clastic sediments of the Feixianguan Formation in Guangxi and Guizho provinces provide important sections for study of the Induan 'extinction aftermath' (Lehrmann *et al.* 2001). Li *et al.* (2007) and Guo *et al.* (2008) examined the cyclicity of strata in a continuous Upper Permian – Lower Triassic section, the Yinkeng Formation in the Pingdingshan section at Chaohu, Anhui Province.

Guo *et al.* in their study recorded the lithology, thickness and magnetic susceptibility of a 44-m section of deep-marine strata, variously comprising sets of limestone–mudstone, limestone–marl–mudstone, or limestone–mudstone–shale, from slightly below the Changhsingian–Induan boundary to above the Induan–Olenekian boundary. Applying spectral analysis to the logged section and wavelet analysis to the magnetic susceptibility data yielded similar results. The authors identified 56 short cycles, which they interpreted as forced by the precession frequency at 19.5 ka (Berger *et al.* 1992), and 12 cycles of bundling at a ratio of 4.67:1, interpreted as the short eccentricity cycle. Guo *et al.* further used this cyclostratigraphic interpretation as a basis for calculating a duration of 1.1 Ma for the Induan stage, which accords well with estimates from other means (Gradstein *et al.* 2004).

Lehrmann *et al.* (2001) examined the cyclicity of the Olenekian carbonates of the Great Bank of Guizhou in the Nanpanjiang basin, South China. These authors found that vertical facies changes in 164 metres of one section defined 83 cycles, or parasequences, that typically shallow upward from subtidal grainstones to intertidal ribbon rock. Changes in thickness of the parasequences throughout the section were interpreted by the authors as reflecting long-term changes in accommodation space within a third-order sequence. Radioisotopic constraints on the duration of deposition of the section suggest that the parasequences represent fifth-order cycles (0.01–0.1 Ma), and a purported 5:1 bundling ratio imply low-amplitude eustatic control of deposition at the precessional frequency (Lehrmann *et al.* 2001).

The German Triassic

Alberti (1834) defined the Triassic for the tripartite nature of the sequence in the Germanic basin (the southern part of the Central European basin), where its thickness exceeds 3000 m. The classic German Triassic stratigraphy consists of the mainly continental Buntsandstein, the marine to marginal-marine Muschelkalk, and the largely continental Keuper (Bachman & Kozur 2004). The poor biostratigraphic record of portions of this sequence long have made precise correlation to the marine realm problematic. However, recent advances in the magnetostratigraphy of the German Triassic and in biostratigraphy based on conchostracans have led to greatly improved correlations to the Tethyan and Boreal realms (Szurlies *et al.* 2003; Bachman & Kozur 2004; Kozur & Bachman 2006; Szurlies 2007). Cyclicity is a prominent characteristic of much of the strata of the Germanic basin, with cycles of varying thickness interpreted as expression of Milankovitch frequencies from 20 ka–400 ka (Bachman & Kozur 2004; Kozur & Bachman 2006). Gaps are evident in the sedimentary section that compromise the ability to identify cycles, particularly in the Middle and Upper Triassic portions of the section.

Buntsandstein. Szurlies (2007) divided the entire Buntsandstein into 60 widely correlatable cycles that he interpreted as forced by climate change at the eccentricity frequency. Furthermore, the author derived a duration of 6 Ma for deposition of the Buntsandstein from this cyclostratigraphy. This estimate accords well with the calculation of Menning *et al.* (2005), which combined the cyclostratigraphy with radio–isotopic constraints on stage boundaries. The stratigraphic trends of the Buntsandstein in the center of the Germanic basin are well-summarized by Bachmann & Kozur (2004) and Kozur & Bachmann (2006). In central Germany, the Lower Buntsandstein comprises roughly 300 m of red-bed siliciclastics and interbedded limestones. Szurlies *et al.* (2003) subdivided this succession into 20 fining-upward cycles that can be correlated across the Central European basin, and hypothesized that they might have been forced by base-level fluctuations driven by Milankovitch climate forcing at the eccentricity frequency. Bachmann & Kozur (2004) and Kozur & Bachmann (2006) described the basinal facies of the Lower Buntsandstein, comprising the Calvörde and Bernburg formations, as consisting of 22 cycles of 10 m–20 m thickness of sandstone to oolite, fining upward to shale. Bachmann & Kozur (2004) attributed the cyclicity of these formations, which are dated as upper Changhsingian to lower Smithian, to orbital forcing at the 100 ka (short eccentricity) frequency.

The Middle Buntsandstein (Smithian–basal Anisian) encompasses the (in ascending order) Quickborn Sandstone and the Volpriehausen, Detfurth, Hardegsen and Solling formations, which collectively display 35–40 cycles that are mostly fining-upward. Bachmann & Kozur (2004) interpret these cycles as resulting from the short eccentricity (100 ka) frequency, but cautioned that unconformities within the section prevent use of the cycles from accurately determining the duration of the Middle Buntsandstein deposition. The Upper Buntsandstein in the central Germanic basin consists of the 150 to 300 metre-thick Röt Formation (lower Anisian), which comprises nine fining-upward cycles. Based on their ability to divide these cycles further into five subcycles, Bachmann & Kozur (2004) interpreted these as short eccentricity cycles.

Orbitally forced cyclicity is interpreted also in the Buntsandstein from regions at the margins of the Germanic basin. For example, Clemmensen *et al.* (1994) examined the Middle Buntsandstein on the island of Helgoland, in the northwest Germanic Basin. These authors recognized arid-humid climatic cyclicity in the alternating eolian–lacustrine facies and interpreted thin (*c*. 2.5 m) cycles as forced by the precession cycle, and thicker (11.0 m) cycles as the result of climate forcing at the eccentricity frequency. Significantly, however, these interpretations lacked statistical rigor because they were based solely on the number of cycles counted and a 10 Ma estimate of the duration of the Scythian, now considered unlikely and superceded by more recent estimates (Gradstein *et al.* 2004).

Bourquin *et al.* (2006) also analyzed the sequence stratigraphy of the Triassic, but in the western Germanic Basin, rather than the centre. These authors defined two major depositional cycles, a Scythian cycle encompassing the Lower to Middle Buntsandstein, unconformably separated from an Anisian–Carnian cycle comprising the Upper Buntsandstein and the entire Muschelkalk. These cycles correspond approximately to super-cycles (Upper Absaroka) UAA-1 and UAA-2 of Haq *et al.* (1987). The overall pattern through most of the Middle Buntsandstein is one of deposition by braided fluvial systems that were laterally equivalent to lacustrine depositional systems situated toward the basin center. Passing into the Upper Buntsandstein, the trend is toward development of lower gradient floodplain and more abundant lacustrine facies, suggesting a closer proximity to the Tethys Seaway late in the Scythian. This is consistent with the interpretation of Haq *et al.* (1987, 1988) of a gradual transgressive trend through most of the Upper Absaroka sequence. Cycles in the Middle and Upper Buntsandstein are attributed by Bourquin *et al.* (2006) to fluctuations in climate and/or sediment supply.

Muschelkalk. The Middle Triassic Muschelkalk comprises the mainly fully marine Lower Muschelkalk, hypersaline facies of the Middle Muschelkalk and the predominantly marine Upper Muschelkalk. In the central Germanic basin, the Lower Muschelkalk consists mainly of limestones and marls of the Jena Formation of Anisian age. Cyclostratigraphic patterns are interpreted from the Muschelkalk sediments as they are in the Buntsandstein (Kozur & Bachmann 2003, 2006; Bachmann & Kozur 2004). The Jena Formation, for example, includes 21 cycles that Bachmann & Kozur (2004) interpreted as short eccentricity cycles. In the central Germanic basin, the Middle Muschelkalk comprises the Karlstadt, Heilbronn and Diemel formations (Anisian in age), which together contain nine cycles. The Upper Muschelkalk consists of the Trochitenkalk and Meissner formations (upper Anisian through lower Ladinian) and together include 40 short eccentricity cycles.

Vecsei & Duringer (2003) interpreted the Middle to Upper Muschelkalk as part of a long-term, third-order transgressive cycle. The authors recognized fourth-order deepening-upward cycles in the deeper shelf environments, caused by high-frequency sea-level changes superimposed on the longer term eustatic trend. They also noted, however, that contemporaneous cycles in coastal bar and lagoonal environments appear to be shallowing-upward, and speculated that the sedimentary systems in these differing environments apparently responded in different ways to sea-level forcing. Menning *et al.* (2005) calculated a 6.4 Ma duration for total Muschelkalk deposition.

Keuper. The high-frequency cyclicity documented in the Muschelkalk continued during the deposition of the largely continental sediments of the Middle to Upper Triassic Keuper (Kozur & Bachmann 2003, 2006; Vecsei & Duringer 2003; Bachmann & Kozur 2004). The Lower Keuper is represented by the Erfurt Formation, which displays eight cycles (Bachmann & Kozur 2004). Fourth and fifth-order cyclicity is evident also in the Ladinian through Norian (through Sevatian) Middle Keuper, which in the central Germanic basin includes the Grabfeld, Stuttgart, Weser formations and Löwenstein (equivalent to Arnstadt) formations (e.g. Bachmann & Kozur 2004). Kozur & Bachmann (2006) identified nine cycles in the (Ladinian) Grabfelt Formation. Reduced rates of sedimentation, condensed sections and substantial stratigraphic gaps prevent clear identification of unambiguous short eccentricity cycles in the remainder of the Middle Keuper, or the Exter Formation (Rhaetian) of the Upper Keuper, although long eccentricity cycles (i.e. 400 ka) have been recognized in the Arnstadt Formation (Bachman & Kozur 2004).

Reinhardt & Ricken (2000) studied the periodicity of the decimeter-scale alternating mudstone–dolomite beds of the Steinmergel Middle Keuper in southern Germany, which they interpreted as reflecting fluctuating hydrological conditions on an extensive playa system, driven by climate change. Using spectral analysis of core and outcrop sections, the authors identified cycle intervals that they correlated to precession (19.8 ka), short eccentricity (109 ka), long eccentricity (413 ka) and very long eccentricity (2 Ma) frequencies of Berger & Loutre (1989, 1994). Combining available radio–isotopic dates with the cyclostratigraphy, Menning *et al.* (2005) calculated a duration for total Keuper deposition of *c*. 40 Ma.

The Alpine Triassic

Fischer & Bottjer (1991) described the Alpine Triassic as 'the classic ground for the recognition of cyclic carbonate platform emergence, presumably a measure of eustatic oscillations'. Triassic sedimentation in the Alpine region was controlled by the interplay of tectonics and eustasy. In the Northern Calcareous Alps, for instance, the Permian through the Early Triassic was characterized mainly by deposition of siliciclastics during a transgression on a passive continental margin, likely formed by Tethyan rifting (Mandl 2000). Carbonate shelf deposition was established on this margin by Middle Triassic, but tectonism, probably during the middle Anisian, caused block faulting that segmented the shelf and created a series of isolated platforms separated by interplatform shelf and basinal environments (Balog *et al.* 1997; Mandl 2000). Progradation of the platforms continued into the early Carnian, followed by an interval of lowstand and emergence. Rising sea-level during the late Carnian and increased carbonate production filled much of the interbasin palaeotopography. During the earliest Norian, a rapid pulse of sea-level rise accompanied accentuated growth of reefs that rimmed these broad platforms.

Latemar. One of the Alpine areas most studied is the Latemar Massif, a carbonate platform of Middle Triassic (upper Anisian–Ladinian) age in the Dolomites of northern Italy. The cyclic facies of the Ladinian-age Latemar Limestone are characterized by sub-metre to metre-scale couplets of subtidal limestone with a thin dolomite caliche cap (Goldhammer 1987; Goldhammer *et al.* 1987; Hinnov & Goldhammer 1991). The orderly and repeated arrangement of these facies clearly suggests episodes of submergence, during which limestone was deposited subtidally, alternating with episodes of subaerial exposure of the carbonate sediments that led to vadose diagenesis. The cycles appear to be further ordered in upward-thinning bundles of five cycles each. Hinnov & Goldhammer (1991) applied spectral analysis to the stratigraphic section and applied an estimate for the duration of the Ladinian stage to obtain an average value of 21 ka for the cyclic couplets and 96 ka and 110 ka for the modulating eccentricity frequency.

Brack *et al.* (1996) and Mundil *et al.* (1996) cast serious doubt on the conclusion that Latemar cyclicity was forced only by Milankovitch frequency orbital cycles. The authors of these studies performed single crystal U–Pb dating on volcaniclastic beds in the Buchenstein Beds, the basinal equivalent of the Latemar platform facies that was deposited in a sediment-starved intra-platform basin. Ages from the beds bracketing the equivalent cyclical facies of the Latemar platform indicated that the time interval represented was too short to accommodate deposition of the 598 precession (*c.* 20 ka) cycles counted by Goldhammer (1987), even with maximum error estimates for the dates. Consequently, Brack *et al.* (1996) and Mundil *et al.* (1996) concluded that the metre-scale cyclicity of the Latemar succession reflects processes operating on a millennial scale ($<$8 ka), a higher frequency than predicted by the Milankovitch hypothesis.

Egenhoff *et al.* (1999) reexamined the facies architecture of the Latemar Massif with an eye toward resolving some of these issues. In their view, the overall facies architecture of the build-up (i.e. alternating cyclical and tepee facies) reflects the effects of third-order sea-level cyclicity on the depth of water over the build-up. The authors found that the individual shallowing-upward cycles, defined by marine flooding surfaces at the base and top, are traceable across the build-up for a distance of several kilometers, although thickness and facies vary considerably within individual cycles, due to varying positions on the platform (i.e. intertidal *versus* lagoonal). They surmised that autocylic processes (e.g. lateral facies migration) are inadequate to explain exposure surfaces that are correlative across the entire platform, and concluded that some order of cyclic sea-level fluctuation likely influenced deposition of the Latemar cycles. However, they left unresolved the issue of the timing of the cycles.

An additional perspective was provided by Preto *et al.* (2001). These authors logged a 160-m section of lagoonal carbonates on the Latemar platform in the so-called Upper Cyclic Facies at cm-scale and applied a depth-rank analysis to the resultant data. Subsequent spectral analysis identified peaks that the authors associated with the precession, obliquity, short eccentricity and long eccentricity cycles. Notably, the authors rejected the issues raised by radio–isotopic dating of the Latemar and equivalent Buchenstein Beds, and stated that 'The Latemar signature thus constitutes the oldest pristine Milankovitch signature yet observed in the geologic record'.

The controversy over the frequency of the Latemar cycles continued as Mundil *et al.* (2003) produced new U–Pb zircon dates from ash beds in the platform interior to better constrain the interval of deposition. These new data indicated that the average length of time represented by individual shallowing-upward cycles must be less than previously calculated, closer to 4 ka. Zühlke *et al.* (2003) generated a new set of cyclostratigraphic measurements from the Latemar section, which they analyzed through spectral analysis. Using the age constraints of Mundil *et al.* (2003), the authors found that although individual cycles occur at a sub-Milankovitch frequency, stacking patterns (1:4–5) produced higher-order cycles that appear to match the precessional frequency, not the short eccentricity frequency, as previously interpreted (Goldhammer *et al.* 1987). Moreover, stacking

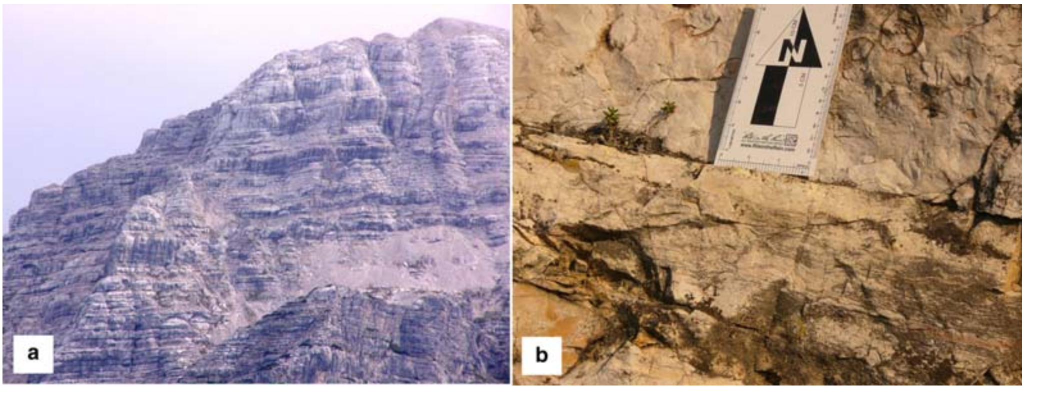

Fig. 4. Cyclicity of the Upper Triassic Dachstein Limestone. (**a**) Classic section of metre-scale cyclically bedded shallow marine carbonates at Loferer Steinberge, southwest of Salzburg, Austria. (**b**) Detail of Lofer cycles in the Dachstein at a quarry at Tata, Hungary. The top of one cycle occurs at the top of the microbial-laminite below the scale. The laminite is overlain by subtidal carbonate containing thick-shelled megalodontid bivalves (to the left and right of scale).

patterns of 1:9.9 and 1:24.0 identified by power spectra appear to match the obliquity and short eccentricity frequencies. Kent *et al.* (2004) contributed to the Latemar discussion with magnetostratigraphic data from the Latemar platform succession that they correlated to the Buchenstein Beds, apparently validating the radio–isotopic age correlations between the platform and the very condensed basinal successions. Hinnov (2006) critiqued the work of Kent *et al.* (2004), particularly in regard to the validity of the correlation between the Latemar platform beds and the Buchenstein Beds, but she offered no effective counter-argument to the constraints provided by the radio–isotopic ages, as pointed out by Kent *et al.* (2006). Meyers (2008) attempted to provide some resolution to the issue through a new analysis of the Latemar data of Preto *et al.* (2001) by utilizing a multitaper-method spectral analysis. The fit of the cycles to orbital frequencies was quantified with an average spectral misfit algorithm that was used to test the probability of various sedimentation rates. Meyers' test rejected the sedimentation rate applied previously by Preto *et al.* (2001), but obtained a significant fit with a much higher rate that is compatible with the age constraints of Mundil *et al.* (2003) and Kent *et al.* (2004). Nevertheless, the spectral analysis of Meyers was able to identify cycles at the precessional, obliquity and short eccentricity frequencies.

Lofer cycles. The classic Upper Triassic carbonate platform succession of the Tethyan margin is presented by the Dachstein Formation, which is widely exposed in the Northern, Southern and Eastern Alps of Austria, Italy, Hungary and Slovakia (Fig. 4a). The stratigraphy of the Alpine Triassic is complex. In some parts of the Northern Calcareous Alps, for example, the Dachstein encompasses the entirety of the Norian and Rhaetian (Fig. 5), whereas in other areas it overlies the Hauptdolomit and is overlain by the Kössen Formation, or is laterally equivalent to these units, as in the Dolomites (Flügel 1981).

The rhythmicity of the bedding of the Dachstein shallow platform carbonates has been long recognized and interpreted as evidence of some ordered cyclicity of depositional processes (Sander 1936), most likely related to sea-level change (Schwarzacher 1948, 1954). Fischer (1964, 1975) described the classic Lofer cycles (named for the Loferer Alps in the Salzburg region of Austria) as deepening-upward transgressive or transgressive–regressive couplets, comprising a basal paleosol, often clayey, overlain by intertidal microbial laminites, and subtidal skeletal wackestone/packstone that may or may not be overlain by another intertidal laminite, all capped by a succeeding palaosol. Fischer (1964, 1975) interpreted these cycles as driven

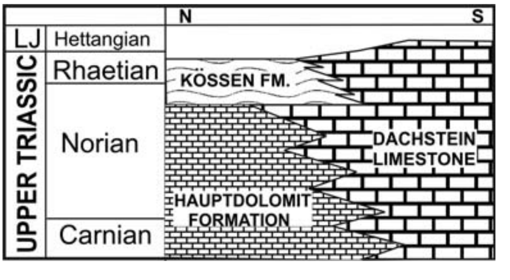

Fig. 5. Generalized stratigraphy of the Upper Triassic in the Northern Calcareous Alps, from north to south across the Bavarian and Tyrolian nappes (adapted from Mandl 2000).

by Milankovitch-frequency eustasy. Subsequent researchers have found that the classic cycles of the Dachstein in fact differ considerably from the description by Fischer. Goldhammer *et al.* (1990), Haas (1994) and Satterley (1996) reinterpreted the classic Northern Alpine cycles as dominantly regressive, shallowing-upward sequences in which a basal palaeosol is overlain directly by subtidal facies, which is in turn succeeded by the intertidal facies (Fig. 4b). Goldhammer *et al.* (1990), in particular demonstrated that the cyclicity failed to display the orderly stacking patterns predicted by Fischer. Balog *et al.* (1997), working in the Transdanubian Range of western Hungary, similarly found that the cycles there displayed quite a varied lithostratigraphy, including transgressive, regressive and transgressive-regressive couplets (Fig. 6), and considered the cyclicity as a genuine artifact of high-frequency (fifth-order) eustasy operating in combination with local changes in accommodation space.

Up to 3 km of platform carbonates are well-exposed in the Transdanubian Range, where inner platform facies comprise cyclically bedded lagoonal-peritidal carbonates. In the Dachstein Limestone of Hungary, modulating cycles, or stacking patterns of individual Lofer cycles are notably absent (Goldhammer *et al.* 1990). Haas (1994) examined in detail the extent of lithostratigraphic variations within the cycles throughout the succession and concluded that individual Lofer cycles likely do represent metre-scale sea-level variations at the precessional frequency, but also concluded that no higher-order composite cyclicity is present in the section, likely as a consequence of superimposed variation in subsidence rate.

Similarly, Balog *et al.* (1997, 1999) examined the metre-scale cyclicity of the Upper Triassic (Norian) Main Dolomite, which underlies the Dachstein in the Transdanubian Range (Hungary). Here the cycles are defined, as they are in the Latemar, by subaerial exposure surfaces, which are characterized by dolomitization and caliche (Fig. 6). They interpreted the cyclicity as most closely approximating a precessional frequency forced by sea-level change, but concluded that modulating cycles were only poorly developed (Fig. 2).

Reijmer & Everaars (1991) hypothesized that facies deposited as the basinal equivalent of the Dachstein platform should display a similar periodicity as the classic Lofer cycles because basinal sediments would have been derived from the platform at rates corresponding to the platform sediment production. The authors tested a sequence of calciturbidites from the Pedata/Pötschen Schichten in the eastern Alps of Austria and found multiple spectral frequencies, some of which seemingly matched Milankovitch frequencies, although others did not.

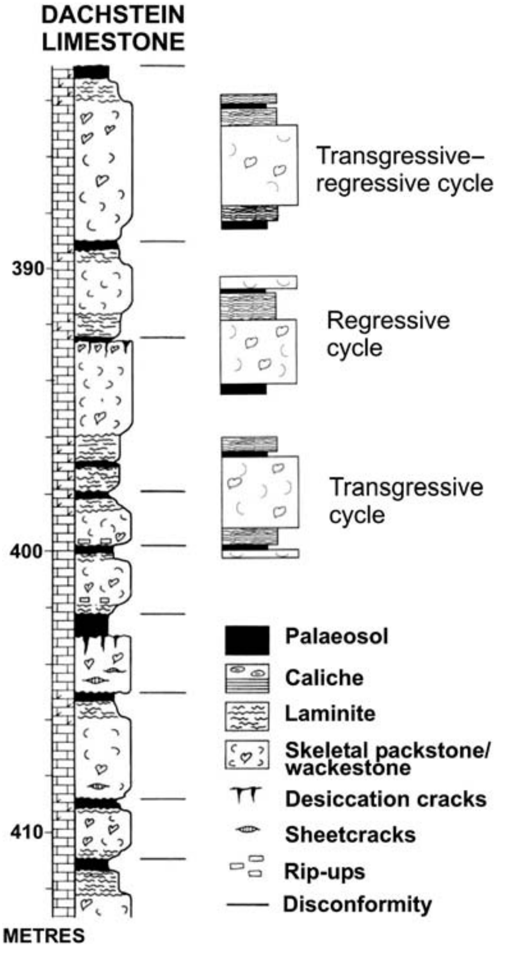

Fig. 6. Measured section of the Dachstein Limestone platform carbonates from a core in the Transdanubian Range (Hungary) illustrates a combination of regressive, transgressive, and transgressive–regressive cycles (adapted from Balog *et al.* 1997).

Satterley & Brandner (1995) and Satterley (1996) presented a rigorous analysis of the classic section at Steinernes Meer, Austria and found that the cycle thickness-frequency distribution displays an exponential pattern which is strongly suggestive of depositional control by non-periodic processes. Satterley (1996) noted in particular that the Lofer cycles on the Steinernes Meer platform displayed limited lateral continuity, low stratigraphic completeness, and a lack of hierarchical bundling. Satterley & Brandner (1995) and Satterley (1996) thus concluded on this basis that autocyclical processes, such as lateral facies migration within a tidal flat island system, and variations in the rate of subsidence, were the over-riding controls on stratigraphic patterns of sediment accumulation. Nevertheless, Cozzi *et al.* (2005) were able to measure 112 cycles in a 271-m thick section of the Dachstein in the Julian Alps, northeastern Italy. Spectral analysis again suggested that these shallowing-upward carbonate cycles were deposited with a periodicity matching precessional frequencies at 19 ka and 22–24 ka, with a potential for 5:1 bundling at 96–128 ka. Similarly, Schwarzacher (2006) discounted alternative (e.g. autocyclic) mechanisms for genesis of the cycles in his spectral analysis and interpretation of several Dachstein Limestone sections in the Northern Calcareous Alps of Austria. He concluded that cyclicity can be attributed directly to orbital forcing at the precessional and eccentricity frequencies.

North America

Newark Supergroup. Van Houten (1962, 1964) first recognized and described an apparent periodicity in the cycles of the sedimentary sequence of the Upper Triassic (Carnian) Lockatong Formation of the Newark basin (Fig. 7a) and proposed that sandstone–mudstone–shale sequences represented transgressive–regressive lacustrine cycles, that is, lake expansion and contraction, in an alluvial–lacustrine basin. Assuming that carbonate-clastic couplets in the dark mudstones recorded annual deposition of varves, Van Houten calculated an average sedimentation rate for the cycles and determined that individual cycles represented an average depositional interval of approximately 20 ka years. Van Houten hypothesized further that these cycles

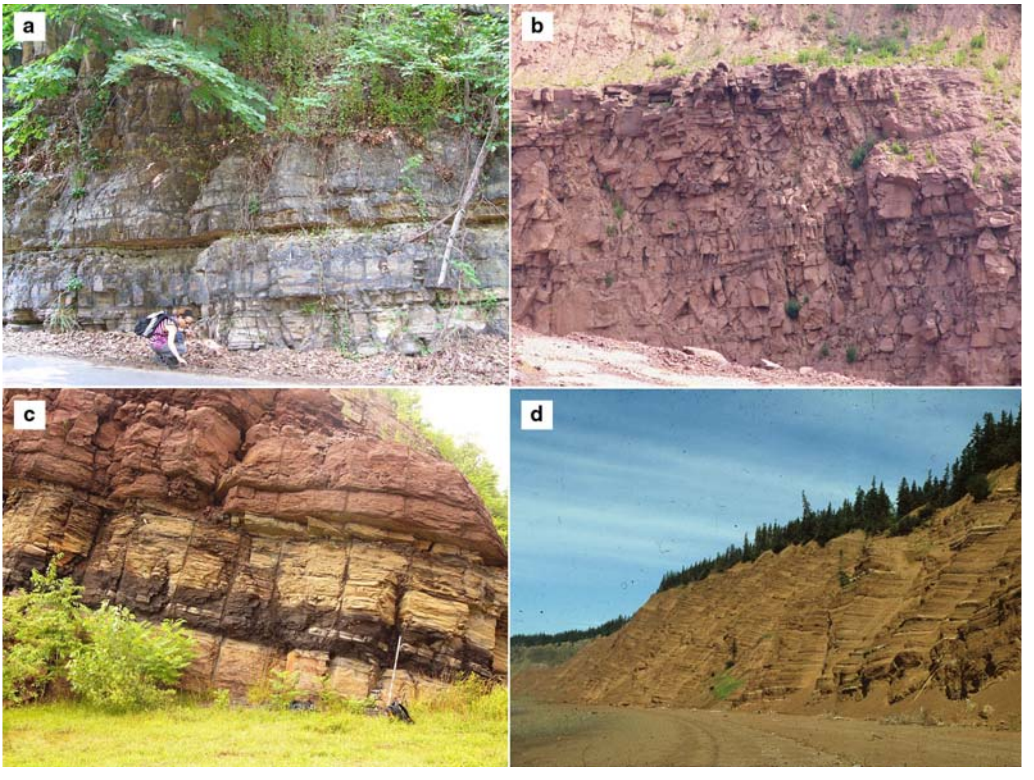

Fig. 7. Cyclic strata of the Newark Supergroup. (**a**) Cyclically bedded lacustrine strata from the (Carnian) Lockatong Formation, Newark basin. Section photographed is below the Palisades Sill in Palisades State Park, New Jersey. (**b**) Strata in the upper Passaic Formation (Norian–Rhaetian) are dominated by fluvial sandstones in this quarry near Clifton, New Jersey. Cliff in the foreground is 10 m high. (**c**) Typical Van Houten cycle in the (Hettangian) East Berlin Formation consists of pale sandstones surrounding dark, organic-rich mudstone, overlain by red mudstone and sandstone. The light-coloured centre of the dark mudstone is a finely laminated carbonate bed. The section is located near Meriden, Connecticut, in the Hartford basin. The staff at lower right is 1.5 m. (**d**) Section of the (Norian–Hettangian) Blomidon Formation on the north shore of the Minas Basin, Nova Scotia (Fundy basin), comprises metre-scale alternating beds of mudstone and fine-grained sandstone. Overlying North Mountain Basalt is visible at cliff top at far left. Staff at lower right is 1.5 m.

were controlled by the precessional signal of the Milankovitch orbital frequencies, although he recognized the imprecision and assumptions inherent in the methodology. Van Houten also recognized groupings of these cycles into thicker compound cycles of five and twenty individual cycles, but he did not speculate as to their origin.

The hypothesis that Milankovitch-frequency cyclicity is recorded by the lacustrine cycles within the Newark basin strata was advanced further by Olsen (1984, 1986; Olsen *et al.* 1989; Olsen & Kent 1996). Olsen, who provided the term 'Van Houten cycles' for the ostensibly precession-forced transgressive–regressive cycles in the Newark Group formations, divided the cycles into seven lithologies and assigned a depth ranking to each lithology; that is, the shallowest-water sediments, such as red mudstones bearing vertebrate tracks and desiccation features, were assigned the rank '0' and the deepest-water lithologies, the organic-rich laminated mudstones, were assigned rank '6'. The recurrence interval of these lithofacies was then examined by Fourier analysis to generate power spectra of the sedimentary cycles in which peak recurrence intervals were statistically tested. The duration of the cycles was calculated by calibrating the cycle thicknesses to the varve counts employed by Van Houten. This permitted assignment of a period of 18 ka to 25 ka to the basic Van Houten precession cycle (Olsen *et al.* 1989). The power spectra also identified the compound cycles originally identified by Van Houten, and allowed assignment of these to the frequencies of the eccentricity cycles, at 95 ka and 125 ka, the long eccentricity cycle at 400 ka, and the very long cycle of *c.* 2000 ka. A peak was also identified at 41 ka, which matches the frequency of the obliquity cycle, but this was not statistically significant. Within the limits of resolution of the available data, these cycle periodicities were broadly supported by the radiometric data available at the time.

The original work of Van Houten (1962, 1964) was limited to the Lockatong Formation. Olsen extended this downward to include the uppermost part of the dominantly fluvial (Carnian) Stockton Formation. Despite the upward-decreasing prominence of lacustrine facies in the Passaic Formation (presumably Norian to early Hettangian; see below), Olsen extended the interpreted cyclostratigraphy upward to include all of this formation (Fig. 7b), as well as the Jurassic-age Feltville, Towaco and Boonton formations. Olsen & Kent (1996) and Olsen *et al.* (1996*a*) continued the investigation of Newark basin cyclostratigraphy by analyzing seven laterally offset, stratigraphically overlapping drill cores obtained from the Newark Basin Coring Project (NBCP). The nearly 7 km of NBCP core provided ostensibly complete sections of the Lockatong and Passaic formations, to which the authors applied the depth-rank analysis technique. The authors analyzed the data thus generated by spectral analysis, including both fast Fourier transform (to define peak cycle thicknesses), and space-frequency analysis (to measure shifts in cycle frequency as a function of stratigraphic position). They found that the individual Van Houten cycles at 4–7 m thickness are the most obvious component of cyclicity at the outcrop scale, but statistically they are more weakly expressed than the thicker modulated cycles. In the cored strata, the authors (Olsen & Kent 1996; Olsen *et al.* 1996*a*) defined: (1) short modulating cycles, comprising five Van Houten cycles (*c.* 100 ka); (2) intermediate modulating cycles, which they termed McLaughlin cycles, comprising four short modulating cycles (*c.* 400 ka long); and (3) long modulating cycles of four to five McLaughlin cycles (*c.* 2 Ma long). Within the Upper Triassic section of the Newark basin, the authors identified 60 McLaughlin cycles in the upper Stockton through Passaic formations that should therefore represent 24 Ma of sedimentation (Kent & Olsen 1999); for example, the correlation of Kent & Olsen (1999) indicates that the Rhaetian of the Newark basin comprises 15 McLaughlin cycles, encompassing approximately 6 Ma.

If the interpretations of the cycle durations are valid, the cyclostratigraphy of the Newark Basin (and by correlation much of the Newark Supergroup) is, in effect, a determinative chronostratigraphy. Given the radiometric dates on the Newark volcanics, which average *c.* 201 Ma, as a reference datum, cycle counting should yield an absolute age for the strata in these basins. Furthermore, magnetostratigraphic correlation of strata in other basins could allow chronostratigraphic correlation to other sections, for example the Tethyan marine (e.g. Channell *et al.* 2003; Gallet *et al.* 2003) or the Somerset Coast of England (see below). In theory, correlation of a chronostratigraphically calibrated section to a biostratigraphically calibrated section then would allow determination of the absolute ages of the stage boundaries.

Olsen *et al.* (1989; see also Olsen 2003; Whiteside *et al.* 2007) applied this methodology to the other basins of the Newark Supergroup (Fig. 7c), from North Carolina (the Danville–Dan River basin) to Nova Scotia (the Fundy basin). In the Fundy basin, for example, Olsen *et al.* (1989) interpreted the cycles of sandstone with a 'sand-patch fabric' (*sensu* Smoot & Olsen 1988) and mudstone in the Blomidon Formation (ostensibly Norian–earliest Hettangian) as sediments deposited in a lacustrine–playa system subject to orbitally forced climate fluctuations with predominantly *c.* 100 ka (eccentricity) cyclicity (Fig. 7d). Mertz & Hubert

(1990), however, interpreted the cyclicity of the Blomidon Formation as a result of autocylic processes on alluvial fans that bordered the playa system. Kent & Olsen (2000) subsequently recalculated the predominant cycle frequency and concluded that it was obliquity related (e.g. *c*. 41 ka) on the basis of their palaeomagnetic correlation of the Blomidon Formation to the Newark basin.

Olsen *et al.* (2002; see also Whiteside *et al.* 2007) used the ordering of the longer period cycles as a basis for intra-basinal temporal correlations, with the volcanics in the respective Newark Supergroup basins serving as a datum. Notably, however, Marzoli *et al.* (2004) presented data on the age of the basalts in Morocco that call into question the assumption of synchroneity of the CAMP eruptions that underlies the intra-basinal correlations of Olsen *et al.* (2002). In some basins (e.g. Hartford and Deerfield), the correlations of Olsen *et al.* (2002) apply mainly to the Jurassic sections because lacustrine facies are rare to absent in much of the Triassic section. Additionally, the authors (Olsen *et al.* 1996*b*; Olsen 2003; Whiteside *et al.* 2007) used the timing of cycles bracketing the volcanics to establish a duration for the extrusive episode in the earliest Jurassic; that is, they concluded that extrusion of the Orange Mountain, Feltville and Preakness basalts in the Newark basin occurred in <600,000 years.

These methods of analysis of sedimentary sections have been applied to other continental Triassic strata in other basins and on other continents that can be correlated to the Newark. Hofmann *et al.* (2000), for example, described facies and metre-scale cyclicity similar to those of the Blomidon Formation in the apparently contemporaneous Bigoudine Formation of the Argana basin, Morocco. In the Upper Triassic strata of the Branscombe Mudstone Formation (of the Mercia Mudstone group) at St. Audrie's Bay (England), Kemp & Coe (2007) used image analysis to record changes in colour of the strata, and identified spectral cycles at 26 cm and 116 cm. The authors concluded that the thicker (116 cm) intervals represent sedimentary cycles forced by the *c*. 100 ka eccentricity frequency, and that the thinner (26 cm) represent the precession frequency at *c*. 22 ka. Furthermore, the authors established a magnetostratigraphic correlation of this section to the Newark basin section that provides a link to the Newark basin chronostratigraphy.

Notably, the age and completeness of the stratigraphic section in the Newark basin is not accepted universally. Kozur & Weems (2005, 2007) examined the conchostracan biostratigraphy of the Newark Supergroup. By correlation with the Germanic Triassic, the authors concluded that the section is neither complete nor appropriately dated. A substantial regional unconformity is interpreted near the base of the section in the lower Carnian (between the Cordevolian and upper Julian). Of greater significance in the attempt to correlate the continental record to the marine is the lack of the uppermost Norian and most of the Rhaetian in the Newark basin.

Kozur & Weems (2005, 2007) found conchostracans of Sevatian (late Norian) age in strata previously dated as Rhaetian (the upper Catharpin Creek and Passaic formations) in the Newark and Culpeper basins, and placed the Triassic–Jurassic boundary within the volcanic sequence, above the Preakness Basalt in the Newark Basin, and above the Sander Basalt in the Culpeper Basin.

Colorado Plateau. The classic nonmarine Upper Triassic sequence of North America is presented by the Chinle Group, ranging in age from Late Carnian to possibly Rhaetian. Strata of the Chinle Group, which are exposed across much of the Colorado Plateau, were deposited in a continental retroarc basin on the western edge of the North American craton. Lucas *et al.* (1997) established correlations between the Upper Triassic marine strata of Nevada and the nonmarine Chinle Group strata of the Four Corners region on the Colorado Plateau (southwestern USA). The authors used these correlations to define unconformity bounded depositional sequences (or third-order cycles) and inferred a eustatic control on their deposition, although Marzolf (1994) previously had argued for a tectonic control.

The influence of sea-level fluctuation on alluvial sedimentation is now well accepted (Posamentier & Allen 1993; Schumm 1993; Shanley & McCabe 1994; Atchley *et al.* 2004), but generally some proximity to the coastline is thought to be required for eustasy to be an effective control on alluvial base level. Studies of the modern Mississippi River system suggest that this influence extends inland no more than a few hundred kilometers (Aslan & Autin 1999; Blum & Törnqvist 2000). Given the likely position of the coastline in central-to-western Nevada during Chinle deposition, Cleveland *et al.* (2007) discounted a eustatic control on Chinle deposition. While accepting the essential sequence stratigraphic architecture of the Chinle Group of Lucas *et al.* (1997), these authors cited tectonics as the more likely control on the depositional sequences.

Tanner (2000) studied the Upper Triassic (Norian) Owl Rock Formation of the Chinle Group on the Colorado Plateau and noted a rhythmicity within the alternating alluvial clastic–palustrine carbonate sequence (Fig. 8). This author speculated that cyclical climate change with the Milankovitch precessional frequency could provide an explanation for the observed rhythmicity through

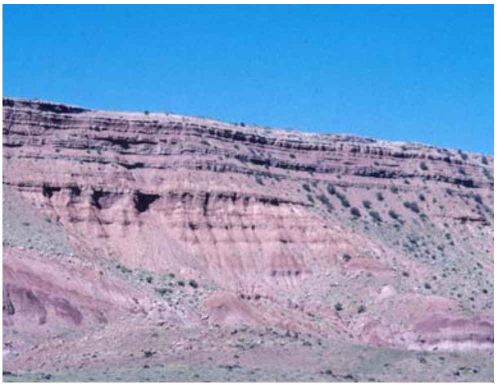

Fig. 8. Type section of the Upper Triassic (Norian) Owl Rock Formation exhibits rhythmic interbedding of alluvial clastics and lacustrine–palustrine–pedogenic carbonates. Orbital forcing of the cyclicity of the sedimentation in this formation, through climatic control of base level, is hypothesized, but remains untested.

strengthening and weakening of a monsoonal climate system (which would drive base-level changes), as has been modeled elsewhere for the Late Triassic (Parrish 1993; Kutzbach 1994; Lutz & Ricken 2000). Tanner pointed out, however, that age data are lacking to test the hypothesis quantitatively.

Discussion

Preservation of a climate signal implies that climate is a controlling influence on the sedimentary record of every environment in which it is interpreted as present; that is, climate has a recognizable imprint over other factors, including tectonics, long-term eustasy, event stratigraphy, and autocyclic processes. Some depositional settings, such as lakes and evaporite basins, are unquestionably more climate sensitive than others, and thus provide a more faithful archive of climate change. The changing strength of the monsoons over the Pangaean continent, controlled by the precession cycle, has been cited as a dominant control on continental sedimentation by some authors (Olsen 1986; Perlmutter & Matthews 1989; Parrish 1993). In environments in which autocyclic processes operate (e.g. alluvial systems), interpretations of allocyclic controls are likely to be questioned. As Schwarzacher (2000) points out, however, the distinction between allocyclic and autocyclic processes in such settings is not always so clear; climate may exercise an extrinsic control over some autocyclic processes (such as avulsion rate) in fluvial systems, thereby clouding the distinction.

Milankovitch-frequency glacio-eustasy is frequently and easily invoked as a dominant factor in marine and marginal marine environments for those times in geological history for which there is clear evidence of continental-scale ice sheets. But other mechanisms must be invoked for generating low-amplitude (metre-scale) sea-level changes during non-glacial intervals, such as the early Mesozoic (Frakes *et al.* 1992). Water flux between mountain glaciers and the oceans with Milankovitch frequencies is a distinct possibility, but would not produce the several-metre sea-level changes required to explain the sedimentary cycles; for example, melting of the entire modern Greenland ice sheet would produce approximately 7 metres of sea-level rise, but there is no evidence for ice mass of this magnitude during the Triassic. The relatively small changes in insolation associated with the orbital cycles also seem inadequate to produce thermal expansion of the ocean of this magnitude.

Changing groundwater storage caused by precession-forced climate changes has been hypothesized to cause metre-scale sea-level fluctuations. Jacobs & Sahagian (1993) reasoned that large-scale fluctuations in the water table in northern Pangaea, as indicated by the changing levels of the Newark Supergroup lakes, forced metre-scale fluctuations in sea-level. Indeed, modelling of the Pangaean climate (Kutzbach & Gallimore 1989; Parrish 1993; Kutzbach 1994) suggested that strengthening of monsoonal flow in the hemisphere in which the summer occurs during the perihelion position of Earth would possibly result in a 25% increase in precipitation in tropical and subtropical regions compared to the mean. The suggestion by Jacobs & Sahagian ignores the symmetry of the climate cycle, however. The opposite hemisphere, in which summer occurs at the aphelion position, would see a similar-scale reduction in precipitation. With nearly equal land mass in each hemisphere, the surplus storage of groundwater in one hemisphere logically should be cancelled by a deficit in the other, thus affecting no net change in ocean-water volume. An alternative interpretation of the effects of orbital forcing is given by Mörner (1976, 1984, 1994), who attributed changes in oceanic circulation and sea-level to cyclic adjustments in the differential rotation of the layered Earth system (hydrosphere, lithosphere, asthenosphere, mantle, core) and changes in the gravity potential of the Earth's surface. This hypothesis remains untested, however, and the issue of the driving mechanism for high-frequency, low-amplitude sea-level change remains largely unresolved.

Carbonate platforms

The interpretations of orbital forcing of cyclic sedimentary sequences found on carbonate platforms are not without controversy (for examples of arguments and counterarguments, see Kozar *et al.* 1990; Koerschner & Read 1990; Hardie *et al.* 1991; Read *et al.* 1991). A number of researchers have advocated that the 'Ginsburg model' (Ginsburg 1971, 1982; Wilkinson 1982) adequately explains the formation of shallowing-upward sequences in carbonates through autocyclic processes. In its essence, this model suggests that carbonate sedimentation on a constantly subsiding shelf will build a shallowing-upward sequence until water depth is too shallow to allow continued carbonate sediment production. A sedimentary hiatus takes place while subsidence continues until a critical threshold depth is reached that allows sedimentation to resume. Hence, repeated shallowing-upward carbonate cycles can occur in the absence of variations in sea-level. Indeed, computer simulations of cyclic carbonate sediments can produce simulated stratigraphic sections similar to those observed in the field with or without input of sea-level changes with Milankovitch frequencies (Goldhammer *et al.* 1990; Hardie *et al.* 1991).

Algeo & Wilkinson (1988) further argued that as cycle period is dependent on cycle thickness, all cycles between 1–20 m thick will yield cycle periods in the Milankovitch range (20 ka–400 ka), regardless of origin. Similarly, Drummond & Wilkinson (1993*a*) contended that the exponential frequency distribution of peritidal carbonate cycles is evidence against periodic accumulation of sediment. Drummond & Wilkinson (1993*b*) further argued that the assumption that each rise in sea-level produces only one cycle is not necessarily valid. Schwarzacher (2000), however, has countered that purely autocyclic models for peritidal carbonate sedimentation fail to explain the repetition of specific cycle thicknesses or the characteristic bundling patterns so frequently observed. Furthermore, as noted by Schwarzacher and others (e.g. Goldhammer *et al.* 1987; Egenhoff *et al.* 1999) the periodic occurrence of subaerial exposure surfaces in these shallow-marine carbonates, in the classic Latemar cycles, for example, is most readily explained by oscillating sea-level.

Newark lakes

Although the operation of orbitally forced climate change with Milankovitch frequencies during the Triassic now seems well-founded, it is noteworthy that several assumptions are implicit in the development of the determinative cyclostratigraphy of the Newark basins. First and foremost amongst these is that the lithofacies changes within the cycles, that is, from red mudstone to grey sandstone to black mudstone, reflect profound changes in water depth within the Newark lakes that were driven entirely by climate change. The model does not allow for other mechanisms, for example, that there was a tectonic component to base-level change. De Wet *et al.* (1998), for instance, noted the importance of tectonics in controlling the development of lacustrine systems in their study of lacustrine carbonates in the Gettysburg basin. Additionally, the classic calculations of cycle duration from varve counts relied on the assumptions that the carbonate–clastic couplet in the dark mudstones did in fact result from seasonal differences in sedimentation during a single year, and that the sedimentation rate estimated from the thickness of these varves can be applied to an entire cycle, which comprises a variety of lithologies, deposited by processes that vary from traction flow to suspension settling. This supposition could be reasonable only if the rate of sedimentation is considered as a function primarily of accommodation space. In such a case, a uniform, time-averaged rate of sediment accumulation may be applicable.

Notably, the Newark cyclostratigraphy also presumes completeness of the stratigraphic record; that is, no significant unconformities or hiatuses occurred throughout the history of sedimentation in the basin over a span of millions of years. This assumption is contradicted by the conchostracan biostratigraphy of Kozur & Weems (2005, 2007). The lakes of the East African Rift basins often have been invoked as a modern analog for the Newark basins (e.g. Olsen 1986), given their subtropical setting in elongated half-grabens. These rift lakes differ considerably from their ancient counterparts in numerous ways, however. Water levels in the modern lakes fluctuate seasonally on a scale of metres. Lake levels have fluctuated by as much as 100 m in historic times, and by hundreds of metres since the late Pleistocene, resulting in major unconformities in the stratigraphy (Scholz *et al.* 1998). Thus, the analogy with the modern African rift lakes suggests that there is a strong potential for major unconformities in the Newark Supergroup cyclostratigraphy, as recognized by Kozur & Weems (2005, 2007).

Conclusions

Studies conducted since the mid-1980s have suggested that high-frequency (fourth- and fifth-order) cycles attributable to orbital forcing are ubiquitous in the stratigraphic record of the Triassic. But identification of these cycles by the methods of spectral analysis long has relied on the assumption that the stratigraphic records under examination were essentially complete; this assumption requires testing on a case-by-case basis. Calculations of the cycle periods often has relied on bundling patterns of the cycles and the assumption that these patterns resulted from the predictable modulation of the basic cycle, that is, the eccentricity cycle superimposed on the precession cycle. Later application of radio-isotopic dating to some of these sections, however, has demonstrated the weakness of these assumptions. Consequently, the application of cyclostratigraphy to chronostratigraphy should be considered robust only where supporting independent age data are available. Evaluation of the accuracy of the chronostratigraphy derived from the Newark Supergroup cyclostratigraphy, for example, requires establishment of an absolute age that brackets the cyclostratigraphic section, in addition to that of the Newark volcanics. Potentially, a magnetostratigraphic correlation to another section containing volcanic materials will allow a future test of this chronostratigraphy against the more recent biostratigraphy. Until then, age correlations so derived should be regarded as tentative.

Finally, many of the arguments on the orbital forcing of cyclical sedimentary sequences result from the assumption of mutually exclusive standpoints, for example, that cyclicity results entirely from orbital forcing, or is completely unrelated to it. But, as demonstrated by Mundil *et al.* (2003) and Meyers (2008), cyclicity in shallow-marine carbonates may display both Milankovitch and non-Milankovitch frequency components. Assuming that the precession and eccentricity cycles were capable of generating metre-scale changes in sea-level during the Triassic, potential Milankovitch-frequency signals may be preserved, among other signals that are noncyclical, or that operated on frequencies not yet understood. Clearly, there remains much to be learned on the depositional controls of cyclically bedded sediments and their stratigraphic application.

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