

Implications of the Newark Supergroup-based astrochronology and geomagnetic polarity time scale (Newark-APTS) for the tempo and mode of the early diversification of the Dinosauria

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ABSTRACT: The Newark-APTS established a high-resolution framework for the Late Triassic and Early Jurassic. Palaeomagnetic polarity correlations to marine sections show that stage-level correlations of continental sequences were off by as much as 10 million years. New U–Pb ages show the new correlations and the Newark basin astrochronology to be accurate. Correlation of Newark-APTS to the Chinle Formation/Dockum Group, Glen Canyon Group, Fleming Fjord Formation and Ischigualasto Formation led to the following conclusions: (1) there are no unequivocal Carnian-age dinosaurs; (2) the Norian Age was characterised by a slowly increasing saurischian diversity but no unequivocal ornithischians; (3) there was profound Norian and Rhaetian continental provinciality; (4) the classic Chinle-, Germanic- and Los Colorados-type assemblages may have persisted to the close of the Rhaetian; (5) the distinct genus-level biotic transition traditionally correlated with the marine Carnian–Norian is in fact mid-Norian in age and within published error of the Manicouagan impact; (6) the end-Triassic marine and continental extinctions as seen in eastern North America were contemporaneous; and (7) compared to Triassic communities, Hettangian and Sinemurian age terrestrial communities were nearly globally homogeneous and of low diversity. Consequently, the complex emerging picture of dinosaur diversification demands biostratigraphically-independent geochronologies in each of the faunally-important regions.

KEY WORDS: Chinle, cyclostratigraphy, dinosaurs, Early Jurassic, Fleming Fjord, geochronology, Glen Canyon, Ischigualasto, Late Triassic

Understanding of the origin and diversification of the Dinosauria has been plagued by a lack of precision and accuracy in both the relative and absolute ages of the geographically dispersed deposits in which bones and traces of early dinosaurs and their relatives are found. This in turn has led to extremely divergent views of the processes involved with the ascent of the dinosaurs to ecological dominance – perhaps the most striking feature of the entire Mesozoic (e.g., Langer *et al.* 2009; Brusatte *et al.* 2010). Fundamental to this problem has been the lack of a reliable time scale for the Late Triassic and Early Jurassic. Published compilations of radioisotopic ages (e.g. Harland *et al.* 1990; Gradstein & Ogg 1996; Gradstein *et al.* 2005), despite valiant efforts, have unfortunately not helped because of a paucity of dates in critical intervals, dates that are compromised internally, or dates from strata which themselves are poorly registered to the marine standard stages. Over-reliance on low-resolution biostratigraphy (both stratigraphically and taxonomically) has further compounded problems by obscuring real faunal differences in time and space (Irmis *et al.* 2010).

One of the principal goals of the Newark Basin Coring Project (NBCP), 20 years old in 2010, was the development of



an astronomically calibrated Late Triassic geomagnetic polarity time scale that had the potential to be exportable globally via magnetostratigraphy. Additional progress in the magnetic polarity stratigraphy of Early Jurassic age continental Newark Supergroup strata of the Hartford basin and Triassic–Jurassic marine sections and major advances in U–Pb geochronology have now made it possible to realise the potential of the Newark Supergroup – Astronomically-calibrated geomagnetic Polarity Time Scale (Newark-APTS) for placing early dinosaur assemblages in a high-resolution temporal context. This paper is a review of that progress and its implications.

1. The Newark-APTS

The NBCP, funded by the US National Science Foundation (1990–1994), recovered the entire Triassic age sedimentary sequence, as well as a small part of the overlying basalt flows and interbedded sediments in the central part of the Newark rift basin (Fig. 1) in seven ~1 to ~1.5 km continuous cores (Kent *et al.* 1995; Olsen *et al.* 1996a). The Newark basin strata were targeted because of their great thickness in unquestioned superposition, promising high accumulation-rates,

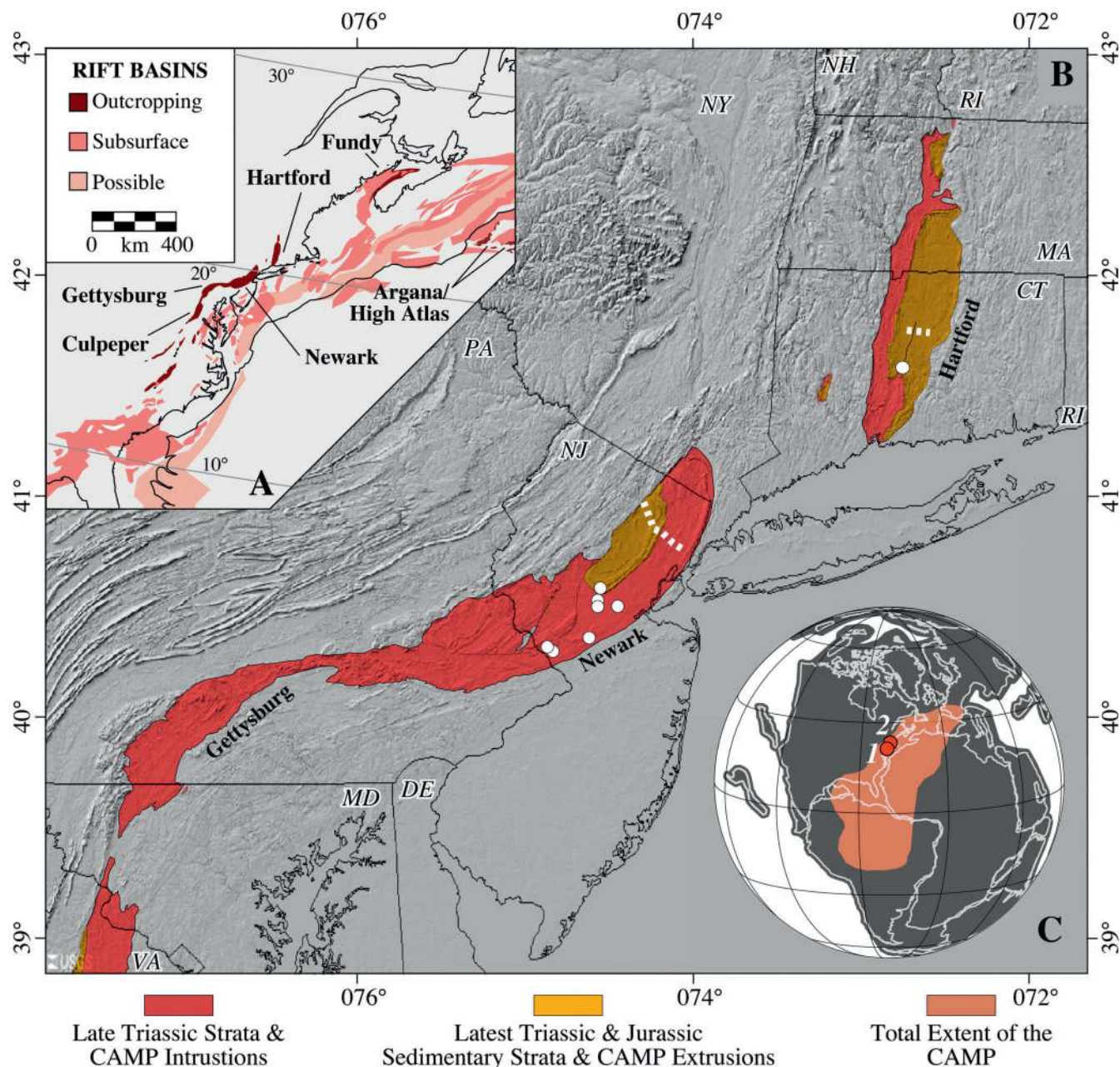


Figure 1 Location of the cores forming the basis of the Newark basin astrochronology and geomagnetic polarity time scale (Newark-APTS): (A) Index map of the Early Jurassic rift zone in central Pangea in earliest Jurassic coordinates (latitudes from Kent & Tauxe 2005; map from Whiteside *et al.* 2007); (B) Locations of cores within the Newark and Hartford basins with present day latitudes and longitudes on shaded relief map (USGS National Map Viewer); white dots in Newark basin show positions of the seven Newark Basin Coring Project (NBCP) cores, while the thick white dashed line indicates the Passaic River Diversion Tunnel Army Corps of Engineers (ACE) core transect; white dot in the Hartford basin shows position of the Silver Ridge B-1 cores, while the thick white dashed line indicates the Park River Flood Control Army Corps of Engineers (Park River) core transect. Note that the numerous outcrop locations used in the construction and testing of the Newark and Hartford basin composite sections are not shown (see Olsen *et al.* 1996a and Kent & Olsen 2008 for these). Abbreviations of states: *CT*=Connecticut; *DE*=Delaware; *MA*=Massachusetts; *MD*=Maryland; *NH*=New Hampshire; *NJ*=New Jersey; *NY*=New York; *PA*=Pennsylvania; *RI*=Rhode Island; *VA*=Virginia; (C) Earliest Jurassic plate configuration showing distribution of the Central Atlantic Magmatic Province (CAMP) (based on latitudes from Kent & Tauxe 2005, based on map from Whiteside *et al.* 2010, based in turn on base map provided by C. Scotese). Locations on map of Pangea: 1=Newark basin; 2=Hartford basin.

high-resolution records, and because of the presence of what had been interpreted as permeating astronomically-controlled lacustrine sedimentary cycles (Van Houten 1962; Olsen 1986). Added to this were a large series of short continuous cores (~100 m each) collected by Army Corps of Engineers (ACE cores) for the Passaic River Diversion Tunnel that covered the entire series of basalt flows and most of the overlying synrift strata (Fedosh & Smoot 1988; Olsen *et al.* 1996b). The large stratigraphic overlap among cores allowed production of a

roughly 5800 m-thick composite stratigraphy, tested by magnetic polarity stratigraphy, well logs and high-resolution lithostratigraphy (Fig. 2). Most of the section recovered proved to be lacustrine and marginal lacustrine, with the promised lithologic cycles (Fig. 3) caused by variations in the Earth's orbit (Olsen & Kent 1996). Augmented by core and outcrop sections from the Hartford basin continuing well into the Early Jurassic (Kent & Olsen 2008), this cyclicity forms the basis of the Newark-APTS.

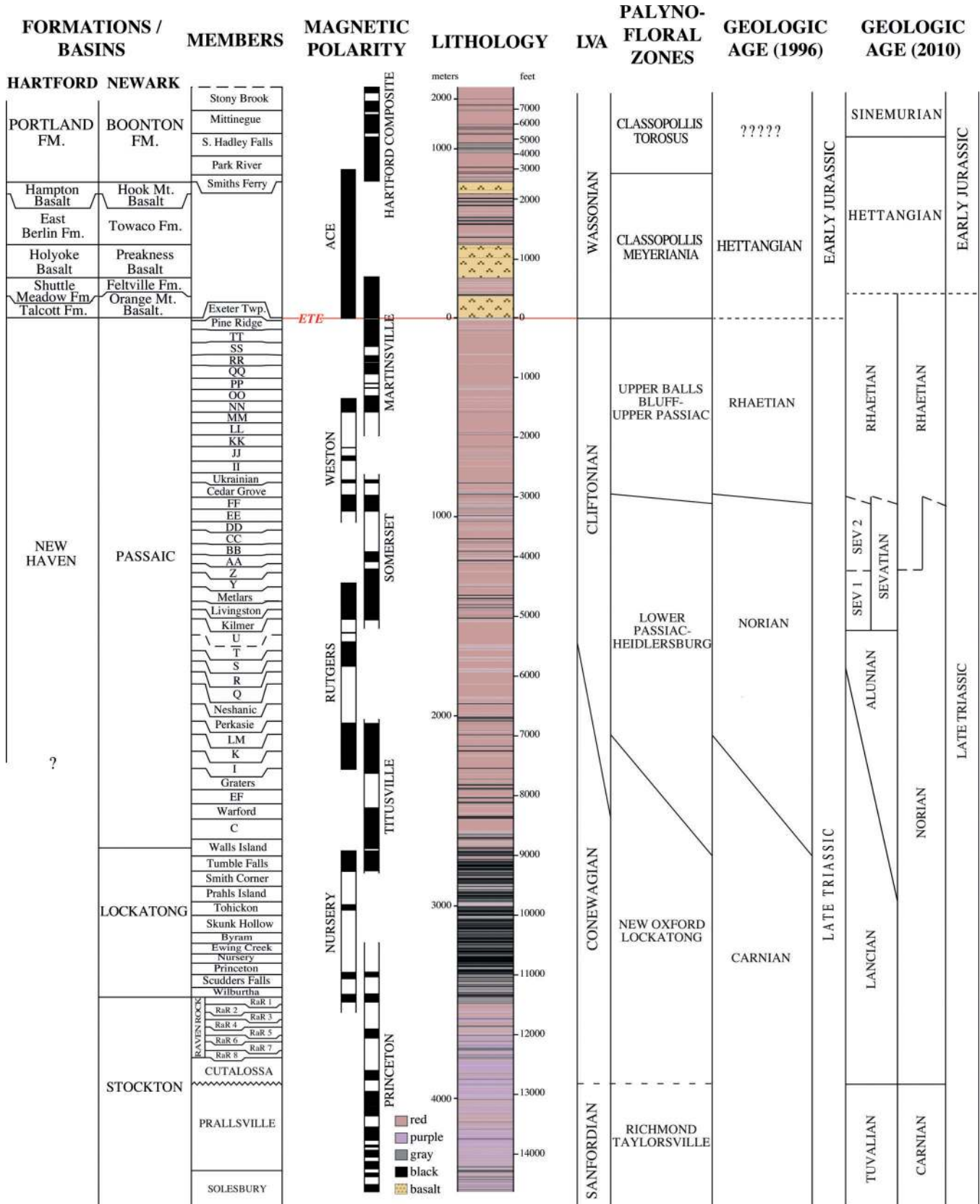


Figure 2 Lithostratigraphy of the Newark basin based on the Newark basin coring project with the ages as they are understood in 1996 and in the Newark-APTS 2010. Adapted from Olsen *et al.* (1996a) and Olsen & Whiteside (2008).

Olsen *et al.* (1996a) termed lithological cycles with a strong thickness mode at ~60 m prevalent above the basal and largely fluvial Stockton Formation and below the basalts as the McLaughlin cycles (Fig. 3) and designated each of them lithostratigraphic members, the boundaries of which are

defined by prominent beds of distinctive lithology. Olsen & Kent (1996) argued that McLaughlin cycles were paced by the ~400 kyr (abbreviations for time as recommended by Aubry *et al.* 2009) eccentricity cycle, which at the time was generally thought to have a period of about 413 kyr (Berger 1977; Berger

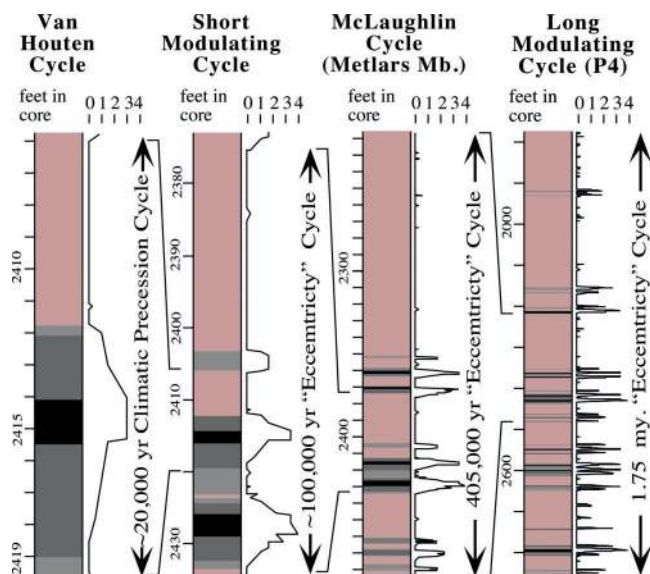


Figure 3 Newark basin hierarchy of lithological cycles with interpreted durations. Adapted from Olsen *et al.* 1996a.

& Loutre 1990). Kent *et al.* (1995) used these members, each corresponding to a McLaughlin cycle, as the basis of the first iteration of the Newark-APTS (Newark-APTS 1995), adding on the cyclostratigraphically calibrated ACE cores analysed by Olsen *et al.* (1996b) (Figs 3, 4). Kent & Olsen (1999) also extended the methodology into the marginal lacustrine and fluvial Raven Rock Member of the upper Stockton Formation based on colour variations, identifying eight additional cycles corresponding to McLaughlin cycles. They also modified the time scale by using a 404 kyr period cycle based on 20 Myr of the La90 solution (Laskar 1990) for the duration of the McLaughlin cycles, as opposed to 413 kyr from Berger (1977) (Fig. 4) to produce the second iteration of the time scale (Newark-APTS 1999A).

Kent *et al.* (1995) recognised 59 magnetozones in the composite section based on a sampling density of about one sample per 20 kyr (~1 sample per 3 m in Newark-APTS 1995). Only polarity zones with two or more successive samples with the same polarity were recognised in the composite section of magnetozones. In Kent & Olsen (1999), 35 polarity transitions out of 60 (E13n to E23r) were resampled at a density of about one sample per 2.2 kyr (~1 sample per 0.3 m). Based on the astrochronology, the duration of the polarity transitions was about 7.9 ± 4.5 kyr, comparable to that seen in the Pleistocene. Kent & Olsen (1999) also modified the designation of the youngest polarity zone (E23n) by splitting off E23n.2n as a separate magnetozone E24n, spanning the extrusive zone and overlying Boonton Formation, and giving greater emphasis to the thin but important reverse polarity interval E23n.1r, which was designated E23r (Fig. 4).

The only suitably precise radioisotopic dates directly relevant to the Newark basin for Newark-APTS 1995/1999A were $^{40}\text{Ar}/^{39}\text{Ar}$ and U–Pb ages from the presumed feeder of some of the basalt flows, the Palisade sill (202.2 ± 1.3 Ma, Sutter 1988; 200.9 ± 1.0 Ma, Dunning & Hodych 1990), averaging about 201.6 Ma. Assuming that this was close to the middle of the time of eruption (the Palisade sill was thought to be a feeder to the Preakness Basalt: Ratcliffe 1988; see below) and that the Felville Formation and Orange Mountain Basalt might add on another 0.5 Myr allowed the Newark-APTS 1995/1999A floating astronomical time scales to be pinned to the radioisotopically calibrated time scale at 202 Ma (after rounding to the nearest 0.5 Myr) for the Triassic–Jurassic boundary.

Pollen and spore assemblages provided a basis for correlation to the marine stages for Newark-APTS 1995/1999A (Cornet 1977, 1993; Cornet & Olsen 1985; Fowell & Olsen 1993; Fowell *et al.* 1994; Fowell & Traverse 1995) via normal literature-based correlation webs. Three stage boundaries were identified within Newark basin sections corresponding to Cornet's three palynological assemblages. The oldest floral boundary in the Newark basin, between the New Oxford–Lockatong and Lower Passaic–Heidlersburg palynofloral zones, was correlated to the Carnian–Norian marine boundary, based largely on the presence of characteristic Carnian and Norian taxon *Camerosporites pseudoverrucatus* in the New Oxford–Lockatong palynoflora and its absence from the overlying Lower Passaic–Heidlersburg palynofloral zone. The boundary between the Lower Passaic–Heidlersburg and Upper Balls Bluff–Upper Passaic palynofloral zones was equated with the Norian–Rhaetian marine boundary largely because of the increase in *Classopollis* (*Corollina*) spp., including the first appearance of *Classopollis torosus*, and the first appearance of *Granuloperculatipollis rudis* in the Upper Balls Bluff–Upper Passaic palynofloral zone.

In contrast, the boundary between the Upper Balls Bluff–Upper Passaic and overlying *Classopollis meyeriana* palynofloral zones is more dramatic, involving the last appearances of many pollen and spore taxa characteristic of the Triassic and the abrupt appearance of a flood of *Classopollis meyeriana*. The first appearance of the characteristic Early Jurassic taxon *Convolutispora klukiforma* occurs within this zone, which extends through the entire basalt flow interval. Thus, the Upper Balls Bluff–Upper Passaic and *Classopollis meyeriana* palynofloral zones were correlated to the Triassic–Jurassic boundary as it was loosely recognised in Europe. These palynological correlations in Newark-APTS 1995/1999A agreed for the most part with contemporaneous correlations based on tetrapod biochronology (Olsen & Sues 1986; Lucas 1993; Lucas & Huber, 1993; Lucas *et al.* 1998).

Olsen & Kent (1999) introduced a refinement of the astronomical calibration of the Newark-APTS 1999A. The member boundaries defined by Olsen *et al.* (1996a) and used by Newark-APTS 1995/1999 are subjectively picked distinctive lithological units and do not correspond in a uniform way to the continuously varying modulators of the precession-scale variability. The age model based on boundaries between individual members (Newark-APTS 1995/1999a) was not suitable for a quantitative tuning of the lake level sequence time series analysis. Instead, Olsen & Kent (1999) used smoothed and filtered sedimentary facies and colour curves to numerically tune the section to a pure 404 kyr sinusoid (Fig. 4) to produce the third iteration, Newark-APTS 1999B. Essentially the same timescale was used without detailed explanation in Olsen (1997). This different tuning procedure produces no change in total duration from Newark-APTS 1999A, but does change the age of some of the polarity boundaries, although only by less than a small fraction of a percent. Newark-APTS 1999B was modified by Olsen *et al.* (2003), with the addition of several 404 kyr cycles and associated magnetic polarity zones based on an analysis of cores and outcrops in the Portland Formation of the Hartford basin (Kent & Olsen 1999; Olsen *et al.* 2002b).

Until 2003, the only link between the Newark-APTS and the marine standard stages was palynology and to a lesser extent vertebrate palaeontology; previous magnetostratigraphic correlations of the Newark to marine sections were mutually inconsistent (e.g. Gallet *et al.* 2000, 2003) and radioisotopic ages were far too sparse. However, Muttoni *et al.* (2004) and Channell *et al.* (2003) independently used magnetostratigraphy to correlate Tethyan marine sections in Italy and Slovakia,

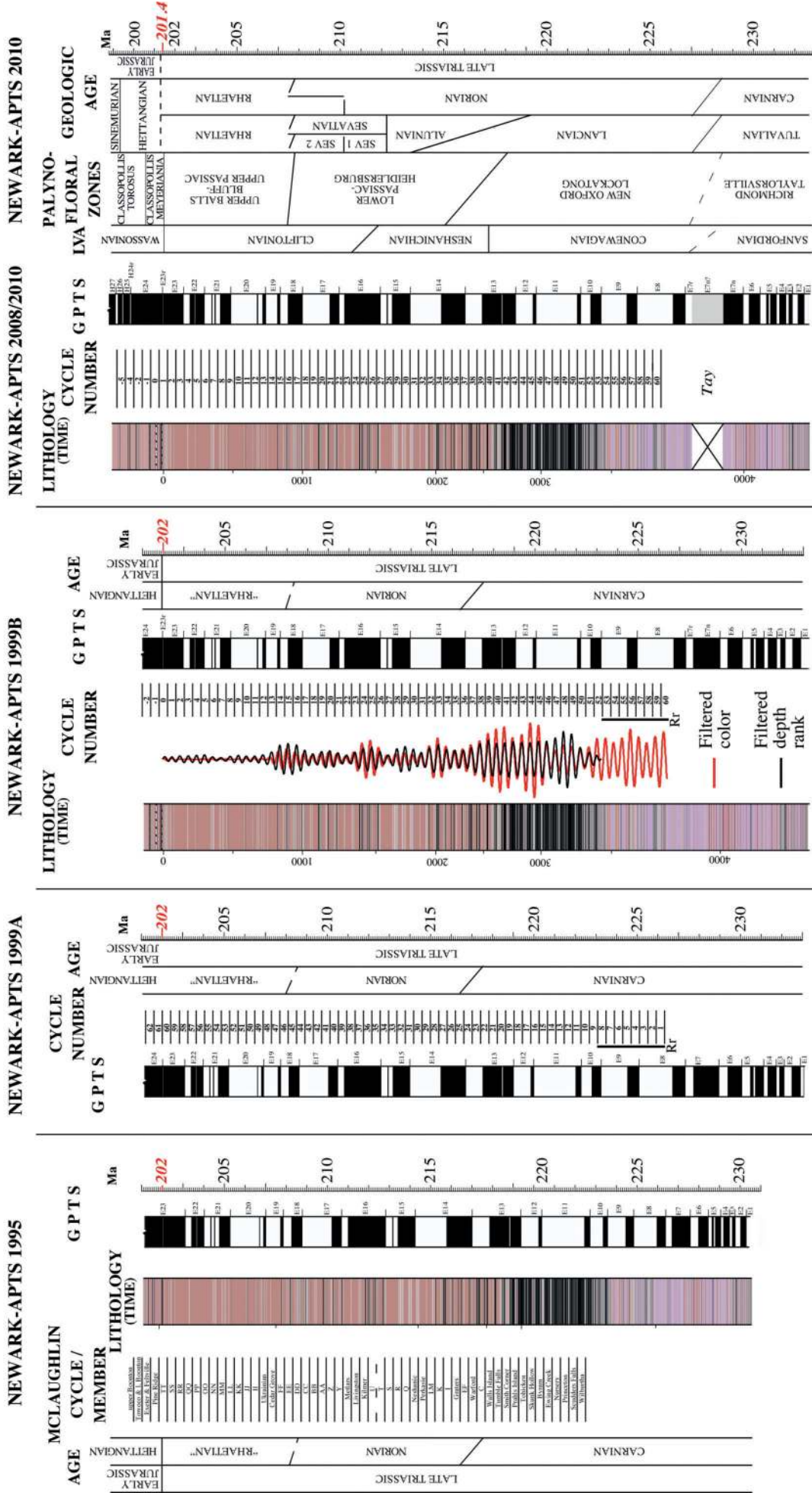


Figure 4 Evolution of the Newark-APTS 1995–2010. Modified from Kent *et al.* (1995), Kent & Olsen (1999), Olsen & Kent (1999) and Olsen & Whiteside (2008).

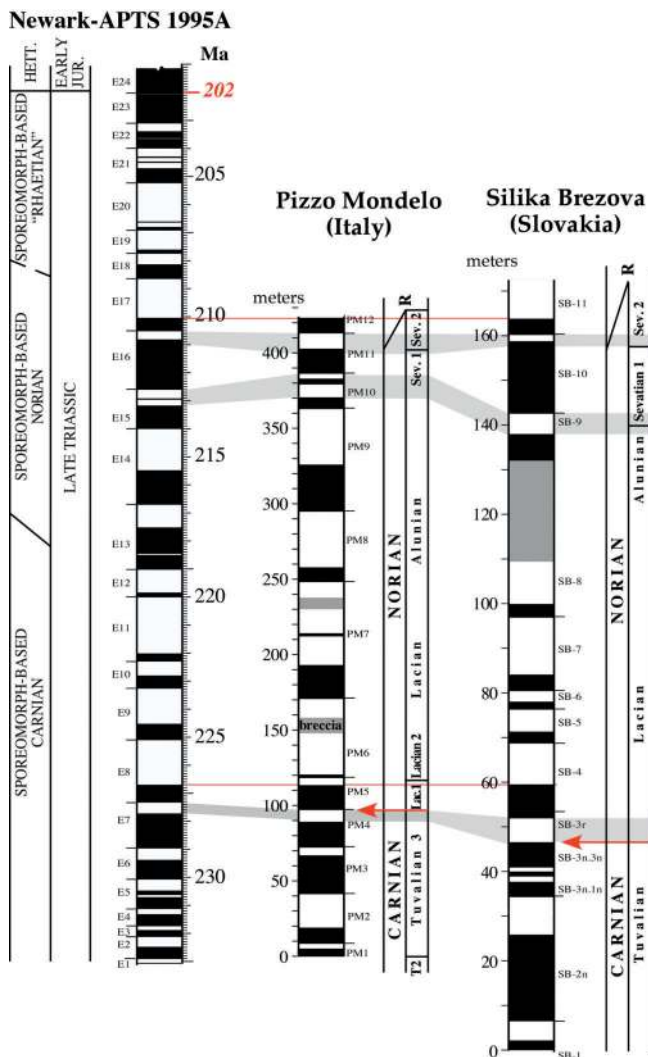


Figure 5 Correlation of the Newark-APTS 1995 with two key Late Triassic marine Tethyan sections. Correlation based on Muttoni *et al.* (2004) and Channell (2003).

respectively with the Newark-APTS. They concluded that the marine Carnian–Norian boundary fell much lower in the Newark basin section than previously recognised. Both Muttoni *et al.* (2004) and Channell *et al.* (2003) correlate the marine Carnian–Norian boundary to magnetozones E7r in Newark-APTS 1999A rather than E13 as suggested by previous interpretations of palynological and tetrapod data (Figs 4, 5). Both papers agreed in the apparent position of the Norian–Rhaetian boundary, which appeared in the same position in Newark-APTS 1999AB. This new correlation produced a change in the position of the Carnian–Norian boundary by 10 million years, making a Norian stage that lasted 20 Myr, suggesting that far-reaching revisions in global tetrapod biochronology were necessary. It is noted that this ‘long Norian’ concept has been incorporated into the recent Geological Society of America time scale of 2009 (Walker & Geissman 2009) and, while it is gaining some acceptance, it remains controversial.

LeTourneau (2003) suggested a slight modification to the Newark-APTS based on the Campbell core from the Taylorsville basin (Fig. 6). Based on the best fit of the lithological correlation between the Newark and Taylorsville basins, magnetozones E7r should be expanded to agree proportionally with Taylorsville magnetozones T1n (Fig. 6). This introduces a small gap in the Newark basin section between the Cutaloosa and Prallsville members of the Stockton Formation

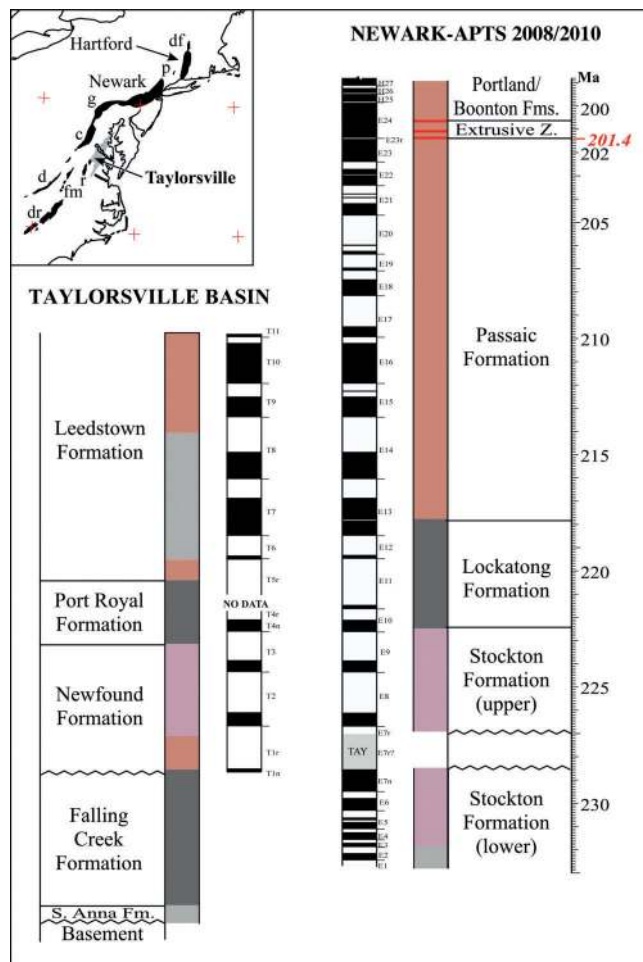


Figure 6 Palaeomagnetic correlation between composite section based on cores from the Taylorsville basin of Virginia, USA and the Newark-APTS 2010, showing the rationale for extending the length of Newark basin chron E7r (TAY). Based on LeTourneau (2003) at the presumed hinge margin unconformity (sawtooth line) between tectonostratigraphic sequences II and III of Olsen (1997). Colours as in Figure 2.

that is in about the position to correlate with the tectonostratigraphic sequence boundary (TS II–TS III) seen in the Taylorsville, Fundy and Argana basins (Olsen 1997; Olsen *et al.* 2000; LeTourneau 2003; Schlische 2003). The timescale of Olsen & Whiteside (2008) (Newark-APTS 2008) incorporates this small gap (Fig. 4d) as well as the magnetozones and cycles of the Portland Formation of the Hartford basin now fully described by Kent and Olsen (2008), as well as explicitly citing the ~400 kyr cycle as 405 kyr (Laskar *et al.* 2004).

2. Newark-APTS 2010

New U–Pb dates from the lowest flow of the North Mountain Basalt of the Fundy basin of Nova Scotia (summarised and updated in Schoene *et al.* 2010) indicate a highly reproducible ($^{206}\text{Pb}/^{238}\text{Pb}$) age of 201.38 ± 0.02 (Schoene *et al.* 2010), indistinguishable from the latest Rhaetian initiation of the end-Triassic extinction (ETE). The North Mountain Basalt is equivalent, probably at the 20 kyr scale, to the oldest flow of the Orange Mountain Basalt, based on basalt geochemistry (Olsen *et al.* 2003; Deenen *et al.* 2010), palaeomagnetic polarity stratigraphy of the immediately underlying strata (Deenen *et al.* 2011), cyclostratigraphy (Olsen *et al.* 2003; Whiteside *et al.* 2007) and palynology (Fowell & Traverse 1995; Whiteside *et al.* 2007), and the new U–Pb date is consistent with the U–Pb age of the Palisade sill that fed at least part of

the Orange Mountain Basalt of the Newark basin (Olsen *et al.* 2003). Puffer *et al.* (2009) show, based on major and trace element data, that at least the early phase of the Palisade sill was comagmatic with the Orange Mountain Basalt, consistent with the stratigraphic and U–Pb dates. Therefore, the Newark-APTS 2010 is tied to the 201.4 Ma age of North Mountain Basalt, which is deemed equivalent to the Orange Mountain Basalt, within error (Fig. 4).

The recognition of the GSSP of the base Hettangian at Kuhjoch, Austria (Morton 2008a, b; Morton *et al.* 2008) requires comment. Although the end-Triassic terrestrial extinction level, or at least its base, remains below the Orange Mountain Basalt, the marker for the base of the Hettangian is the first appearance datum of the ammonite *Psiloceras spelae* that occurs above the base of the marine extinctions. Based on palynological and carbon isotopic correlation with the Newark basin section (Hounslow *et al.* 2004; Whiteside *et al.* 2007, 2010; Ruhl *et al.* 2010), the base Hettangian should correlate to the middle Feltville Formation at about 150 kyr after the beginning of the end-Triassic extinction event; this placement is compatible with an $^{206}\text{Pb}/^{238}\text{U}$ age of 201.33 ± 0.13 from an ash just above the first occurrence of *P. spelae* in New York Canyon, Nevada USA (Schoene *et al.* 2010). The position of the Rhaetian–Hettangian (Triassic–Jurassic) boundary is thus shown to be above that of both the base of the *Classopollis meyeriana* palynofloral zone and the base of the Orange Mountain Basalt (see Fig. 7). It is noted also that correlation of the Newark-APTS to the $\delta^{13}\text{C}$ curves from the Newark and marine strata indicates that the CAMP event was synchronous with at least some of the extinctions within the end-Triassic extinction interval (Whiteside *et al.* 2010), bolstering a widely held view that CAMP provides a parsimonious explanation of the timing and duration of the event (e.g. Rampino & Stothers 1988; Courtillot *et al.* 1996; McElwain *et al.* 1999; Hesselbo *et al.* 2002; Beerling & Berner 2002; Marzoli *et al.* 1999, 2004).

The other major change from Newark-APTS 2008 to Newark-APTS 2010 is the inclusion of two options for the base of the Rhaetian: one based on the traditional base Rhaetian as it was understood by Cornet (in Olsen *et al.* 1996a) and correlated to the European section palynologically; and the other based on the inclusion of the Sevastian 2 into the Rhaetian and correlated by means of polarity magnetostratigraphy from the proposed Austrian GSSP (Krystyn *et al.* 2007a, b) by Hüsing *et al.* (2011) (see section 5, below).

It is noted that, in many ways, the application of marine stages and substages of Tethyan origin to non-marine sections often implies unsubstantiated temporal correlation of a marine biostratigraphy to non-marine sections. In this present paper, the substage terms Julian and Tuvallian (within the Carnian), Lancian and Alaunian (within the Norian) and Sevastian 1 and Sevastian 2 (Late Norian and Rhaetian) of Tethyan are used because they are the vocabulary for the abstractions of biostratigraphic concepts used in the critical papers that discuss the Tethyan ‘standard stages’ of the marine Late Triassic (e.g. Krystyn 2007a). It is recognised that because these substages (and stages!) are not formally referenced to specific sections and points (GSSPs), recognition of these substages (and stages), even in Tethyan marine sections, can hardly be better than the biostratigraphy on which they are based.

Relevant to discussions to follow, the Newark-APTS Carnian–Norian boundary at E7r has a nominal age of 227–229 Ma. However, this portion of the Newark basin section lacks cyclical lacustrine strata, and these ages represent an extrapolation. Radiometric constraints on the marine Carnian–Norian boundary (discussed below) suggest that the uncertainty in the stage boundary age is actually closer to

6 Myr (225–231 Ma) when comparing this boundary to other areas where magnetic polarity stratigraphy is lacking.

2.1. Agreement between radioisotopic ages and Newark-APTS 2010

The last few years have seen a revolution in the use of new U–Pb techniques, producing high precision and apparently accurate dates that allow independent tests of the Newark-APTS (Fig. 8). Table 1 has a list of the dates used. There are three published U–Pb ($^{206}\text{Pb}/^{238}\text{U}$) dates from eastern North America, two of which can be precisely linked to the Newark cycle stratigraphy. The youngest is from basalt flows: 201.38 ± 0.02 Ma, from gabbroid of the North Mountain Basalt of the Fundy basin (Schoene *et al.* 2010). The North Mountain basalt is the geochemical and cyclostratigraphic equivalent of the Orange Mountain Basalt of the Newark basin (see review in Olsen *et al.* 2003 and Whiteside *et al.* 2007), both lying close above the palynological transition between the Upper Balls Bluff–Upper Passaic and *Classopollis meyeriana* palynofloral zones. The other two dates have lower precision and are from sedimentary calcite (Table 1): 208.5 ± 2.1 Ma, from stromatolite calcite from the lower Metlars Member of the Passaic Formation (Rasbury *et al.* 2003); and 211.9 ± 2.1 Ma, from calcrete calcite from the lower middle New Haven Formation of the Hartford basin (Wang *et al.* 1998), whose correlation to the Newark basin section is constrained by a single palynoflorule (FOREST of Cornet 1977) at nearly the same level in the New Haven Formation. This palynoflorule is comparable to the Lower Passaic–Heidlersburg palynofloral zone (Cornet 1977), but not correlatable at a finer level (Fig. 8).

Ash fall layers interbedded with marine units have provided a series of high-resolution dates within the last few years. Improvements from previous efforts come largely from single crystal dating and the chemical abrasion technique (CA-TIMS) (Pálffy & Mundil 2006; Furin *et al.* 2006; Friedman *et al.* 2008; Schaltegger *et al.* 2008; Schoene *et al.* 2010). These dates are from marine sequences correlated largely by ammonite and radiolarian-based biostratigraphy to the European standard ages, including the apparent GSSP for the base of the Hettangian at Kuhjoch, Austria (Morton, 2008a, b; Morton *et al.* 2008). Correlation of the latest Triassic and Early Jurassic dates to the younger part of Newark-APTS 2008 is afforded via biostratigraphic and magnetostratigraphic correlation to the Montcornet core (Yang *et al.* 1996) from the Paris basin (Kent & Olsen 2008); correlation of the Late Carnian age U–Pb date (Furin *et al.* 2006) is by biostratigraphy to the marine magnetostratigraphies of Muttoni *et al.* (2004) and Channell *et al.* (2003) and thence to the Newark-APTS by magnetostratigraphy.

A U–Pb date of 225 ± 3 (Gehrels *et al.* 1987) from the Puppets Formation rhyolite interbedded with marine strata of the Alexander terrane in southern Alaska is between earliest Norian or Late Carnian and late Early Norian based on conodonts (Savage & Gehrels 1987; Savage quoted in Gehrels *et al.* 1987) and cited as within the lower Norian *Epigondolella quadrata* Zone by Kozur & Bachmann (2008). Furthermore, megafossil invertebrates constrain a thick (~300m) sequence below the dated rhyolite to ‘earliest early Norian or latest Carnian’ age (Berg 1973; Berg & Cruz 1982). This is the only Norian marine U–Pb date of which we are aware.

Correlation of the Newark-APTS 2010 McLaughlin cycles to the U–Pb dates by least squares regression yields a line with a slope of 413 ± 11 kyr/cycle, validating the assumed period of 405 kyr (Laskar *et al.* 2004) and a y-intercept of 201.1 ± 0.3 Ma corresponding to the age of the 0th cycle (Fig. 8). The present authors view this as very strong independent support

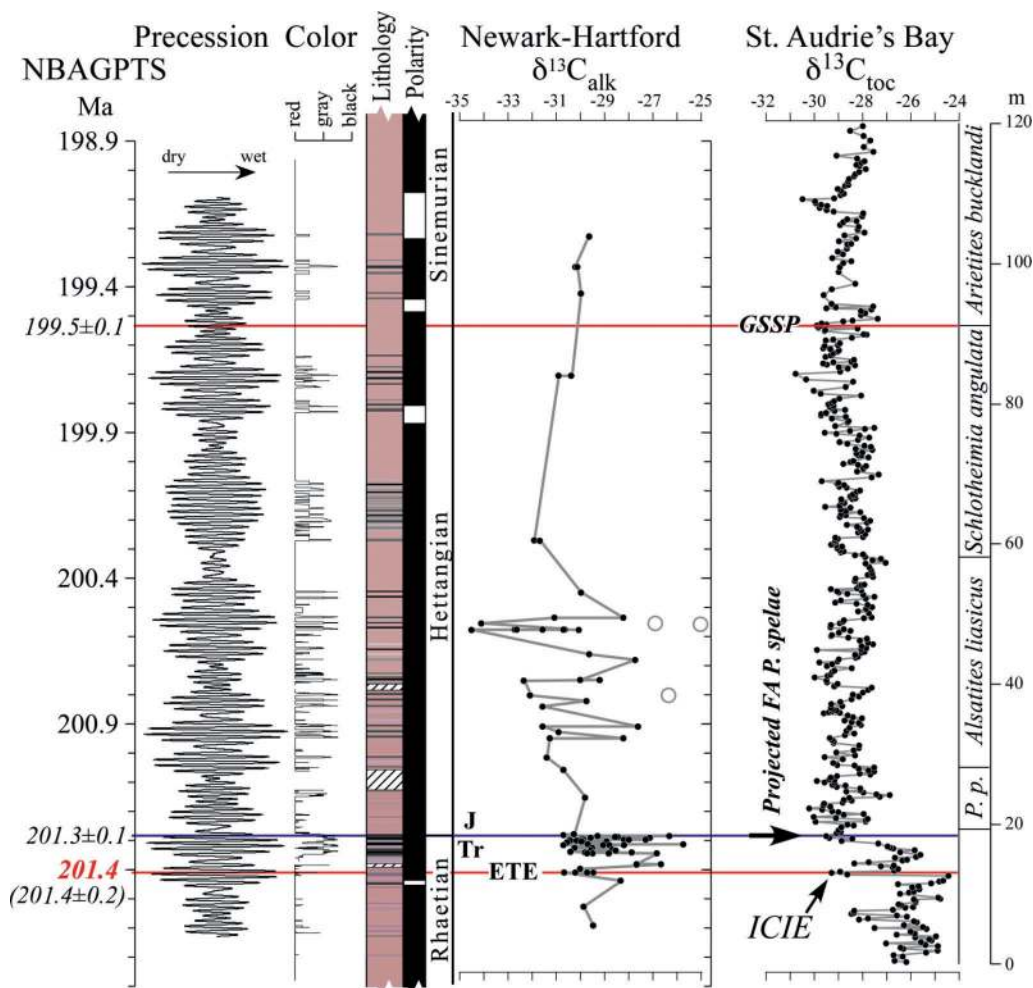


Figure 7 Compound-specific carbon isotopic records from Newark and Hartford basin strata interbedded with the CAMP lava flows (diagonal hachures) compared to marine total organic carbon ($\delta^{13}\text{C}_{\text{toc}}$) records from St Audrie's Bay (and East Quantoxhead), UK (Ruhl *et al.* 2010). Compound-specific carbon isotopes are of the weighted mean odd $\text{C}_{25}\text{-C}_{31}$ n-alkanes ($\delta^{13}\text{C}_{\text{alk}}$). Newark and Hartford sections calibrated in time with Newark-Hartford orbitally tuned time scale (Newark-APTS 2010). Dates in italics are $^{206}\text{Pb}/^{238}\text{U}$ single crystal CA-TIMS ages from the North Mountain Basalt of the Fundy basin (bold red), correlative with the Orange Mountain Basalt and Talcott Formation of the Newark and Hartford basins, and from marine ammonite-bearing strata from Peru (black), correlated to the St Audrie's Bay isotope curve using the bio- and isotope-stratigraphy in Ruhl (2010) and Ruhl *et al.* (2010). The St Audrie's Bay section is shown in depth, with the fiducial levels of correlation (red lines) among the sections being the base of the ETE (extinction level), and the Hettangian-Sinemurian boundary constrained in the Newark and Hartford basins by palaeomagnetic stratigraphy (Kent & Olsen 2008) (polarity) and cyclostratigraphy (from Ruhl *et al.* 2010). The blue line indicates the projected Triassic-Jurassic boundary (J/Tr), based on correlation to the first appearance datum (FAD) of the ammonite *Psiloceras spelae*, chosen as the marker for the base of the Hettangian at the GSSP in Kuhjoch, Austria (Hillebrandt *et al.* 2007) and projected to the Newark and Hartford data from St Audrie's Bay, itself correlated to Kuhjoch by Ruhl *et al.* (2009). Abbreviations: ETE=end Triassic extinction (initiation); GSSP=global stratotype section and point for the base of the Sinemurian at St Audrie's Bay (East Quantoxhead); ICIE=initial carbon isotopic excursion of reference 10; J/Tr=base of Triassic-Jurassic boundary; P. p.=Planorbis Zone. The open grey circles indicate points in the Hartford and Newark sections rejected because of thermal alteration or very low CPI values. (Adapted from Whiteside *et al.* 2010).

for the Newark-APTS, which agrees with all recent available independent quantitative information. Based on the Newark-APTS, a series of conclusions can be drawn, with major implications for the tempo and mode of dinosaurian origin, diversification and rise to ecological dominance. Each of these is discussed below with a heading corresponding to a conclusion derived from the Newark-APTS.

3. The end-Triassic faunal and floral break in the Newark-APTS is indistinguishable in age from the initial marine extinction

As with other purported mass extinction events, much debate has focused on the possible synchrony between the marine and

terrestrial extinctions at the close of the Triassic. The palynological data and interpretations of Cornet and colleagues (Cornet 1977, 1993; Cornet & Traverse 1975; Cornet & Olsen 1985) and tetrapod faunal data (Olsen *et al.* 1987, 2002a) supported a tight correlation between the two. However, a U-Pb date of 199.6 ± 0.3 Ma from an ash bed in latest Rhaetian age strata of British Columbia (Pálffy *et al.* 2000) was (barely significantly) younger than the available ages ($^{40}\text{Ar}/^{39}\text{Ar}$ and U-Pb) of the oldest CAMP lavas cited as about 200.6 Ma, suggesting that the continental extinctions led the marine extinctions (Pálffy *et al.* 2000). However, subsequent single crystal CA-TIMS dating of the same ash layer yielded a more precise and more accurate date of 201.7 ± 0.6 Ma (Friedman *et al.* 2008), nominally older but statistically

Cycles vs. Ages

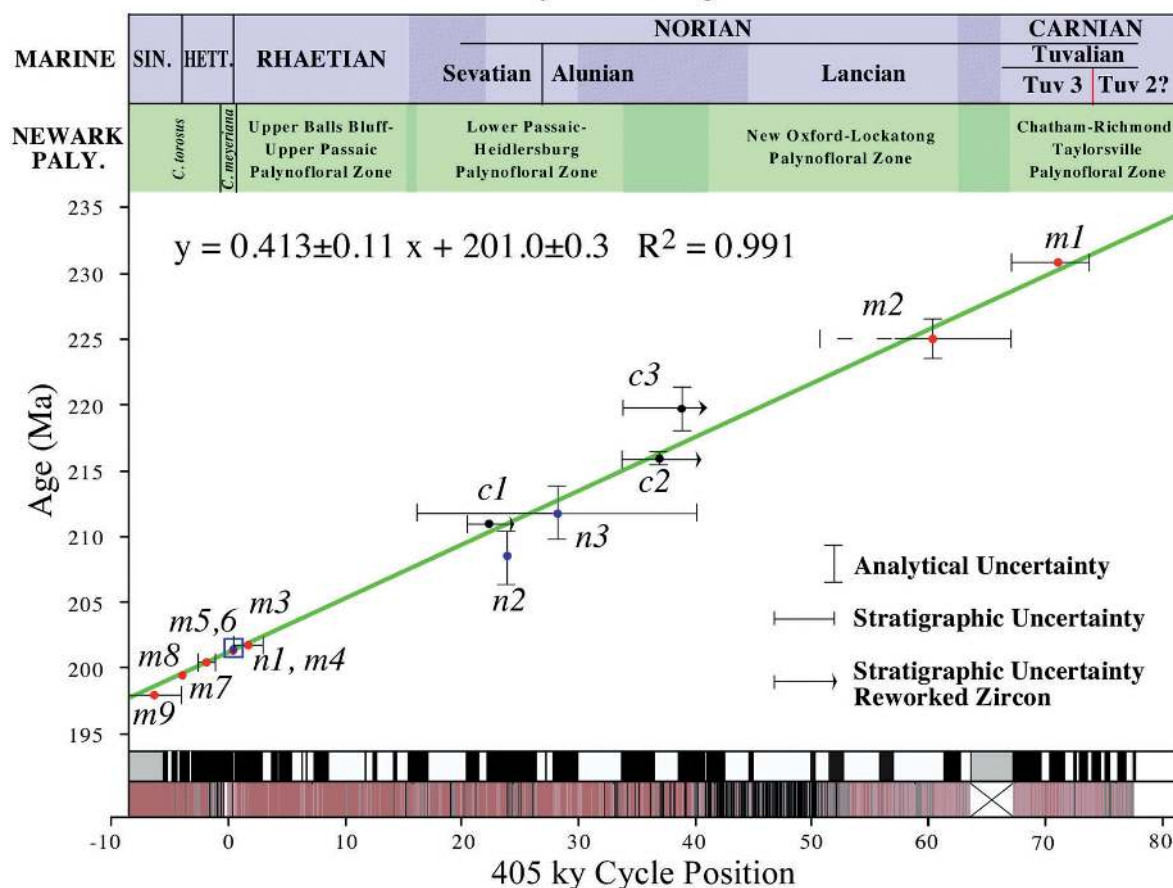


Figure 8 Correlation between number of putative 405 kyr cycles in the Newark and Hartford basin sections (from the Newark-APTS 2010) and ²⁰⁶Pb/²³⁸U ages, with linear regression yielding a slope of 411 ± 11 kyr/cycle, indistinguishable from the hypothesised 405 kyr duration of the cycle. Ages are from marine sections (red dots, *m* labels), the Newark and Fundy basins (blue dots, *n* labels) and the Chinle Formation (black dots, *c* labels) (see Fig. 10). See Table 1 for list of ages used and their sources. The upper Bluewater Creek date of Irmis & Mundil (2008) is here correlated to the upper Blue Mesa Member or basal Sonsela Member, based on Ramezani *et al.* (2010).

Table 1 U–Pb ages used to test age model for the Newark-APTS 2010.

Labels* from Figures 8 and 9	²⁰⁶ Pb/ ²³⁸ U age and error (Ma)	Depositional environment	Sources
<i>c1</i>	211.0 ± 0.7	Fluvial Chinle	Heckert <i>et al.</i> 2009
<i>c2</i>	216 ± 1	Fluvial Chinle	Dickinson & Gehrels 2009
<i>c3</i>	219.2 ± 0.7	Fluvial Chinle	Mundil & Irmis 2008
<i>m1</i>	230.91 ± 0.33	Marine	Furin <i>et al.</i> 2006
<i>m2</i>	225 ± 3	Marine	Gehrels <i>et al.</i> 1987
<i>m3</i>	201.7 ± 0.6	Marine	Friedman <i>et al.</i> 2008
<i>m4</i>	201.40 ± 0.18	Marine	Schoene <i>et al.</i> 2010
<i>m5</i>	201.36 ± 0.13	Marine	Schoene <i>et al.</i> 2010
<i>m6</i>	201.33 ± 0.13	Marine	Schoene <i>et al.</i> 2010
<i>m7</i>	200.8 ± 0.6 / - 0.4	Marine	Friedman <i>et al.</i> 2008
<i>m8</i>	199.53 ± 0.29	Marine	Schaltegger <i>et al.</i> 2008
<i>m9</i>	198.0 ± 0.6	Marine	Palfy & Mundil 2006
<i>n1</i>	201.38 ± 0.02	Basalt flow	Schoene <i>et al.</i> 2010
<i>n2</i>	208.5 ± 2.1	Stromatolite	Rasbury <i>et al.</i> 2003
<i>n3</i>	211.9 ± 2.1	Pedogenic calcite	Wang <i>et al.</i> 1998

indistinguishable from U–Pb dates from the North Mountain Basalt and the age of the end-Triassic-extinction level in the Newark-APTS of 201.4, based on the age of the North Mountain Basalt (Schoene *et al.* 2010). These dates are in turn completely compatible with dates on ashes from marine strata elsewhere, bracketing the last appearance of Triassic-aspect

ammonites such as *Choristoceras* and the first appearance of Jurassic-aspect ammonites including *Psiloceras spelae* (e.g. Schaltegger *et al.* 2008; Schoene *et al.* 2010).

Both the palynological transition and last appearances of Triassic-aspect non-crocodylomorph, suchian footprints such as *Brachychirotherium* and *Apatopus* appear abruptly in the

Newark basin (data graphed in sections in Olsen *et al.* 2002a). Last appearances of Triassic-aspect ammonoids are also abrupt and synchronous, although recent detailed studies of the distribution of palynomorphs and other microfossils in European marine Triassic–Jurassic boundary sections (Hounslow *et al.* 2004; Hillebrandt *et al.* 2007; Kürschner *et al.* 2007; Hillebrandt & Krystyn 2009) and continental sections in Greenland (McElwain *et al.* 2007) suggest a somewhat more protracted extinction sequence.

The fact that the Newark end-Triassic extinction was contemporaneous with marine extinctions at the <100 kyr level does not mean that all continental terrestrial extinction intervals are similarly correlated. In fact there are no other places in the world with as precise geochronological ties to the marine ETE as the Newark, a point that is discussed below in relation to Triassic ornithischians, for example. Because there is a clear magnetostratigraphic signature of the end-Triassic extinction level comprised of tiny chron E23r in a sea of normal polarity (E23n and E24n), at least in principle, other areas in which there is a continental faunal transition could be resolved at a similar level of precision.

4. There is no substantive evidence of a gap just below the basalts in the Newark basin

Van Veen (1995), Kozur & Weems (2005, 2007, 2010), and Gallet *et al.* (2007) have argued for a significant gap in the Newark sections of several million years below the sporomorph assemblage typical of the igneous extrusive zone (i.e., CAMP interval) that omits minimally the middle and lower Rhaetian. This is a challenge to the usefulness of the Newark-APTS, especially for the Triassic–Jurassic transition, and challenges the apparent abruptness of the ETE and the ecological ascent of the dinosaurs. In fact, if there is such an unconformity, the entire continental ETE could be a protracted affair, spanning millions of years and could be completely disconnected from the marine extinction. At face value, the correlation between McLaughlin cycles and radioisotopic ages would exclude any major gaps (millions of years) in the Newark section, as do the magnetostratigraphic correlations of Hüsing *et al.* (2011) of the Newark and Alpine Rhaetian, in which the Newark is shown to have strata correlative to the middle and lower Rhaetian.

4.1. Palynology and provincialism

Sections in Exeter Township, Pennsylvania, have abundant palynologically productive levels (Fowell & Olsen 1993), tetrapod fossils (e.g. footprints), a well-developed cyclostratigraphy and a palaeomagnetic polarity sequence (Olsen *et al.* 2002a, c) (Fig. 9), and have been the focus of discussions of a gap in the Newark sequence. Palynological assemblages from the Exeter area, at multiple sections spanning ~1 km along strike, show a dramatic change ~8–12 m below the Orange Mountain Basalt. Palynoflorules (n=10) within 80 m below this level are characterised by 5–60% vesiculate, monosaccate pollen, including *Patinasporites densus*, *Enzonalasporites* spp. and *Vallisporites ignacii* (probably all from the same basic kind of conifer), 5–75% *Classopollis* spp. (mostly *Classopollis torosus*), and *Ovalipollis ovalis* (Cornet 1977; Cornet & Olsen 1985; Fowell & Olsen 1993; Fowell *et al.* 1994). These assemblages can be very diverse, with abundant bisaccates, monosulcates, and spores, many of which are unknown outside of the Triassic. There is no doubt that these assemblages are of Triassic age and closely resemble assemblages from kilometres lower in the Newark basin section.

These typical Late Triassic assemblages are succeeded by a thin interval with 15–89% spores that was first discovered by

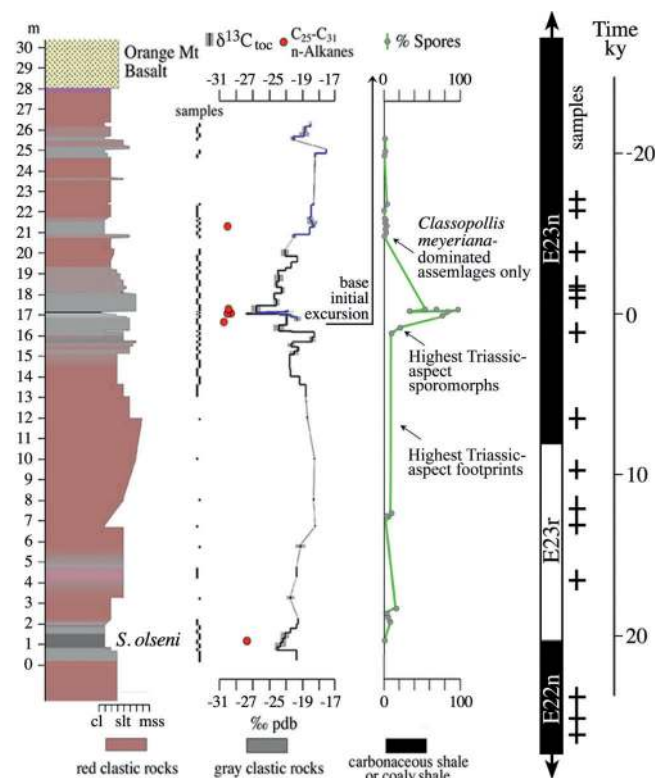


Figure 9 Section of uppermost Passaic Formation, Exeter Township, Pennsylvania, USA showing (from left to right) the litho-, chemo-, bio- and magnetostratigraphy and the position of the conchostracan *Shipingia olsenii*. Magnetostratigraphy from Olsen *et al.* (2002a).

Litwin (cited in Smith *et al.* 1988) and described by Fowell and colleagues (Fowell & Olsen 1993; Fowell 1994; Fowell *et al.* 1994; Olsen *et al.* 2002a, c). The trilete spores *Anapiculatisporites*, *Converrucosisporites deltoispora*, *Dictyophyllidites*, *Granulatisporites*, *Kyrtomisporis*, *Porcellispora*, *Reticulatisporites*, *Todisporites* and *Verrucosisporites* are present, along with *Classopollis* spp. This assemblage lacks any taxa unique to the Triassic and, because of the abundance of fern spores, has been called a fern spike (Olsen *et al.* 2002a, c). The last occurrence of taxa unique to the Triassic is an assemblage about 75 cm below this fern spike (sample 6–2 of Fowell 1994) dominated by *Classopollis* (73%) but with ~10% *Patinasporites* (Olsen *et al.* 2002c).

Until recently, there was only one palynoflorule from the Exeter area above the fern spike, JB4 of Cornet (1977) (Olsen *et al.* 2002a, c). This assemblage is dominated by *Classopollis meyeriana* (99%; Cornet 1977), with some spores. However, 12 additional levels were found to be productive at a temporary excavation (Fig. 9) and all are very strongly dominated (>95%) by *Classopollis meyeriana*. Rare bisaccates, monosulcates and spores are present, but the vesiculate, monosaccate pollen, including *Patinasporites densus* and in fact all Triassic-aspect sporomorphs, are absent. These assemblages closely resemble those of the overlying Feltville and Towaco formation assemblages (e.g. Cornet 1977). This transition, occurring through an interval less than 1 m thick, is the most dramatic in the entire Newark basin sequence and in fact in all of eastern North America.

Cornet (1977) noted, as have other authors since, that the Triassic-aspect assemblages below the fern spike lack taxa typical of the Rhaetian of Europe and Greenland. In particular, *Triancoraesporites* spp., *Cornutisporites seebergensis*, *Rhaetipollis germanicus*, *Heliosporites reissingeri*, *Ricciisporites tuberculatus*, *Zebraesporites* spp. and *Acanthotriletes varius* (Cornet 1977) have not been found in eastern North America.

Van Veen (1995) points out that in Europe, vesiculate pollen virtually disappear at the base of the Rhaetian. Hence, because he did not dispute the Jurassic age of the assemblages above the fern spike, Van Veen (1995) argued that the Newark basin section is condensed near the Triassic–Jurassic boundary and the sedimentary cycles present are not of Milankovitch origin (as in Gradstein *et al.* 1994, p. 24,056), with the implication that the entire Rhaetian is missing or extremely condensed. Kürschner *et al.* (2007), Lucas & Tanner (2007) and Cirilli *et al.* (2009) agreed with this hypothesis. However, Cornet (1997), Cornet & Olsen (1985) and Fowell & Olsen (1993) argue that this lack of European Rhaetian taxa is due to geographic provincialism, not an age difference. The idea that the vesiculate monosulcate taxa *Patinasporites*, *Enzonasporites* and *Vallisporites* might be geographically provincial is not completely unconventional. For example, although such taxa are common in parts of the Tethyan realm (Buratti & Cirilli 2007) they are much less common or absent from localities in the boreal realm regardless of age (Hochuli *et al.* 1989; Mørk *et al.* 1992; Hochuli & Vigran 2010). Likewise, they are rare or absent from the southern hemisphere high-latitude Ipswich assemblage (Dolby & Balme 1976; Traverse 2007). Cirilli *et al.* (2009) argue that because of the wide geographic distribution of the *Patinasporites* and vesiculate cohorts, climatic provinciality cannot be the cause of the absence of these forms from the Rhaetian of alpine and central Europe. However, in the Late Triassic that region was on the border between the arid belt and temperate realms and translated 20° northward through at least the Norian and Rhaetian (Kent & Tauxe 2005). There is a corresponding time-transgressive shift in facies in continental strata, reflected in vertical successions from red beds and evaporates to grey strata, sometimes with coals in the northern sections. Similarly, classic Rhaetian taxa of Europe, such as *Rhaetipollis germanicus* and *Zembrasporites* spp., extend into the Early Carnian near the Late Triassic North Pole in northern Middle Siberia (Kozur & Weems 2007; Ilyina & Egorov 2008). Thus, it is no surprise that the tropics contained floras that differed from the temperate region, or that a flora might be time-transgressive as central Pangea translated northward.

It follows that because at any given time the region in which *Patinasporites et al.* were common was latitudinally and presumably climatically limited, and central Pangea drifted northward through the latter Triassic, the absence of classic European taxa such as *Rhaetipollis* in the latest Triassic of the tropics is to be expected. Consequently, while the sporomorph taxa may be extremely useful in demarcating a floral event, they may be of limited use in correlation between biotic provinces or across climate belts. Forcing correlation by introduction of hiatuses that lack independent methods of testing, biostratigraphic or otherwise, eliminates biologically informative patterns that are potentially much more informative than the correlations themselves. Thus, the present authors do not regard the lack of ‘standard Rhaetian’ sporomorph taxa, or the presence of vesiculate monosulcate pollen as significant evidence of a hiatus in the Exeter section, or elsewhere in the Newark basin, or elsewhere in eastern North America or Morocco below the oldest basalt.

4.2. Conchostracan biostratigraphy

Another line of evidence cited as indicating a major hiatus near the palynological ETE in the Newark Supergroup in general is conchostracan biostratigraphy, championed by Kozur & Weems (2005, 2007, 2010). Based on their interpenetration of the biostratigraphy of early Mesozoic representatives of this ubiquitous yet remarkably sparsely studied group, Kozur & Weems assert the presence of a 5 Myr hiatus below the

palynological ETE in the Newark basin and elsewhere in Eastern North America. The best-documented area is in the Newark basin, again in the Exeter section (Fig. 9).

A well-developed dark grey lacustrine bed is present ~16 m below the fern spike and the highest occurrence of Triassic-aspect palynomorphs in the Exeter area marking the base of the Exeter Township Member (Olsen *et al.* 1996a) (Fig. 9). In addition to abundant *Patinasporites* and other sporomorphs, the unit also produces conchostracans (clam shrimp) that have been used for biostratigraphy. Kozur & Weems (2005, 2007, 2010) have documented the occurrence of the conchostracan form *Shiopingia olseni* from this unit. According to them, this taxon indicates a Late Norian (middle Sevatian) to Early Rhaetian (Late Sevatian) age. They further identify conchostracans above the lowest basalt (Midland Basalt) of the Culpeper basin as *Euestheria brodieana*. The latter conchostracan occurs in the Cotham Member of the Lilstock Formation in England (Mayall 1983) that is Late Rhaetian, based on the definition of the base Jurassic by ammonites (*Psiloceras planorbis* as a proxy for *P. spelaes*), which lies in superposition. It also occurs in lower Rhaetian strata (late Sevatian) in Germany (cited by Kozur & Weems 2005 without mention of locality or reference). In Great Britain it appears to occur at the top of the contorted interval interpreted as a seismite (Mayall 1983; Simms 2007), corresponding to the base of the ‘initial’ isotopic excursion of Hesselbo *et al.* (2002) and within the ‘dead zone’ that marks the marine extinction level (Mander *et al.* 2008). The present authors have been able to ascertain that a form indistinguishable from the Midland form (*Euestheria brodieana*) occurs in the lower Shuttle Meadow Formation (Hartford basin), homotaxial and time equivalent of the Midland Formation (N. G. McDonald collection, Museum of the Earth, Ithaca, NY). Kozur & Weems (2007, fig. 10), agreeing in kind but not in detail with Van Veen’s (2005) interpretation, argue that there is a ‘significant unconformity’ spanning the entire early Rhaetian (late Sevatian plus early traditional Rhaetian: Fig. 9) in the Newark basin, and in the Newark Supergroup in general, below the oldest basalt and above the *E. olseni* zone, and specifically between the grey shale marking the base of the Exeter Township Member of the Passaic Formation and the Orange Mountain Basalt, as discussed above.

Kozur & Weems (2005, 2007) argue that conchostracans they call *Bulbilimnadia sheni* that occur with *Euestheria brodieana* in the Midland Formation (and succeeding Hickory Grove Basalt, Turkey Run Formation and Sander Basalt in the Waterfall Formation) indicate a Hettangian age, because they are found with the conchostracans *Palaeolimnadia* cf. *longmenshanensis* and *P. cf. semicircularis*. However, *Bulbilimnadia sheni* is unknown from strata directly dated by marine invertebrates, whereas *Palaeolimnadia longmenshanensis* and *P. semicircularis* are only known from China (Chang *et al.* 1976), from continental strata correlated to the marine stages by means of floral remains. Kozur & Weems (2007, 2010) also cite *Bulbilimnadia sheni* from the middle East Berlin Formation of the Hartford basin (Westfield Fish Bed), and the present authors have found this taxon in the exact homotaxial and time equivalent in the Newark basin, ‘cycle P3’ of McCune (1990) (Olsen 2010).

Kozur & Weems (2005, 2007) identified another conchostracan assemblage from the upper Waterfall Formation of the Culpeper basin. This assemblage is dominated by *Bulbilimnadia froelichi*, with scarce *Palaeolimnadia baitianbaensis* known from China (Kozur & Weems 2005), and is asserted to belong in the later part of the early Hettangian.

On the basis of these conchostracans, Kozur & Weems (2007) conclude that the Triassic–Jurassic boundary (base

Hettangian) lies near the middle of the CAMP zone, which is about the position of the Preakness Basalt in the Newark basin, not at the fern spike, below the Orange Mountain Basalt. The present authors do not necessarily disagree with this correlation of Kozur & Weems of the base Hettangian in general, except to note that what is hypothesised to be Late Rhaetian is based on the presence of *Euestheria brodieana* that Kozur & Weems agree extends into the Hettangian, and based on the apparent absence of the Hettangian forms. However, the latter are either, thus far, endemic to eastern North America or from strata that are not directly tied to a marine fauna themselves. There are no conchostracans from the Early Hettangian of England or the Germanic basin, because those sections are marine. Thus, while their placement of the base Hettangian may be correct, the taxa used for correlation have no direct ties to the marine stage boundaries, let alone the first appearance datum of *Psiloceras spelae*. The position of the first appearance datum of *Psiloceras spelae* is projected by Whiteside *et al.* (2010) to be below that suggested by Kozur & Weems (2007), but still between their highest purported Rhaetian and their lowest purported Hettangian conchostracans, in the lower Feltham and Lower Shuttle Meadow formations (Fig. 7).

The GSSP definition for the base Hettangian is the level marking the FAD of *P. spelae* at Kuhjoch, Austria, a boundary definition detached from what must now be termed the end-Triassic extinction (ETE), and becomes a datum of little apparent relevance to any specific process. Hence its correlative position in eastern North America does not appear to bear on any specific process-oriented problem. After all is said and done, the placement of the Triassic–Jurassic boundary within the basalt flow sequence has no apparent bearing on the relationship of the extinction event to the CAMP. This is a point that is seemingly lost in quite a few recent papers (e.g. Lucas & Tanner 2007; Kozur & Weems 2008; Cirrilli *et al.* 2009). However, the hypothesised gap below the basalts remains pertinent to the nature of the extinction and to the time scale, and hence to the rise of dinosaur ecological dominance.

Support for the gap hypothesised below the oldest basalt in eastern North America of Kozur & Weems (2005, 2007, 2010) comes down basically to the apparent juxtaposition of strata with *Euestheria brodieana* above and *Shipingia olseni* below, without intervening strata containing *Anyuanestheria?* n. spp. without *S. olseni*. The latter are known from the Exter Formation of Germany and Polish strata proposed to be correlative to the lower Rhaetian. However, it is pointed out that the strata containing all of these lack the guide fossils (ammonites and conodonts) of the Alpine sections on which the yet to be formally defined Rhaetian is based, and thus their relative age is tenuous as well. The recognition of this gap depends on the one hand with substage-level correlation between the mostly continental lower Rhaetian facies of Germany and Poland with the fully marine Alpine facies of the sub-stages of the Rhaetian and, on the other hand, with near perfect fidelity of faunas separated by thousands of kilometres and across climate zones. The present authors doubt either of these requirements is met. This seems to be a repeat of the same problem that plagues the palynology of this interval, but at a smaller temporal scale. Indeed, present-day conchostracan species, genera, and even some families, are known to be endemic at varying scales, despite their reproductive strategies that would seem to encourage wide distributions. For example, in a recent review of freshwater branchiopod diversity, Brendonck *et al.* (2008, pp. 172–173) state, “Some clam shrimp genera like *Cyzicus* and *Eocyzicus* appear to be Laurasian, with their current ranges encompassing Eurasia, Africa and North America. The genus *Lepthesteriella*, in contrast, seems

Gondwanan, and occurs in Africa, Madagascar and Asia. Lynceids are cosmopolitan, save in Antarctica. *Cyclestheria hislopi* (if representing only one species, which is uncertain) is pantropical”. Individual genera and species of conchostracans tend to exhibit greater endemism (e.g. Naganawa & Zagaswith 2002; Tims 2009). It is not obvious why early Mesozoic forms would be expected to behave profoundly differently, and be less subject to biotic provincially, than those of today.

The absence of a taxon of a poorly known group in a poorly studied region is insufficient grounds for inserting a hiatus in a section for which there is no physical evidence for one (see below). Indeed, the correspondence between ages assessed using conchostracan biostratigraphy and independent radioisotopic ages is poor (see below). Therefore, the present authors are not compelled by the conchostracan biostratigraphy suggesting a significant hiatus below the oldest basalts, and argue instead that there remains an important biostratigraphic signal. A hypothesis consistent with conchostracan distribution and independent radioisotopic ages prior to the onset of the end-Triassic extinction, is that Triassic conchostracans exhibited considerable provinciality, while after the ETE they were more cosmopolitan, perhaps including widespread ‘disaster taxa’ (cf. Roland & Bottjer 2001).

4.3. Palaeomagnetic polarity stratigraphy

Gallet *et al.* (2007) argue that the Rhaetian is at least partly missing in the Newark basin, based on palaeomagnetic polarity stratigraphy from highly condensed marine Alpine facies carbonates in Turkey. However, their stratigraphic arguments rest almost completely on the acceptance of the hypothesised gap below the basalts of Kozur & Weems (2005). While Gallet *et al.* (2007) assert that, “. . . the top-Triassic magnetostratigraphy now appears well established from several data sets . . .”, exclusive of the Newark, in fact none of the marine sections of the Alpine facies of the late Norian and Rhaetian examined by Gallet *et al.* (2007) and Krystyn *et al.* (2007a, b) extend to the base of the Jurassic on the basis of palaeontological criteria, or deep into the Norian without intervening faults of unknown throw (Fig. 10). In fact, these marine sections are so short that attempts at correlating them to each other using biostratigraphy require so much distortion that the composite ‘Tethyan Sevatian–Rhaetian’ ends up being virtually arbitrary, because the most fundamental time proxies in stratigraphy are essentially lost: superposition for the arrow of time and thickness as a proxy of its duration.

Instead, it is argued that many Tethyan sections are riddled with significant lacunae that result in the different patterns of polarity stratigraphies of the sections. Multiple hypothesised gaps (11 in four sections) are required to reconcile the polarity sequences of biostratigraphically correlated Carnian–Norian sequences in adjacent nappes for the parts of the Tethyan sections examined by Gallet *et al.* (2000), once the idea that the two nappes came from different hemispheres (Gallet *et al.* 1992, 1993) was abandoned. The presence of significant gaps in the Rhaetian Tethyan sections is also suggested by the simple observation that there are significantly more polarity zones in the Newark basin sequence than in any of the Tethyan sections that are thought to correlate in a broad way (e.g. Fig. 10). It is concluded that hiatuses and attendant missing or truncated polarity zones most probably occur in the Tethyan sections, and there is no evidence based on the magnetostratigraphic data alone that demands there be a hiatus in the Newark. Indeed, the high-resolution sampling of the proposed base-Rhaetian GSSP of Hüsing *et al.* (2011) demonstrate a particularly good match with the Newark, showing that the supposed gap in the Newark does not exist.

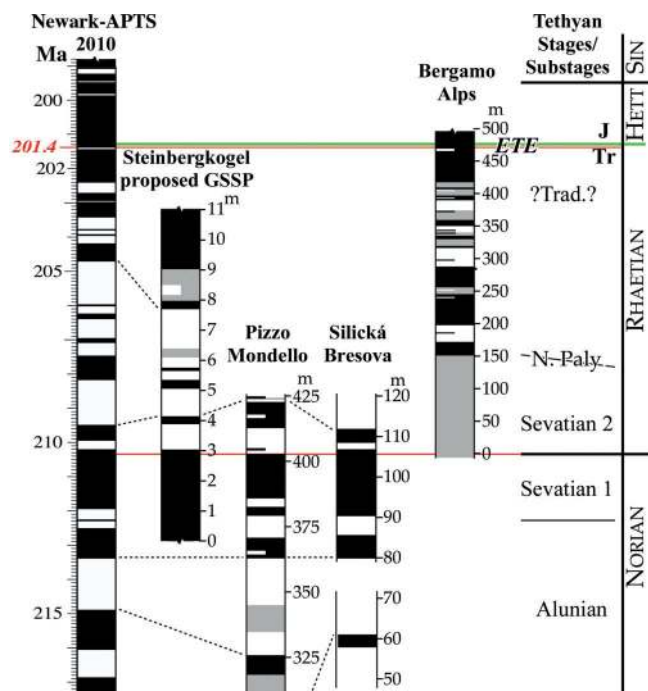


Figure 10 Comparison of Alpine and Sicilian Rhaetian sections with the younger part of the Newark-APTS 2010, with correlation based on original authors and Hüsing *et al.* 2011. Principal magnetostratigraphically-independent fiducials are ETE (end-Triassic extinction initiation) and Alunian–Sevatian boundary (for the marine sections). Steinbergkogel section from Hüsing *et al.* 2011; Pizzo Mondello section from Muttoni *et al.* 2004; Silická Bresová section from Channell *et al.* 2003; Italcementi Quarry and Brumano sections merged into Bergamo Alps section (retaining uninterpretable intervals from both sections), from Muttoni *et al.* 2010. Black indicates normal polarity; white reverse polarity; grey uninterpretable or ambiguous polarity; and half bars indicate single samples of uninterpretable polarity. ‘N. Paly’ indicates position of the palynological transition regarded by Cornet (1977) and Cornet & Olsen (1985) as indicating the Norian–Rhaetian boundary. ‘?Trad?’ indicates the highly uncertain relative position of the ‘traditional’ Norian–Rhaetian boundary of Mojsisovics (1869, 1893).

Identification of the very short chron E23r at multiple localities, both within and outside the Newark basin, also argues for no gap in the upper Passaic Formation. Originally, E23r was identified in the Martinsville core near the top of the Passaic Formation (Fig. 11) and in outcrops at Grist Mills in Exeter Township about 113 km away, and then about 1 km east of the Grist Mills section. At both latter locations the base of E23r is in contact with the conchostracan-bearing shale containing *Shipingia olseni* and underlies more *Patinasporites densus*-bearing shales (Lucas *et al.* 2011). Recently, Deenen *et al.* (2010) identified E23r below the Argana basalt, again surrounded by pollen and spore assemblages with vesiculate pollen, in this case *Enzonasporites vigenis*; Whiteside *et al.* (2007) report the related *Patinasporites densus* from the same strata. Deenen *et al.* (2011) also identified E23r from the Fundy basin at Partridge Island, near Parrsboro, Nova Scotia, again within strata containing vesiculate pollen. In all cases, E23r bears a consistent relationship with the overlying sporomorph extinction level as well as underlying strata with *Shipingia olseni*, consistent with the differences in accumulation rate between the basins. The initial palynological extinction horizon is then overlain by the oldest basalt in each basin, except in Morocco where the basalt is in direct contact with vesiculate pollen-bearing strata plausibly at the extinction level (Marzoli *et al.* 2004; Deenen *et al.* 2010). It is thus extremely hard to envision a significant erosional or non-depositional hiatus in these rift sequences between either the youngest

Shipingia-bearing beds or the youngest vesiculate pollen-bearing bed and the extinction level and overlying basalt in multiple basins on two continents. Instead, these observations are far more consistent with more or less continuous deposition.

4.4. Cyclostratigraphy

The cyclostratigraphy of the Newark basin sequence has long been used to estimate the duration of the CAMP event in the basin (Olsen *et al.* 1996b, 2003; Whiteside *et al.* 2007). Independent, strong corroboration of these estimates and the underlying Milankovitch origin of the cycles themselves have been recently obtained from high-precision U–Pb ages from the basalts themselves (Blackburn *et al.* 2009). This cyclostratigraphy also provides evidence against the presence of a major unconformity (Olsen *et al.* 2003; Whiteside *et al.* 2007).

Passaic Formation strata starting a few tens of metres below the Orange Mountain Basalt exhibit an upward increase in the amplitude of cyclical climate sensitive sedimentary facies fluctuations, compared to underlying strata. The increase in grey and black shales in these cycles is consistent with being deposited during an interval of high precession variance in a ~100 kyr eccentricity cycle. Strata of the overlying lower Feltville Formation have cyclical facies changes indicating even higher precessional variability consistent with the next 100 kyr cycle. Together, they are most parsimoniously interpreted as two successive 100-kyr cycles in the portion of a 405-kyr cycle characterised by peak precessional variability (Olsen *et al.* 2003; Whiteside *et al.* 2007). With this interpretation, any hiatus present would have to be a rather precise multiple of 400 kyr, which is not a simple interpretation.

5. The Rhaetian is relatively long (+6 Myr)

Traditionally, the duration of the Rhaetian has been considered short, especially compared to the Norian or Carnian stages. This is largely because it was generally thought of as thin with few biozones – in fact originally only one. That was the *Avicula contorta* zone of Mojsisovics (1893), now known to be restricted to a specific facies and a poor guide fossil. The Rhaetian was dropped as a recognised stage for a decade in North America because of this (Tozer 1979) and then reinstated by bureaucratic fiat (IGCP–Subcommission on Triassic Stratigraphy: Visscher 1992). The base of the Rhaetian remains formally undefined, but there are proposals resulting in a somewhat expanded Rhaetian including the so-called Sevatian 2, not formally defined but usually grouped with the Norian (also not formally defined) (e.g. Krystyn *et al.* 2007a, b) (Fig. 12), with two ammonite zones and three or more conodont zones. Apart from these definitional issues enlarging the scope of the Rhaetian, and the thinness of the stage at a number of sections, there are no geochronological constraints on the duration of the Rhaetian, other than the Newark-APTS.

The problem of the duration of the Rhaetian and correlation to the Newark-APTS is intimately related to the problem of the supposed gap in the upper Passaic Formation, discussed above. Correlation of upper Passaic strata of the Newark basin with the Rhaetian had been based purely on palynology in the Newark basin. Cornet recognised the Norian–Rhaetian transition (i.e. the base of the Balls Bluff–Upper Passaic palynofloral zone) by the appearance of *Classopollis torosus* and *Granuloperculatipollis rudis* and an increase in *Classopollis* spp. abundance, especially *Classopollis meyeriana* that is abundant to dominant in most samples (Cornet 1977; Cornet & Olsen 1985). As already discussed, many typical European Rhaetian sporomorph taxa are absent in the Newark basin and *Patinasporites* and related vesiculate taxa are common, evidently because of

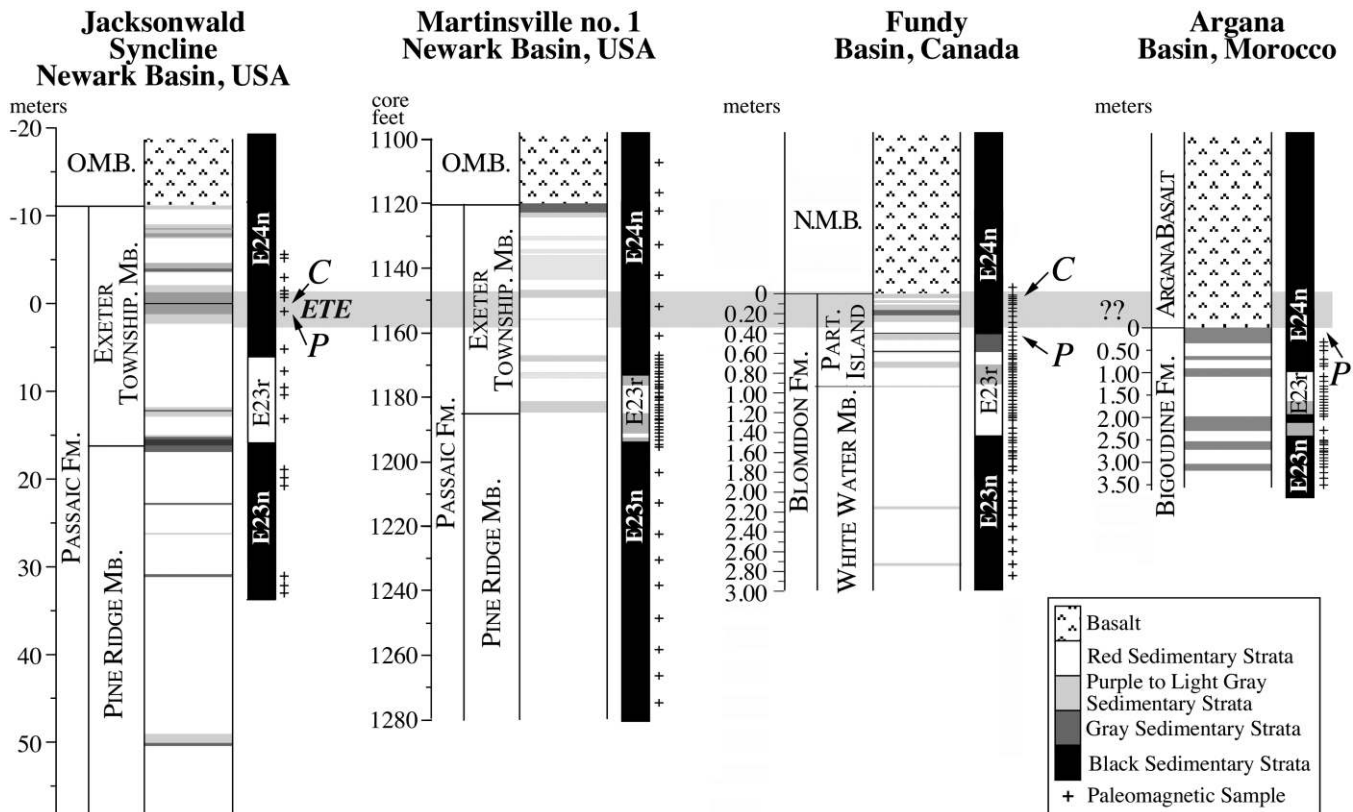


Figure 11 Sections in which magnetostratigraphic zone E23r has been observed. These sections are correlated to each other on the basis of two levels: first, by the ETE, marked by the last appearance of vesiculate pollen (including *Patinasporites densus*); and second, by the midpoint of E23r itself. The Jacksonwald syncline and Martinsville no. 1 sections from the Newark basin are modified from Kent & Olsen 1999 and Olsen *et al.* 2002a. The Argana basin and Fundy basin sections are modified from Deenen *et al.* 2010 and 2011, respectively. *P* is the highest occurrence of vesiculate pollen and *C* lowest occurrence of a sporomorph assemblage lacking vesiculate pollen, based on Olsen *et al.* 2002a, Fowell & Traverse 1995, Marzoli *et al.* 2004, Whiteside *et al.* 2007 and Cirilli *et al.* 2009. Note the consistent relationship between the ETE and E23r, which is not what would be expected if the ETE itself marks an unconformity representing millions of years.

		AMMONITE		CONODONT		OTHER BIOEVENTS
		ZONES	EVENTS	ZONES	EVENTS	
RHAETIAN OPTIONS	3	<i>Choristoceras haueri</i>	<i>Vandaites stuerzenbaumi</i>	<i>Misikella hersteini</i> - <i>M. posthernsteini</i>		LO FO <i>Limbosporites lundbladii</i>
	2	<i>Paracohloceras suessi</i>	<i>Sagenites reticulatus</i>	<i>"Epigondolella" bidentata</i> - <i>M. posthernsteini</i>	<i>"E." bedentata</i> / <i>P. metternichi</i>	? <i>Heterastridium</i> "Norian" sporomorphs
	1	<i>Metasiberites spinescens</i>	<i>Sagenites quinquepunctatus</i>	<i>"Epigondolella" bidentata</i>	<i>M. posthernsteini</i> <i>M. hernsteini</i>	<i>Rhaetogonyaulax rhaetica</i> <i>Monotis salinaria</i> (+ large monotids) <i>Triasina hantkeni</i> ? <i>Rhaetavicula contorta</i>
NORIAN	Sevatian 1		<i>S. (with nodes)</i> <i>Metasiberites</i>			<i>dwarf Monotis</i>

Figure 12 Recent revisions of the definition of Rhaetian according to Krystyn *et al.* (2007a) showing the correlation of ammonoid and conodont zones based on data from the proposed GSSP at Steinbergkogel, with integration of additional bioevents from elsewhere. Option 3 at the top of the Sevatian 2 is the base of the 'traditional' Rhaetian, but is not represented in the exposed section at the proposed GSSP section in Steinbergkogel; options 2 and 3 (favoured by Krystyn *et al.* (2007a, b) would place a portion of the 'traditional' upper Norian (Sevatian 2) in the Rhaetian.

provinciality (Kozur & Weems 2007). However, the correlation between the Tethyan Norian–Rhaetian boundary and Newark-APTS is relatively weak, especially because the definition of the

boundary was not in place in 1997 (it still is not formalised) and the palynology of the transition is still not worked out in Tethyan strata (Kürschner in Krystyn *et al.* 2007a, b).

Magnetostratigraphy provides a potential correlation tool, but the fundamental correlation problem is obvious; the lower half of the Newark section above the conventional Norian is predominately reverse polarity, and until very recently there have been no comparable dominantly reverse polarity sequences seen in Tethyan sections (Fig. 10). In contrast, the magnetostratigraphic correlation between the Tethyan Norian and the Newark appears fairly secure (Muttoni *et al.* 2004; Channell *et al.* 2003). Most of the Tethyan sections examined appear too short to be of much use (Fig. 10), except to help define the lower boundary of the Rhaetian.

Tectonic omission by faults may play a role in the comparison between the Tethyan sections and the Newark. Until the recent work by Muttoni *et al.* (2010), the only Tethyan section that purportedly spanned the Triassic–Jurassic boundary to the base of the Rhaetian was the Oyuklu section of southwestern Turkey totalling ~29 m (Gallet *et al.* 2007). Unfortunately, the base of that section, also the base Rhaetian, is a significant thrust fault that overturns the underlying section. In addition, another fault, not discussed in Gallet *et al.* (2007), bounds the base of the upper three-quarters of the section. This upper interval of mostly normal polarity is thought to extend into Jurassic age strata (although this is based solely on the disappearance of conodonts) and is structurally detached from the lower interval that has slightly more reverse polarity. Comparison of this section with the Newark-APTS is thus problematic.

Muttoni *et al.* (2010) provide palaeomagnetic polarity stratigraphies for thick Tethyan sections in the southern Alps near Bergamo, Italy totalling ~480 m, more than an order of magnitude thicker than the Oyuklu section (Fig. 10). Both the end-Triassic extinction level and the putative Norian–Rhaetian boundary are present, with the latter defined by the FAD of the conodont species *Misikella posthernsteini*, defining the base Rhaetian (according to Krystyn *et al.* 2007a, b) and *Misikella hernsteini* extending up from the Late Norian Age strata. Perhaps unsurprisingly there are more polarity zones per unit time in the expanded Italian sections (represented by more than one sample) than in the condensed Oyuklu section, and more yet in the putatively correlative and thick Newark section (Fig. 10), which is evidence of omissions in the thinner sections. The argument against this, perfectly plausible on face value, is that the Norian–Rhaetian boundary is placed too low in the Newark section. However, placing that boundary higher in the Newark results in exacerbating the larger number of polarity zones in the Newark compared to the Tethyan Norian sections, given the fact that Gallet *et al.* (2003, 2007) agree with the placement of the Carnian–Norian boundary. Thus, there must be gaps or highly condensed intervals in the Tethyan section relative to the Newark.

A thin Rhaetian section at Steinbergkogel in Austria has been proposed as the GSSP for the base of the Rhaetian (Krystyn *et al.* 2007a, b). The magnetostratigraphy from this and an adjacent section did not provide a convincing correlation to the Newark basin because of the very few polarity zones present and because of a lack of agreement between adjacent sections. Hüsing *et al.* (2011) recently reexamined the section at Steinbergkogel, resulting in a polarity stratigraphy with more polarity zones and more convincing correlation to the nearby section. This results in a more reasonable correlation to the Newark as well as the more expanded marine sections at Pizzo Mondello and Silická Brezová (Slovakia) (Fig. 10).

The GSSP for the Norian–Rhaetian boundary has yet to be defined, with two alternative proposed conodont-based options being: (1) the First Occurrence (FO) of *Misikella hernsteini*; or (2) the first appearance datum (FAD) of *Misikella posthernsteini*; both fall close to the boundary

between Sevatian 1 and Sevatian 2. Hüsing *et al.* (2011) correlate the base of Sevatian 2 to the top of E16n, falling at 210.1 Ma in the Newark-APTS 2010. Unfortunately, the upper boundary of Sevatian 2, the traditional base of the Rhaetian, has not been located in this section, as the critical ammonites have not been found. The extension of the Rhaetian base from 207.6 Ma to 210.1 Ma reflects the inclusion of Sevatian 2 into the Rhaetian. There may be no clear marker of the Sevatian 1–2 boundary in the continental realm. In the Newark basin, *Granuloperculatipollis rudis* has its first occurrence in the upper part of the lower Passaic–Heidlersburg palynological assemblage (Cornet 1977), consistent with the Newark-APTS 2010.

Palaeomagnetic polarity correlation between the Newark-APTS and Tethyan Norian seems much more straightforward (Channell *et al.* 2003; Gallet *et al.* 2003; Muttoni *et al.* 2004; Hüsing *et al.* 2011) than the Rhaetian correlation. Because the astronomical calibration through the section above the Norian and below the latest Rhaetian radioisotopic dates (Pálffy & Mundil 2006; Schaltegger *et al.* 2008; Schoene *et al.* 2010) comprises the only geochronological constraint on the duration of the Rhaetian (and the duration of any putative unconformity), the Newark-APTS 2010 estimated duration of 6.2 Myr for the traditional Rhaetian and 9.7 Myr for the Rhaetian including Sevatian 2 stands. We look forward to testing this hypothesis with radioisotopic ages from ashes and flows in marine sequences.

6. The Norian is long (18–20 Myr)

Perhaps the biggest surprise from correlation between the Newark-APTS and marine sections was the realisation that the Norian stage is the longest stage of the Triassic and considerably longer (and starts earlier) than given in several prominent recent geologic time scales (e.g., GTS2004) (Fig. 4). The Carnian–Norian boundary in the Newark basin was originally identified by Cornet (1977) as between the New Oxford–Lockatong palynoflora and the Lower Passaic Heidlersburg palynoflora (localities S2a in the Walls Island Member of the Lockatong Formation and M6 of member L–M of the Passaic Formation). However, when long marine Tethyan palaeomagnetic polarity sequences became available, this correlation became untenable (Channell *et al.* 2003; Gallet *et al.* 2003; Muttoni *et al.* 2004) and suggested that the Carnian–Norian boundary had to be much lower in the upper Stockton Formation.

In fact, the palynological data are not as discrepant as they might seem. Cornet (1977) used the presence of *Camerosporites pseudoverrucatus* of the New Oxford–Lockatong palynoflora as indicative of a Carnian age because it is present in the older Chatham–Richmond–Taylorsville palynoflora of undoubted pre-Norian age and becomes rare or absent above the Lockatong Formation. Cornet (1977) used *Camerosporites verrucatus*, present in Lower Passaic Heidlersburg palynoflora, as an indicator of Norian age, although he later found this taxon in the Lockatong Formation, in a level below locality S2a (Cornet in Olsen & Flynn 1989). Absent from the New Oxford–Lockatong palynoflora is *Camerosporites seccatus*, a form common in the European Carnian and in the Chatham–Richmond–Taylorsville palynoflora but absent from the Norian of Europe, while *Camerosporites verrucatus* is common in Norian strata and absent in Carnian age strata (Litwin & Skog 1991). On face value, based on *Camerosporites* spp., the Lockatong Formation would seem to be Norian in age. However, such one-taxon palynological correlations are probably not very useful over intercontinental distances and, in fact, the *Camerosporites seccatus* occurrences in the Chinle,

long thought to indicate a Carnian age, appear to be Norian as well (see below). There are no tetrapod taxa that by themselves argue for a Carnian age associated with the New Oxford–Lockatong palynoflora.

Kozur & Weems (2007, 2010) define conchostracan zones for the Triassic of eastern and western North America. In the Newark basin they conclude that the *Euestheria ovata*–*E. princetonensis* Zone of the Lockatong Formation of the Newark basin (and its correlatives in other Newark Supergroup basins) correlates with Kozur and Weem's *Laxitextella freybergi* n. sp. in the Germanic basin that they interpret to be Tuvolian (Late Carnian) in age, based on the shared presence of *Euestheria hausmanni*. Note however that the Newark conchostracan zone is correlated to the Germanic basin by a shared taxon, and the Germanic basin conchostracan zone is then correlated to the Alpine standard stages by a correlation web. Thus, we are at least three steps away from correlation with the Alpine Triassic. Because there are no magnetostratigraphies or radioisotopic ages from the putative Tuvolian of the Germanic basin, there are no available biostratigraphically-independent tests of this correlation. However, the Lockatong Formation is correlative with the lower Chinle Formation (Blue Mesa and Bluewater Creek Members), based on palaeomagnetic polarity stratigraphy (see above: Steiner & Lucas 2000), palynology (Litwin *et al.* 1991), vertebrate biostratigraphy (Lucas 1990; Lucas & Huber 1993) and shared conchostracans (Kozur & Weems 2008); as discussed above and in more depth below, the lower Chinle has produced U–Pb ages from ashes that are too young to be Carnian (Fig. 15; see section 9 below). This is a *prima facie* falsification of the conchostracan biostratigraphic argument, and the statement in Kozur & Weems (2007) that “(t)hese conchostracan faunas show that all paleomagnetic correlations so far made between the Newark Supergroup and the Tethys region are wrong” should be viewed in that light.

Based on the age of the Triassic–Jurassic boundary of 201.3 Ma (first appearance of *Psiloceras spelae* in Schoene *et al.* 2010) and the early Norian date of 225 ± 3 Ma (Gehrels *et al.* 1987), which is supported by a late Carnian U–Pb date of 230.9 ± 0.33 Ma (Furin *et al.* 2006), the Norian plus early to middle Rhaetian cannot be less than ~ 23 Myr or more than ~ 29 Myr in duration, constraints that are fully consistent with the Newark-APTS 2010. If ~ 6 Myr is accepted as the duration of the pre-late Rhaetian, pre-end-Triassic extinction, the Norian should be between ~ 17 to 23 Myr long, easily allowing the Newark-APTS 2010 duration of 20.1 Myr for the Norian if the traditional definition of the Rhaetian is used, or 17.6 Myr if Sevastian 2 is included in the Rhaetian (see section 5 above). If the Rhaetian proves shorter, the Norian would be correspondingly longer. The present authors are not aware of any quantitative data or convincing biostratigraphic data contradicting these assessments.

7. The Carnian is short (7 Myr)

The base of the Carnian is estimated at 235 Ma by Muttoni *et al.* (2004). Although the base of the Carnian has yet to be formally defined and there are no direct dates, the age of 235 Ma is completely consistent with U–Pb ages from ashes and intrusions in marine Tethyan Ladinian age strata (Mundil *et al.* 1996; Brack *et al.* 1997, 2005; Pálffy *et al.* 2003; Furrer *et al.* 2008). If the Carnian–Norian boundary is at 228 ± 2 Ma based on Newark-APTS 2010, and the base of the Carnian is at 235 ± 2 (Brack *et al.* 2005), the duration of the Carnian is $\sim 7 \pm 4$ Myr. Taking the maximum age for the base of the Norian of ~ 230 (based on the age of Furin *et al.* 2006) the Carnian could be a short as 3 Myr.

8. The rest of the Triassic is short (~ 17.5 Myr)

A corollary to the age of the base of the Carnian at ~ 235 Ma is that the rest of the Triassic is quite short, shorter in fact than the Norian. The base of the Triassic (GSSP) is at ~ 252.5 Ma (see review in Metcalfe & Isozaki 2009), and therefore the rest of the Triassic (Early plus Middle Triassic) must be ~ 17.5 Myr. The duration of the Early Triassic at only 5.5 Myr is better constrained than that of the Middle Triassic (Metcalfe & Isozaki 2009). This reemphasises the very long duration of the Norian at ~ 22 Myr and of the Late Triassic at 34 Myr, which constitutes 2/3 of Triassic time.

9. The Chinle and Dockum may be entirely Norian and Rhaetian

Traditionally, the Chinle Formation of the Colorado Plateau and environs and the equivalent Dockum Group of the High Plains (together grouped by Lucas 1993 in the Chinle Group) (Fig. 13) have been correlated with nearly the entire Late Triassic. Lucas (1993) summarised and revised the biochronology as it was understood at the time (Figs 13, 14) and recognised four tetrapod faunachrons (from oldest to youngest A, B, C, D) that he correlated to the European standard stages. Martz (2008) provides a review of the older literature that established the basis for recognising these assemblages. Lucas & Hunt (1993) gave these faunachrons names, Otischalkian, Adamanian, Reveultian and Apachean, respectively. The Otischalkian plus Adamanian were correlated to the Carnian, and the Reveultian and Apachean were correlated to the Norian, that at the time included the Rhaetian. The correlations were based upon key tetrapod taxa that are supposedly shared with sequences in Europe of unquestioned age. These tetrapod correlations were supported by the palynological zonations and correlations of Litwin & Skog (1991), Litwin *et al.* (1991) and Cornet (1993), as well as by the floral zones of Ash (1980, 1987), although there has been significant criticism (e.g., Langer 2005; Rayfield *et al.* 2005, 2009; Irmis *et al.* 2010). Later, Lucas (1998, 2010) correlated the Apachean with the re-recognised Rhaetian, stressing that part could still be Norian which otherwise was just represented by the Reveultian. Furthermore, in the western US, the Adamanian–Reveultian and Reveultian–Apachean boundaries were interpreted as unconformities and sequence boundaries (Tr-4, Tr-5) by Lucas (1993) and correlated to marine sequence boundaries in Nevada by Lucas (1991), Lucas & Huber (1994) and Marzolf (1993). These interpretations remain in wide use (e.g. Cleveland *et al.* 2007, 2008), despite being questioned (e.g. Woody 2006).

Late Triassic faunachrons of the western United States were correlated to a similar set of faunachrons developed for eastern North America (Newark Supergroup) by Huber *et al.* (1993) and correlated globally (Lucas 1998; Lucas & Huber 2003) (Fig. 14). The palynology of the Newark Supergroup seemed to be at least broadly compatible with this correlation and with correlation to the European Triassic. The correlations between the eastern and western North American faunachrons were also corroborated by palaeomagnetic polarity stratigraphy from Adamanian and Reveultian strata in the Colorado Plateau (Steiner & Lucas 2000; see section 2.1). These Newark Supergroup faunachrons were used in all the pre-2003 versions of the Newark-APTS. However, with the correlations to the marine sections by Muttoni *et al.* (2004) and Channell *et al.* (2003), it became clear that correlation of both the western and eastern faunachrons with the European Triassic and South American Triassic required serious revision (also see Schultz 2005 and Langer 2005). Correlation between the western and

Stage or Age	Tetrapod faunachrons: Lucas, 1993	Land Vertebrate Ages: Lucas & Hunt, 1993	Fish Assemblages	Floral Zone	Palynofloral Zone	Calcareous Microfossil Assemblages	Unionid Abundance
NORIAN	D	Apachean	middle Norian assemblage	<i>Sanmiguelia</i> floral zone	upper Petrified Forest palynofloral zone	small <i>Darwinula</i> assemblage	unionoids low abundance
	C	Revueltian	early Norian assemblage				
CARNIAN				<i>Dinophyton</i> floral zone	lower Petrified Forest palynofloral zone		unionoids high abundance
	B	Adamanian	late Carnian assemblage				
	A	Otischalkian		<i>Eoginkoites</i> floral zone	Temple Mt. palynofloral zone	large <i>Darwinula</i> assemblage	

Figure 13 Chinle and Dockum biozonation from Lucas (1993) and Lucas & Hunt (1993) as they were first formulated. Hachures indicate either a hiatus or lack of data.

SER	STAGE	SBST	South American LVF	Argentina	Brazil	Newark LVF	Chinle LVF & Sub-LVF	Greenland		
UPPER TRIASSIC (KEUPER)	RH		Coloradian	Los Colorados Fm		Cliftonian	Apachean			
		NORIAN				Sev	Revueltian	Lucianoan		Fleming Fjord Fm
	Alun					Barrancan				
	Lanc									
	CARNIAN	Tuvalian		Ischigualastian	Ischigualasto Fm	Caturrita Fm	Conewagian	Adamanian	Lamyian	
						Santa Maria Fm		St. John'sian		
		Jul			Sanfordian		Otischalkian			

Figure 14 Conventional correlations of faunachrons and dinosaur-bearing formations of South America, eastern United States, western United States and Greenland based on Lucas (2010), Lucas *et al.* (2007), Hunt *et al.* (2005) and Heckert & Lucas (2006). Hachures indicate either a hiatus or lack of data.

eastern North American faunachrons was largely unaffected, however, because both the Adamanian and the Conewagian can be correlated to the Lower Norian independently via U–Pb dates and astrochronology and magnetostratigraphy.

The palaeomagnetic polarity stratigraphy of Steiner & Lucas (2000) does, however, require some modification based on interpretations of lithostratigraphic correlations across Petrified Forest National Park. Including that of Steiner & Lucas (2000), there have been at least ten attempts (reviewed in Martz & Parker 2010) at correlating the southern sections of the park, where the lower part of the polarity section and the upper part of the sections in the northern outcrops were sampled for palaeomagnetic stratigraphy. These attempts have

produced results that are grossly similar but irreconcilable in detail, an indication that such correlations are far from straightforward. Martz & Parker (2010) conclude that Steiner & Lucas (2000), among others, mis-correlated sandstones from the north and south end of the park, with the result that about one third of the total exposed park stratigraphy was not sampled palaeomagnetically corresponding to most of what is now included in the Sonsela Member (Fig. 15). However, this revised stratigraphy only requires a modest change in the palaeomagnetic correlation to the Newark basin.

Taken at face value, the palaeomagnetic correlations of Steiner & Lucas (2000), coupled with those of Muttoni *et al.* (2004) and Channell *et al.* (2003), suggest there may be little or

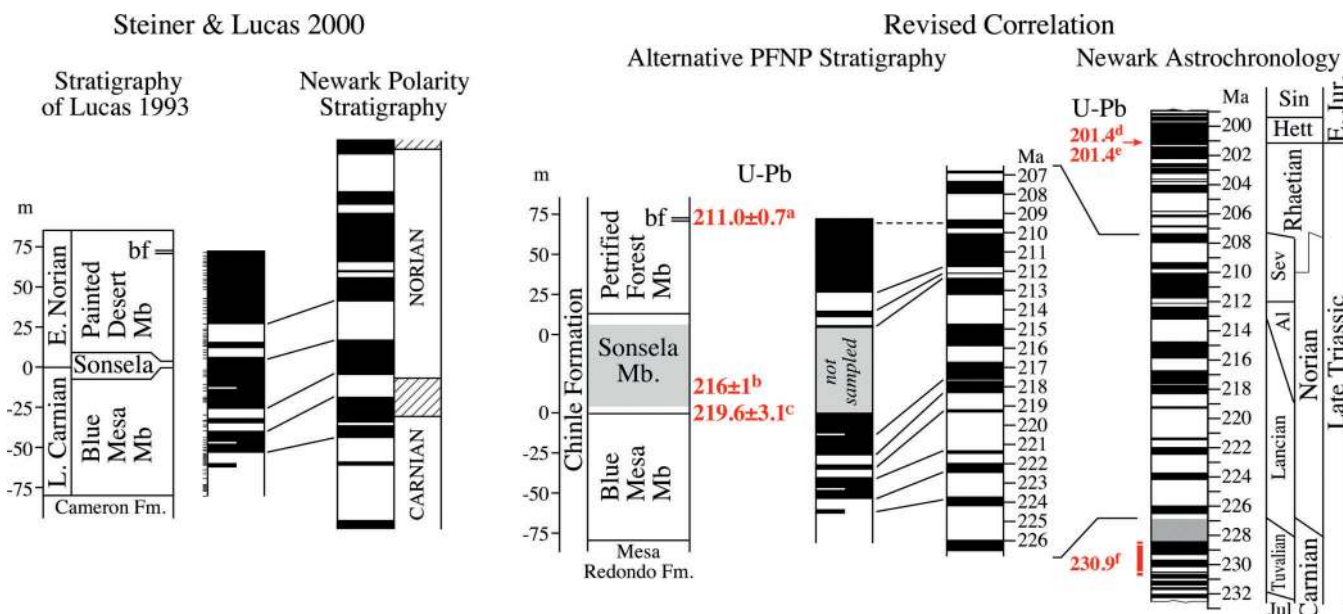


Figure 15 Comparison of stratigraphy and palaeomagnetic data from the Chinle Formation of the Petrified Forest National Park and the Newark-APTS 2010, and implications for correlation of using a more recent alternative stratigraphy of the Sonsela Member (from Martz & Parker 2010). Under 'Revised Correlation', U-Pb ($^{206}\text{Pb}/^{238}\text{U}$) dates on zircons are: a and b are c_1 and c_2 of Table 1; c is c_3 of Table 1 from Mundil & Irmis (2008), revised to correlate with the basal Sonsela Member according to Ramazani *et al.* (2010); d, e, and f correspond to m_1 , m_4 , m_5 and m_1 , respectively of Table 1. The Black Forest bed is indicated as 'bf' in the Petrified Forest sections.

no Carnian age continental strata in the western United States, and that the strata previously thought to be Carnian is Early Norian in age. This interpretation is in agreement with U-Pb dates from detrital zircons from the lower Chinle Formation of Petrified Forest National Park in Arizona and the surrounding area (e.g., Mundil & Irmis 2008; Dickinson & Gehrels 2009; Heckert *et al.* 2009; Ramezani *et al.* 2010) which are all younger than the U-Pb date from Early Norian marine strata from southern Alaska of 225 ± 3 (Gehrels *et al.* 1987) and the only date from marine Late Carnian strata of 230.91 ± 0.33 Ma (Furin *et al.* 2006; Ramezani *et al.* 2009). These Chinle dates are closely comparable to several as yet unpublished ages by Ramezani *et al.*, quoted in Kozur & Weems (2010). Further analysis of the abundant reworked ashes in the Chinle will allow a robust test of this correlation (Fig. 15) (c.f., Irmis & Whiteside 2010).

Thus, the Adamanian–Reveultian boundary, long thought to correlate with the Tethyan Carnian–Norian boundary, is actually a mid-Norian age close to, and may be correlative to, the Tethyan Lanciaan–Alunian substage boundary (Figs 4, 16), however vaguely that may be defined based on interpolation between the secure parts of marine biostratigraphy (see Irmis *et al.* 2010). This falls at about 213–216 Ma in Newark-APTS 2010 at the Lower Passaic–Heidlersburg palynofloral zone boundary (also originally thought to mark the Carnian–Norian boundary), an age compatible with the U-Pb ages from the Chinle itself. This age is also within error of the Manicouagan impact structure in Quebec (215.5 Ma, Ramezani *et al.* 2005; 215.56 ± 0.05 Ma, Ramezani cited by van Soest *et al.* 2009). A plausible hypothesis is that the faunal and floral turnover seen in the Chinle, Newark, and in marine environments at between 213–216 Ma, actually correlated with the effects of the Manicouagan impact (e.g. Dunlavey *et al.* 2009; Parker & Martz 2011). Previous assessments that there is no sign of any biotic effect of Manicouagan (e.g. Hallam 2002; Tanner *et al.* 2004; Walkden & Parker 2008; Heckert *et al.* 2009; Tackett *et al.* 2009) are attributable to a lack of registry between the strata containing the palaeobiological information

and of an adequate geochronologic time scale that overlaps with Manicouagan.

The Otischalkian faunachron, which is supposed to be the oldest of the eastern US Late Triassic faunachrons, may also be Early Norian in age. The type assemblage in the Cooper Canyon Formation near 'Otis Chalk' (Howard County, Texas) lies rather high in the local section and has an ambiguous relationship with the rest of the Dockum Formation (Martz 2008). Martz (2008) also argues that there is so much faunal overlap between the Otischalkian and Adamanian assemblages that they cannot be practically distinguished (also see Langer 2005). Otischalkian assemblages probably pertain to the basal Adamanian.

The oldest strata in the Chinle Formation on the Colorado Plateau and environs is the Shinarump Member and its equivalents, which because of their generally coarse nature have not provided much in the way of tetrapod remains. Detrital zircons analysed by Dickinson & Gehrels (2009) by LA-TIMS yield ages consistent also with an Early Norian age. The youngest single zircon grains from three different localities in the Shinarump Member yield ages of 215 ± 7 Ma, 222 ± 3 Ma, and 224 ± 6 Ma, on the young side of the 227.7 ± 0.7 Ma of the Carnian–Norian boundary in Newark-APTS 2010, although the averages of the youngest populations tend to give older ages, as would be expected given that the Shinarump Member is a basal conglomerate. Martz (2008) noted that Gehrels & Dickinson (1995) and the pioneering studies of Riggs *et al.* (1996) used detrital zircons to correlate the Shinarump Member with the marine Auld Lang Syne Group, which is early Norian in age, which completely agrees with the newer detrital zircon ages. Detrital zircons from the Santa Rosa Formation of the Dockum, which is the basal unit, at least locally, was also correlated to the Auld Lang Syne Group by Riggs *et al.* (1996), although the youngest single zircon crystals reported by Dickinson & Gehrels (2009) are pre-Triassic and hence cannot reflect the depositional age. CA-TIMS ages are needed for a definitive estimate of maximum age, however. Nonetheless, it is difficult to argue that

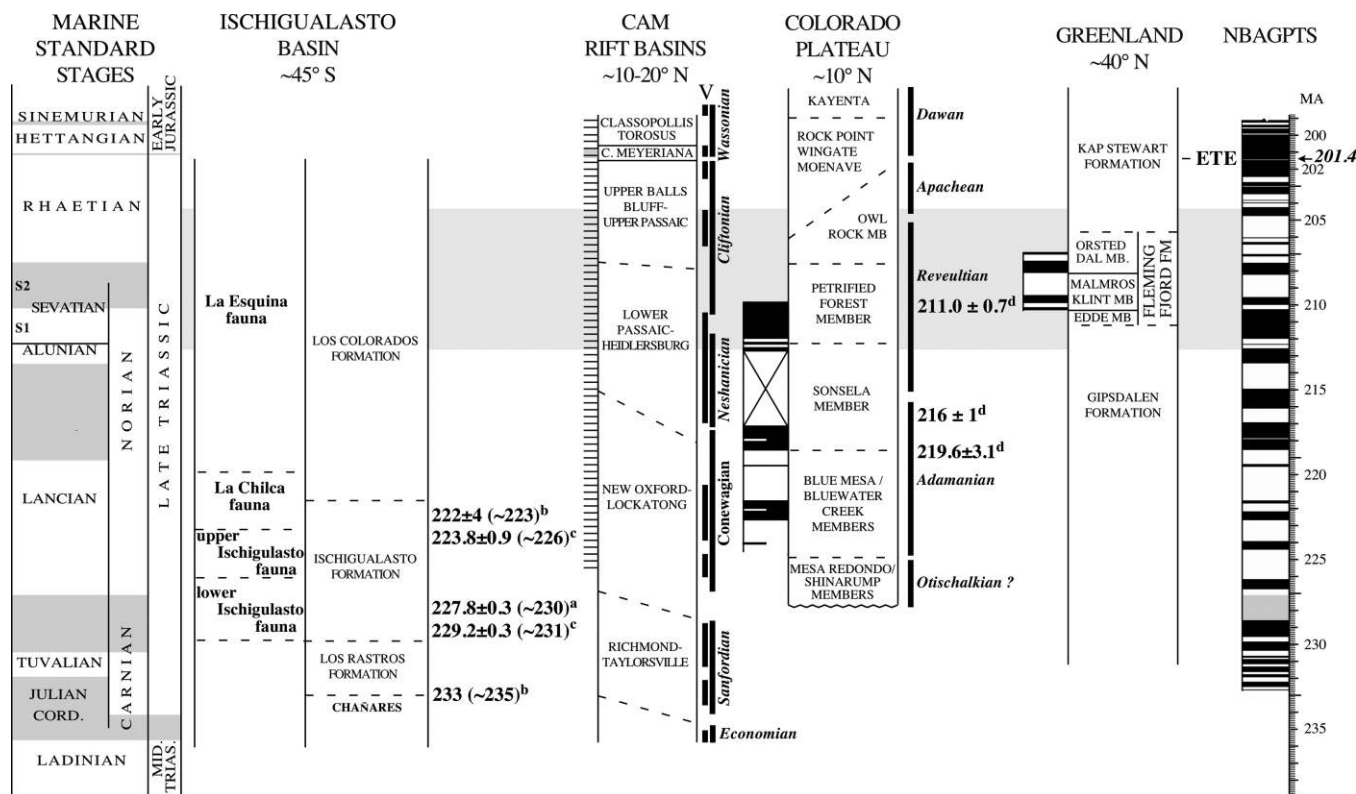


Figure 16 Revised correlations of important Triassic tetrapod assemblages based on the Newark-APTS 2010. The black and grey vertical bars represent the ranges of dates associated with the Ischigualasto basin; those in parentheses are $^{40}\text{Ar}/^{39}\text{Ar}$ dates and the dates in parentheses are ‘corrected’ to the assumed equivalent U–Pb ages. Diagonal dashed lines indicate the temporal uncertainty of the boundaries imposed by the uncertainty in accuracy of the $^{40}\text{Ar}/^{39}\text{Ar}$ versus U–Pb=corrected dates relative to the Newark-APTS 2010. For the Colorado Plateau, the ages are $^{206}\text{Pb}/^{235}\text{U}$ ages from Figure 9. Sources of the ages are: ^aRogers *et al.* 1993; ^bShipman 2004 and Tabor *et al.* 2006; ^cMartinez *et al.* 2011; ^dFigure 9. Palaeolatitudes are representative of the time interval represented by the grey band in which basal sauropodomorphs (‘prosauropods’) are abundant at the high latitudes and absent at low latitudes; latitudes are extrapolated from Kent & Tauxe (2005). Abbreviations: CORD=Cordevolian; FM=Formation; MB=Member; V=intervals (black lines below) with multiple tetrapod skeletal remains.

there is positive evidence from the U–Pb dates that the depositional age of any of the Chinle Formation or Dockum Group is Carnian (Fig. 16). Single crystal CA-TIMS ages should go far to remove remaining ambiguity. The critical implication of these correlations is that all of the Late Triassic fossil material from the western United States is Norian or younger in age and the major faunal and floral changes that are seen may be correlative with the Manicouagan impact, and that the Chinle–Dockum faunas remain relatively similar from the Otischalkian though the Apachean and plausibly right up to the end-Triassic extinction event.

10. The Ischigualasto is older than the Chinle but still at least mostly Norian: there may be no Carnian dinosaurs

The Ischigualasto Formation of the Ischigualasto–Villa Union basin, northwestern Argentina, is famous for its rich Triassic assemblages, especially early dinosaurs, amongst which are arguably the oldest (e.g. Langer 2005). As with other wholly continental assemblages, its age has proven problematic despite the presence of dated and datable ashes. As pointed out by Langer (2005), because of its distinctive tetrapod assemblage Bonaparte (1966) coined the term Ischigualastian that was later co-opted as a faunachron (Lucas 1998). Lucas (1998), Heckert & Lucas (2002a), and Lucas & Huber (2003) correlated the Ischigualastian to the Adamanian and the Conewagian and hence the Carnian.

A $^{40}\text{Ar}/^{39}\text{Ar}$ date of 227.8 ± 0.3 Ma from the ‘Herr Toba’ ash bed near the base of the formation (Rogers *et al.* 1993) has provided a critical constraint on the age of the unit and bears on the age of all of the South American Triassic assemblages (e.g. Langer 2005). The date of 227.8 ± 0.3 Ma was rather uncritically considered a strong Carnian age at the time using the available compiled time scales (e.g. Gradstein & Ogg 1996) as well as Newark-APTS 1999A (Kent & Olsen 1999; Muttoni *et al.* 2004). However, at face value, it now falls nearly on the Carnian–Norian boundary of Newark-APTS 2010 which, because virtually all the Ischigualasto fossils fall above the ash bed, makes most of the Ischigualastian faunal assemblages Norian in age. Other $^{40}\text{Ar}/^{39}\text{Ar}$ dates from higher in the Ischigualasto have been cited without supporting data but range from 218 to 223 Ma (Shipman 2004; Tabor *et al.* 2006; Currie *et al.* 2009). At face value these are also Norian ages (Fig. 16).

Recently, Martinez *et al.* (2011) provided two new $^{40}\text{Ar}/^{39}\text{Ar}$ dates from the Ischigualasto Formation: one is 229.2 ± 0.3 , a recalculation, with different constants, of the Herr Toba bentonite date of Rogers *et al.* (1993) of 227.8 ± 0.3 ; the other is from an ash near the local top of the formation (610 m above the Herr Toba bed) with a date of 223.8 ± 0.9 . These nominal ages are all younger than the Late Carnian marine date of Furin *et al.* (2006).

Clearly, the most relevant is the older date of Rogers *et al.* (1993) and Martinez *et al.* (2011) and it requires a closer look. It has become standard when comparing $^{40}\text{Ar}/^{39}\text{Ar}$ and U–Pb ages to ‘correct’ the former age based on an apparent shift

towards younger values in the $^{40}\text{Ar}/^{39}\text{Ar}$ compared to the U–Pb systems (Min *et al.* 2000; Mundil *et al.* 2006). Irmis & Mundil (2008) also did this (recalculating to revised $^{40}\text{Ar}/^{39}\text{Ar}$ constants) and obtained a U–Pb-equivalent age of 231.4 Ma (the same -231.4 ± 0.3 Ma as published by Martinez *et al.* (2011), which is within error of the Furin *et al.* (2006) date of 230.91 ± 0.33 from an ash interbedded with latest Carnian age *Metapolygnathus nodosus* zone limestones (Tuvalian 3), when the uncertainties of the $^{40}\text{Ar}/^{39}\text{Ar}$ age are propagated. The criterion that must be met for any sequence to be considered as Carnian is that it must be securely older than 231 Ma in age; this criterion is not even met for the Herr Toba date after corrections amounting to 3.6 Myr. In addition, because the Herr Toba ash is so low in the section, most of the overlying section of Ischigualasto Formation is likely to be at least in part Norian in age and, indeed, the loosely ‘corrected’ ages from high in the formation give a range of 220–226 Ma, which is still Norian in the Newark–APTS 2010. Even the ‘corrected’ age for the ash from the upper Ischigualasto Formation (225.9 ± 0.9) is within error of the 225 ± 3 (Gehrels *et al.* 1987) early Norian date. Accordingly, all of the ages fall within the uncertainty of the marine Carnian–Norian boundary and, therefore, there is significant doubt about how much if any of the Ischigualasto is of Carnian age. This discussion applies to the biostratigraphically correlative Ischigualastian assemblages of Brazil as well (e.g. Martinez *et al.* 2011). Clearly, modern U–Pb CA-TIMS dates are needed from this succession to compare with dates from the marine Triassic.

Although there can be little doubt that most if not all Chinle Formation assemblages are significantly younger as argued by Langer (2005) and Irmis & Mundil (2008) (Fig. 16), the available radioisotopic constraints on the Ischigualasto do not support correlation with the Adamanian or with any part of the Chinle or Dockum (Irmis & Mundil 2008). Taken at face value and accepting Newark–APTS 2010, this would make the oldest dinosaurs in the world Norian in age; there would be no known dinosaurs securely known as Carnian. This does not diminish the fact that the Ischigualasto and correlative units in Brazil do contain the oldest known dinosaurs.

Both Rogers *et al.* (1993) and Martinez *et al.* (2011) document a disappearance of dinosaurs and rhynchosaurs in the middle of the formation and a 100% change into the overlying upper Los Colorados Formation. The age of the later transition within the Late Triassic is essentially unknown beyond that it should be post-early-Norian and pre-Jurassic. If the older part of the Ischigualasto Formation is of Carnian age the faunal break could be correlate to the marine Carnian–Norian boundary, but because dinosaurs are completely absent thus far from the upper Ischigualasto Formation but are clearly present in the overlying Los Colorados Formation, it is impossible to assess whether this represents a local ecological, a taphonomic, or a taxonomic turnover. Assessing the significance of this faunal change relative to global patterns requires appropriate, independent geochronological data, which is thus far lacking.

11. There is dramatic provinciality in the Late Triassic

In attempts to correlate among various assemblages globally, there is a tendency to focus on taxonomic similarity and deemphasise geographic differences in the struggle to temporally seriate assemblages. However, there are geographic differences that reflect more than sampling differences. The fact that there were strongly differentiated faunal provinces in the Late Triassic seems odd because of the lack of water



Figure 17 Distribution of the main localities discussed in text on a map of Pangea at about the time of the ETE (~ 201.4 Ma). Red localities are those in which vesiculate pollen taxa (e.g., *Patinasporites densus*) are present to the ETE; green localities are those where vesiculate pollen taxa disappear much earlier or are absent and *Rhaetipollis* is present to the Triassic–Jurassic boundary; blue localities are those with the Ipswich-type sporomorph assemblages and *Dicroidium*-dominated macroflorules; white localities are those where pollen has not been recovered from strata close to and below the ETE. Localities: 1=Newark basin, USA; 2=Hartford basin, USA; 3=Fundy basin, maritime provinces, Canada; 4=St Audrie’s Bay in the Bristol Channel basin, England; 5=Dockum Group, Palo Duro basin, Texas and New Mexico, USA; 6=Chinle Formation, Colorado Plateau, western USA; 7=Germanic basin, Germany; 8=Fleming Fjord Formation, Jameson Land basin, East Greenland; 9=Ischigualasto and Los Colorados formations, Argentina; 10=Laguna Colorada Formation, Patagonia, Argentina; 11=Elliot and Clarens formations, Ladysmith, South Africa; 12=northern Middle Siberia, Russia; 13=Eiberg basin (including Kuhjoch), Austria; 14=Pizzo Mondelo, Italy; 15=Argana and Central High Atlas basins, Morocco. Reconstruction courtesy of C. Scotese.

barriers in Pangea. Nonetheless Olsen & Galton (1984) and Cornet & Olsen (1985) recognised clear Late Triassic faunal provinces that tracked to some extent floral provinces (e.g. Dolby & Balme 1976; Artabe *et al.* 2003) and that such provinces were a major impediment to biostratigraphic correlation (see also Irmis *et al.* 2010).

This provinciality can be shown by considering two regions (Fig. 17): (1) the tropical Chinle–Dockum assemblages that are of Norian–Rhaetian age; and (2) the Germanic basin type assemblages, known from Central Europe and Greenland of Carnian–Rhaetian age. Both areas have produced a wealth of material and both assemblages have aquatic and fully terrestrial components. There are some common elements at low taxonomic levels, although these tend to be uncommon and in some cases very ambiguous. More conspicuous than the similarities are the differences. In the Germanic assemblages, basal sauropodomorph (‘prosauropod’) dinosaurs (especially *Plateosaurus*), plagiosaurid temnospondyl amphibians and the temnospondyl *Cyclotosaurus* are the most common tetrapods. None of these taxa are known from the Late Triassic of North America. This pattern is reflected in the phenetic grouping of Germanic, Triassic age assemblages with Early Jurassic assemblages rather than with the coeval North American assemblages (Holtz *et al.* 2004). Support for this provinciality has been provided by very recent cladistic biogeographic analysis

of Ezcurra (2010). In addition, an interesting aspect of the provinciality is that during the Late Triassic, the higher latitudes tend to have similar faunas, showing that dispersal must have been possible, even though a low latitude province persisted in between (Olsen & Galton 1984; Ezcurra 2010).

It is necessary to have an independent way of assessing age when comparing different areas with unknown biogeographic patterns. We can do this for the Triassic by comparing different assemblages correlated on the basis of non-biostratigraphic criteria, namely magnetostratigraphic polarity stratigraphy (Figs 16, 17). There is magnetostratigraphy for Germanic type assemblages in the Fleming Fjord Formation of Greenland (Kent & Clemmensen 1996). The faunal assemblages from this sequence have been described largely by Gatesy *et al.* (1999) and Jenkins *et al.* (1993, 1994, 1997, 2001, 2008). The most abundant tetrapods from the Fleming Fjord are *Gerrothorax* and *Plateosaurus*. Based on the paleomagnetic polarity correlation, the relatively high-latitude Fleming Fjord Formation correlates to the upper Petrified Forest Member and probably to the lower Owl Rock Member of the Chinle Formation and, based on the U–Pb and $^{40}\text{Ar}/^{39}\text{Ar}$ ages from the Chinle and Ischigualasto formations, to part of the upper Los Colorados Formation (La Esquina Fauna, Bonaparte 1982) (Fig. 16), although this hypothesis requires testing by palaeomagnetic data from the Los Colorados Formation itself. The tropically located Reveultian and possible lower Apachean Chinle assemblages, based on abundant bones, completely lack plagiosaurid amphibians, including *Gerrothorax*, and sauropodomorphs, including *Plateosaurus*. Plagiosaurid amphibians are again absent from the Los Colorados Formation, but sauropodomorphs are abundant (see review of Arcucci *et al.* 2004). In fact, for the Germanic assemblages in general, there is greater similarity through time from the Carnian through the Rhaetian than between any specific time and North America (as also noted by Ezcurra 2010). Likewise, the Chinle Formation and Dockum Group assemblages show continuity in time in overall composition and little similarity to the Germanic assemblages.

Similarly, Martinez *et al.* (2011) show that dinosaurs comprise a significant component (up to 33% of individuals) in the lower Ischigualasto Formation that was deposited at even higher southern palaeolatitudes than the overlying Los Colorados Formation. Regardless of these assemblages Carnian or Norian age, dinosaurs are unequivocally rare in assemblages that are broadly correlative (Early Norian and Late Carnian age) in tropical Pangea.

Thus, there are clear geographic provinces apparently tracking latitude to a first approximation. However, these provinces were not isolated, because recent cladistic analyses of both sauropodomorphs (Pol 2005; Upchurch *et al.* 2007; Yates *et al.* 2009) and early theropods (e.g. Nesbitt *et al.* 2009b) show no coherent mapping between geography and cladistic relationships, indicating that at least some migration between provinces occurred. These points have been mentioned (Irmis *et al.* 2007b; Irmis & Mundil 2008; Nesbitt *et al.* 2009b; Ezcurra 2010), and are highlighted in the present paper, because in order to see the geographic patterns that are present it is necessary to have clear non-biostratigraphic means of correlation. The tendency otherwise is to temporally seriate the assemblages in an attempt to minimise the faunal differences resulting in a synthetic, but inaccurate, biochronology.

It should come as no surprise that other groups of organisms show provinciality in the Late Triassic. The provinciality of spore morphs has already been alluded to, but macrofossil plants also show large-scale geographic differences (Fig. 17). The most obvious of these is the *Dicroidium–Thinnfeldia* domain in the southern hemisphere (Olsen & Galton 1984;

Dobruskina 1993; Artabe *et al.* 2003), and although there are sporadic reports of rare members of this assemblage in the northern hemisphere, no one would confuse one of these Gondwanan floral assemblages with one from Germany or from the Chinle Formation. It is expected that some of the problems associated with conchostracan biogeography will also sort themselves out as a consequence of this provinciality.

12. There are no definitive Triassic ornithischian dinosaurs

A major impediment to understanding the larger context of dinosaurian evolution is the ability to independently determine the relative ages of dinosaur-bearing strata. There are very few places where this is better seen than in the Molteno, Elliot and Clarens formations of the Karoo basin of southern Africa (Fig. 17). The latter two formations have yielded some of the best-preserved tetrapod assemblages of the early part of the early Mesozoic, including the best-preserved and most diverse assemblages of early ornithischian dinosaurs in the world, along with abundant sauropodomorphs.

The oldest unquestionable occurrence of ornithischians, *Eocursor parvus* (Butler *et al.* 2008), is from the lower Elliot Formation in the southern African section. Although not independently dated, this strata is purportedly of Late Triassic age, based on the specimen coming from 5.5 m below a nodular horizon conventionally used as a regional marker of the Triassic–Jurassic boundary (Smith & Kitching 1997). This is a lithostratigraphic marker and has no geochronological support for its assumed age. Tetrapod assemblages (e.g. ‘Tritylodon Acme Zone’; Kitching & Raath 1984) that are conventionally identified as Jurassic aspect (Olsen & Galton 1977, 1984) that lack taxa of Triassic aspect occur above this marker bed. *Eocursor* occurs 10.5 m above an articulated skull and skeleton of *Melanosaurus readi* (Yates 2005, 2007; Butler *et al.* 2007), a taxon considered to be Triassic in age (Knoll 2004).

A major problem with correlation of the Elliot and Clarens formations with marine standard ages is a lack of shared taxa, not just between the marine Tethyan sections and the southern African continental sections, but also with continental strata elsewhere that are dated with reasonable confidence. In fact, there is no justification from a biochronological or geochronological perspective for placing the Triassic–Jurassic boundary at a nodule horizon within the Elliot Formation. Indeed, correlation with the Triassic is based largely on the level of evolution within the sauropodomorphs, amphibians, the presence of a traversodont cynodont (Knoll 2004), and the Triassic aspect of the ichnofauna (Olsen & Galton 1977, 1984; Knoll 2004). Knoll (2004) considers the age of the lower Elliot and underlying Molteno formations to be Norian–Rhaetian, but the Molteno Formation could easily be Carnian age. However, even if *Melanosaurus* is restricted to the Triassic, *Eocursor* is 10.5 m above this last Triassic-age fossil. The meaning of this thickness can be assessed by considering a plausible average accumulation rate for the Elliot and Clarens in the vicinity of the *Eocursor* locality. The lower Elliot Formation is ~55 m thick (Smith & Kitching 1997) and the middle plus upper Elliot Formation is ~85 m thick (Butler *et al.* 2007). The overlying Clarens Formation is estimated at more than ~130 m thick (Kitching & Raath 1984). Using 150 m for an estimate of the Clarens Formation and 55+85 m for the Elliot Formation, the total thickness is ~290 m. The only tolerably reliable geochronological information constraining the age of the Clarens Formation is from the Drakensburg (Karoo) Lavas and associated pyroclastics that overlie and in part interfinger with it, yielding $^{40}\text{Ar}/^{39}\text{Ar}$ dates clustering at 183 ± 2 Ma (Pálffy &

Smith 2000) and U–Pb dates ranging from 182.1 ± 2.9 Ma to 179.9 ± 1.8 Ma (Riley *et al.* 2004). These dates correspond to the Toarcian of the late Early Jurassic (Pálffy & Smith 2000) and show that the Elliot, together with the Clarens, may span as much as ~ 44 Myr (26 Myr for Norian–Rhaetian + 18 Myr for the base Hettangian to the age of the Drakensburg Lavas). Thus the average accumulation rate is 6.5 m/Myr. Given this very slow accumulation rate, the interval between *Eocursor* and the youngest Triassic-aspect vertebrate (*Melanorosaurus*) would be 1.62 Myr, and from *Eocursor* to the Tritylodon Acme Zone is ~ 2.54 Myr. Thus, within the biostratigraphic constraints, which themselves are of unclear significance, the uncertainty in age is ~ 4.16 Myr. For comparison, the Hettangian spans ~ 1.8 Myr (Ruhl *et al.* 2010). Without independent geochronological data, it is not possible to determine the Triassic vs. Jurassic age of *Eocursor*. It could be Triassic, but it could be as young as Sinemurian in age.

Two other putative Triassic ornithischians include *Pisanosaurus* from the Ischigualasto Formation and a putative heterodontosaurid from the Laguna Colorado Formation of Patagonia (Baez & Marsicano 2001) (Fig. 17). Irmis *et al.* (2007a) have recently reviewed the status of these two forms. They regard *Pisanosaurus* as plausibly belonging to the Ornithischia, however they note that the possibility of it not being an ornithischian has not been rigorously explored. While the characters visible on the fragmentary Laguna Colorado maxilla are consistent with a heterodontosaurid ornithischian, it is so fragmentary and there is so much apparent convergence among non-dinosaurian archosaurs with ornithischians that its relationships are in doubt pending more complete material. In addition, the age of the Laguna Colorado Formation itself is poorly constrained (age-relevant information in Pol & Powell 2007). There are floral remains belonging to the *Dicroidium* flora, conventionally considered Triassic over- and underlying the tetrapod-bearing levels (Jalfin & Herbst 1995; Gnaedinger & Herbst 1998), and the sedimentary strata are intruded by La Leona Formation granitoids, yielding an Rb–Sr isochron age of 203 ± 2 (Pankhurst *et al.* 1993) that is permissive of a Late Triassic age. However, the time of extinction of the *Dicroidium* floras is itself very poorly constrained and the Rb–Sr age is within error of the Early Jurassic and may itself not be accurate, given the younger range of ages from other related intrusions (Varela *et al.* 1991; Pankhurst *et al.* 1993). Other examples of fragmentary possible ornithischians of Triassic age are probably referable to other groups (Irmis *et al.* 2007a). It can be concluded that the hypothesis that there are no Triassic ornithischians has yet to be definitively disproved by unambiguous material.

Saurischian diversity and abundance appears to have been increasing through the Late Triassic, with sauropodomorphs becoming very abundant in the higher latitudes (Fig. 17), which stands in dramatic contrast to the lack of definitive ornithischian remains from definitive Triassic age strata. Convincing ornithischian footprints in the form of the ichnogenus *Anomoepus* are restricted to Jurassic age strata (Olsen & Rainforth 2003), including in the Newark and Hartford basin strata that form the basis for the Newark-APTS 2010. If, however, heterodontosaurids are basal ornithischians (e.g. Butler *et al.* 2008) their footprints might go unrecognised as such because they lack the manual specialisations seen in *Anomoepus* (Olsen & Rainforth 2003). It is necessary to stress, however, that while the present authors vigorously assert that unequivocal ornithischians have yet to be documented in Triassic age strata, they acknowledge that available anatomical data from these scrappy specimens is permissive of inclusion within the Ornithischia and, based on ghost lineages (i.e., presence of fossils of their closest sister group, Saurischia) their

presence should be predicted in the Late Triassic strata. However, given the fragmentary nature of these fossils and the problems with identifying Triassic ornithischians in the past, it would not be a surprise if they turned out to belong to a different and possibly non-dinosaurian clade. Regardless, at best, Triassic-age ornithischians are extraordinarily rare, and the dramatic change into the Jurassic in the abundance of osteological and ichnological specimens represents a significant ecological, if not evolutionary, event.

13. The Rhaetian tetrapod record is poor

The Rhaetian tetrapod record has long been regarded as poorly known (e.g., Ezcurra & Cuny 2007). This deficit becomes all the more apparent when trying to seriate known assemblages globally on the basis of biostratigraphically independent criteria. However, amongst assemblages with abundant osteological remains, the correlations of Kozur & Bachmann (2008) would have at least the younger components of the classic Germanic basin, such as the upper Stubensandstein (upper Löwenstein Formation) and Knollenmergel (Trossingen Formation), as being Rhaetian. Even a larger part of the Germanic basin section would be Rhaetian by including Sevastian 2, but biostratigraphically independent data are lacking. The Fleming Fjord Formation is Rhaetian based on correlation to the Newark-APTS 2010 time scale and to the Steinbergkogel section by magnetostratigraphy (Kent & Clemmensen 1996; Hüsing *et al.* 2011). The Los Colorados Formation is likely at least in part Rhaetian, as is the upper Petrified Forest and Owl Rock members, although again these correlations require more rigorous independent confirmation. However, osteological faunas from the demonstrably youngest Rhaetian strata are still very poorly known, and this hampers our understanding of the Triassic–Jurassic transition (e.g. Tanner *et al.* 2004; Lucas & Tanner 2007; Ezcurra & Cuny 2007).

It is clear that there is much to be learned about Rhaetian assemblages. If the apparent Rhaetian age of the new assemblages from Poland (Dzik *et al.* 2008a) and Portugal (Witzmann & Gassner 2008) are corroborated, many taxa, such as dicynodonts (e.g. Dzik *et al.* 2008a, b) thought to have had their last appearances much earlier, may have persisted through the entire Triassic. Such range extensions amplify our perception of the magnitude of the end-Triassic extinction event. They come from areas in which there were no formerly Rhaetian forms at all and may represent entirely new faunal entities.

14. Diversity is high in the Late Triassic

At least four basic kinds of diversity can be identified: taxonomic richness, relative taxonomic abundance, morphological disparity and biogeographic occurrence. The most common way diversity has been tabulated through time is via taxonomic diversity – various metrics of tabulations of the standing number, and first and last appearances. This is almost always what is referred to in discussions of mass-extinctions. For the Late Triassic, taxonomic richness is clearly climbing rapidly, as assemblages are sorted out with more rigour than before with strange and wonderful animals to be found (e.g. *Effigia*, Nesbitt 2007; *Vancleavea*, Nesbitt *et al.* 2009a). However, ecosystems can be dominated by just one or a few abundant forms, and most of the taxonomic diversity can consist of rare species. In the fossil record this is usually indistinguishable from low species richness, because the sample size is almost never large enough to capture many rare forms. Rarefaction

analysis, rarely done, is necessary to allow comparison of relative abundance of taxa. Although relative abundances have not been quantified through time in any region, it appears that qualitatively, taxonomic relative abundances are stable or becoming more equable through the Late Triassic. Morphological disparity, how different things are from one another (e.g. Erwin 2007), is an additional important aspect of diversity, especially ecologically. Brusatte *et al.* (2008) have shown that disparity was relatively high in the Late Triassic, and increasing through the period, when overall fossil abundance is accounted for. We have commented on the high biogeographic provinciality of the Late Triassic, present despite the contiguity of the Pangean plate configuration. In all ways, diversity in the Late Triassic appears to have been high, but further advances require adherence to the search for tight independent temporal constraints allowing correlation and seriation among assemblages.

Although yet to be tested quantitatively, the overall pattern of high diversity in the late Triassic in all four senses listed above stands in dramatic contrast to the lower diversity seen in Early Jurassic age assemblages. The end-Triassic extinction event appears to have affected all aspects of diversity, and at least for higher-level taxonomic categories or in terms of gross morphological disparity, the recovery appears to have been slow (Brusatte *et al.* 2008). However, although the problems with Late Triassic global correlations have been detailed, and some solutions suggested, largely coming out of the Newark-APTS (which extends only a few million years into the Jurassic) and new radioisotopic ages, the situation for the continental Early Jurassic is much worse. Stage-level correlations are largely not possible for most diverse Early Jurassic assemblages such as the lower Lufeng Formation of China or the Kayenta Formation of the American Southwest. Seriating and dating these assemblages will require considerable effort.

15. Concluding remarks

Construction of biostratigraphically independent methodologies for seriation, correlation and numerical calibration of important palaeobiological assemblages globally, including the development and refinement of the Newark-APTS as described here, is essential for understanding the tempo and mode of the rise of the dinosaurs. Although considerable effort has been made to show that dinosaur-bearing continental deposits are plausibly entirely Norian or younger in age, correlations to the Carnian or Norian are not regarded as intrinsically important for the origin and early history of dinosaurs. Correlation to these Tethyan marine constructs has become standard in discussions of early Mesozoic continental faunal change to a degree that far surpasses the actual usefulness of the concepts, and has often obscured or even hindered our understanding of temporal and geographic distributions. Indeed, in some ways, the names of the intervals have tended to become more important than the course of events. It is suggested that the focus should instead be on the pattern of biotic change through long sequences within single sedimentary basins, and how those changes can be relatively seriated with other changes globally to reveal biogeographic patterns, and then numerically calibrated to determine quantitative rates of change and correlation to physical events such as bolide impacts or large igneous provinces.

Magnetostratigraphic and radioisotopic correlation to the Newark-APTS 2010 demonstrates that the relative numerical timing of key time-stratigraphic intervals (*sensu* Hedberg 1948), such as the Tethyan marine standard stages and their presumed continental correlates, have often been grossly mis-

interpreted, conflating interesting and important biogeographic patterns with temporal sequencing. In particular, the Rhaetian and Norian stages are much longer than generally assumed and the Carnian is correspondingly shorter. Based on correlation to the Newark-APTS 2010, it is concluded that the present record of dinosaurian diversification appears to be post-Carnian in age; that saurischian diversity and abundance was increasing slowly through the ~26 million year-long Norian plus Rhaetian interval; that the convincing record of ornithischian diversification is only post-Triassic in age; and that tetrapod diversity in all its meanings increased during the Triassic, with perhaps an abrupt though modest turnover associated with the Manicouagan impact (215.5 Ma, Ramezani *et al.*, 2005), only to be cut back dramatically at the end-Triassic extinction event, itself closely correlated to the time of eruption of the CAMP. Only after the end-Triassic extinction event did dinosaurs become ecologically dominant globally.

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