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Implications of astronomical climate cycles to the chronology of the Triassic

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with 2 figures and 1 table

Abstract: A high resolution climate record from a thick, continuous sedimentary sequence in the Newark basin provides the basis for an astronomically calibrated time scale for the Late Triassic. The astronomical vernier, indexed to radiometric dates that indicate an age of 202 Ma for the Triassic/Jurassic boundary, suggests that the Late Triassic was about 31 m.y. long, or constituted about 2/3 of the entire Triassic. A detailed geomagnetic polarity time scale developed in conjunction with the cycle stratigraphy provides a mechanism to extend the astronomical chronology to other sections in the world.

Introduction

Construction of a numerical geologic time scale for the Mesozoic has traditionally involved the integration of radiometric dates, biozones and stage boundaries. However, even the most recently compiled inventory of radiometric dates is inadequate to constrain directly the ages of most stage boundaries (Gradstein et al. 1994). Stage boundary ages therefore need to be interpolated using some proxy of time. The Cenozoic time scale is mainly scaled by biostratigraphic correlations to an age-calibrated geomagnetic polarity reversal sequence derived from marine magnetic anomalies (Cande and Kent 1992, 1995, Berggren et al. 1995b). However, this unifying interpolation mechanism is available only back to the middle Jurassic (e.g. Channell et al. 1995). In the absence of magnetic anomaly profiles for older parts of the Mesozoic, expedient but not well justified concepts such as equal-duration of stages (e.g. Harland et al. 1982) or more commonly equal-duration of biozones (e.g. Kent and Gradstein 1985) have been used for interpolation between tie-points. As summarized by Gradstein et al. (1994), differences in selection criteria for the few and often inconsistent radiometric dates, combined with different interpolation schemes, have led to a wide variety of published Mesozoic time scales.

A phenomenon whose application is revolutionizing the precision and accuracy of geologic time scales is Milankovitch cyclicity. This technique relies on matching continuous, high resolution records of climate change to known quasi-periodic variations in Earth's orbital parameters. The astronomical dating technique has been hugely successful in the Plio-Pleistocene (Shackleton et al. 1990,

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Hilgen 1991) where it now constitutes the definitive time scale for the past 5.3 Ma (Berggren et al. 1995a,b). Although complete solutions to the celestial mechanics of Earth's orbital motions become less certain with increasing age, specific astronomical variations are likely to have remained stable or changed only slowly in a statistical sense over time scales that encompass the Mesozoic and longer (Berger et al. 1992). Application of Milankovitch cyclicity thus has the potential for making precise estimates of durations, ideally to within a precession cycle (~20 k.y.), for significant parts of geologic history. This would greatly increasing the resolution of geologic time scales when integrated with biochronological, magnetochronological and geochronological constraints.

We have recently developed an astronomically tuned time scale for more than 30 m.y. of the Late Triassic, based on an exceptionally thick (4000+ meter) sedimentary sequence that was continuously cored under the Newark Basin Coring Project (NBCP) in the Newark rift basin of eastern North America (Kent et al. 1995, Olsen and Kent 1996, Olsen et al. 1996a). The high resolution internal chronology was developed in entirely non-marine, mainly lacustrine, sedimentary facies. However, available palynofloral and land vertebrate biostratigraphies allow stage-level correlation to standard subdivisions of the Triassic. In addition, a characteristic geomagnetic reversal sequence, consisting of 58 polarity zones with a mean duration of about 0.5 m.y., provides a framework for more detailed correlation on a regional to global scale. The Late Triassic geomagnetic polarity time scale is described elsewhere (Kent and Olsen 1999). Here we summarize the chronostratigraphy of the Newark section and explore some of the implications of the astronomically tuned chronology for Triassic time scales.

Late Triassic time scale

The Newark basin is one of a series of Mesozoic rift basins in eastern north America that formed in the initial stages of breakup of Pangea and contains several thousand meters of continental sediments and volcanics referred to as the Newark Supergroup. Palynofloral assemblages indicate that the Newark section is Late Triassic to Early Jurassic in age (Cornet and Olsen 1985, Cornet 1993). The Carnian/Norian, Norian/Rhaetian, and Triassic/Jurassic boundaries are apparently all recorded in the Passaic Formation (Fig. 1). The land vertebrate faunachrons identified in the Newark basin are generally consistent with these palynofloral age assignments (Huber and Lucas 1996) and compare well with those of the Chinle Group of the western U.S. that has a recognized late Carnian through late Norian/Rhaetian age (Lucas and Hunt 1993).

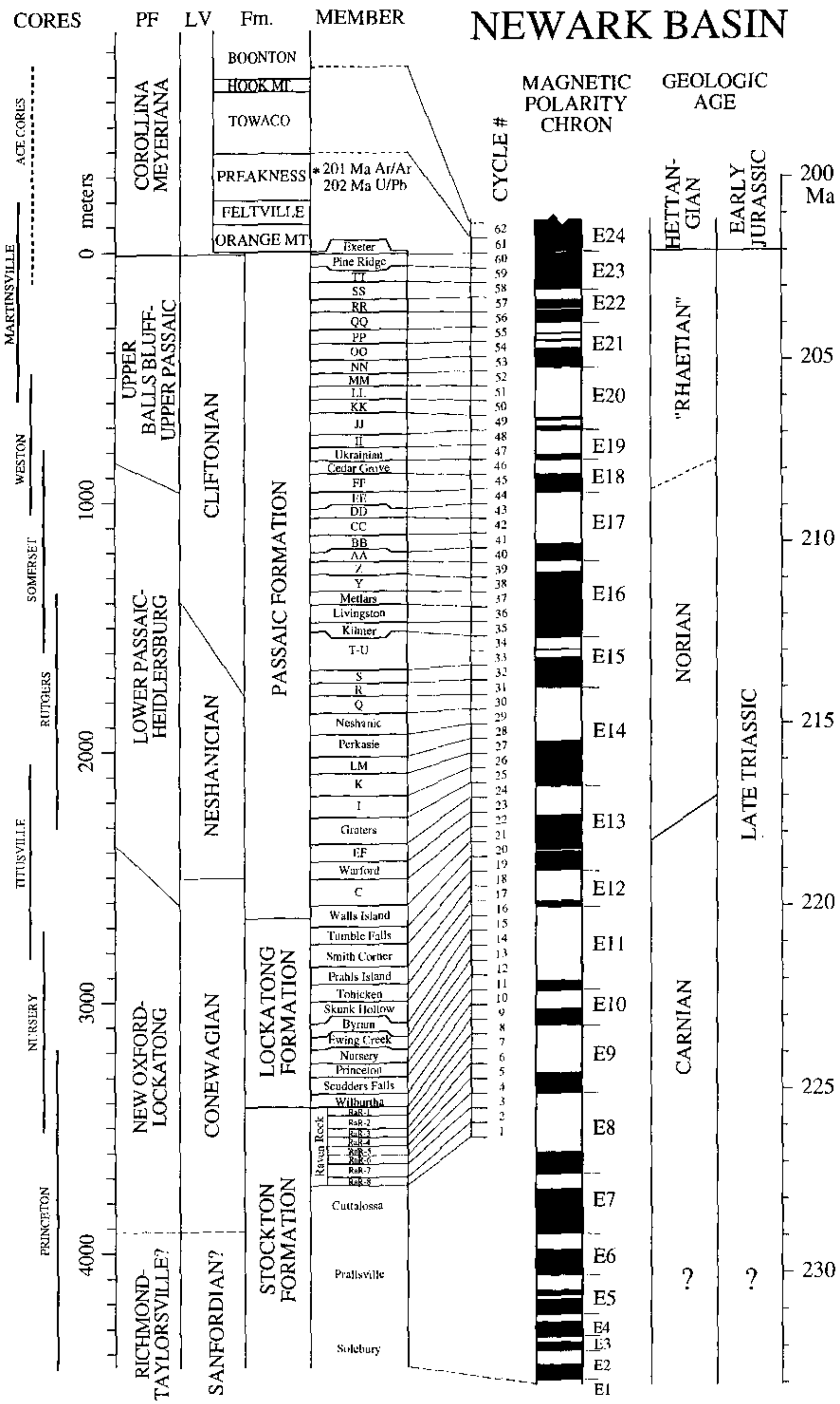
In the Newark Basin, the Triassic/Jurassic palynological boundary has been identified in the Exeter member in the uppermost Passaic Fm., a few meters below the first lava flows (Fowell and Olsen 1993, Fowell et al. 1994). Where the interval has been sampled in sufficient detail, the Triassic/Jurassic boundary is bracketed above by the lavas and below by a short (~25 k.y.) reverse polarity Chron E23r (renamed from E23n.1r; Kent and Olsen [1999]) that straddles the base of the Exeter member (Olsen et al. 1996a). Cycle stratigraphic analysis indicates that the entire interval between the base of the Exeter member and the base of the lavas is only about three precession cycles long (Fowell and Olsen 1993, Fowell et al. 1994). The preservation of a fern/spore abundance peak at the boundary (Fowell et al. 1994) and the consistent occurrence of a closely associated short reverse polarity magnetozone (Chron E23r) in sections more than 100 km apart (Kent et al. 1995, Olsen et al. 1996a, Kent and Olsen 1999) suggest that the Triassic/Jurassic boundary interval is continuous and not associated with a hiatus.

The only radiometric dates in the Newark basin suitable for time scale calibration are concordant U-Pb and $^{40}Ar/^{39}Ar$ dates from a feeder intrusion of the basalt flows which indicate an age of 201–202 Ma (Dunning and Hodych 1990, Ratcliffe 1988, Sutter 1988). Milankovitch cyclostratigraphy of the sedimentary units interbedded with the lavas in the Newark basin indicates that the entire igneous extrusive sequence erupted over less than 600 k.y. (Olsen et al. 1996b). This leads to a rounded estimate of 202 Ma for the subjacent Triassic/Jurassic boundary. Virtually the same age (202 ± 1 Ma) was inferred for the palynological Triassic/Jurassic boundary in the Fundy basin on the basis of U-Pb zircon dates associated with the North Mountain Basalt (Hodych and Dunning 1992).

The continuous NBCP drill core makes possible detailed cycle stratigraphic analysis of the fluvial-deltaic to lacustrine facies of the upper Stockton, Lockatong and Passaic formations where a complete spectrum of Milankovitch climate variations is expressed as lithofacie indicators of lake level (Olsen et al. 1996a, Olsen and Kent 1996). The variations range from the precession cycle of ~20 k.y. to modulating eccentricity cycles of ~100 k.y., ~400 k.y., and even longer periodicities. The most readily recognized of these variations is the 404 k.y. eccentricity cycle which corresponds to the mappable lithostratigraphic members or McLaughlin cycles that can be correlated throughout the basin.

The 404 k.y. eccentricity cycle is believed to be the most stable of the Milankovitch orbital variations (Berger et al. 1992; Laskar 1999) and provides a robust metric for scaling a stratigraphic section in time. A total of 60 complete McLaughlin cycles plus the truncated Exeter member have been delineated in the upper Stockton, Lockatong and Passaic formations (Olsen and Kent 1996, Kent and Olsen 1999). The cyclical Late Triassic part of the Newark section therefore represents about 24.3 m.y. of time. In the Princeton drill core, there are 662 meters (in NBCP-normalized depth units, Olsen et al. [1996a]) of Stockton Fm. below the lowermost McLaughlin cycle (RaR-8). Extrapolation using an average sedimentation rate of 96.2 meters/m.y. (in NBCP-normalized depth units) for the upper cyclical part of the Stockton Fm. in the Princeton drill core implies that an additional 6.9 m.y. is represented by the mainly fluvial sediments of the lower to middle Stockton Fm.

Biostratigraphic constraints on the age of the Stockton Formation, unfortunately, are not definitive. At least the upper part of the Stockton Formation belongs to the New Oxford-Lockatong palynofloral zone of late Carnian (Tuvalian) age although no diagnostic palynofloral assemblages have been recovered from the lower and middle Stockton Fm. (Cornet 1993). The palynofloral evidence is nevertheless



consistent with vertebrate fossils which indicate that the upper Stockton Fm. corresponds to the Conewagian land vertebrate faunachron of late Carnian age (Huber and Lucas 1996). An isolated occurrence of a very large non-metoposaurid amphibian (Sinclair 1917) would suggest, although not conclusively, an early Carnian (Julian) age for the fossil locality near the base of the exposed Stockton Formation, based largely on correlation with the Moroccan Triassic section (e.g., Lucas 1998).

According to the cycle stratigraphy of the Newark section, the Late Triassic is therefore estimated to be a minimum of about 24 m.y. If the base of the Stockton is indeed within the Carnian, the Late Triassic could be extrapolated to be at least another 6.9 m.y., or a total of about 31 m.y. or longer in duration (Fig. 1). Combined with an age of 202 Ma for the Triassic/Jurassic boundary, the cycle stratigraphy would therefore make the beginning of the Late Triassic no younger than 226 Ma and possibly 233 Ma or older. Interestingly, the time scale of Harland et al. (1990) obtained an age of 235 Ma for the Middle/Late Triassic (= Carnian/Ladinian) boundary based on an assessment of radiometric dates. Other recently published time scales, however, tend to give younger age estimates for this boundary, for example, 227.4 ± 4.5 Ma by Gradstein et al. (1994) (Fig. 2). Pertinent to this problem is a high precision $^{40}Ar/^{39}Ar$ date of 227.8 ± 0.3 Ma obtained from a bentonite interbedded in the Ischigualasto Formation of northwestern Argentina (Rogers et al. 1993). The Ischigualasto Formation contains a vertebrate fauna assigned a late Carnian age (Hunt and Lucas 1991, Lucas et al. 1992). The reported $^{40}Ar/^{39}Ar$ date is therefore more compatible with an older (e.g., 233 Ma) age estimate for the Carnian/Ladinian boundary.

Fig. 1. Composite stratigraphy of continental sediments and interbedded basalt in the Newark basin determined from 7 long NBCP drill cores (Olsen et al. 1996a) and a series of short cores taken by the Army Corps of Engineers (ACE; Fedosh and Smoot 1988) whose stratigraphic range is shown at left. Formations (Fm.) and members are described by Olsen et al. (1996a, b) and Kent and Olsen (1999). Depth in composite section based on stratigraphic thicknesses normalized to Rutgers drill core using log correlations in overlap intervals (Olsen et al. 1996a). Palynofloral (PF) zonation (Cornet and Olsen 1985, Cornet 1993) was based on outcrop samples and provides the stage-level biostratigraphic dating. Land vertebrate (LV) faunachrons from Huber and Lucas (1996). $^{40}Ar/^{39}Ar$ dates of 201 ± 1.7 Ma (Sutter, 1988) and U-Pb zircon dates averaging 202 ± 1 Ma (Dunning and Hodych 1990) are for Palisade Sill which is most likely co-magmatic with the Preakness Basalt. Magnetostratigraphy (normal polarity in black, reverse polarity in open bars) of NBCP cores is from Kent et al. (1995) and data for Jurassic igneous extrusive zone (Orange Mt. Basalt, Feltville Fm., Preakness Basalt, Towaco Fm., Hook Mt. Basalt, and Boonton Fm.), all of normal polarity, are summarized by Witte et al. (1991). Polarity chrons are labeled E1 to E24 from Kent et al. (1995). Note that Chron E24n is renamed from Chron E23n.2n in the original Newark nomenclature and corresponds to the long normal polarity magnetozone that begins just below the Triassic/Jurassic boundary and extends through the entire extrusive zone. Stratigraphic thickness was converted to time by assuming each lithologic member is a 404 k.y. orbital eccentricity cycle and indexing the astronomical chronology to an age of 202 Ma for the Triassic/Jurassic boundary. Ages in the lower and middle Stockton Fm. are based on extrapolation of the mean sedimentation rate in the cyclical upper Stockton Fm.

Middle and Early Triassic

The age range of the Late Triassic estimated from cycle stratigraphy places important constraints on the chronology of the Middle and Early Triassic (Fig. 2; Table 1). For the older boundary of the Triassic, recently estimated ages have ranged from only 245 Ma (Harland et al. 1990) to 250 Ma (Forster and Warrington, 1985). An age at the older end of this spectrum is supported by recent work using $^{40}Ar/^{39}Ar$ data on volcanic tuffs in marine sections in southern China which yield a date of 250 ± 0.2 Ma for the Permian/Triassic boundary (Renne et al. 1995). Accordingly, if the base of the Carnian (Late Triassic) is 233 Ma as suggested by the Newark chronology, the Early and Middle Triassic together would be only about 17 m.y. long. This is more expansive than the 10 m.y. allotted to the Early and Middle Triassic in the widely used Harland et al. (1990) geologic time scale but considerably shorter than the 21 m.y. duration estimated in the more recent Mesozoic time scale by Gradstein et al. (1994) (Fig. 2).

The age of the Early/Middle Triassic boundary has been consistently estimated between 240–242 Ma in many geologic time scales, for example, 241.7 ± 4.7 Ma by Gradstein et al. (1994) (Fig. 2). However, new high precision U-Pb zircon dates from ash layers in the Ladinian Buchenstein Beds from the Southern Alps (Italy) range from 238 to 241 Ma (Brack et al. 1996, Mundil et al. 1996). These dates, although not without controversy (Hardie and Hinnov 1997), point to an age of about 241 Ma for the base of the Ladinian (Mundil et al. 1996) and would imply that the Early/Middle Triassic boundary should be another ~2 m.y. older, or about 243 Ma, to accommodate the Anisian following Harland et al. (1990).

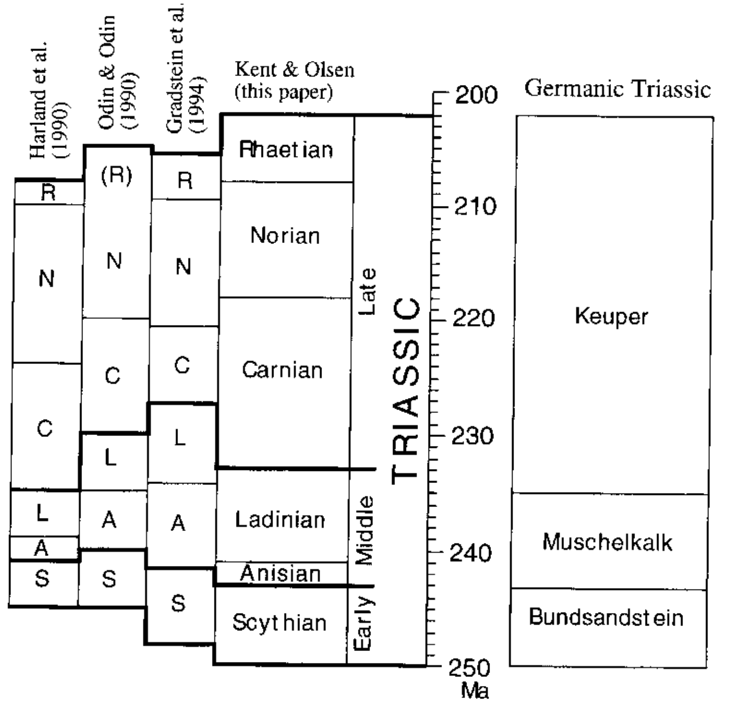


Fig. 2. Comparison of some recently published time scales for the Triassic and a chronology suggested here that includes astronomical tuning of the Late Triassic in the Newark basin section (Table 1). Subdivision and correlation of Germanic Triassic to standard stages is after Menning (1995).

Table 1. Age estimates for stage boundaries of the Triassic.

Stage boundary	Age, Ma	Source of age estimate
Rhaetian/Hettangian (Triassic/Jurassic)	202	$^{40}Ar/^{39}Ar$: Sutter (1988); U/Pb: Dunning and Hodych (1990), Hodych and Dunning (1992)
Norian/Rhaetian	208	Newark astrochronology
Carnian/Norian	218	Newark astrochronology
Ladinian/Carnian (Middle/Late Triassic)	233	Newark astrochronology
Anisian/Ladinian	241	U/Pb: Mundil et al. (1996)
Scythian/Anisian (Early/Middle Triassic)	243	Anisian/Ladinian plus 2 m.y.
Tatarian/Scythian (Permian/Triassic)	250	$^{40}Ar/^{39}Ar$: Renne et al. (1995)

Discussion

The 202 Ma age we favor for the Triassic/Jurassic boundary is generally younger than most published estimates, for example, 205 Ma by Odin and Odin (1990), 208 Ma by Harland et al. (1990) and 210 Ma by Haq et al. (1987). Nevertheless, 202 Ma is within the formal quoted uncertainty of 205.7 ± 4.0 Ma in the recent Mesozoic time scale by Gradstein et al. (1994). The only individual date in the listing of Gradstein et al. (1994) that apparently conflicts with a 202 Ma Triassic/Jurassic boundary age is item A478 which is based on K-Ar dating of plutons that crosscut greenshist metamorphosed Upper Triassic sediments and volcanics in Idaho (Armstrong and Besancon 1970). A 210 ± 6 Ma age is cited by Gradstein et al. (1994) for item A478. However, Armstrong and Besancon (1970) reported K-Ar dates that range from 181 to 200 Ma for biotite and 201 and 217 Ma for hornblende separates and simply took the mean of the three highest dates as their best choice for a minimum age. Given also the uncertain stratigraphic relationships of the samples, these results do not seem sufficiently precise for a modern calibration of a geologic period boundary. New U-Pb dates on ash layers in ammonoid-bearing marine strata from the North American Cordillera also seem to point to a young age of about 200 Ma for the Triassic/Jurassic boundary (Palfy et al. 1998).

The Triassic may therefore have a duration of about 48 m.y., extending from 202 Ma to 250 Ma. Cycle stratigraphy of the Newark section shows that the Late Triassic is at least 24 m.y. long and may be as long as 31 m.y., with the Carnian at ~15 m.y. becoming the longest stage in the Triassic. The Late Triassic would thus constitute at least one-half to perhaps two-thirds of the entire Triassic period. For the eponymous tripartite division of the Germanic Triassic, a consequence of the astronomically tuned time scale outlined here is that the Keuper (late Ladinian to Triassic/Jurassic boundary) must occupy at least one-half to perhaps two-thirds of the total time represented by the sediments in the basin (Fig. 2).

Finally, from the standpoint of magnetic stratigraphy, the astronomically tuned geomagnetic polarity time scale from the Newark section indicates an average reversal rate of 1.9 m.y.$^{-1}$ for 31 m.y. of the Late Triassic (Kent and Olsen 1999). A magnetostratigraphic framework for the Early and Middle Triassic is being developed and there are still stratigraphic gaps in the Middle Triassic. Nevertheless, recent compilations of the most reliable data indicate there are about 16 polarity chrons in the Early Triassic and at least 22 polarity chrons in the Middle Triassic (Ogg and Steiner 1991, Opdyke and Channell 1996, Muttoni et al. 1997). A total of about 38 polarity chrons for the estimated 17 m.y. duration of the Early and Middle Triassic gives a mean reversal rate of about 2.2 m.y.$^{-1}$. This is not very different from the better established, astronomically calibrated reversal rate for the Late Triassic. With the polarity chrons documented in the Newark basin for the Late Triassic, the entire Triassic has a total of about 100 polarity chrons providing a rich and powerful medium for temporal correlation.

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References

Armstrong RL, Besancon J (1970) A Triassic time scale dilemma: K-Ar dating of Upper Triassic mafic igneous rocks, eastern U.S.A. and Canada and post-Upper Triassic plutons, western Idaho, U.S.A. Eclogae Geol Helvetica 63:15–28

Berger A, Loutre MF, Laskar J (1992) Stability of the astronomical frequencies over the Earth's history for paleoclimate studies. Science 255:560–566

Berggren WA, Hilgen FJ, Langereis CG, Kent DV, Obradovich JD, Raffi I, Raymo ME, Shackleton NJ (1995a) Late Neogene chronology: New perspectives in high-resolution stratigraphy. Geol Soc America Bull 107:1272–1287

Berggren WA, Kent DV, Swisher CC, Aubry MP (1995b) A revised Cenozoic geochronology and chronostratigraphy, in Berggren WA, Kent DV, Aubry M-P, Hardenbol J, eds, Geochronology, Time Scales and Global Stratigraphic Correlations. SEPM Special Vol 54:129–212

Brack P, Mundil R, Oberli F, Meier M, Rieber H (1996) Biostratigraphic and radiometric age data question the Milankovitch characteristics of the Latemar cycles (Southern Alps, Italy). Geology 24:371–375

Cande SC, Kent DV (1992) A new geomagnetic polarity time scale for the Late Cretaceous and Cenozoic. J Geophys Res 97:13,917–13,951

Cande SC, Kent DV (1995) Revised calibration of the geomagnetic polarity time scale for the Late Cretaceous and Cenozoic. J Geophys Res 100:6093–6095

Channell JET, Erba E, Nakanishi M, Tamaki K (1995) Late Jurassic-Early Cretaceous time scales and oceanic magnetic anomaly block models. In: Berggren WA, Kent DV, Aubry M-P, Hardenbol J (eds) Geochronology, Time Scales and Global Stratigraphic Correlations. SEPM Special Volume 54:51–63

Cornet B (1993) Applications and limitations of palynology in age, climatic, and paleoenvironmental analyses of Triassic sequences in North America. NM Mus Nat Hist Science Bull 3:75–93

Cornet B, Olsen PE (1985) A summary of the biostratigraphy of the Newark Supergroup of eastern North America with comments on Early Mesozoic provinciality. In: Weber R (ed) Simposio Sobre Floras del Triasico Tardio, su Fitogeografia y Paleoecologia: Memoria, III Congresso Latinoamericano de Paleontologia, Mexico, p 67–81

Dunning GR, Hodych JP (1990) U/Pb zircon and baddeleyite ages for the Palisades and Gettysburg sills of the northeastern United States: Implications for the age of the Triassic/Jurassic boundary. Geology 18:795–798

Fedosh MS, Smoot JP (1988) A cored stratigraphic section through the northern Newark basin, New Jersey. US Geol Surv Bull 1776:19–24

Forster SC, Warrington G (1985) Geochronology of the Carboniferous, Permian and Triassic. In: Snelling, NJ (ed) Chronology of the Geological Record, Memoir No. 10: London, Blackwell Scientific Publications, p 99–113

Fowell SJ, Olsen PE (1993) Time calibration of Triassic/Jurassic microfloral turnover, eastern North America. Tectonophysics 222:361–369

Fowell SJ, Cornet B, Olsen PE (1994) Geologically rapid Late Triassic extinctions: Palynological evidence from the Newark Supergroup. Geological Society of America Special Paper 288:97–206

Gradstein FM, Agterberg FP, Ogg JG, Hardenbol J, Van Veen P, Thierry J, Huang Z (1994) A Mesozoic time scale. J Geophys Res 9:24,051–24,074

Haq BU, Hardenbol J, Vail PR (1987) Chronology of fluctuating sea levels since the Triassic. Science 235:1156–1168

Hardie LA, Hinnov LA (1997) Biostratigraphic and radiometric age data question the Milankovitch characteristics of the Latemar cycle (Southern Alps, Italy): Comment. Geology 25:470–471.

Harland WB, Cox AV, Llewellyn PG, Pickton CAG, Smith AG, Walters R (1982) A geologic time scale. Cambridge, Cambridge University Press, 131 p

Harland WB, Armstrong RL, Cox AV, Craig LE, Smith AG, Smith DG (1990) A geologic time scale 1989. London, Cambridge University Press, 263 p

Hilgen FJ (1991) Extension of the astronomically calibrated (polarity) time scale to the Miocene/Pliocene boundary. Earth Planet Sci Lett 107:349–368

Hodych JP, Dunning GR (1992) Did the Manicouagan impact trigger end-of-Triassic mass extinction? Geology 20:51–54

Huber P, Lucas SG (1996) Vertebrate biochronology of the Newark Supergroup. Museum of Northern Arizona Bull 60:179–186

Hunt AP, Lucas SG (1991) A new rhynchosaur from West Texas (USA) and the biochronology of Late Triassic rhynchosaurs. Paleontology 34:927–938

Kent DV, Gradstein FM (1985) A Cretaceous and Jurassic geochronology. Geol Soc America Bull 96:1419–1427
Kent DV, Olsen PE (1999) Astronomically tuned geomagnetic polarity time scale for the Late Triasssic. J Geophys Res 104: 12,831–12,841
Kent DV, Olsen PE, Witte WK (1995) Late Triassic-earliest Jurassic geomagnetic polarity sequence and paleolatitudes from drill cores in the Newark rift basin, eastern North America. J Geophys Res 100:14,965–14,998
Laskar J (1999) The limits of Earth orbital calculations for geological time-scale use. Trans Roy Soc Lond A, 357, 1735–1759
Lucas SG (1998) *Placerias* (Reptilia, Dicynodontia) from the Upper Triassic of the Newark Supergroup, North Carolina, USA, and its biochronological significance. N Jb Geol Paläont Mh 1998:432–448
Lucas SG, Hunt AP (1993) Tetrapod biochronology of the Chinle Group (Upper Triassic), western United States. NM Mus Nat Hist Sci Bull 3:327–329
Lucas SG, Hunt AP, Long RA (1992) The oldest dinosaurs. Naturwissenschaften 79:171–172
Menning M (1995) A numerical time scale for the Permian and Triassic periods. In: Scholle P, Peryt TM, Ulmer-Scholle DS (eds) Permian of the northern continents. Heidelberg, Springer-Verlag, p 77–97
Mundil R, Brack P, Meier M, Rieber H, Oberli F (1996) High resolution U-Pb dating of Middle Triassic volcaniclastics: Time-scale calibration and verification of tuning parameters for carbonate sedimentation. Earth Planet Sci Lett 141:137–151
Muttoni G, Kent DV, Brack P, Nicora A, Balini M (1997) Middle Triassic magnetostratigraphy and biostratigraphy from the Dolomites and Greece. Earth Planet Sci Lett 46:107–120
Odin GS, Odin C (1990) Echelle numerique des temps geologiques. Geochronologie 35:2–20
Ogg JG, Steiner MB (1991) Early Triassic magnetic polarity time scale – integration of magnetostratigraphy, ammonite zonation and sequence stratigraphy from stratotype sections (Canadian Arctic Archipelago). Earth Planet Sci Lett 107:69–89
Olsen PE, Kent DV (1996) Milankovitch climate forcing in the tropics of Pangea during the Late Triassic. Paleogeog Paleoclimatol Paleoecol 122:1–26
Olsen PE, Kent DV (1999) Long-period Milankovitch cycles from the Late Triassic and Early Jurassic of Eastern North America and their implications for the calibration of the early Mesozoic timescale and the long-term behavior of the planets. Phil Trans R Soc London, Series A 357: 1761–1786
Olsen P, Kent DV, Cornet B, Witte WK, Schlische RW (1996a) High-resolution stratigraphy of the Newark rift basin (early Mesozoic, eastern North America). Geol Soc America Bull 108:40–77
Olsen PE, Schlische RW, Fedosh MS (1996b) 580 Ky duration of the Early Jurassic flood basalt event in eastern North America estimated using Milankovitch cyclostratigraphy. In: Morales M (ed) The Continental Jurassic. Bull 60, Mus North AZ p 11–22
Opdyke ND, Channell JET (1996) Magnetic Stratigraphy. Int Geophys Ser 64, Academic Press, 346 p
Palfy J, Smith PL, Mortenson JK (1998) A U-Pb and ^{40}Ar-^{39}Ar time scale for the Jurassic. 5th International Symposium on the Jurassic System. Vancouver, August 1998 Abstracts, p 72
Ratcliffe NM (1988) Reinterpretation of the relationship of the western extension of the Palisades sill to the lava flows at Ladentown, New York, based on new core data. US Geol Surv Bull 1776:113–135
Renne PR, Zichao Z, Richards MA, Black MT, Basu AR (1995) Synchrony and causal relations between Permian-Triassic Boundary crises and Siberian flood volcanism. Science 269:1413–1416

Rogers RR, Swisher CC, Sereno P, Monetta AM, Forster CA, Martinez RN (1993) The Ischigualasto tetrapod assemblage (Late Triassic, Argentina) and 40Ar/39Ar dating of dinosaur origins. Science 260:794–797
Sinclair WJ (1917) A new labyrinthodont from the Triassic of Pennsylvania [*Calamops paludosus*]. American Journal of Science 43:319–321
Shackleton NJ, Berger A, Peltier WR (1990) An alternative astronomical calibration of the lower Pleistocene timescale based on ODP Site 677. Trans R Soc Edinburgh Earth Sci 81:251–261
Sutter JF (1988) Innovative approaches to the dating of igneous events in the early Mesozoic basins of the Eastern United States. US Geol Surv Bull 1776:194–200
Witte WK, Kent DV, Olsen PE (1991) Magnetostratigraphy and paleomagnetic poles from Late Triassic-earliest Jurassic strata of the Newark Basin. Geol Soc America Bull 103:1648–1662

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