

The Triassic timescale: an introduction

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Abstract: German geologists began to study rocks now recognized as Triassic during the late 1700s. In 1823, one of those German geologists, a very astute mining engineer named Friedrich August von Alberti (1795–1878), coined the term ‘Trias formation’ for an *c.* 1 km thick, tripartite succession of strata in southwestern Germany – the Bunte Sandsteine, Muschelkalk and Keuper of the German miners. Alberti also recognized Triassic rocks outside of Germany, throughout much of Europe and as far away as India and the United States. By the end of the nineteenth century, Triassic rocks had been identified across Europe and Asia, and in North America, South America and Africa. Indeed, in 1895, the Austrian geologist Edmund von Mojsisovics (1839–1907) and his collaborators published a complete subdivision of Triassic time based on ammonoid biostratigraphy and, in so doing, introduced many of the Triassic chronostratigraphic terms still used today. The twentieth century saw the elaboration of an ammonoid-based Triassic timescale, especially due to the work of Canadian palaeontologist E. Timothy Tozer (1928–). During the last few decades, work also began on developing a global magnetic polarity timescale for the Triassic, a variety of precise numerical ages tied to reliable Triassic biostratigraphy have been determined, and conodont biostratigraphy has become an important tool in Triassic chronostratigraphic definition and correlations.

The current Triassic chronostratigraphic scale is a hierarchy of three series (Lower, Middle, Upper) divided into seven stages (Lower = Induan, Olenekian; Middle = Anisian, Ladinian; and Upper = Carnian, Norian, Rhaetian) further divided into 15 substages (Induan = upper Griesbachian, Dienerian; Olenekian = Smithian, Spathian; Anisian = Aegean, Bithynian, Pelsonian, Illyrian; Ladinian = Fassanian, Longobardian; Carnian = Julian, Tuvanian; Norian = Lacinian, Alauian, Sevatian). Ammonoid and conodont biostratigraphies provide the primary basis for the chronostratigraphy. A sparse but growing database of precise radioisotopic ages support these calibrations: base of Triassic *c.* 252 Ma, base Olenekian *c.* 251 Ma, base Anisian *c.* 247 Ma, base Ladinian *c.* 242 Ma, base Jurassic *c.* 201 Ma. A U/Pb age of *c.* 231 Ma from the Italian Pignola 2 section is lower Tuvanian, and U/Pb ages on detrital zircons from the non-marine Chinle Group of the western USA of *c.* 219 Ma are in strata of late Carnian (Tuvanian) age based on the biostratigraphy of palynomorphs, conchostracans and tetrapods. These data support placement of the Norian base at *c.* 217 Ma, and indicate that the Tuvanian is more than 10 million years long and that the Carnian and Norian are the longest Triassic stages. Magnetostratigraphic data establish normal polarity for all of the Triassic stage bases except Anisian and Ladinian. An integrated biostratigraphic correlation web for the marine Triassic consists of ammonoids, bivalves, radiolarians and conodonts, whereas a similar web exists for the nonmarine Triassic using palynomorphs, conchostracans and tetrapods. Critical to cross correlation of the two webs is the Triassic section in the Germanic basin, where a confident correlation of nonmarine biostratigraphy to Triassic stage boundaries has been achieved. The major paths forward in development of the Triassic timescale are: finish formal definition of all Triassic stage boundaries, formally define the 15 Triassic substages, improve the integration of the Triassic biostratigraphic webs and develop new radioisotopic and magnetostratigraphic data, particularly for the Late Triassic.

Today, the Subcommittee on Triassic Stratigraphy (STS; part of the IUGS International Commission on Stratigraphy) advocates a Triassic chronostratigraphic scale of three series (never a subject of debate) and seven stages (much debated) (Fig. 1). The boundaries of the Triassic System are defined by global stratotype sections and points (GSSPs), and the numerical ages of those boundaries appear to be determined with a precision of about 1%. Nevertheless, much work remains to be done to refine the Triassic timescale. Precise numerical age control within the Triassic is generally sparse

and uneven, and a global polarity timescale for the Triassic is far from established. Chronostratigraphic definitions of most of the 15 Triassic substages widely used today remain unfinished, and many issues of marine biostratigraphy are still unresolved. In the nonmarine Triassic realm, much progress has been made in correlation, especially using palynomorphs, conchostracans and tetrapods (amphibians and reptiles), but many problems of correlation remain, especially the cross correlation of nonmarine and marine chronologies.

		series	stage	substage
TRIASSIC	UPPER	Rhaetian		
			Norian	Sevastian
				Alaunian
		Lacian		
		Carnian	Tuvalian	
			Julian	
	MIDDLE	Ladinian	Longobardian	
			Fassanian	
		Anisian	Illyrian	
			Pelsonian	
			Bithynian	
			Aegean	
	LOWER	Olenekian	Spathian	
			Smithian	
Induan		Dienerian		
		Griesbachian		

Fig. 1. The Triassic chronostratigraphic scale.

This book reviews the state-of-the-art of the Triassic timescale, and this introductory chapter provides an overview of this book. It also presents a Triassic timescale based on the data presented in several chapters in this book.

Triassic chronostratigraphy

In this volume, Lucas (2010a) reviews the nearly two-century-long development of the Triassic chronostratigraphic scale, which is now a hierarchy of three series, seven stages and 15 substages developed during nearly two centuries of research (Fig. 1). The first geological studies of Triassic rocks began in Germany in the late 1700s and culminated when Alberti (1834) coined the term Trias for the Bunten Sandsteins, Muschelkalk and Keuper of southwestern Germany, an *c.* 1 km thick succession of strata between the Zechstein (Permian) and the Lias (Jurassic).

Recognition of the Trias outside of Germany soon followed, and included early work on a similar succession of Triassic strata in Great

Britain (Warrington *et al.* 1980). By the 1860s Austrian geologist Edmund von Mojsisovics began constructing a detailed Triassic chronostratigraphy based on ammonoid biostratigraphy. In 1895, Mojsisovics and his principal collaborators, Wilhelm Waagen and Carl Diener, published a Triassic timescale that contains most of the stage and substage names still used today (Mojsisovics *et al.* 1895). Spath (1934) proposed a Triassic ammonoid-based biochronological timescale congruent with that of Mojsisovics *et al.* (1895). Tozer (e.g. 1965, 1967, 1984, 1994) proposed a Triassic ammonoid-based timescale based on North American standards, particularly in the Canadian Arctic islands and the Cordillera of British Columbia and Nevada. Distinctive features of Tozer's timescale included proposal of four Lower Triassic stages (Griesbachian, Dienerian, Smithian and Spathian) and abandonment of the Rhaetian as the youngest Triassic stage.

The STS began its work in the 1970s and now recognizes seven Triassic stages in three series (Fig. 1). Strata pivotal to the development of a Triassic timescale were originally spread across much of the Boreal and Tethyan periphery of Pangaea during the Triassic (Fig. 2). The 1990s saw the rise of Triassic conodont biostratigraphy so that four agreed on (or nearly agreed on) Triassic GSSPs use conodont events as defining features. Most of the bases of the Triassic stages have been (or will soon be) defined by GSSPs:

1. The base of the Induan Stage (= base of Triassic, = base of Lower Triassic) is defined by the lowest occurrence (LO) of the conodont *Hindeodus parvus* at the Meishan section in Guangxi, southern China (Yin 1996; Yin *et al.* 1996, 2001).
2. The base of the Olenekian Stage may be defined by the LO of the conodont *Neospathodus waageni* at the Mud section in Spiti, India (Krystyn *et al.* 2007a), though this is still under discussion.
3. The base of the Anisian Stage (= base of the Middle Triassic) may be defined by the LO of the conodont *Chiosella timorensis* at the Deşli Caira section in Romania (Orchard *et al.* 2007).
4. The base of the Ladinian Stage is defined by the LO of the ammonoid *Eoprotrachyceras curioni* at the Bagolino section in Italy (Brack *et al.* 2005).
5. The base of the Carnian Stage (= base of the Upper Triassic) is to be defined by the LO of the ammonoid *Daxatina canadensis* at the Stuoeres Wiesen section in Italy (Mietto *et al.* 2007; Gaetani 2009).
6. The base of the Norian Stage is the farthest from decision, with a GSSP located either at

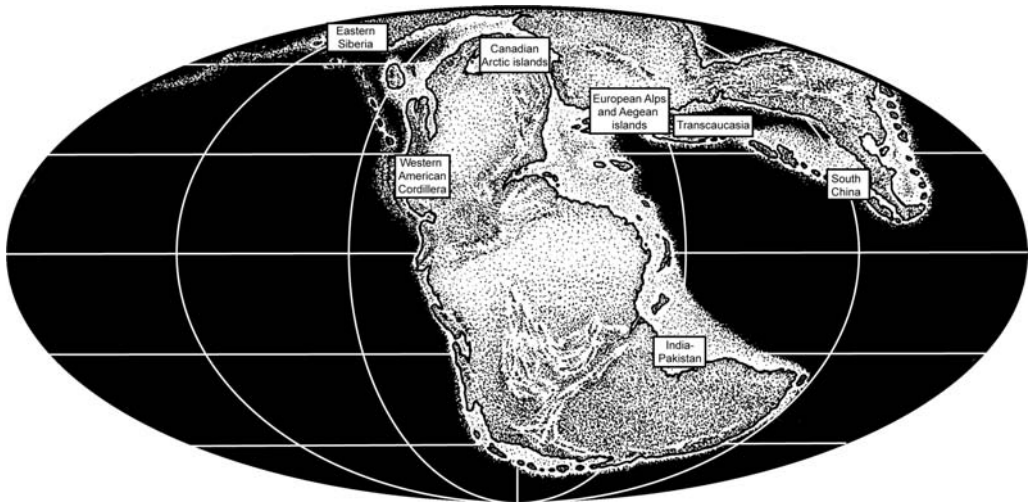


Fig. 2. Triassic world map with areas pivotal to construction of a Triassic timescale indicated. Artwork by Matt Celeskey.

Black Bear Ridge in British Columbia, Canada or at Pizzo Mondello in Sicily, and it probably will be based on a conodont event close to the base of the *Stikinoceras kerri* ammonoid zone, which has been the traditional Norian base in North American usage (M. Orchard, written communication, 2009).

7. The base of the Rhaetian Stage is to be defined by the LO of the conodont *Misikella posthernsteini* at the Steinbergkogel section in Austria (Krystyn *et al.* 2007b).
8. The base of the Hettangian Stage (= base of the Jurassic, = base of the Lower Jurassic) is to be defined by the LO of the ammonoid *Psiloceras spelae* at the Kuhjoch section in Austria (Von Hillebrandt *et al.* 2007).

These GSSPs define boundaries of the seven Triassic stages recognized by the STS and also define the boundaries of the three Triassic Series and of the Triassic System. Most of the bases of the 15 Triassic substages (Fig. 1), however, still lack formal definition. They provide a more refined subdivision of Triassic time than do the stages, and should be the focus of future chronostratigraphic research.

Radioisotopic ages

A precise and detailed numerical timescale does not yet exist for the Triassic. This is partly because of the relatively low level of Triassic volcanism recorded in fossiliferous rocks, which resulted in a dearth of datable volcanic ash beds (in contrast to

some of the other geological systems such as the Cretaceous, which had a much more extensive record of volcanism). Nevertheless, some important advances have been made in the last two decades. The Early and Middle Triassic have the best numerical age constraints, and these demonstrate that the Early Triassic only represents about five million years, whereas the Middle Triassic is about 10 million years long; the Late Triassic thus is more than two-thirds of the entire duration of the Triassic.

In this volume, **Mundil *et al.* (2010)** review the Triassic numerical timescale to produce a significantly different calibration than that published in the most recent compilation by Ogg (2004). The differences mostly reflect the availability of new radioisotopic ages, but some of them also reflect different selection criteria and different approaches to attempting to eliminate the biases (both systematic and random) in the ages. The ages Mundil *et al.* (2010) use to calibrate the Triassic timescale are from U–Pb analyses applied to zircons with uncertainties at the permil level or better. According to their compilation, the age of the beginning of the Triassic is 252.3 Ma, and the end of the Triassic is 201.5 Ma. Robust age constraints also exist for the Induan–Olenekian boundary (251.2 Ma) and the Early–Middle Triassic (Olenekian–Anisian) boundary (247.2 Ma), so the Early Triassic is approximately five million years long. The Anisian–Ladinian boundary is constrained to 242.0 Ma by new U–Pb and $^{40}\text{Ar}/^{39}\text{Ar}$ ages reported by Mundil *et al.* Nevertheless, radioisotopic ages for the Late Triassic are scarce, and the only reliable and biostratigraphically controlled age is from a Carnian (lower

Tuvalian) tuff dated at 230.9 Ma. This means that the Late Triassic is about 30 million years long.

Magnetostratigraphy

The global polarity timescale for rocks of Late Jurassic, Cretaceous and Cenozoic age provides a valuable tool for evaluating and refining correlations that are based primarily on radioisotopic ages or biostratigraphy. However, there is no agreed geomagnetic polarity timescale (GPTS) for the Triassic, although a composite GPTS is now becoming available based on successions cobbled together from marine and nonmarine sections in North America, Europe, and Asia.

Hounslow & Muttoni (2010) review Triassic magnetic polarity history in this volume. They note that Lower Triassic magnetostratigraphy is primarily calibrated by ammonoid biostratigraphy in Canada and Svalbard. In addition, extensive magnetostratigraphic studies of the Permian–Triassic and Olenekian–Anisian boundaries are calibrated by conodont biostratigraphy. Various magnetostratigraphic studies of nonmarine Lower Triassic strata validate and cross-correlate the marine-based ages into some nonmarine successions. The Middle Triassic magnetostratigraphic timescale is well constrained by conodont and ammonoid zonations from multiple Tethyan sections, and it is consistent with detailed data from several nonmarine Anisian sections. The middle Carnian is the only significant interval in the Triassic for which biostratigraphic calibration of the magnetostratigraphy is not well resolved. Problems with the Norian and early Rhaetian magnetostratigraphy focus on properly constraining the magnetostratigraphic correlation between nonmarine strata, such as the Newark Supergroup of eastern North America, and the polarity timescale based on marine Tethyan sections. Hounslow & Muttoni's (2010) review concludes that average magnetozone duration is about 240,000 years for the Lower and Middle Triassic, and about twice that for the Upper Triassic. In sum, they recognize 133 valid magnetozones for the Triassic Period.

Isotope stratigraphy

In this volume, **Tanner** (2010*a*) reviews the use of isotopes in Triassic stratigraphy. As he notes, measurements of $\delta^{13}\text{C}$, $\delta^{18}\text{O}$, $\delta^{34}\text{S}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ provide information about the state of the water column in which deposition took place. The most widely studied isotope is $\delta^{13}\text{C}$, and, indeed, the carbon isotope record for the Triassic System is now known in some detail, and it is complex. Thus, a pronounced negative excursion begins

below the base of the Triassic and continues into the lowermost Triassic. Isotopic instability characterizes most of the Lower Triassic, with positive and negative excursions continuing through the basal Middle Triassic. Unlike the Lower Triassic, relative isotopic stability characterizes much of the Middle and Upper Triassic, with rising values of $\delta^{13}\text{C}$ likely due to environmental recovery (after the end-Permian mass extinction) and increasing storage of organic carbon in terrestrial environments. A pronounced negative excursion near the Triassic–Jurassic boundary has been linked to significant biotic turnover.

The causes of the Triassic carbon isotope excursions remain a topic of discussion, with the most likely mechanisms being outgassing during volcanic activity, changes in productivity, ocean anoxia, and seafloor methane releases. These processes evidently perturbed the global carbon cycle and forced episodic biotic extinctions.

The construction of a global carbon isotope curve for the Triassic is thus well underway. This curve, with some judicious calibration, should become an increasingly important tool for Triassic correlation. However, isotope curves, like magnetostratigraphy, are not independent correlation tools and always need to be tied to biostratigraphic or radioisotopic data in order to be of value in correlation.

Cyclostratigraphy

In this volume, **Tanner** (2010*b*) reviews the use of cycles in Triassic stratigraphy, and he notes that high frequency (fourth- and fifth-order) cyclicity is a common feature of sedimentary sequences in Triassic depositional settings. Tectonism and autocyclicity clearly drove some of this cyclicity, but many Triassic cycles have been attributed to orbital-forced variations in solar insolation at the Milankovitch frequencies (the precession, as well as the short and long eccentricity cycles at scales of tens of thousands to hundreds of thousands of years). This orbital forcing is thought to have controlled sedimentation through periodic changes in climate or sea-level. Examples of interpreted Milankovitch-frequency cyclicity throughout the Triassic record include much of the Germanic Triassic section, the Newark Supergroup of eastern North America, and parts of the Alpine Triassic. The cyclostratigraphy of these sections has been used as a tool for intrabasinal correlation and for chronostratigraphy. However, conceptual arguments and radioisotopic age data call some of these interpretations into question. At present, Triassic cyclostratigraphic studies remain far from the goal of developing a reliable, astronomically-calibrated Triassic timescale.

Biostratigraphy

The distribution of fossils in marine Triassic strata has provided the primary basis for construction of the Triassic timescale. The most important taxa in this regard are conodonts, radiolarians, bivalves and ammonoids. Nonmarine Triassic biostratigraphy has also been developed, based primarily on palynomorphs, conchostracans, tetrapod (amphibian and reptile) footprints and tetrapod body fossils.

Conodonts

Conodonts are microscopic tooth-like structures composed of calcium phosphate that are abundant and widespread in Triassic marine strata. Although the biological source of conodonts was long unknown, they are now clearly associated with chordates.

In this volume, **Orchard** (2010) reviews Triassic conodont biostratigraphy, which now plays a pivotal role in the delineation of a Triassic timescale. The base of the Triassic (base of the Induan) is defined by the LO of the conodont *Hindeodus parvus*; a parallel zonation is provided by *Neogondolella* species. The LO of *Neospathodus waageni* within a plexus of similar species is favoured to define the Olenekian base, accompanied by species of *Borinella* and *Eurygnathodus* (Krystyn *et al.* 2007a). The base of the Anisian is close to the LO of *Chiosella*, with *Triassospathodus* and *Spathicuspus* characterizing the late Olenekian, and *Gladigondolella tethydis* and *Nicoraella* restricted to the Anisian. The early evolution of *Budurovignathus* species provides a proxy for the base of the Ladinian, which is defined by an ammonoid event. The Carnian base, also defined by an ammonoid event, is close to the LO of *Metapolygnathus* (including *M. polygnathiformis* and *M. tadpole*). The base of the Norian is characterized by a conodont faunal turnover featuring many new species, as well as an abundance of *M. primitius* and *M. echinatus* in the basal Norian. The Rhaetian base will be defined by the evolution of *Misikella* in Europe, with coeval changes recognized in North American *Epigondolella*. Conodont extinction was long thought to mark the end of the Triassic, but recently published data indicate a minimal survival of conodonts into the basal Jurassic (Pálfy *et al.* 2007).

Radiolarians

Radiolarians are marine zooplankton which secrete a skeleton of opaline silica. In the Modern oceans they form massive skeletal accumulations (radiolarian oozes) on the seafloor in deep waters (up to 4000 m deep). Their Triassic fossils are typically

found in deep-marine deposits associated with chert horizons.

In this volume, **O'Dogherty *et al.*** (2010) review the Triassic radiolarian record. They summarize 30 years of research on Triassic radiolarian biostratigraphy and present a correlation of radiolarian zonation currently used in Europe, Japan, Siberia and North America. O'Dogherty *et al.*'s up-to-date assessment of the stratigraphic ranges of the 281 valid Triassic genera of radiolarians indicates that they are useful in substage-level correlations.

After the end-Permian extinction, the most severe extinction in radiolarian history, a long recovery until the early Anisian was followed by a rapid diversification. Maximum generic diversity was during the early Carnian when the first severe within Triassic extinctions took place. Diversity declined through the Norian and Rhaetian, culminated by a mass extinction of radiolarians at the Triassic–Jurassic boundary.

One of the most complete Triassic radiolarian biozonations is for Japan, largely a function of the extensive Triassic record of radiolarites in Japan and the intensity of study (Sugiyama 1997). Extensive radiolarian biostratigraphy also exists for western Europe (Kozur & Möstler 1994, 1996; Kozur *et al.* 1996) and for eastern Siberia (Bragin 1991). Further development of the Triassic record of radiolarians promises to make them a very robust tool in Triassic marine correlations.

Bivalves

Late Palaeozoic seas were dominated by pelmatozoans, brachiopods and bryozoans, but molluscs dominated the Triassic seas (Vermeij 1977; Sepkoski 1981). Bivalves (pelecypods) were common Mesozoic molluscs that underwent a substantial Triassic diversification to dominate many level-bottom, reefal and pelagic settings (e.g. McRoberts 2001; Fraiser & Bottjer 2007). Earliest Triassic bivalve assemblages are mostly epifaunal pteriomorphs and detritus-feeding nuculoids, and they are very abundant as fossils. The Middle–Late Triassic saw a diversification of arcoid, mytiloid, trigonoid and veneroid genera. The thin-shelled bivalves *Claraia*, *Peribositria*, *Enteropleura*, *Daonella*, *Aparimella*, *Halobia* and *Monotis* (the so-called ‘flat clams’ because of their very thin shells and narrow valve convexity) are characteristic Triassic forms widely used in biostratigraphy.

In this volume, **McRoberts** (2010) reviews the application of the ‘flat clams’ to Triassic biostratigraphy and biochronology, noting that these bivalves generally are widely distributed and have very high species turnover rates, making them excellent biostratigraphic indexes of portions of the Triassic.

Their biostratigraphic value has long been recognized, and McRoberts (2010) reviews previous zonations and proposes his own, which is based on the first global summary of Triassic bivalve zonation. In McRoberts' (2010) zonation, the Lower Triassic encompasses two to three *Claraia* zones that represent the Induan and lower Olenekian. In the upper Olenekian, species of *Peribositria* are useful zonal indexes. During the Middle Triassic, *Enteropleura* (middle Anisian) and *Daonella* (upper Anisian through Ladinian) have significant records in the circum-Pacific and Boreal realms. McRoberts divides the Upper Triassic into 8 to 13 bivalve zones based on the succession of species of *Halobia*, *Eomonotis*, and *Monotis sensu lato*.

Ammonoids

Most prominent of the Triassic molluscs were ammonoid cephalopods, a group whose rapid diversification during the Triassic provides a fossil record that has long subdivided Triassic time. Most Triassic ammonoids were ceratitids, with relatively simple suture lines, descended from only two ammonoid stocks that survived the end-Permian mass extinction: the otoceratids and the xenodiscids. Triassic ammonoid genera define at minimum three broad marine palaeobiogeographic provinces around the Pangaeian periphery (Tethyan, Boreal and notal), but the ammonoid palaeobiogeography of Triassic Panthalassa was complex and remains little understood (e.g. Dagens 1988).

Ammonoids have long been the workhorses of Triassic marine biostratigraphy, and most of the Triassic timescale was built on ammonoid biostratigraphy. In this volume, Lucas (2010a) reviews the historical development of the Triassic chronostratigraphic scale, which is largely a review of the application of ammonoids to Triassic chronostratigraphy.

Also, in this volume, Balini *et al.* (2010) review Triassic ammonoid biostratigraphy. The study of Triassic ammonoids began during the late 1700s, and Mojsisovics *et al.* (1895) published an essentially complete Triassic chronostratigraphic scale based on ammonoid biostratigraphy. This scale introduced many of the Triassic stage and substage names still used today, and all terminology of stages and substages subsequently introduced has been based on ammonoid biostratigraphy.

Early Triassic ammonoids show a trend from cosmopolitanism (Induan) to latitudinal differentiation (Olenekian), and the four Lower Triassic substage (Griesbachian, Dienerian, Smithian and Spathian) boundaries are globally correlated by widespread ammonoid biotic events. Middle Triassic ammonoids have provinciality similar to that of the Olenekian and provide a basis for recognizing six Middle Triassic substages. Late Triassic

ammonoids provide a basis for recognizing three stages divided into five substages. Significantly, the main uncertainty for the future of Triassic ammonoid biostratigraphy is not the decline of the ammonoids as a tool for dating and correlation of Triassic strata, but rather the dramatic decrease in the number of palaeontologists who study Triassic ammonoids, due to the lack of replacement of experienced specialists who started their activity in the 1950s and 1960s.

Other marine biostratigraphy

Some other Triassic marine fossils have been useful in biostratigraphy, but have not provided the robust biostratigraphies of the Triassic given by radiolarians, conodonts, bivalves and ammonoids. These other fossils include foraminiferans, brachiopods and nautiloids.

Triassic foraminiferans are particularly well studied in Europe and in the former Soviet Union, where a complete Triassic zonation based on foraminiferans has been proposed for the Caucasus (e.g. Efimova 1991; Vuks 2000, 2007). Much more sampling and study remains to determine the global biostratigraphic utility of Triassic foraminiferans.

Triassic nautiloid cephalopods appear to have undergone relatively little change at the end of the Permian, but reached great diversity in the Triassic to suffer an extensive (but not complete) extinction near the end of the period. Some Triassic biostratigraphic zonations based on nautiloids have been proposed (e.g. Kummel 1953; Gradinaru & Sobolev 2006), but the rarity of nautiloids in most Triassic facies limits their value to correlation.

Brachiopods did not suffer total extinction at the end of the Permian, although their numbers were greatly reduced, but they were relatively minor but persistent components of Triassic marine faunas. A diverse published biostratigraphy of Triassic brachiopods (e.g. Dagens 1974; Hoover 1991; Benatov 2001; Chen *et al.* 2005; and Shen *et al.* 2006 represent a small sampling) suggests a fair amount of provincialism and relatively slow turnover rates, which limit the broad applicability of brachiopods to problems of Triassic correlation.

Palynomorphs

Spores and pollen are the microscopic reproductive structures of vascular plants. They have organic walls that resist pressure, desiccation and microbial decomposition, so they are often well preserved in sedimentary rocks, and Triassic strata are no exception. Because of their abundance (one plant may produce thousands of palynomorphs), durability and easy dispersal (often by wind), palynomorphs

are found in both nonmarine and marine strata, so they provide an important means for cross correlation of nonmarine and marine strata based on shared palynomorph taxa. On the other hand, most palynomorphs are only dispersed within a few km or less of the plant that produces them, and any provincialization of the paleoflora hinders their use in broad scale correlation. Furthermore, plants are very environmentally sensitive, so palaeoenvironmental and facies restrictions of extinct plants affect the distribution of their palynomorphs. During the Triassic, the palaeoflora was provincialized into at least three or more provinces (see below), and correlations based on fossil plants and the palynoflora have even proven to be difficult between portions of Triassic Pangaea that were in relatively close proximity, such as Western Europe and eastern North America.

In this volume, **Kürschner & Herngreen** (2010) discuss the microfossil trends during the Triassic in the Germanic and Alpine domains, emphasizing diversity fluctuations and related palaeoenvironmental changes. They also propose a set of nine palynomorph zones (with several subzonal subdivisions) for the European (mostly Germanic) Triassic that they correlate to the Triassic marine timescale based largely on the correlation of the German section proposed by Kozur & Bachmann (2005, 2008) (Fig. 3).

Cirilli (2010) reviews Upper Triassic–Lower Jurassic palynological assemblages and palynozonations for the Northern and Southern hemispheres. She examines the evolutionary progression of palynological assemblages in the Tethyan domain to conclude that there has been a gradual change in palynofloral composition from the Carnian to uppermost Rhaetian/lower Hettangian. According to Cirilli, the biostratigraphic resolution based on Upper Triassic palynological assemblages is rather low due to the rarity of palynomorphs associated with other means of age determination (i.e. ammonoids, conodonts, isotopes, palaeomagnetism), microfloristic palaeoprovinciality, palaeoenvironmental conditions and the varied preservational grade of Upper Triassic palynological assemblages.

Conchostracans

Conchostracans are bivalved crustaceans that live in freshwater lakes and ponds. Their minute, drought-resistant eggs can be dispersed by the wind, and this guaranteed a broad geographic range to some conchostracan taxa across much of Triassic Pangaea. Triassic conchostracan biostratigraphy has been developed by several workers, most recently by Kozur & Weems (2005, 2007) in Europe and North America.

In this volume, **Kozur & Weems** (2010) present a revised Triassic conchostracan biostratigraphy. Again, key to their correlation is the Germanic Basin Triassic section, which yields numerous conchostracan assemblages from the Buntsandstein and Keuper.

According to Kozur & Weems, Triassic conchostracan zones often provide a stratigraphic resolution comparable to ammonoid and conodont zones of the marine Triassic. Kozur & Weems thus present a conchostracan zonation for the Late Permian–Early Jurassic of the Northern hemisphere and correlate it to the marine timescale. This conchostracan zonation is especially well developed for the Changhsingian to lower Anisian, upper Ladinian to Julian and Rhaetian to Hettangian intervals, but remains preliminary for most of the Middle and Upper Triassic.

Tetrapod footprints

Fossil footprints of Triassic tetrapods, which have been studied since the early 1800s, are common in some Triassic nonmarine strata and have very broad palaeogeographic distributions. Furthermore, some Triassic nonmarine strata that lack or nearly lack a tetrapod bone record have an extensive footprint record. Therefore, various workers have used Triassic tetrapod footprints in biostratigraphy, beginning with the pioneering work of Haubold (1969, 1971*a, b*; Demathieu & Haubold 1972, 1974).

In this volume, **Klein & Lucas** (2010) review the use of tetrapod footprints in Triassic biostratigraphy. They argue that several characteristic Triassic footprint assemblages and ichnotaxa have restricted stratigraphic ranges and thus represent distinct time intervals. Klein & Lucas thus identify five distinct Triassic tetrapod-footprint-based biochrons: (1) dicynodont tracks (Lootsbergian); (2) *Protochirotherium* (*Synaptichnium*), also includes *Rhynchosauroides* and *Procolophonichnium* (Nonesian); (3) *Chirotherium barthii*, also includes *C. sickleri*, *Isochirotherium*, *Synaptichnium*, *Rotodactylus*, *Rhynchosauroides*, *Procolophonichnium*, dicynodont tracks and *Capitosauroides* (Nonesian–Perovkan); (4) *Atreipus-Grallator* (“*Coelurosaurichnus*”), which also includes *Synaptichnium*, *Isochirotherium*, *Sphingopus*, *Parachirotherium*, *Rhynchosauroides* and *Procolophonichnium* (Perovkan–Berdyanian); and (5) *Brachychirotherium*, which also includes *Atreipus-Grallator*, *Grallator*, *Eubrontes*, *Apatopus*, *Rhynchosauroides* and dicynodont tracks (Otischalkian–Apachean).

Tetrapod footprints prove useful for Triassic biostratigraphy and biochronology, but compared to the tetrapod body fossil record with eight biochrons, the five footprint-based biochrons provide less temporal resolution. Nevertheless, in

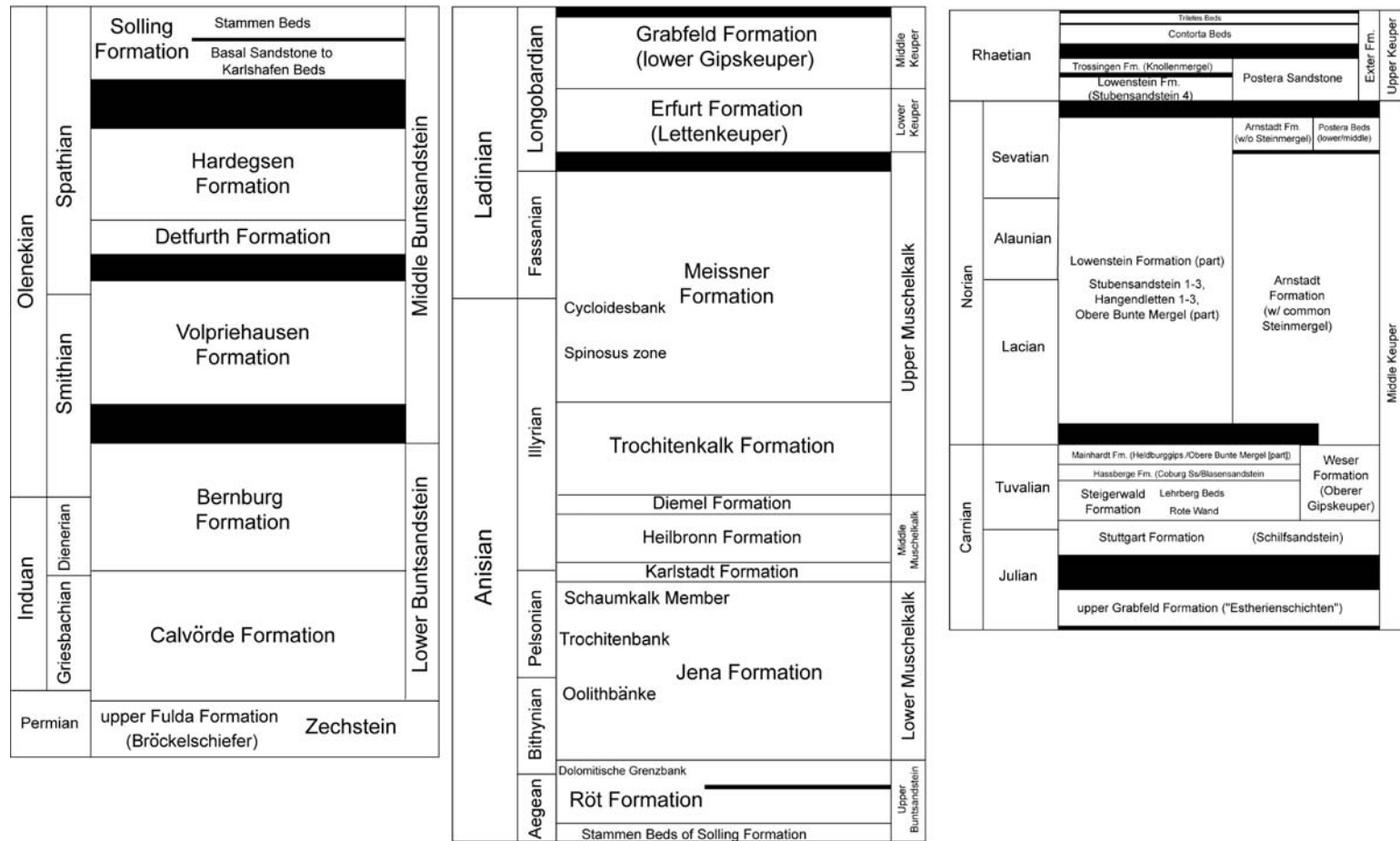


Fig. 3. Summary of the Germanic Basin Triassic section correlated to the Triassic chronostratigraphic scale (modified from Kozur & Bachmann 2005, 2008).

nonmarine Triassic strata where body fossils are rare, tetrapod footprints can be useful for biostratigraphy and biochronology.

Tetrapods

Triassic tetrapod (amphibian and reptile) fossils have long been used in nonmarine biostratigraphy, with a tradition extending back to at least the 1870s. Lucas (1990) advocated developing a global Triassic timescale based on tetrapod evolution, and Lucas (1998) presented a comprehensive global Triassic tetrapod biochronology that divided the Triassic into eight time intervals (land-vertebrate faunachrons: LVFs) based on tetrapod evolution. In this volume, Lucas (2010*b*) presents the current status of the Triassic tetrapod-based timescale.

The Early Triassic tetrapod LVFs, Lootsbergian and Nonesian, have characteristic tetrapod assemblages in the Karoo basin of South Africa, the *Lystronotus* assemblage zone and the lower two-thirds of the *Cynognathus* assemblage zone. The Middle Triassic LVFs, Perovkan and Berdyankian, have characteristic assemblages from the Russian Ural foreland basin, the tetrapod assemblages of the Donguz and the Bukobay svitas ('formations'). The Late Triassic LVFs, Otischalkian, Adamanian, Revueltian and Apachean, have characteristic assemblages in the Chinle basin of the western USA, the tetrapod assemblages of the Colorado City Formation of Texas, Blue Mesa Member of the Petrified Forest Formation in Arizona, and the Bull Canyon and the Redonda formations in New Mexico. Since the Triassic LVFs were introduced, subdivision of several of them has been proposed: Lootsbergian can be divided into three sub-LVFs, Nonesian into two, Adamanian into two and Revueltian into three. However, the broad correlation of most of these sub-LVFs remains to be demonstrated.

Records of nonmarine Triassic tetrapods in marine strata, palynostratigraphy, conchostracan biostratigraphy, magnetostratigraphy and radioisotopic ages provide some basis for correlation of the LVFs to the standard global chronostratigraphic scale. These data indicate that Lootsbergian = uppermost Changhsingian, Induan and possibly earliest Olenekian; Nonesian = most of the Olenekian; Perovkan = most of the Anisian; Berdyankian = latest Anisian? and Ladinian; Otischalkian = early–earliest late Carnian; Adamanian = late Carnian; Revueltian = early–middle Norian; and Apachean = late Norian–Rhaetian.

Other nonmarine biostratigraphy

Some other nonmarine Triassic fossils have been employed in biostratigraphy, including charophytes, megafossil plants, ostracods, bivalves and fishes.

None of these groups has provided what can be considered a robust global or even provincial biostratigraphy, but all have some potential to aid in Triassic correlations.

Charophytes are the calcified egg cases (gyrogonites) of characeous algae, and they have been documented from some Triassic lacustrine deposits (e.g. Kaesler & Feist 2005). However, too little is known of the Triassic charophyte record to allow its use in biostratigraphy. Furthermore, much of the variation in gyrogonite morphology is ecophenotypic, and therefore more a function of environmental variation than a consistent evolutionary signal. Thus, I suspect that the long-ranging charophyte genera now known from the Triassic (e.g. *Stellatochara*) will not segregate into temporally successive species useful in biostratigraphy.

During the Permian and Triassic, there was a complex and prolonged global change from pteridophyte-dominated floras of the Palaeozoic to the gymnosperm-dominated floras that characterized much of the Mesozoic, which is when the arborescent lycopods and sphenopsids of the Permian gave way to Triassic floras dominated by seed ferns, ginkgophytes, cycads, cycadeoids and conifers. Distinct Gondwanan and Laurasian floras can be recognized, and within Laurasia two or three provinces are recognized during the Triassic – a more boreal Siberian province and a more equatorial Euramerican province. The Triassic Laurasian floras were dominated by primitive conifers, ferns, cycads, bennettitaleans and sphenopsids. Conifers were the dominant large trees, whereas the other plant types formed the understory. In coastal settings, stands of the lycopoid *Pleuromeia* were dominant. Gondwana floras of the Triassic were dominated by a wide range of seed ferns, especially the genus *Dicroidium*. These floras were generally composed of only a few (no more than ten) genera. *Dicroidium* was dominant in a variety of vegetation types, from heath to broad-leaved forest to dry woodland. Other important elements of Gondwana floras were conifers and some Laurasian groups of cycadaleans and ginkgos. Near the end of the Triassic, the *Dicroidium* flora declined and was replaced by a cosmopolitan conifer–bennettitalean flora.

Megafossil plant biostratigraphy of the Triassic has been developed at regional and more global scales. At the regional scale, a good example is Ash (1980, 1987), who proposed a succession of three floral zones useful in correlating North American Upper Triassic palaeofloras. Despite subsequent range extensions and stratigraphic refinements (Axesmith & Kroehler 1988; Lucas 1997, 2006), these zones do allow broad correlation of lower Chinle Group and lower Newark Supergroup palaeofloras, but the zonal index taxa extend no farther palaeogeographically. A cautionary tale

Ma	magnetostratigraphy	Stage/ Substage		Ammonoid zones		Conodonts (North America)	Radiolarians (Japan)	Conchostracans (Germanic basin)	Palynomorphs (Germanic basin)	Tetrapod LVFs				
		American Cordillera	Tethyan											
242		Ladinian		Longobardian	<i>F. sutherlandi</i>	<i>Frankites regoledanus</i>	<i>Paragondolella inclinata</i>	<i>Spongoserrula dehli</i>	<i>Euestheria minuta</i>	<i>Heliosaccus dimorphus</i>				
					<i>Macl. maclerani</i>	" <i>Protrachy.</i> " <i>neumayri</i>								
					<i>Meginoceras meginiae</i>	<i>Protrachy. longobardicum</i>								
				Fassanian	<i>Tuchodicerias poseidon</i>	<i>"Eoprotrachy." gredleri</i>	<i>Budorovignathus hungaricus</i>				<i>Muelleritortis cochleata</i>	<i>Euestheria franconica</i>		
													<i>Protrachy. margaritosum</i>	
													<i>Eoprotrachyceras matutinum</i>	<i>Eoprotrachyceras curionii</i>
		Anisian		Illyrian	<i>Frechites occidentalis</i>	<i>Nevadites</i>	<i>Paragondolella ex. gr. excelsa</i>	<i>Yeharaia elegans group</i>	3A Spine A2	<i>Xiangxiella bicostata</i>	<i>Stellapollenites thiergartii</i>			
					<i>Parafrechites meeki</i>	<i>Hungarites</i>								
					<i>Gymnoceras rotelliformis</i>	<i>Paraceratites</i>								
					<i>Gymnoceras mimetus</i>									
				Pelionian	<i>Gymnoceras weitschati</i>	<i>Balatonites</i>	<i>Balatonites</i>					<i>Neogondolella regalis</i>	<i>Triassocampe deweveri</i>	<i>Diaplexa tiganensis</i>
				Brennian	<i>Acrochordiceras hyatti</i>	<i>Paracrochordiceras</i>	<i>Paracrochordiceras</i>					<i>Neogondolella regalis</i>	<i>Triassocampe coronata group</i>	<i>Euestheria albertii albertii</i>
Aegean	<i>Lenotropites caurus</i>	<i>Paracrochordiceras</i>	<i>Paracrochordiceras</i>	<i>Neogondolella regalis</i>	<i>Eptingium nakasekoi group</i>	<i>Euestheria albertii mahlerselli-P. alsatica alsatica</i>								
							<i>Silberingites mulleri</i>							
247		Anisian		<i>Pseudokyeserlingites guexi</i>	<i>Japonites welleri</i>	<i>Chiosella timorensis</i>	<i>Eptingium nakasekoi group</i>	<i>Euestheria albertii mahlerselli-P. alsatica alsatica</i>	<i>Stellapollenites thiergartii</i>					

Fig. 5. Middle Triassic timescale.

Ma	Stage/ Substage	Ammonoid zones		Conodonts (North America)	Radiolarians (Japan)	Conchostracans (Germanic basin)	Palynomorphs (Germanic basin)	Tetrapod LVFs			
		American Cordillera	Tethyan								
201	Rhaetian	Choristoceras <i>crickmayi</i>	Choristoceras <i>marshi</i>	<i>Norigondolella</i> sp.	<i>Haeckelicyrtium</i> <i>breviora</i>	<i>Euestheria</i> <i>brodieana</i>	<i>Rhaetipollis</i> <i>germanicus</i>	Apachean			
			Vandates <i>stuerzenbaumi</i>	<i>Miskella</i> <i>posthernsteini</i>							
		Paracochloceras <i>amoenum</i>	<i>Sagenites</i> <i>reticulatus</i>	<i>Cypridodella</i> <i>mosheri</i>	Skirt F	<i>Gregoriusella</i> <i>polonica</i>					
	Norian	Sevastian	<i>Gnomohalorites</i> <i>cordilleranus</i>	<i>Sagenites</i> <i>quinque-</i> <i>punctatus</i>	<i>Cypridodella</i> <i>bidentata</i>	<i>Praemesosatumalis</i> <i>pseudokahleri</i>	<i>Shipingia</i> <i>olseni</i> <i>Redondestheria</i> <i>grovetonensis</i>	<i>Granuloperculatipollis</i> <i>rudis</i>	Revueltian		
										Alaunian	<i>Mesohimavallites</i> <i>columbianus</i>
		<i>Cypridodella</i> <i>postera</i>	<i>Lysemelas</i> <i>olbia</i>	<i>Noriestheria</i> <i>barnaschi-</i> <i>Shipingia</i> <i>mcdonaldi</i>							
		<i>Cypridodella</i> <i>spiculata</i>			<i>Trialatus</i> <i>robustus-</i> <i>Lysemelas</i> <i>olbia</i>	small <i>Shipingia</i> and large <i>Euestheria</i>					
		Lacian	<i>Drepanites</i> <i>rutherfordi</i>	<i>Cyrtopleurites</i> <i>bicrenatus</i>			<i>Cypridodella</i> <i>multidentata</i>			<i>Capnodoce-Trialatus</i>	<i>Euestheria</i> <i>buravasi-</i> <i>Euestheria</i> n. sp. <i>Palaeolimnadia</i> <i>schwanbergensis</i>
					<i>Juvavites</i> <i>magnus</i>	<i>Juvavites</i> <i>magnus</i>					
		<i>Malayites</i> <i>dawsoni</i>	<i>Malayites</i> <i>pauciei</i>	<i>Epigondolella</i> <i>quadrata</i>							
		Carnian	Tuvallian		<i>Klamathites</i> <i>macrolobatus</i>	<i>Arotropites</i> <i>sponosus</i>	<i>Metapolygnathus</i> <i>primitus</i>			<i>Poulpus</i> <i>carcharus</i>	<i>Laxitextella</i> <i>freybergi-</i> <i>P. schwanbergensis</i> <i>Laxitextella</i> <i>freybergi</i> <i>Laxitextella</i> <i>seegisi</i>
				<i>Tropites</i> <i>welleri</i>							
					<i>Tropites</i> <i>dilleri</i>	<i>Tropites</i> <i>dilleri</i>	<i>Metapolygnathus</i> <i>polygnathiformis</i>				
	Julian			<i>Sirenites</i> <i>nanseni</i> <i>Austrotrachyceras</i> <i>obesum</i>				<i>Austrotrachyceras</i> <i>austriacum</i>	<i>Metapolygnathus</i> <i>tadpole</i>		
			<i>Trachyceras</i> <i>desalfoyense</i>		<i>Trachyceras</i> <i>anoisoides</i> <i>Trachyceras</i> <i>aon</i>						
				<i>Daxalina</i> <i>canadensis</i>		<i>Daxalina</i> <i>canadensis</i>	<i>Metapolygnathus</i> <i>intermedius</i>	<i>Spongoserrula</i> <i>dehli</i>		<i>Gregoriusella</i> <i>fimbriata-</i> <i>Laxitextella</i> <i>laxitexta</i> <i>Laxitextella</i> <i>multireticulata</i>	

Fig. 6. Late Triassic timescale.

that demonstrates the facies dependence of megafossil plants is provided by Ash (1980), who considered the Santa Clara flora of Sonora, Mexico to be Rhaeto–Liassic, whereas intercalated marine invertebrates clearly indicate it is of Carnian age (Alencaster de Cserna 1961).

At a broader scale, Dobruskina (1994) reviewed the Triassic megafossil plants of Eurasia, comparing them to the global record. She recognized at least three floral provinces ('phytochoria') during the Triassic–Siberian, European–Sinian and Gondwanan provinces. At the scale of her review, three temporally successive global floral zones can be recognized: Induan–Anisian, Ladinian–Carnian and Norian–Rhaetian.

Ostracods are bivalved crustaceans having calcareous shells. Most nonmarine Triassic ostracods

are darwinulaceans: simple, bean-shaped and unornamented. Although they have provided the basis for some Triassic biostratigraphy (e.g. Pang 1993), their taxonomy strikes me as unreliable: there are not enough morphological characters preserved to reliably recognize species. Nevertheless, some other nonmarine Triassic ostracods, such as *Lutkevichinella*, do have ornamentation and may be more readily separated into reliable species of use to Triassic ostracod biostratigraphy.

Nonmarine bivalves have a diverse record in Triassic strata but they have not been studied on a global basis. Like charophytes and ostracods, ecophenotypic variation is a problem for Triassic nonmarine bivalve taxonomy. A recent example of a nonmarine Triassic bivalve biostratigraphy stems from a revision of the extensive unionid bivalve

record of the Upper Triassic Chinle Group in the western USA by Good (1998). He recognized two zones applicable within the Chinle basin (tetrapods define at least four zones in the Chinle), but the broader correlation of these zones is undemonstrated.

A robust nonmarine biostratigraphy based on Triassic fishes does not exist and probably never will because nonmarine fishes are typically very limited in their distribution by particular lithofacies, so that their record is facies controlled and characterized by endemism. Regional biostratigraphy has been proposed for some nonmarine Triassic fish successions, such as in the Upper Triassic strata of North America: Chinle Group and Newark Supergroup. But, correlation within and between these successions is imprecise at best (Olsen *et al.* 1982; Huber *et al.* 1993; Milner *et al.* 2006).

A Triassic timescale

The Triassic timescale presented here (Figs 4–6) is based primarily on data in the chapters in this book. The numerical ages are from Mundil *et al.* 2010, and are only placed at the stage boundaries with precise numerical age control. Thus, no numerical ages are assigned to the bases of the Carnian, Norian or Rhaetian stages. The magnetostratigraphy is from Hounslow & Muttoni 2010, but has been simplified by eliminating less reliable magnetozones. The ammonoid zones follow Balini *et al.* (2010), the conodont zones are from Kozur (2003) and Orchard (2010), and the radiolarian zones for Japan (the most complete and broadly applicable Triassic zonation) are from O’Dogherty *et al.* (2010). Conchostracan zonation is that of Kozur & Weems (2010), the palynomorphs are the Germanic basin zonation of Kuerschner & Herngreen (2010), and the land–vertebrate faunachrons are from Lucas (2010*b*).

Some imprecision and uncertainty exists in the correlation of some of the biostratigraphic zonations to each other. Thus, the ammonoid and conodont zonations are fairly precisely matched to each other, but the match to the radiolarian zonation is much less precise (see O’Dogherty *et al.* 2010). The conchostracan, palynomorph and tetrapod biozonations are readily matched to each other, but are less precisely correlated to the marine biostratigraphy. The absence of horizontal lines between some of the zonal indicators, especially in the radiolarian and the conchostracan zonations, reflects this imprecision.

The Early Triassic (Fig. 4) and the Middle Triassic (Fig. 5) timescales are essentially scaled vertically to the radioisotopic ages. However, the Late Triassic (Fig. 6) is not. Here, I reject the ‘long Norian’ of Muttoni *et al.* (2004), which

places the Norian base at *c.* 228 Ma. Instead, I follow arguments articulated by Kozur & Weems (2005, 2007, 2010) and Lucas (2010*b*) that the nonmarine biostratigraphy confirms a Norian base near the base of the Passaic Formation of the Newark Supergroup (eastern North America). This, coupled with an age of *c.* 219 Ma in Chinle Group (American SW) upper Carnian strata, places the Carnian–Norian boundary close to the 217 Ma estimated by Olsen & Kent (1999) from the Newark cyclostratigraphy. Nevertheless, such a conclusion creates a very long Tuvanian, at least 10 million years long, because of the *c.* 230 Ma age reported by Furin *et al.* (2006) from lower Tuvanian marine strata in Sicily. Clearly, there are problems reconciling the radioisotopic age data, magnetostratigraphy and biostratigraphy across the Carnian–Norian boundary. These problems, and similar issues, make any Triassic timescale, such as the one presented here, a work in progress that will continue to be modified and refined in the light of new data.

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