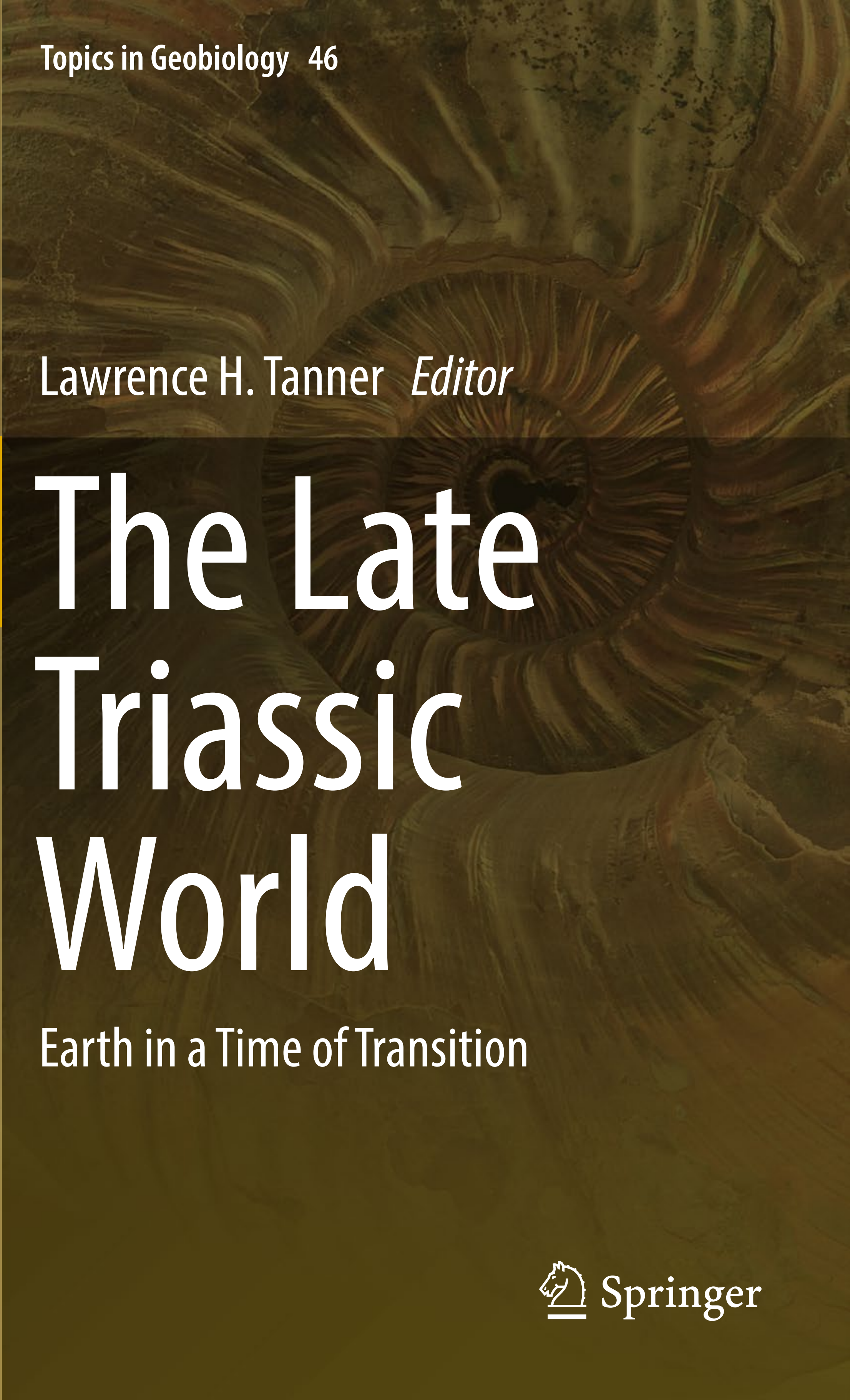

Topics in Geobiology 46

Lawrence H. Tanner *Editor*

The Late Triassic World

Earth in a Time of Transition

Springer

Topics in Geobiology

Volume 46

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Metabactrites fuchsi De Baets et al. 2013, PWL2010/5251-LSmiddle Kaub Formation, Bundenbach (Hunsrück, Germany). This is one of the most plesiomorphic and oldest ammonoids known. Image by courtesy of Markus Poschmann (Mainz, GDKE).

Lawrence H. Tanner
Editor

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Preface

This volume grew out of a personal interest in the Late Triassic, an interest that was nurtured by the realization early in my career that this roughly 30 million-year interval is unique in Earth's history. The Late Triassic saw the origination of dinosaurs and pterosaurs, but the near simultaneous decline of many other archosaur groups; it witnessed the spread of reptiles in the oceans and on land, the first appearance of mammals. All of this was against a backdrop of climate, tectonics, bolide impacts, and the eruptions of one of the largest of the Large Igneous Provinces, all of which made for an Earth far different from today's world.

This collection of peer-reviewed papers, from researchers distinguished for their work on this time period, presents both reviews and compilations of the latest studies, as well as fresh ideas and new data. Everyone, professionals and students, whose work or interests intersect the Late Triassic will find this collection an essential addition to their library.

The volume begins with an overview of the Earth on which the biologic events played out, starting with a review by Spencer Lucas of the timescale of the Late Triassic, including the certainties and uncertainties of the stage boundaries. Next, Jan Golonka and colleagues provide a global overview of the tectonic activity of the period. The climate of this time, what we know, or suspect, and how we know it, is reviewed by Lawrence Tanner. Andrea Marzoli and colleagues provide a thorough description of the largest volcanic event of the entire early Mesozoic, the eruption of the Central Atlantic magmatic province. More than one bolide impact occurred during the Late Triassic, and the evidence for these, and their consequences, is discussed by Michael Clutson and colleagues.

The next section of the volume is dedicated to the marine environment. Much Triassic biostratigraphy depends on conodonts, and Manuel Rigo and colleagues propose a new Upper Triassic biozonation. Similarly, ammonoids are an essential tool of biostratigraphers, and Spencer Lucas reviews their biostratigraphy and key biotic events. The radiation of the marine reptiles during the Late Triassic is reviewed by Renesto and Dalla Vecchia. Finally, Tintori and Lombardo examine the diversification of actinopterygian fish through the lens of the superbly preserved fossil deposits in the Zorzino Limestone.

The final portion of this collection is centered on the land environment. Spencer Lucas provides a review of terrestrial tetrapods, with attention to their biostratigraphy and key biotic events. The cynodonts and their evolutionary transition to mammals are the focus of the chapter by Abdala and Gaetano. Next, Adrian Hunt and colleagues present a wide-ranging review of the diverse trace of fossils, both vertebrate and invertebrate, found in nonmarine strata of the Upper Triassic. The floral kingdom is not ignored here; Evelyn Kustatscher and colleagues provide a global overview of Upper Triassic floral diversity. Next, Conrad Labandeira and colleagues review the diverse Molteno flora in the course of describing the record of plant-arthropod interactions of this time. To conclude, Lucas and Tanner give a close eye to the biotic decline at the end of the Triassic and the putative mass extinction that marks the end of this period.

In addition to the authors, who rose quite admirably to the challenge of producing these chapters, more or less on deadline, I must thank the numerous individuals who contributed measurably to the success of this project. One of these would have to be Zachary Romano, of Springer US, who invited me to consider the project and encouraged me as I developed the concept. Spencer Lucas, my friend and colleague of many years, was a major factor in bringing this project to completion, through his chapter contributions, chapter reviews, and suggestions regarding authors and reviewers. Finally, there are the many individuals I list here who agreed to lend their time and expertise in reviewing the chapters herein: Gloria Arratia, Sid Ash, Brian Axsmith, Marion Bamford, Paula Dentzian-Dias, Ezat Heydari, Mark Hounslow, Adrian Hunt, Jim Jenks, Julien Kimmig, Tea Kolar-Jurkovšek, Karl Krainer, Evelyn Kustatscher, Spencer Lucas, Michael Orchard, Rose Prevec, John Puffer, Manuel Rigo, Martin Sanders, Martin Schmieder, Hans Sues, Valery Vernikovsky, and Robert Weems.

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Chapter 1
The Late Triassic Timescale

Spencer G. Lucas

Abstract The Upper Triassic chronostratigraphic scale consists of one Series, the Upper Triassic, divided into three stages (in ascending order)—Carnian, Norian and Rhaetian. Only the base of the Carnian currently has an agreed on GSSP (global boundary stratotype section and point), though agreement on GSSPs for the bases of the Norian and Rhaetian is imminent. Substages of the Carnian and Norian provide more detailed subdivisions of Late Triassic time than do the relatively long Carnian and Norian stages. These substages need boundary definitions and greater use in Late Triassic correlations. Numerical chronology of the Late Triassic is based on very few radioisotopic ages from volcanic ash beds directly related to marine biostratigraphy. The numerical calibration of the Late Triassic favored here is Carnian ~220–237 Ma, Norian ~205–220 Ma and Rhaetian ~201–205 Ma. Late Triassic magnetostratigraphy is fraught with problems because the most complete record from the Newark Supergroup of eastern North America cannot be correlated based on pattern matching to any co-eval magnetostratigraphy from a marine section. The long Norian (beginning at ~228 Ma) was created by magnetostratigraphic correlations that abandoned biostratigraphic constraints and has produced extensive miscorrelation, particularly of nonmarine Carnian strata. A reliable Late Triassic magnetostratigraphy is a succession of multichrons that identifies the Carnian-early Norian and late Norian-Rhaetian as dominantly of normal polarity. Late Triassic cyclostratigraphy of the Newark Supergroup has been advanced as a floating astrochronology of the Late Triassic, but is problematic given evident hiatuses in the Newark record and the presence of non-cyclical lithofacies. Isotope stratigraphy of the Late Triassic, for example the late Rhaetian carbon-isotope excursion, has great potential for use in Late Triassic correlations. The Late Triassic timescale is still very much a work in progress that needs more precise chronostratigraphic definitions, additional numerical ages directly related to marine biostratigraphy, a wholesale rethinking of magnetostratigraphic correlations and additional cyclostratigraphic and isotopic data to achieve greater precision and stability.

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1.1 Introduction

The Late Triassic was a major juncture in Earth history when the vast Pangean supercontinent began its fragmentation, and numerous biotic groups first evolved or suffered extinction on land and in the sea (e.g., Lucas 1999; Lucas and Orchard 2004; Sues and Fraser 2010). The temporal ordering of geological and biotic events during Late Triassic time thus is critical to the interpretation of some unique and pivotal events in Earth history. This temporal ordering is based on the Late Triassic chronostratigraphic scale integrated with numerical ages and other geochronologic tools, notably magnetostratigraphy, cyclostratigraphy and isotope stratigraphy. Here, I review the Late Triassic timescale to highlight ongoing issues and to present its current status.

1.2 Some History

Recognition of a distinctive interval in Earth history (originally identified as a distinct succession of stratified rocks) that corresponds to the current concept of Triassic began in Germany more than 200 years ago. Alberti's (1834) monograph in which he coined the term Trias culminated this early work. The 200-year-long history of the development of a Triassic relative timescale (the standard global chronostratigraphic scale) has been reviewed by Zittel (1901), Silberling and Tozer (1968), Tozer (1984) and Lucas (2010).

Alberti's type Triassic in southwestern Germany (Fig. 1.1) is a sandwich of dominantly nonmarine red beds (Buntsandstein and Keuper) with a restricted marine middle portion (Muschelkalk). Already in the nineteenth century, the recognition of Muschelkalk-equivalent marine strata, based largely on their content of ceratites (ammonoids), became key to recognition of the Trias outside of Germany.

The Alps contain a relatively complete section of Triassic marine strata, so extension of the Triassic into the Alpine marine strata became central to further subdivision and correlation of Triassic time. This subdivision owes more to Austrian geologist Edmund von Mojsisovics (1839–1907) than to any other geologist. Recognition of subdivisions of Triassic time based on ammonoids by Mojsisovics and his collaborators produced most of the stage-level terminology of Triassic time still used today.

This work was culminated by Mojsisovics et al. (1895), the singlemost important article written on the Triassic timescale. It coined the names of most of the marine stages and sub-stages recognized today. This timescale was refined subsequently,

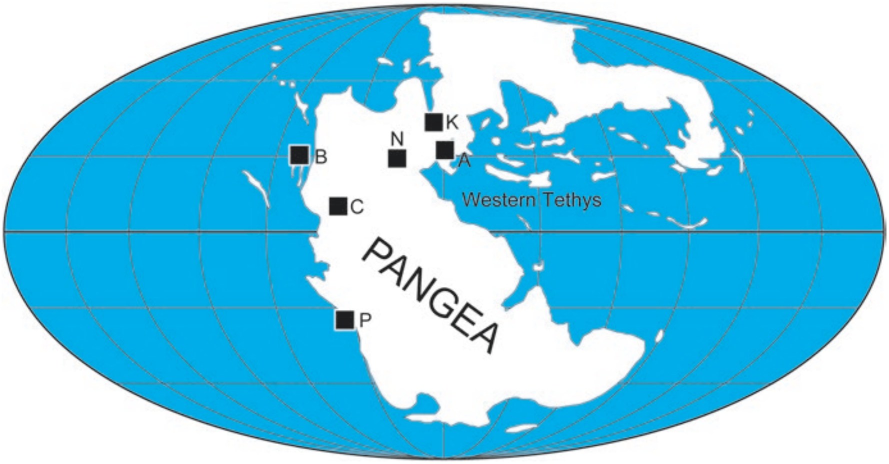
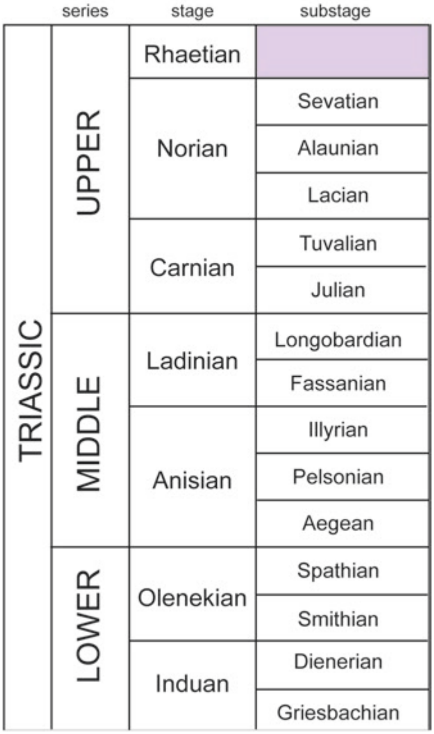


Fig. 1.1 The Triassic world with locations of some key sections and outcrop areas discussed in the text. *A* Southern Alps/central Europe (mainly Austria and northern Italy, see Fig. 1.3), *B* British Columbia, Canada; *C* Chinle basin, western USA, *K* Keuper, Germanic basin, northern Europe (principally Germany), *N* Newark basin, NJ, Pennsylvania, USA; *P* Peru

especially by the addition of Bittner's (1892) Ladinian, but remained the basic Triassic timescale until at least the 1960s.

Beginning in the 1960s, Canadian paleontologist E. Timothy Tozer (1928–2010), in part collaborating with American geologist Norman J. Silberling (1928–2011), assembled a Triassic timescale based on North American ammonoid zones (e.g., Silberling and Tozer 1968; Tozer 1971, 1974, 1984, 1994). Key components of Tozer's Triassic timescale were that it defined Triassic stage boundaries based on North American ammonoid localities and it rejected the Rhaetian as a distinctive stage. During the 1970s and 1980s, Tozer's timescale found wide acceptance in the English language literature on the subdivision of Triassic time, though few abandoned the Rhaetian (e.g., Kummel 1979; Harland et al. 1982, 1990).

Conceived in 1968, and beginning its meetings in the 1970s (Tozer 1985), the Subcommission on Triassic Stratigraphy (STS), as part of the International Commission on Stratigraphy (ICS), was primarily charged to establish a global Triassic timescale based on GSSP (global stratotype section and point) definitions of the bases of the Triassic stages (e.g., Gaetani 1996). The STS began its published discussion (in the STS journal *Albertiana*) with a lively debate over the Tozer timescale—particularly over whether or not to recognize the Rhaetian as a separate stage, which Tozer had regarded as a substage of the Norian. After initial acceptance in 1984 of most aspects of the Tozer timescale, in 1991, the STS agreed on a stage nomenclature of the Triassic that included the Rhaetian as a separate stage (Fig. 1.2). To date, GSSPs in the Upper Triassic have been defined only for the bases of the Carnian (base of Upper Triassic Series) and the Hettangian (base of the Jurassic System) (Fig. 1.2).



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

Fig. 1.2 The Triassic chronostratigraphic scale (after Lucas 2010)

1.3 Upper Triassic Chronostratigraphy

1.3.1 Upper Triassic Series

The most significant thing we have learned about the Triassic timescale from numerical chronology is that the three traditional Triassic series are of very uneven duration. The traditional Early Triassic is about 5 million years long, the traditional Middle Triassic is about 10 million years long and the rest of the Triassic (the traditional Late Triassic) is about 36 million years long (Mundil et al. 2010; Ogg 2012; Ogg et al. 2014). Thus, by numerical chronology, the Early and Middle Triassic together make up only about the first third of the period.

Therefore, Lucas (2013) advocated recognizing four Triassic series (epochs) of more even duration. Note that Mojsisovics et al. (1895) also divided the Triassic into four series similar to (but not exactly congruent with) those recognized by Lucas (2013). The four Triassic series that Lucas (2013) proposed are the (ascending order) Scythian, Dinarian, Carnian and Norian. The first two names are from Mojsisovics et al. (1895), and the last two are elevation of the very long Carnian and Norian stages to series rank. However, the traditional and agreed on single Upper Triassic Series and three stages—Carnian, Norian and Rhaetian—are used here (Fig. 1.2).

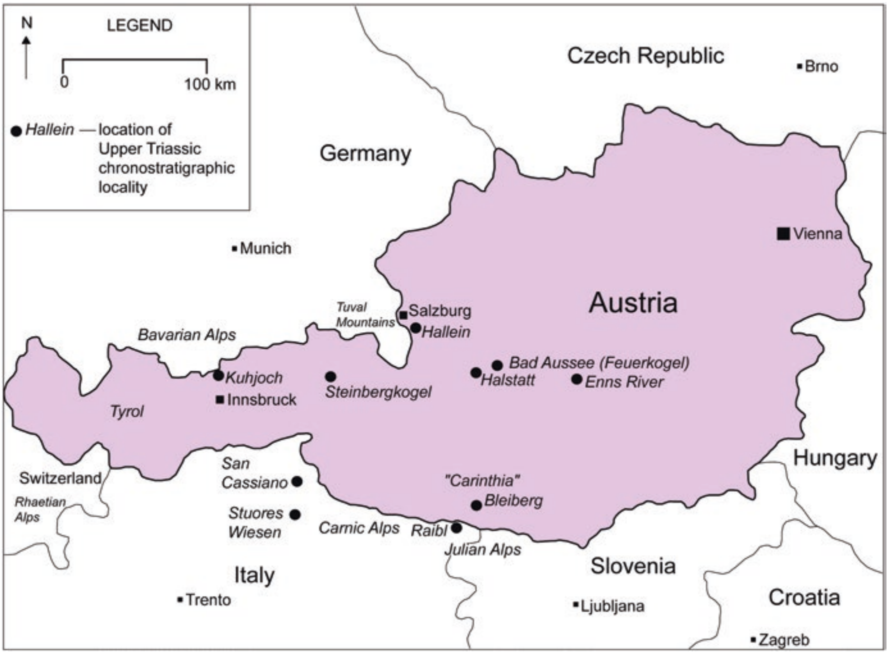


Fig. 1.3 Map of Austria and adjacent areas showing localities important to Upper Triassic chronostratigraphy that are discussed in the text

Marine sections critical to definition of Upper Triassic chronostratigraphic subdivisions are primarily those in the Alps of central and southern Europe (Figs. 1.1 and 1.3).

1.3.2 Carnian Stage

Mojsisovics (1869: 127) introduced the term Carnian Stage for ammonoid-bearing strata in the Austrian state of Kärnten (Carinthia). He initially and erroneously regarded it as younger than the Norian. Mojsisovics (1874) assigned three ammonoid zones to the Carnian (ascending order): *Trachyceras aon, Trachyceras aonoides* and *Tropites subbullatus* zones. Later, Mojsisovics (in Mojsisovics et al. 1895) divided it into three substages (ascending order): Cordevolic (=Aon zone), Julic (=Aonoides Zone) and Tuvalic (= Subbullatus Zone).

Tozer (1984) regarded the type locality of the Carnian as vague, as it was stated to refer to the *Trachyceras* and *Tropites* beds of the Hallstatt Limestone, but also included localities at Raibl, Bleiberg and San Cassiano (Fig. 1.3). Lieberman (1980) proposed the Raibl section as the stratotype of the stage. Tozer (1984) and some others have spelled the name "Karnian," but this spelling has not been widely adopted.

Today, the Carnian Stage is typically divided into two substages named by Mojsisovics (in Mojsisovics et al. 1895)—Julian (lower) and Tuvalian (upper). However, Mojsisovics (in Mojsisovics et al. 1895) also recognized a third (lowermost) Carnian substage, the Cordevolian, still used by some workers. Based on the St. Cassian Beds, Cordevolian derives its name from the Cordevol people who lived in the type area in northern Italy (Mojsisovics et al. 1895: 1298). Krystyn (1978) discussed the original definition of the Cordevolian and argued that it essentially referred to the same time interval as the Julian (also see Tozer 1967, 1974).

The Julian was based on the Raibl Formation in the Julian Alps (southern Alps) by Mojsisovics (in Mojsisovics et al. 1895: 1298), and has come to be viewed by most workers as the lower Carnian (cf. Krystyn 1980; Tozer 1984, 1994; Lucas 2010) (Fig. 1.2). Mojsisovics (in Mojsisovics et al. 1895: 298) took the name Tuvalian from the Tuval Mountains (Bavaria-Austria), which was the Roman name for the area between Hallein and Berchtesgarden in Austria-Germany. He based it on the *Tropites subbullatus* ammonoid zone. Krystyn and Schlager (1971) suggested using the section at Feuerkogel near Aussee, Austria, as the Tuvalian stratotype as well as the place to define the base of the Norian, in large part because the original ammonoids of Mojsisovic's stratotype Tuvalian came from syntectonic fissure fills at Rappolstein. The term Tuvalian has come to be used by most workers to refer to the entire upper Carnian (e.g., Krystyn and Schlager 1971; Tozer 1984, 1994; Lucas 2010) (Fig. 1.2).

A GSSP for the base of the Carnian Stage (= base of the Upper Triassic) has been agreed on (Gaetani 2009). It is the LO (lowest occurrence) of the ammonoid *Daxatina canadensis* (Whiteaves) at the Parti di Stuores/Stuores Wiesen section in northern Italy (Mietto et al. 2007a, b, 2012; Jenks et al. 2015) (Fig. 1.3).

With regard to ammonoid bioevents (Balini et al. 2010; Jenks et al. 2015; Lucas 2017 this volume), the Julian is dominated by Trachyceratinae, in particular *Trachyceras* and *Austrotrachyceras*, and by Sirenitinae. The base of the Tuvalian is marked by one of the major changes in the evolution of Triassic ammonoids, namely the near extinction of the Trachyceratinae, whose only survivor in the late Carnian is *Trachysagenites*, as well as the radiation of Tropitidae (e.g., *Tropites* and closely allied forms) and to a lesser extent Arpaditinae. Among the conodonts, the development of *Metapolygnathus* from *Paragondolella* and the diversification of *Mesogondolella* species marks the base of the Carnian (Orchard 2010).

1.3.3 Norian Stage

Mojsisovics (1869: 127) named the Norian Stage for the Roman province of Noria, which was south of the Danube and included what is now the area of Hallstatt, Austria. He based the stage on the Hallstatt Limestone of the Salzkammergut in Austria, strata containing "*Ammonites" (Pinacoceras) metternichi* Mojsisovics (Tozer 1984). Mojsisovics originally thought the Norian was between the "Alpine Muschelkalk" and the Carnian. When that mistake was discovered, Mojsisovics (1892) moved the term Norian to refer to pre-Carnian Hallstatt strata and named the Juvavian Stage, which is now regarded as synonymous with the Norian. This caused an acrinomius debate with fellow Austrian geologist Bittner (1892), who argued to retain Norian as originally defined and proposed Ladinian to refer to the time interval before the Carnian (Zittel 1901: 494–497; Tozer 1984). Adding further to the confusion, Mojsisovics also provided no type section for the Juvavian, but instead referred to a succession of ammonoid zones (Mojsisovics 1902), a succession critiqued by Kittl (1903) and Diener (1921, 1926).

The stratotype of the Norian has been considered to be the Bicrenatus Lager at Sommeraukogel, Hallstatt (Zapfe 1971; Krystyn and Schlager 1971; Krystyn et al. 1971) (Fig. 1.3). The Norian is generally divided into three substages: Lacian (early), Alaunian (middle) and Sevatian (upper).

Mojsisovics (in Mojsisovics et al. 1895: 1298) used the term Lacian to refer to the "lower Juvavian." He took the name from the Roman name Lacia, which referred to the Salzkammergut area in Austria, and based it on the *Cladiscites ruber* and *Sagenites giebeli* ammonoid zones of the Hallstatt Limestone. As Tozer (1974) stressed, technically the Lacian was based on upper Norian ammonoids, so it is not a designation for the lower Norian, as it is now recognized. However, this technicality has been largely ignored, and Lacian is frequently used to refer to the lower Norian substage (Fig. 1.2).

Mojsisovics (in Mojsisovics et al. 1895: 1298) named the Alaunian substage for the Alauns, a people who lived around the Hallein, Austria area during Roman times. He based it on what is now the *Cyrtopleurites bicrenatus* ammonoid zone, and it is well accepted as the name of the middle Norian substage.

Mojsisovics (in Mojsisovics et al. 1895: 1298) named the Sevatian substage for a Celtic people who lived between the Inn and Enns Rivers in Austria. It was based on the *Pinacoceras metternichi* and *Sirenites argonautae* ammonoid zones in the Hallstatt area. The term is used by many workers to refer to the upper Norian, though Tozer (1974, 1984), who did not recognize the Rhaetian, did not use it. Problems with the Sevatian have largely been associated with defining a Rhaetian base.

The base of the Norian Stage will likely be defined by a GSSP located either at Black Bear Ridge in British Columbia, Canada or at Pizzo Mondello in Sicily (Fig. 1.1), 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 (Orchard 2010, 2013, 2014). Both candidate sections have relatively poor ammonoid records but good conodont records. However, the choice of a conodont-based GSSP for the Norian base has been delayed for years by changing stratigraphic ranges and the fluid taxonomy of the relevant conodonts (e.g., Mazza et al. 2010, 2011, 2012; Orchard 2010, 2013, 2014).

The base of the Norian and of the Lacian is characterized by major ammonoid biochronological events (Balini et al. 2010; Jenks et al. 2015; Lucas 2017, this volume): the nearly complete disappearance of Tropitidae and the appearance of new members of Juvavitinae, such as *Guembelites* and *Dimorphites*, and of the Thisbitidae, such as *Stikinoceras*. The base of the Alaunian is marked by the appearance of new genera of Cyrtopleuritidae (*Drepanites* and *Cyrtopleurites*). Members of this family (including *Himavatites*, *Mesohimavatites*, *Neohimavatites*), together with some Haloritinae, such as *Halorites,* and Thisbitidae, such as *Phormedites*, characterize the Alaunian. The base of the Sevatian is characterized by a decrease in ammonoid diversity and the first heteromorphic ammonoid, *Rhabdoceras*. Common Sevatian ammonoids are Haloritinae (*Gnomohalorites* and *Catenohalorites*) and Sagenitidae (*Sagenites* ex gr. *S. quinquepunctatus* Mojsisovics).

Among conodonts, there is a turnover in *Metapolygnathus* species that has been used to mark the base of the Norian (Orchard 2010).

1.3.4 Rhaetian Stage

Gümbel (1859, 1861: 116) used the term “Rhätische Gebilde” to refer to the uppermost Triassic strata (Kössen beds) in the Bavarian Alps. The name was either for the Roman province of Rhaetium or the rätische Alpen. No type locality was specified, but Gümbel did refer to the “Schichten der *Rhaetavicula contorta*” (beds with the bivalve *R. contorta*). Thus, to Mojsisovics et al. (1895), the Rhaetian was the “Zone der *Avicula contorta*.”

Lengthy debate about the Rhaetian (e.g., Pearson 1970; Ager 1987; also see above) has focused on three issues: (1) whether or not the stage should be assigned to the Jurassic; (2) whether or not the stage should be recognized or just subsumed into the Norian; and (3) how to define the Rhaetian base.

The Subcommission on Triassic Stratigraphy now recognizes a distinct Rhaetian, which is the youngest Triassic stage (Fig. 1.2). The currently favored definition of the Rhaetian base is the FAD (first appearance datum) of the conodont *Misikella posthersteini* (Krystyn 2010).

In about 2007, the proposed definition of a GSSP for the base of the Rhaetian was at the classic Steinbergkogel section near Hallstatt in Austria based on the FAD (first appearance datum) of the conodont *Misikella posthernsteini* (Krystyn et al. 2007a, b). The favored definition of the Rhaetian base has as its primary signal the FAD of the conodont *Misikella posthernsteini*. This produces a so-called “long” Rhaetian composed of two or three ammonoid zones. The youngest substage of the Norian, the Sevatian, is thereby reduced to one ammonoid zone. However, after 2007, the formal proposal to ratify the base Rhaetian GSSP at Steinbergkogel never went to the International Commisssion on Stratigraphy.

Some would say that was a fortunate delay, as Giordano et al. (2010) and Rigo et al. (2016) concluded that the LO (lowest occurrence) of *Misikella posthernsteini* is actually younger at Steinbergkogel than it is in the section they studied in the Lagonegro basin in northern Italy, though the taxonomy of *M. posthernsteini* may also be an issue. Thus, the LO of *M. posthernsteini* at Steinbergkogel is not the FAD (first appearance datum) of the species. Currently, the Pignola section in the Lagonegro basin is also proposed as the GSSP location for the base of the Rhaetian (Giordano et al. 2010; Rigo et al. 2016; Bertinelli et al. 2016; Casacci et al. 2016).

The appearance of the heteromorphy ammonoids *Cochloceras* and *Paracochloceras* marks the Rhaetian base among ammonoid bioevents (Balini et al. 2010; Jenks et al. 2015; Lucas 2017 this volume). A substantial drop in diversity of conodonts characterizes the Rhaetian, and the appearances of *Epigondolella mosheri* and *Misikella posthersteini*, though not co-eval, approximately mark its base (Orchard 2010).

The base of the Hettangian Stage (= base of the Jurassic, = base of the Lower Jurassic) is defined by the FAD of the ammonoid *Psiloceras spelae* at the Kuhjoch section in Austria (2013). This, of course, defines the top of the Rhaetian (= top of Triassic, = top of Upper Triassic).

1.3.5 Other Upper Triassic Chronostratigraphic Scales

Current stratigraphic practice seeks to recognize a single global stage for each interval of time, and each series and system base corresponds to the base of a stage. Furthermore, the definition of stages is now based on the GSSP concept and the practice of integrated stratigraphy that applies multiple data sets to the definition of chronostratigraphic units (e.g., Salvador 1994; Remane et al. 1996; Walsh et al. 2004; Smith et al. 2015). However, the provinciality of fossil taxa compounded by limitations of facies distributions (rarely is any taxon or facies global in extent) have often prevented universal recognition and use of a single chronostratigraphic terminology. Indeed, there remains great value in provincial stages, which Cope (1996) has aptly called the "secondary standard" in stratigraphy.

The Triassic has a variety of secondary standards, including that for New Zealand—(ascending) Oretian, Otamitan, Warepan and Otapirian stages encompass the Upper Triassic (e.g., Carter 1974). Here, I do not review these provincial scales, but note that their regional utility will guarantee their continued use.

1.4 Radioisotopic Ages

Ogg (2004, 2012), Mundil et al. (2010) and Ogg et al. (2014) reviewed the Late Triassic numerical timescale (Fig. 1.4). A precise and detailed numerical timescale does not yet exist for the Late Triassic because of the rarity of datable volcanic ash beds that can be correlated unambiguously to marine biostratigraphy.

The few ages that meet those criteria, and that have been published in full, are: (1) various U-Pb ages on ash beds in marine Ladinian strata that indicate the base of the Carnian is no older than 237 Ma (Mundil et al. 2010; Stockar et al. 2012; Ogg et al. 2014); (2) a U-Pb single zircon age of 230.9 ± 0.3 Ma on an ash bed in Italy within the upper Carnian (Tuvalian) *Metapolygnathus nodosus* conodont zone (Furin et al. 2006); (2) U-Pb ages of 205.70 ± 0.15 Ma and 205.30 ± 0.14 Ma on ash beds that bracket the base of the Rhaetian (picked largely on the disappearance of

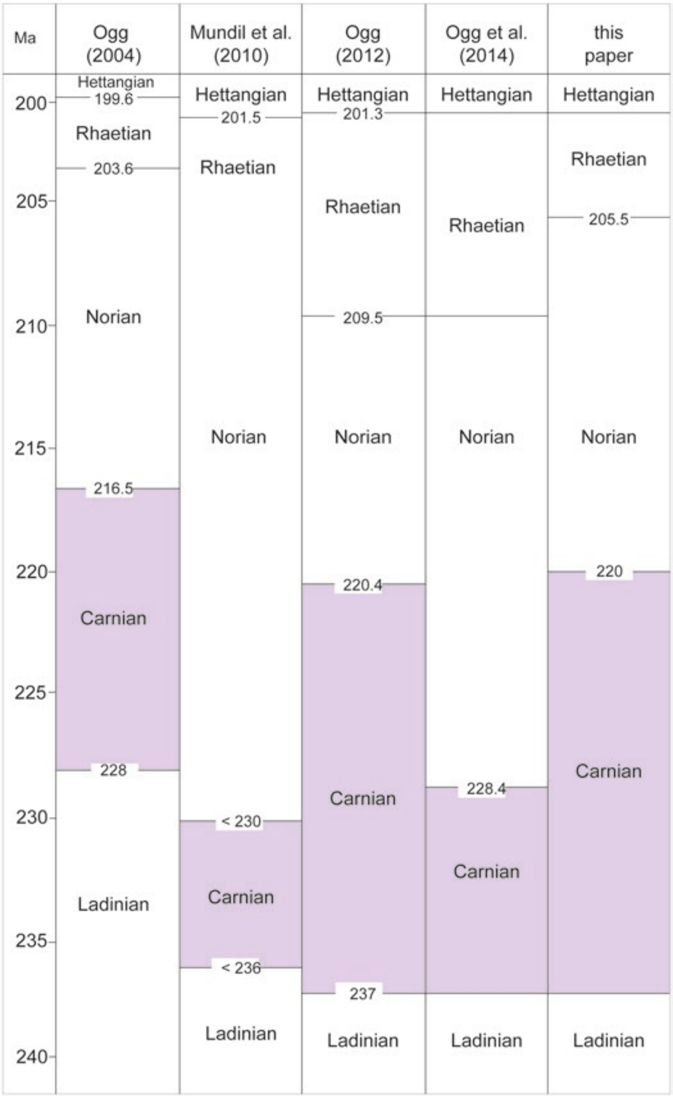


Fig. 1.4 Some Late Triassic numerical timescales of the last 20 years

the bivalve *Monotis*) in Peru (Wotzlaw et al. 2014); and (3) another ash bed in the Peruvian section that yields a U-Pb age of 201.36 ± 0.17 Ma that is just below the LO of *Psiloceras spelae*, and thus just below the base of the Jurassic (Schaltegger et al. 2008; Schoene et al. 2010; also see the detrital zircon ages of Rhaetian strata in western Canada reported by Golding et al. 2016). Most of the other numerical ages being used to calibrate the Late Triassic timescale are detrital zircon ages, which means they are from reworked zircon grains, and thus provide maximum ages of deposition at best.

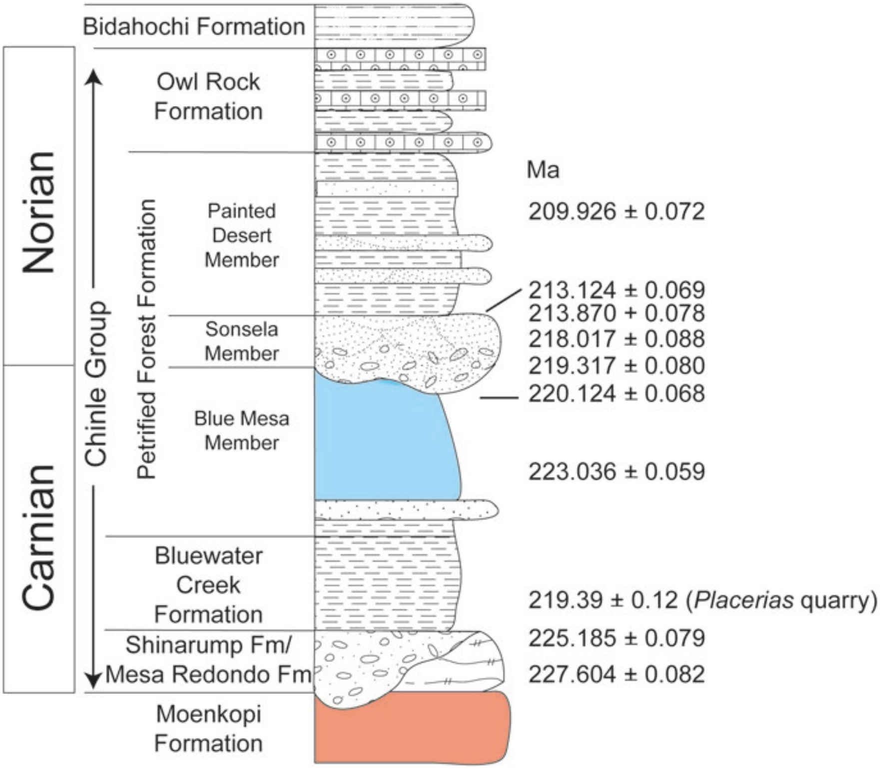


Fig. 1.5 Summary of most of the Chinle Group detrital zircon ages placed on a generalized Chinle lithostratigraphy of the Petrified Forest National Park in Arizona. Sources of numerical ages are primarily Ramezani et al. (2011, 2014). Note that stratigraphic position, supported by biostratigraphy, indicates the age of the *Placerias* quarry reported by Ramezani et al. (2014) is younger than stratigraphically higher ages

Lucas et al. (2012) reviewed these detrital zircon ages, which are mostly from the Upper Triassic Chinle Group, nonmarine fluvial strata in the American Southwest (Fig. 1.5). They also reviewed some other, non-detrital ages, such as those from the Carnian Ischigualasto Formation in Argentina (Rogers et al. 1993; Shipman 2004; Currie et al. 2009; Martínez et al. 2013; Kent et al. 2014). Using the biostratigraphy of palynomorphs, conchostracans and vertebrate fossils advocated by Lucas et al. (2012, and references therein), the lower part of the Chinle Group is Carnian, with the base of the Norian close to the base of the Sonsela Member of the Petrified Forest Formation and its correlatives. The Chinle Group detrital zircon ages (Fig. 1.5) indicate that the inferred base of the Norian (~ base of Sonsela Member) is no older than about 220–222 Ma, and the other ages reviewed by Lucas et al. (2012) are either consistent with that conclusion or are unreliable.

Since the review of Lucas et al. (2012), only a few numerical ages relevant to the age of the Norian base have become available. Thus, in an abstract, Diakow et al. (2011) reported a U-Pb age of 224.52 ± 0.22 Ma from a tuff below early middle

Norian conodonts and 223.81 ± 0.78 Ma from a tuff below early Norian conodonts. These ages suggest a Norian base older than 223 Ma, but remain to be fully documented. Indeed, given that the two ages repoported by Diakow et al. (2011) are out of order (older above younger), the reliability of these ages may be questioned.

Atchley et al. (2013) reported two detrital zircon U-Pb ages from Chinle Group strata in Arizona—227.604 ± 0.082 Ma at about the base of the Chinle Group (Carnian by the Lucas et al. 2012 correlation) and 220.124 ± 0.068 Ma from a stratigraphic level close to the Carnian-Norian boundary using the Lucas et al. (2012) correlation. These ages are concordant and consistent with Chinle Group detrital zircon ages reported by Ramezani et al. (2011) (see Ramezani et al. 2014, Fig. 2) and suggest a Norian base no older than about 220–222 Ma.

However, a U-Pb age recently reported from Chinle Group strata in eastern Arizona by Ramezani et al. (2014) is not consistent with the earlier published ages. This is an age of 219.39 ± 0.16 Ma from near the base of the Chinle Group at the *Placerias* fossil locality in Arizona. Stratigraphic position puts this age well below a series of ages in the 220–227 Ma range reported by Ramezani et al. (2011) and Atchley et al. (2013). To explain this contradiction, Ramezani et al. (2014) claim massive lateral facies changes in the lower Chinle lithosome, and even conclude that "geochronological correlation independent of conventional stratigraphic methods [lithostratigraphy, biostratigraphy] is the only viable means for deciphering the depositional history of rock similar to the Chinle Formation" (p. 995). I prefer instead to rely on a century of geologic mapping, detailed lithostratigraphic analysis and the biostratigraphy of palynomorphs, conchostracans and vertebrates (e.g., Heckert and Lucas 2002 and references cited therein, particularly Darton 1910, 1928; Cooley 1957; Stewart et al. 1972) that demonstrates that the *Placerias* quarry numerical age of Ramezani et al. (2014) is stratigraphically below many older numerical ages. The *Placerias* quarry age is thus anomalously young, possibly due to postcrystallization lead loss.

Very recently, Kohút et al. (2017) published the ages of syn-sedimentary volcanic zircons from the Carnian of Slovakia that have a concordia age of 221.2 ± 1.6 Ma. This also runs contrary to the "long Norian" having a base as old as 227–228 Ma.

In summary, numerical ages can be assigned to the Upper Triassic stage boundaries with varying degrees of precision (Fig. 1.4; also see Mundil et al. 2010; Lucas et al. 2012; Ogg et al. 2014). However, more numbers on primary ash fall deposits that can be correlated unambiguously to marine biostratigraphy are needed to resolve current uncertainties and contradictions among datasets.

1.5 Magnetostratigraphy

There is no agreed GPTS (global polarity timescale) for the Triassic, although a composite GPTS is now becoming available based on successions assembled from marine and nonmarine sections in North America, Europe, and Asia. Hounslow and Muttoni (2010) provided a comprehensive review of Triassic magnetic polarity history. I rely on this review and some more recent data and reappraisals (e.g., Lucas et al. 2011, 2012) and also emphasize the multichron concept of Lucas (2011), which recognizes intervals of dominant polarity rather than individual polarity chrons. The reason for this is that we are a long way from a well-established succession of Triassic polarity chrons that can receive numbers (or names), like those of the Late Cretaceous-Cenozoic GPTS. We do, however, at least seem to know the polarity of each of the Triassic stage boundaries and the dominant polarity of the stages with some confidence (Hounslow and Muttoni 2010).

One of the largest hindrances to developing a Triassic GPTS is the polarity record of the Newark Supergroup of eastern North America, which has confounded all attempts to correlate it to other Late Triassic magnetostratigraphic records (Fig. 1.6). The Newark Supergroup is the thick (up to 4.5 km) succession of nonmarine sedimentary and intercalated igneous rocks of Triassic and Jurassic age that filled a series of half-graben extensional basins that developed along the eastern seaboard of North America as Pangea began to fragment (e.g., Manspeizer et al. 1978; Froehlich and Olsen 1984; Manspeizer 1988; Olsen 1997; Weems et al. 2016) (Fig. 1.1). A complete Newark magnetostratigraphy, obtained from overlapping drill cores in the Newark basin of New Jersey-Pennsylvania, USA, is arguably the single most complete record of Late Triassic magnetic polarity history available (Fig. 1.6).

Given the great thickness of the Newark section (~ 4 km of section is equivalent to much of the Late Triassic), it likely captures a more complete polarity history than do the much thinner marine sections in Europe for which a magnetic polarity record is available. That, however, is the only thing to recommend the Newark magnetic polarity record, because age control of this record is highly problematic. For decades, the Triassic-Jurassic boundary was located incorrectly in the Newark, below the CAMP basalt sheets; this has only recently been corrected (Kozur and Weems 2005, 2007, 2010; Lucas and Tanner 2007; Cirilli et al. 2009; Lucas et al. 2011).

Biostratigraphic placement of the Carnian-Norian boundary in the Newark (near the base of the Passaic Formation) is one of the few tiepoints to the SGCS and is based on reinforcing correlations from palynomorphs, conchostracans and vertebrate biostratigraphy (Lucas et al. 2012). Abandonment of this boundary was based on an unsupportable correlation of magnetostratigraphy in the marine section at Pizzo Mondello in Italy with the Newark and, coupled with a supposed astronomically-calibrated timescale based on Newark cyclostratigaphy, created the proposal that the Carnian-Norian boundary is at about 228 Ma, the so-called “long Norian” (Muttoni et al. 2004). Correct placement of the Carnian-Norian boundary in the Newark section means it and the beginning of the Jurassic are the only reliable biostratigraphic tiepoints for the Newark magnetic polarity stratigraphy. Placement of any subdivisions of the Carnian and Norian, including identification of the base of the Rhaetian, are currently impossible in the Newark section.

From its initial publication, no convincing correlation of the Newark magnetostratigraphy to broadly correlative magnetostratigraphies could be made, simply because it contains approximately 10 times the number of reversals found in correlative marine sections (Fig. 1.6). Indeed, alternative correlations of the Newark magnetostratigraphy to a GPTS for the Late Triassic based on marine sections are at

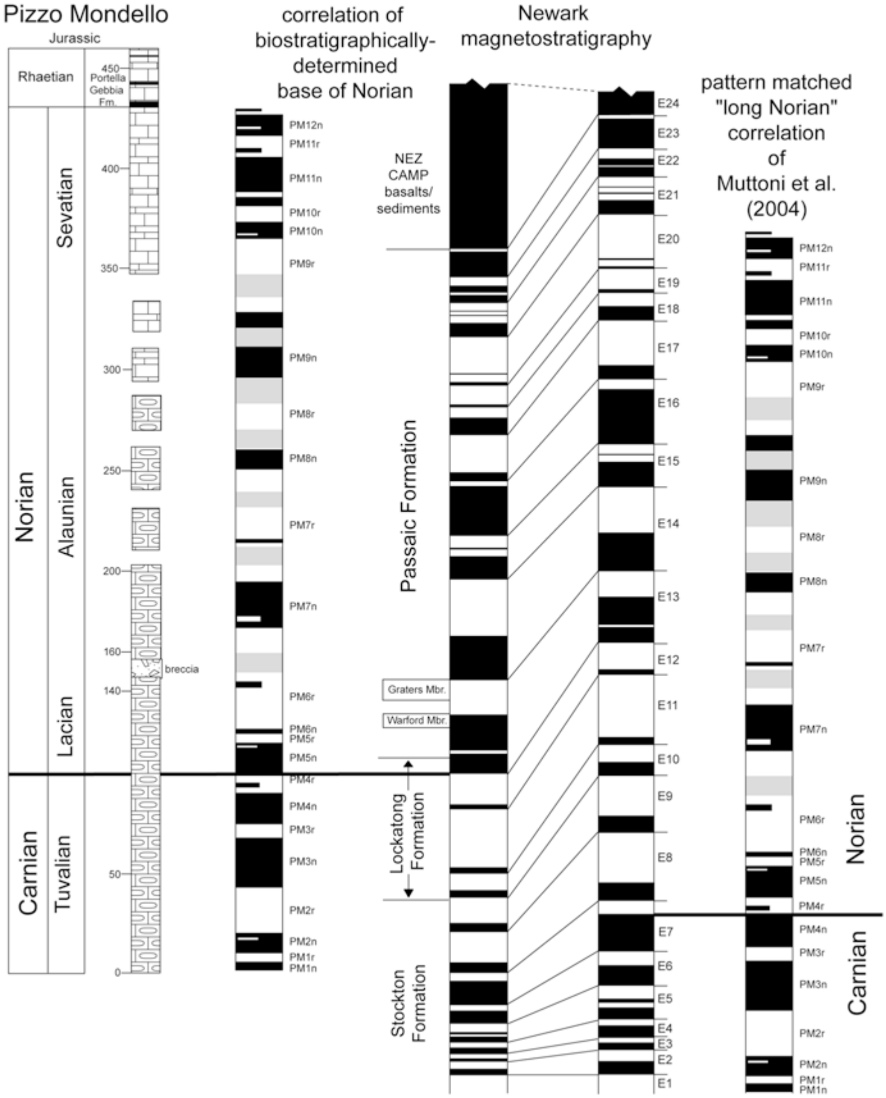


Fig. 1.6 Magnetostratigraphic correlations of the Pizzo Mondello (Sicily) and Newark (USA) sections. On the left, the correlation matches the marine and nonmarine, biostratigraphically-determined Carnian-Norian boundary. On the right is the "pattern matched" correlation of Muttoni et al. (2004), which became the basis of the "long Norian" (after Lucas et al. 2012)

best multichron matches, not detailed correlations of chrons (Hounslow and Muttoni 2010, Fig. 12). Given what I call the rubber ruler effect—sedimentation rate stretches or contracts magnetic polarity chron thicknesses so that matching patterns can be difficult—and the lack of biostratigraphic tiepoints, how could any unambiguous correlation of the Newark magnetostratigraphy be made to other polarity stratigraphies? And, why use the Newark polarity history as the standard column for the Late Triassic if nothing else can be correlated to it? Indeed, attempts to correlate the Newark polarity record to broadly co-eval records have produced a fractious literature with little agreement on what correlations are reliable. Both Hounslow and Muttoni (2010) and Ogg (2012) have presented the "Solomenesque" solution of advocating at least two correlations ("long Carnian" and "long Norian"), neither of which is defensible (Lucas et al. 2012).

More recent problems with attempting to pattern match the magnetostratigraphy of Rhaetian marine sections to the Newark section are well revealed by Muttoni et al. (2010), Hüsing et al. (2011) and Maron et al. (2015). Thus, Hüsing et al. (2011) present the magnetostratigraphy of the Rhaetian section at Steinbergkogel, Austria (it is mostly of reversed polarity) and match the Rhaetian base to the E16n chron in the Newark magnetostratigraphy. Using the astrochronology of the Newark section of Kent and Olsen (1999), they assign the Rhaetian base an age of ~211 Ma. Muttoni et al. (2010) report the magnetostratigraphy of Rhaetian marine sections in the southern Alps of northern Italy. The polarity patterns (mostly normal polarity) of these sections are very different from that reported by Hüsing et al. (2011). Muttoni et al. (2010) pattern match their results to the Newark magnetostratigraphy to correlate the Rhaetian base to the E17r-E19r interval of the Newark, which is in the range of 207–210 Ma according to the Newark astrochronology. In contrast, Maron et al. (2015) honor a Rhaetian base at ~205 Ma in their attempt to correlate the magnetostratigraphy of Rhaetian strata in the Lagonegro basin of Italy. However, there is no clear pattern match of the Newark magnetostratigraphy to the magnetostratigraphies of the Italian and Austrian sections, as is clear from Maron et al. (2015, Fig. 1.6).

The Late Triassic magnetic polarity timescale I advocate is a set of multichrons (Fig. 1.7). This is a realistic abstraction of what we now know about the Late Triassic GPTS. The obvious way forward in advancing Late Triassic magnetostratigraphy is to ignore the Newark record for the time being and improve the GPTS for the Late Triassic based on marine sections (cf. Hounslow and Muttoni 2010). This still faces the problem that if the Newark polarity record is more complete than the marine records, then the marine sections must contain substantial hiatuses. Much more needs to be understood about Late Triassic magnetic polarity history to make it an important part of Triassic correlation and timescale definition.

1.6 Cyclostratigraphy

At present, a cyclostratigraphy-based numerical timescale, called the astronomical timescale (ATS), is reasonably well-established for much of Cenozoic time. Older parts of the timescale have less complete, disconnected cyclostratigraphies that have been referred to as "floating astrochronologies" (e.g., Hinnov and Ogg 2007). The Newark Supergroup strata in the Newark basin have an inferred cyclostratigraphy that has been proposed as one such floating astrochronology capable of providing a high resolution geochronometry for most of the Late Triassic and the older part of

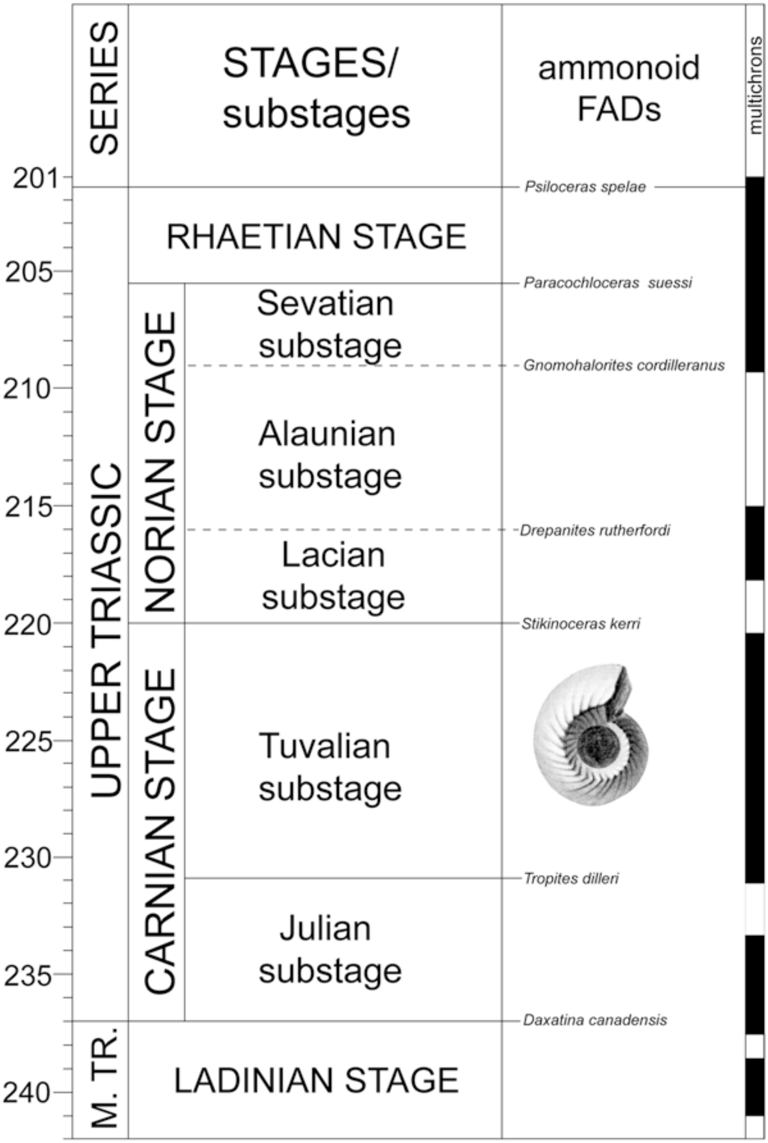


Fig. 1.7 A Late Triassic timescale

the Early Jurassic (Olsen and Kent 1996; Olsen et al. 1996, 2011; Kent and Olsen 1999; Olsen and Whiteside 2008; Ogg 2012; Kent et al. 2017).

Thus, spectral analyses of apparent cyclicity of Triassic-Jurassic strata in the Newark basin have been used to generate peak recurrence intervals within the sequence. When calibrated to sedimentation rates derived from varve counts in lacustrine mudstones, these recurrence intervals yield cycles inferred to correspond to orbital forcing at basic precession, eccentricity and long eccentricity frequencies. Consequently, the Newark basin cyclostratigraphy has been proposed as a floating astrochronology capable of providing a continuous high resolution geochronometry for most of the Late Triassic and part of the Early Jurassic.

Orbitally-forced cyclicity does appear to be the dominant control of some portions of the Newark basin section. But, the application of the Newark basin cyclostratigraphy as chronostratigraphy requires that the stratigraphic record is complete (no substantial erosional or depositional gaps exist) and cyclical throughout. Several lines of evidence indicate that these requirements are not met (Tanner and Lucas 2015). Outcrop and core data demonstrate that portions of the Newark Basin stratigraphic section are non-cyclic, particularly in the fluvial-dominated strata of the upper Passaic Formation and the Stockton Formation. Correlation of available biostratigraphic data, including both pollen and conchostracan zones between the Newark Supergroup and the Germanic Keuper, indicates that most of Rhaetian and a portion of late Norian time is not represented by sediment in the Newark basin and elsewhere in the Newark Supergroup (Kozur and Bachmann 2005, 2008; Kozur and Weems 2005, 2007, 2010; Weems and Lucas 2015; Weems et al. 2016). This suggests that at least 3 million years of Late Triassic time are not recorded by strata in the Newark Basin.

Indeed, the inability of the Newark cyclostratigraphy to locate and date the base of the Rhaetian or to produce a numerical age for the base of the Norian compatible with independently derived constraints demonstrate that the Newark Basin cyclostratigraphy is not a valid "floating astrochronology." At best, only the middle late Carnian through early late Norian interval, about 10 my in duration, may be sufficiently complete to be useful for astrochronological purposes (Tanner and Lucas 2015).

Ikeda and Tada (2014) have presented another "floating astrochronology" for the Triassic-Early Jurassic based on bedded cherts in Japan that they claim record a range of orbitally-forced cycles. They refer to this as the Inuyama ATS, principally tuned by 405-kyr eccentricity cycles and anchored to the end-Triassic radiolarian extinction to which they assign a numerical age of 201.4 ± 0.2 Ma. However, this astrochronology is questionable. As an example, Ikeda and Tada (2014) claim that their astrochronology establishes a Rhaetian base (identified as close to the LO of the conodont *Epigondolella* and of the radiolarian *Betraccium deweveri*: Carter and Orchard 2007) close to 210 Ma, which conflicts with what appear to be reliable radioistopic ages that make it much younger, close to 205 Ma. Similarly, the Inuyama ATS supposedly supports the long Norian with its base close to 228 Ma. Instead, the presentation of the cyclostratigraphy of the Japanese bedded cherts is very incomplete and not convincingly tied to Milankovitch cycles, which may explain its evident inaccuracy as an ATS.

1.7 Isotope Stratigraphy

Determination of the history of fluctuations in isotopic values in stratigraphic successions—isotope stratigraphy or chemostratigraphy—is increasingly important in the Triassic (Tanner 2010; Ogg 2012; McArthur et al. 2012; Saltzman and Thomas

2012). In order to create a usable isotope stratigraphy the isotopic history of multiple sections with well established ages needs to be obtained so that local effects can be ruled out and a global pattern can be established. At present, such data are being established in parts of the Triassic for carbon and strontium isotopes. In the Late Triassic, only the late Rhaetian negative excursion of carbon has been verified in multiple sections with good age constraints and thus is of value to correlation (Lucas et al. 2007).

The most widely studied isotope has been $\delta^{13}C$, and, indeed, the carbon isotope record for the Triassic System is now known generally, and, in some parts of the Triassic, it has been established in some detail. Relative isotopic stability characterizes much of the Middle and Upper Triassic, with pronounced negative excursions in the early Carnian and late Rhaetian that have been linked to significant biotic turnover (e.g., Korte et al. 2005; Dal Corso et al. 2012). A brief positive excursion of $\delta^{13}C$ at the Norian-Rhaetian boundary coincides with an extinction of deep water invertebrates (Sephton et al. 2002; Rigo et al. 2016). Some workers have considered the late Rhaetian carbon isotope excursion to be at the Triassic-Jurassic boundary (for example, McElwain et al. 2007), but it is actually well constrained in various sections as a late Rhaetian event (Lucas et al. 2007; von Hillebrandt et al. 2013).

General trends in the fluctuation in $^{87}Sr/^{86}Sr$ ratios have also been established for the Late Triassic (e.g., Korte et al. 2003; McArthur et al. 2012; Tackett et al. 2014). The strontium isotope stratigraphy shows an early Carnian minimum, and a peak in the late Norian followed by a fall during the Rhaetian.

The construction of reliable global carbon and strontium isotope curves for the Late Triassic is thus well underway. These curves, with judicious calibration, should become an increasingly important tool for Late 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.

1.8 Conclusion: A Late Triassic Timescale

The Late Triassic timescale presented here (Fig. 1.7) incorporates the traditional chronostratigraphic subdivisions. Numerical age control of the bases of the Carnian, Rhaetian and Hettangian stages is relatively good, but the numerical age of the base of the Norian remains open to discussion. The magnetostratigraphic record is a series of multichrons that identify the Carnian, early Norian and late Norian-Rhaetian as dominantly of normal polarity. Ammonoid bioevents that could potentially define stage and substage bases are indicated.

This review demonstrates that the Late Triassic timescale is still very much a work in progress. Greater precision and stability needs more precise chronostratigraphic definitions, additional numerical ages directly related to marine biostratigraphy, a wholesale rethinking of magnetostratigraphic correlations and additional cyclostratigraphic and isotopic data.