The Permian timescale: an introduction

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Abstract: The Permian timescale has developed over about two centuries of research to the current chronostratigraphic scale advocated by the Subcommission on Permian Stratigraphy of three series and nine stages: Cisuralian (lower Permian) – Asselian, Sakmarian, Artinskian, Kungurian; Guadalupian (middle Permian) – Roadian, Wordian, Capitanian; and Lopingian (upper Permian) – Wuchiapingian and Changhsingian. The boundaries of the Permian System are defined by global stratotype sections and points (GSSPs) and the numerical ages of those boundaries appear to be determined with a precision better than 1‰. Nevertheless, much work remains to be done to refine the Permian timescale. Precise numerical age control within the Permian is very uneven and a global polarity timescale for the Permian is far from established. Chronostratigraphic definitions of three of the nine Permian stages remain unfinished and various issues of marine biostratigraphy are still unresolved. In the non-marine Permian realm, much progress has been made in correlation, especially using palynomorphs, megafossil plants, conchostracans and both the footprints and bones of tetrapods (amphibians and reptiles), but many problems of correlation remain, especially the cross-correlation of non-marine and marine chronologies. The further development of a Permian chronostratigraphic scale faces various problems, including those of stability and priority of nomenclature and concepts, disagreements over changing taxonomy, ammonoid v. fusulinid v. conodont biostratigraphy, differences in the perceived significance of biotic events for chronostratigraphic classification and correlation problems between provinces. Future research on the Permian timescale should focus on GSSP selection for the remaining undefined stage bases, the definition and characterization of substages, and further development and integration of the Permian chronostratigraphic scale with radioisotopic, magnetostratigraphic and chemostratigraphic tools for calibration and correlation.

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Permian chronostratigraphy

Lucas & Shen (2016) review the nearly two century long development of the Permian chronostratigraphic scale, which is now a hierarchy of three series and nine stages (Fig. 1). The boundaries of the Permian System and six of its nine stages are defined by global stratotype sections and points (GSSPs). The numerical ages of the system boundaries appear to be determined with a precision better than 1‰, but precise numerical age control within the Permian is generally sparse and uneven. A global polarity timescale for the Permian is being developed, but is not complete. Chronostratigraphic definitions of most of the 13 substages used by some workers to subdivide the Permian stages remain unfinished. For the non-marine Permian strata, correlations based on palynomorphs, conchostracans and tetrapods (amphibians and reptiles) have been proposed, but many problems of correlation remain, especially the cross-correlation of Permian non-marine and marine chronologies.

This volume reviews the state of the art of the Permian timescale and this introductory chapter provides an overview of the book. It also presents the current Permian timescale of the SPS.

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| Series  | Stage          | Substage          |
|---------|----------------|-------------------|
| Lopingian | Changhsingian | Meishanian        |
|         |                | Baoqingian        |
|         | Wuchiapingian  | Laoshanian        |
|         |                | Laibinian         |
| Guadalupian | Capitanian     | Cathedralian      |
|         | Wordian        | Hessian           |
|         | Roadian        | Baigendzhinian    |
|         | Kungurian      | Aktustinian       |
| Cisuralian | Artinskian     | Sterlitamakian    |
|         |                | Tastubian         |
|         | Sakmarian      | Shikhanian        |
|         | Asselian       | Uskalykian        |
|         |                | Sjuranian         |

Fig. 1. Permian chronostratigraphic scale showing the ratified GSSPs of the stage bases.

Guadalupian (middle Permian) – Roadian, Wordian, Capitanian; and Lopingian (upper Permian) – Wuchiapingian and Changhsingian. The 1990s saw the rise of Permian conodont biostratigraphy so that all Permian GSSPs now use conodont evolutionary events as the primary signals for correlation. Most
of the bases of the Permian stages have been defined by GSSPs (Figs 1 & 2):

(1) In 1998, the base of the Asselian (=base of the Permian) was defined by the GSSP at Aidaralash Creek in western Kazakhstan (Davydov et al. 1998). The primary criterion (signal) for correlation of the GSSP is the first appearance datum (FAD) of the conodont *Streptognathodus isolatus* in the *S. wabaunensis* chronomorphocline. At Aidaralash Creek, the lowest occurrence (LO) of *S. isolatus* is c. 6 m below the secondary signal, which is the LO of the fusulinid *Sphaeroschwagerina fusiformis*, and it is c. 27 m below the traditional Asselian base determined by ammonoid biostratigraphy (Bogoslovskaia et al. 1995).

(2) There is no official GSSP to define the base of the Sakmarian, one of three Permian GSSPs that remain to be agreed. The most recent proposal is the Usolka section in southern Russia, where the primary signal for correlation is the FAD of the conodont *Mesogondolella monstra* in the hypothesized evolutionary lineage *M. uralensis*–*M. monstra*–*M. manifesta* (Chernykh et al. 2016).

(3) There is no ratified GSSP for the base of the Artinskian. The currently proposed GSSP for the base of the Artinskian Stage is the Dal’ny Tulkas section in southern Russia, with its primary signal for correlation the FAD of the conodont *Sweetognathus* aff. *S. whitei* in the hypothesized chronomorphocline *Sw. aff. Sw. merrilli*–*Sw. binodosus*–*Sw. anceps*–*Sw. aff. Sw. whitei* (Chuvashov et al. 2013).

(4) There is no agreed GSSP for the base of the Kungurian. Henderson et al. (2012a) proposed the Rockland section near Wells, Nevada, USA, as a GSSP for the base of the Kungurian, where the primary signal for correlation is the FAD of the conodont *Neostreptognathodus pnevi* in a lineage from *Neostreptognathodus paeoniensis* to *N. pnevi*. Chernykh et al. (2012) advocated the Mechetlino section in Russia as the GSSP candidate, with the same conodont event as its primary signal. They recently proposed moving the GSSP candidate section to the nearby Mechetlino Quarry section, which has better rock quality for conodonts and chemostratigraphy.

(5) The base of the Roadian Stage is defined by its GSSP in Stratotype Canyon, Guadalupe Mountains National Park, Texas, USA. The primary signal for correlation is the FAD of the conodont *Jinogondolella nankingensis*, hypothesized to have descended from its ancestors among *Mesogondolella idahoensis lamber* (Glenister et al. 1999; Mei & Henderson 2002; Henderson et al. 2012b), but the precise first occurrence of the serrated *Jinogondolella* needs to be investigated further.

(6) The base of the Wordian is now defined by its GSSP at Gateway near Guadalupe Pass in the Guadalupe Mountains National Park.
Its primary signal for correlation is the FAD of the conodont *Jinogondolella aserrata* in a hypothesized lineage as the descendant of *J. nankingensis* (Glenister et al. 1999; Mei & Henderson 2002; Henderson et al. 2012b). However, this definition has not been confirmed by recent studies and needs to be studied further.

(7) The base of the Capitanian is defined by its GSSP at Nipple Hill in the Guadalupe Mountains National Park. Its primary signal for correlation is the FAD of the conodont *Jinogondolella post serrata* within the hypothesized lineage from *J. nankingensis* to *J. aserrata* to *J. post serrata*. However, very rare specimens (c. 1%) among abundant *J. aserrata* can be recovered at the top of Nipple Hill and further collecting is not possible.

(8) The Wuchiapingian base (=base of the Lopingian) is defined by the GSSP in the Penglaitan section in southern China. Its primary signal for correlation is the FAD of the conodont *Clarkina post bitteri post bitteri* within a hypothesized evolutionary lineage from *C. post bitteri hongshuiensis* to *C. dukouensis* (Jin et al. 2001, 2006a; Henderson et al. 2012b).

(9) The base of the Changhsingian is defined at the GSSP at Meishan Section D, southeastern China, where the primary signal is the FAD of the conodont *Clarkina wangi* within the hypothesized *C. longicuspidata–C. wangi* lineage (Mei et al. 2004; Jin et al. 2006b; Henderson et al. 2012b).

(10) The base of the Induan (base of the Triassic = end of the Permian) is defined by the FAD of the conodont *Hindeodus par vus* at the Meishan Section D in southern China (Yin 1996; Yin et al. 1996, 2001).

Thus ratified GSSPs define the boundaries of six of the nine Permian stages recognized by the SPS and also define the boundaries of the three Permian Series and of the Permian System. The bases of most of the Permian substages (Fig. 1) lack formal definition. They provide a more refined subdivision of Permian time than 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 Permian. This is partly due to the relatively low level and sporadic distribution of late early–middle Permian volcanism recorded in fossiliferous rocks. This has resulted in a dearth of datable volcanic ash beds, in contrast with some of the other geological systems (such as the Cretaceous), which have a much more extensive record of volcanism. Nevertheless, some important advances have been made in the last two decades. The Lopingian and the Permian–Triassic boundary have been best dated with high-precision chemical abrasion isotope dilution thermal ionization mass spectrometry (Shen et al. 2011; Burgess et al. 2014). A series of high-precision U–Pb dates were also obtained from many volcanic ash beds in the Asselian, Sakmarian and Artinskian in the southern Urals (Schmitz & Davydov 2012). A high-precision U–Pb age for the base of the Guadalupian in South China has been published (Wu et al. 2017).

Ramezani & Bowring (2017) provide a concise and up to date review of the numerical calibration of the Permian timescale. This review demonstrates that the age of the base and top of the Permian are well constrained at 298.92 ± 0.19 and 251.90 ± 0.10 Ma, respectively. The ages of the bases of the Sakmarian and Artinskian stages are also determined with some precision at 293.52 ± 0.17 and 290.1 ± 0.2 Ma, respectively. There are extensive data to calibrate the Lopingian stage boundaries. However, numerical age control from the Artinskian through Capitanian remains sparse, although the newly published age by Wu et al. (2017) calibrates the base of the Guadalupian with some precision at 272.95 ± 0.11 Ma.

Ramezani & Bowring (2017) also provide a new age to calibrate a stratigraphic level c. 23 m below the base of the Capitanian at 265.2 ± 0.3 Ma, which is within the error range of the older published age, but much more precisely constrained. More numerical age data are clearly needed to precisely calibrate the Artinskian–Capitanian interval and this will bring the next great advance in numerical calibration of the Permian timescale.

**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. Permian magnetostratigraphy has long been thought to consist of the Kiaman Reversed Polarity Superchron, which lasted from the Pennsylvanian through to the early part of the middle Permian (about 50 myr), followed by the Illawara Mixed Polarity Superchron of middle–late Permian age. However, there is no agreement on a geomagnetic polarity timescale for the Permian, although a composite geomagnetic polarity timescale is now becoming available based on...
successions correlated to each other from marine and non-marine sections in North America, Europe and Asia.

Hounslow & Balabanov (2016) review the current status of Permian magnetostratigraphy. They note that within the reverse polarity Kiaman Superchron, long considered to have no normal polarity magnetochnrons, there appear to be three normal magnetochnrons during the early Permian: during the early Asselian, late Artinskian and mid-Kungurian. According to Hounslow & Balabanov (2016), the mixed polarity Illawara Superchron begins in the early Wordian at about 267.08 ± 0.35 Ma. The Wordian to Capitanian interval has a strong bias to normal polarity, but the basal Wuchiapiングnan marks the beginning of a significant interval dominated by reverse polarity. The late Wuchiapiングnan and Changhsingian have roughly equal durations of normal and reverse magnetochnrons. No significant gap in magnetostratigraphic data exists in the Permian geomagnetic polarity record.

Steiner (2001, 2006) identified the beginning of the Illawara Superchron as late Wordian and its identification as early Wordian by Hounslow & Balabanov (2016) appears to be based on a mis-correlation. Thus the Illawara Superchron begins in the shallow marine to shelfal Grayburg Formation of New Mexico, USA, which was deposited landwards of the famous Capitanian reef complex. All agree that the Grayburg Formation is correlative to some part of the basinal Cherry Canyon Formation, which indicates it is of Guadalupian age. However, more important is the fact that the Grayburg Formation directly overlies the San Andres Formation, which is Roadian–Wordian in age in its upper part (e.g. Kerans et al. 1993). Thus an age of the Grayburg of early Wordian is unlikely and the late Wordian age assigned to it, and thus to the base of the Illawara Superchron, is correct (Steiner 2001, 2006).

Hounslow & Balabanov (2016) calibrate the early Cisuralian magnetochnrons to a succession of fusulinid zones and they calibrate the later Cisuralian and Guadalupian magnetochnrons to fusulinid and conodont biostratigraphy. The Lopingian magnetochnrons are calibrated to conodont zonations. Hounslow & Balabanov (2016) also provide numerical age calibration of the magnetochnrons based on more than 15 U–Pb numerical ages. The numerically dated control points are most numerous in the Gzhelian–Asselian and Changhsingian intervals, giving 95% confidence intervals to the chron ages. In their summary of Permian magnetostratigraphy, Hounslow & Balabanov (2016) identify three or four very short normal polarity chrons in the Kiaman interval, followed by five normal multi-chrons in the Guadalupian and three normal multi-chrons in the Lopingian.

Carbon isotope stratigraphy

The use of carbon isotopes in stratigraphic correlation has grown dramatically during the last decade, but this volume lacks a review of Permian carbon isotope stratigraphy. Therefore we present a brief review here. First, we note that isotope curves that plot the composition of carbon or changes in the ratio of $\delta^{13}C$ to $\delta^{12}C$ have the potential to provide a means of correlation essentially independent of other methods. However, like magnetostratigraphy, this record needs calibration to a datum or to datums, either biostratigraphic or radioisotopic.

Saltzman & Thomas (2012, fig. 11.5) published a compiled carbon isotope record for the Permian based primarily on records from the USA (Nevada) and China (Saltzman 2003). That compilation shows $\delta^{13}C$ fluctuating around 2‰, with major negative excursions at the Asselian–Sakmarian, Artinskian–Kungurian, Wordian–Capitanian, Capitanian–Wuchiapingian and Changhsingian–Induan (Permio-Triassic) boundaries. However, as Buggisch et al. (2015) observed, the values of the Saltzman and Thomas compilation are lower than the mean values of other $\delta^{13}C$ records.

Henderson et al. (2012b, fig. 24.9) presented a generalized $\delta^{13}C$ curve for the Permian based primarily on data published by Shen et al. (2010) and Buggisch et al. (2011). This curve shows a general trend of decreasing values through the Permian, with notable positive excursions at about the Sakmarian–Artinskian, Kungurian–Roadian, Roadian–Wordian, Capitanian–Wuchiapingian and Permio-Triassic boundaries.

The most recent compilation, by Buggisch et al. (2015, fig. 9), does not show an overall negative trend (Fig. 3). Buggisch et al. (2015) reviewed data from sections in South China, the Moscow basin, the Southern Alps and Kansas, USA. Their review shows generally high values throughout the Permian, punctuated by sharp negative excursions of several per mil. It also shows substantial gaps of what Buggisch et al. (2015) consider to be reliable carbon isotope data during the entire middle Permian and parts of the early Permian.

Carbon isotope excursions during the Asselian–Sakmarian have been attributed to the change in oceanic carbon isotope composition during the final phase of the late Palaeozoic ice ages (Isbell et al. 2003). As reviewed by Buggisch et al. (2011), the waxing and waning of continental ice sheets is known to coincide with positive or negative shifts in $\delta^{13}C$, although there is no simple causal connection between ice volume and $\delta^{13}C$ values. Two negative shifts in C isotope values near the Asselian–Sakmarian boundary correspond to the major collapse of Gondwana ice sheets (Zeng et al. 2012).
Analyses of carbon isotope records across the Artinskian–Kungurian boundary have produced strikingly different results. Thus some sections (USA Midcontinent; Naging, China) show a negative shift across the Artinskian–Kungurian boundary, whereas others (Guadalupe Mountains, Southern Alps, Urals) show a positive shift (Bugisch et al. 2015, fig. 9). The compilation of Henderson et al. (2012b) shows a negative shift, but there is no clear global pattern (Bugisch et al. 2015).

The end-Guadalupian extinction has long been viewed as coinciding with (causing) a major negative shift in carbon isotopes (e.g. Baud et al. 1989; Bond et al. 2010). Thus it has been argued that the excursion is a global signal of large fluctuations right in the extinction, which has been dated as mid-Capitanian by some researchers (Wignall et al. 2009; Bond et al. 2010). The carbon isotope excursion has been linked to the release of methane by volcanism. This predates an interval of unusually heavy δ¹³C isotope values that has been called the Kamura event, hypothesized to reflect long-term cooling due to extensive high marine productivity drawing down atmospheric CO₂ values (Isozaki et al. 2007a, b). The inference here is a catastrophic release of methane to produce a major carbon excursion after the extinction. If correct, this is a global event best seen in sections in southern China. However, whether or not there was a single mass extinction has been questioned (Clapham et al. 2009) and carbon isotope excursions near the Guadalupian–Lopingian boundary are highly variable in both pattern and magnitude (Shen et al. 2013).

Korte & Kozur (2010) provided a comprehensive review of the carbon isotope record across the Permo-Triassic boundary (PTB). They compiled at least 40 globally widespread records of the PTB carbon isotope record in both marine and non-marine sections. There is a marked negative excursion at this boundary of a 4–7‰ decrease over about half a million years. Korte & Kozur (2010) argued that this trend was gradual, beginning about 500 000 years before the PTB, but was interrupted by a short-term positive event at

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**Fig. 3.** Permian carbon isotope curve after Buggisch et al. (2015).
the marine extinction event, which then decreased to a first minimum just below the PTB, followed by a one- or two-peaked minimum. The positive spike at the main extinction boundary and the decrease beginning before the main extinction obviate the extinction as the cause of the negative carbon trend. Thus Korte & Kozur (2010) argued that the negative carbon excursion had multiple causes, including the effects of Siberian Trap volcanism and the possibility of anoxic waters reaching shallow sea-levels. However, a recent study has shown that significant diagenesis has also affected carbon isotope values around the PTB (Li & Jones 2017), so the analysis of Korte & Kozur (2010) may need to be re-evaluated.

Thus the δ13C records from Permian strata in different locations contain evident contradictions that are, in part, underlain by regional differences. Buggisch et al. (2015) identified the following factors as responsible: (1) stagnant basin conditions; (2) restricted circulation between shallow water carbonate platforms, epicontinental seas and open oceans; (3) local up- and downwelling of waters; and (4) freshwater input in coastal areas. Thus they suggested that contradictory (opposite) trends in δ13C in the Midcontinent USA and the Russian Urals, and in the Guadalupe Mountains of Texas and the Naqing section in southern China, during the late Artinskian–Kungurian could be due to closure of the Ural gateway, which may have caused the upwelling of cold, nutrient-rich deep water and a change to colder water environments.

Buggisch et al. (2015) concluded that, at the current state of knowledge, Permian carbon isotope records are not particularly useful in stratigraphic correlation (Fig. 3). This is in part due to a general lack of study of multiple records for many Permian time intervals. They state that the only definitive global negative trend during the Permian is at the PTB. More carbon isotope stratigraphy is clearly needed from more sections to establish a robust carbon isotope curve for all of Permian time.

Marine biostratigraphy

The distribution of fossils in marine Permian strata has provided the primary basis for construction of the Permian chronostratigraphic scale. The most important taxa in this regard are conodonts, fusulinids, non-fusulinid forams and ammonoids. Brachiopods, rugose corals and radiolarians also provide some biostratigraphy of Permian marine strata. These groups are reviewed by papers in this volume and we also briefly discuss the biostratigraphic value of Permian marine bivalves and gastropods.

Conodonts

Conodonts are microscopic tooth-like structures composed of calcium phosphate and are abundant and widespread in Permian marine strata. Although the biological source of conodonts was long unknown, they are now clearly associated with chordates. In the 1990s, conodonts became the preferred tool for defining Permian chronostratigraphic boundaries. Thus the six defined GSSPs of the Permian stages have conodont events as their primary correlation signals and the three stages awaiting GSSP definition will also use conodont events as their primary correlation signals.

Korte & Ullmann (2016) review the strontium isotope stratigraphy of the Permian. They note that the secular evolution of the 87Sr/86Sr ratios in Permian seawater record information about global tectonic processes, palaeoclimate and palaeoenvironments, including the early Permian deglaciation, the amalgamation of Pangaea and the PTB mass extinctions (also see Dudás et al. 2017). The marine 87Sr/86Sr curve can also be used for robust correlations when other bio-, litho- and/or chemostratigraphic markers are inadequate. The accuracy of marine 87Sr/86Sr reconstructions, however, depends on high-quality age control of the reference data and on sample preservation, both of which generally decrease in quality for older time intervals.

According to Korte & Ullmann (2016), Permian seawater 87Sr/86Sr values show a decrease from c. 0.7080 in the earliest Permian (Asselian) to c. 0.7069 in the latest Guadalupian (Capitanian), followed by a steepening increase from the latest Guadalupian towards the PTB (c. 0.7071–0.7072) and into the Early Triassic. Various higher order changes in the slope of the Permian 87Sr/86Sr curve are indicated, but cannot currently be verified due to lack of sampling and disagreement over published 87Sr/86Sr records. Thus, like carbon isotope stratigraphy, the strontium isotope stratigraphy of the Permian is in an early phase of development.

Strontium isotope stratigraphy

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develop Permian conodont zonations are depicted by Henderson (2016) in relationship to the geo-
chronological ages of Permian stages.

Thus a total of 75 biozones based on the ranges of conodonts are summarized by Henderson (2016).
Forty of these are regarded as standard international biozones and the other 35 are referred to as cor-
relative regional biozones. However, due to several factors, only a few of the biozones have a truly global character. These factors include regional glaciation in the earliest Permian, major lowstands of sea-level in the Kungurian and Capitanian–
Wuchiapingian boundary interval, significant levels of provincialism, especially from the early Kungur-
ian to the early Changhsingian, and the high degree of morphological plasticity displayed by key taxa.

The last factor underlies widely different opinions on conodont taxonomy, which affect the correlation potential of Permian conodonts. As Henderson (2016) concludes, Permian conodonts, regardless of the taxonomic approach, exhibit low to moderate diversity and two major lineages provide most of the biostratigraphic control: the sweetognathid and gondolellid lineages. Future progress in Permian conodont biostratigraphy will come from more taxonomic refinement of these lineages to delineate better evolutionary events by which to define zonation.

Radiolarians

Radiolarians are marine zooplankton that 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 Permian fossils are typically found in deep marine deposits associated with chert horizons.

Zhang et al. (2017) review the Permian radiolarian record and its application to biostratigraphy. They recognize and review 17 Permian conodontic lineages. Among these, seven zones are recognized in the uppermost Carboniferous to lower Permian (in ascending order): Pseudoalbaillella bulbosa Assemblage Zone, Pseudoalbaillella uforma–
Pseudoalbaillella elegans Abundance Zone, Pseudoalbaillella lomentaria–Pseudoalbaillella sak-
marianensis Assemblage Zone, Pseudoalbaillella rhombothoracata Interval Zone, Albaillella xiao-
dongensis Assemblage Zone, Albaillella sinuate Abundance Zone and Pseudoalbaillella ishigai Abundance Zone. Five zones are recognized in the middle Permian (ascending order): Pseudoalbaille-
lla globoas Interval Zone, Follicucullus monacan-
thus Interval Zone, Follicucullus porrectus Interval Zone, Follicucullus scholasticus Interval Zone and Follicucullus charveti Interval Zone. Five zones belong to the uppermost middle Permian to upper

Permian (ascending order): Albaillella cavitata Interval Zone, Albaillella levis Interval Zone, Albaillella excelsa Interval Zone, Albaillella triangularis Interval Zone and Albaillella yaoi Abundance Zone. Zhang et al. (2017) discuss these Permian radiolarian biozones and their correlations with the conodont zones and other chronostratigraphic schemes. They conclude that more continuous successions are needed to produce a more refined and robust radiolarian biostratigraphy of the Permian.

Rugose corals

Wang et al. (2017) review the Permian record of rugose corals. They recognize two coral realms, Tethyan and Cordilleran–Arctic–Uralian. The Tethyan realm is characterized by the families Kepingphyllidae and Waagenophyllidae during the Cisuralian, Waagenophyllidae during the Guadalupian and the subfamily Waagenophyllinae during the Lopingian. By contrast, the Cordille-
ran–Arctic–Uralian realm is characterized by the families Durhaminidae and Kleopatrinidae during the Cisuralian and the almost total disappearance of colonial and disseminated solitary rugose corals from the Guadalupian to the Lopingian.

According to Wang et al. (2017), the geographical barrier resulting from the amalgamation of Pangaea controlled the development of these coral realms. Changes in the composition and diversity of Permian rugose corals suggest that an evolutionary turnover event might have occurred at the end of the Sakmarian, probably due to a global drop in sea-level. It was characterized by the change from mixed Pennsylvanian and Permian coral faunas to typical Permian coral faunas. In addition, three coral extinction events are evident (end-Kungurian, end-Guadalupian and end-Permian), which Wang et al. (2017) argue were triggered (respectively) by the northwards movement of Pangea, Emeishan volcanism and subsequent global regression, and global warming induced by the Siberian Trap eruptions. The Permian record of rugose corals thus documents important evolutionary and palaeobiogeographical events, but does not provide a robust biostratigraphy.

Ammonoids

Ammonoids were long the workhorses of Permian marine biostratigraphy, so that much of the Permian timescale was early built on ammonoid biostratigra-
phy. Leonova (2016) reviews the application of ammonoids to Permian chronostratigraphy.

Leonova (2016) notes that almost all stages of the Permian System were originally based on ammonoids. Thus, traditionally, ammonoid ‘zones’
of the lower and middle Permian were used as the equivalents of stages (Glenister 1981), whereas for the upper Permian these zonal subdivisions have been much more detailed. Two ‘zones’ of the scale of Böse (1917) have been used by stratigraphers for many decades: the Perrinites and Waagenoceras zones, corresponding to the Artinskian and Wordian stages, respectively. Miller (1938), working in North America, introduced two more zones so that the resulting zonal scheme was Properrinites and Perrinites for the lower Permian and Waagenoceras and Timorites for the upper Permian.

Ruzhentsev (1955) recognized seven successive ammonoid assemblages corresponding to the Asselian, Sakmarian, Aktastinian, Baigendzhinian, Sicilian (or Wordian), Capitanian and Dzhulfian stages. On the basis of these assemblages, Glenister & Furnish (1961) recognized six stages: Asselian, Sakmarian, Artinskian (with Aktastinian and Baigendzhinian substages), Wordian, Capitanian and Dzhulfian. Furnish (1966) introduced the Roadian Stage for the uppermost beds of the lower Permian. In addition, he subdivided the upper Permian series into three stages: Guadalupian, Chidruan and Dzhulfian. Furnish (1973) later proposed a more refined Permian chronostratigraphy based on ammonoids and Ruzhentsev (1976) proposed a less refined version of the global scale.

The ammonoid-based definition of the Carboniferous–Permian boundary is based on the first appearance of four new families – Paragastrioceratidae (Svetlanoceras), Metalegoceratidae (Juresantes), Popanoceratidae (Protopopanoceras) and Perrinitidae (Subperrinites, Properrinites) – and seven new genera that became the bases of the Asselian, Sakmarian, Artinskian (with Aktastinian and Baigendzhinian substages), Wordian, Capitanian and Dzhulfian. Furnish (1966) introduced the Roadian Stage for the uppermost beds of the lower Permian. In addition, he subdivided the upper Permian series into three stages: Guadalupian, Chidruan and Dzhulfian. Furnish (1973) later proposed a more refined Permian chronostratigraphy based on ammonoids and Ruzhentsev (1976) proposed a less refined version of the global scale.

The ammonoid-based definition of the Carboniferous–Permian boundary is based on the first appearance of four new families – Paragastrioceratidae (Svetlanoceras), Metalegoceratidae (Juresantes), Popanoceratidae (Protopopanoceras) and Perrinitidae (Subperrinites, Properrinites) – and seven new genera that appeared in previously existing families – Vanartinskia, Mescalites, Kargalites, Cardiella, Martoceras, Prostachoeoceras and Tabantalites (Bogoslovskaya et al. 1995). The lower Permian stages were established in the South Urals, beginning with the Artinskian ammonoids discovered in the 1800s (Murchison et al. 1845). The Artinskian was the first Permian stage to be recognized (Karpinsky 1874, 1889; Krotow 1885). Ruzhentsev (1938, 1951, 1954) recognized three diverse, temporally successive ammonoid assemblages that became the bases of the Asselian, Sakmarian and Artinskian stages.

Thus, on a global scale, all nine stages of the Permian are relatively completely characterized by ammonoids, which are successfully used for biostratigraphy and interregional correlations. Nevertheless, ammonoid localities in Permian sections are relatively rare and sections that document changes in species and genera, characterizing long intervals of geological time, are extremely rare. This diminishes the use of ammonoids as primary signals in the GSSP definition of Permian stages, although their value as secondary signals for GSSP correlation remains undiminished.

Non-fusulinid forams

Non-fusulinid forams are abundant in many Permian marine strata and some taxa have very broad distributions in shallow marine carbonate and evaporite facies. This has led to the use of non-fusulinid forams in Permian biostratigraphy, especially in Europe, North America and Asia. Vachard (2016) reviews the biostratigraphy of Permian smaller forams belonging to four classes: Fusulinata, Miliolata, Nodosariata and Textulariata. Biostratigraphic markers of these classes are mainly found in the orders and superfamilies Lasiodiscoidae, Bradyinoidea and Globivalvulinoidae (Fusulina), Cornuspirida (Miliolata) and in the class Nodosariata. The class Textulariata is too little known during the Permian to be of biostratigraphic significance, although the appearance of the order Verneuilinida is probably an important bioevent. The main genera among the lasiodiscids include Mesolasidiscus, Lasidiscus, Lasiotrochus, Asselodiscus, Pseudovoladulina and Xingshandiscus. Among the bradyinoids, the main genera are Bradyna and Postendothyra; and, among the globivalvulinoids, Globivalvula, Septoglobivalvula, Labioglobivalvula, Paraglobivalvula, Sengoerina, Dagmarita, Danielita, Louisettia, Paradagmarita, Paradagmaritopsis and Parempirateria. The biostratigraphically significant genera of miliolates are Rectogordius, Okimuraites, Neodiscus, Multidiscus, Hemigordiopsis, Lysites, Shania and Gloomidiellopsis, and the genera of tubiphytids and ellesmerellids, which may be specialized miliolate and cyanobacterium consortia. The Nodosariata marks belong to Nodosinelloides, Tezquauna, Polarisella, Geinitzina, Pseudolangella, Calvezina, Cryptoseptida, Cylin- drocolaniella, Colaniella, Frondina and Ichthyofrondina, but their lineages are too poorly understood to allow their accurate use in Permian biostratigraphy. Vachard (2016) thus concludes that broad correlations using these genera allow the recognition of 12 intervals of Permian time, many roughly equivalent to a stage.

Fusulinids

The study of Permian fusulinids began in the early to middle 1800s and the first attempt at a Permian fusulind biostratigraphy was published by Schellwien (1898) based on his studies in the Carnic Alps of southern Europe (Douglass 1977). Detailed Permian biostratigraphy based on fusulinids has been developed in the twentieth century, primarily in Russia,
China, the USA, Japan and Tajikistan. It has long been recognized that Permian fusulinids were provincialized and this has hampered global correlations using fusulinids. Zhang & Wang (2017) review Permian fusulinid biostratigraphy. They note that the rapid evolution of Permian fusulinids has rendered them important taxa in correlating Permian strata globally. Thus Zhang & Wang (2017) draw attention to key evolutionary events among fusulinids that define biostratigraphic boundaries. The FADs of *Pseudoschwagerina* or *Sphaeroschwagerina* mark the base of the Asselian stage. These schwagerinids and pseudoschwagerinids gave rise to *Paraschwagerina*, *Zelitella*, *Darvasites* and *Robustoschwagerina* during the Sakmarian. During the Yakhthashian, *Levenella* and *Pamirina* originated from the Tethyan region and formed the basis of the neoschwagerinids. The first occurrences of *Brevaxina*, advanced *Misellina*, *Neoschwagerina* and *Yabeina/Lepidolina* define the bases of the Bolorian, Kubergandian, Murgabian and Midian stages, respectively. Both neoschwagerinids and schwagerinids became extinct at the end of the Midian stage. The remaining fusulinids of the late Permian are small-sized *Codonofusiella* and *Reichelina* and a few new genera such as *Palaeofusulina* and *Gallowayinella*. *Palaeofusulina*, in particular the advanced species *P. sinensis*, is characteristic of the Changhsingian. According to Zhang & Wang (2017), these are the main evolutionary milestones of fusulinids that provide the basis of fusulinid biostratigraphy across Tethys.

By contrast, there is a different evolutionary history of fusulinids in the North American cratonic region. The main differences between the Tethyan region and the North American craton are seen in the fusulinid faunal compositions from the Leonardian Stage to the Capitanian Stage. The fusulinids of North America are characterized during this interval by the dominance of schwagerinids such as *Parafusulina* and *Polydiedoxina*. However, *Parafusulina* plays a minor part from the Kubergandian to Midian in the Tethyan region. Therefore the direct and precise correlation of middle Permian fusulinid biostratigraphy between the Tethyan region and the North American craton region requires further detailed investigation. Thus, as has long been known, Permian fusulinids are powerful biostratigraphic tools, but this biostratigraphy is long been known, Permian fusulinids are powerful biostratigraphic tools, but this biostratigraphy is long been known, Permian fusulinids are powerful biostratigraphic tools, but this biostratigraphy is long been known, Permian fusulinids are powerful biostratigraphic tools, but this biostratigraphy is long been known, Permian fusulinids are powerful biostratigraphic tools, but this biostratigraphy is long been known, Permian fusulinids are powerful biostratigraphic tools, but this biostratigraphy is long been known, Permian fusulinids are powerful as one of the animal groups hardest hit by the end-Permian extinctions.

In his review of Permian brachiopod biostratigraphy, Shen (2016) stresses the difficulty in establishing a Permian biochronological scheme for global correlation based on brachiopods due to provincialism and endemism. However, numerous new brachiopod assemblages have been described during the last 40 years, making it possible to improve and update the brachiopod biostratigraphy in different regions. The Permian biogeography of brachiopods is characterized by three distinctive realms (Boreal, Palaeoequatorial and Gondwanan) and two transitional zones developed between these realms. The brachiopods from the two transitional zones show a mixture of the cold water brachiopods of the two anti-tropical realms and the warm water brachiopods of the Palaeoequatorial realm. Therefore they provide a bridge to facilitate correlation between the different realms.

Shen (2016) gives a brief overview of Permian brachiopod successions in the five major palaeobiogeographical realms. Based on a global database of Permian brachiopods, a characteristic brachiopod assemblage represented by the genera *Bandoparticulatus, Punctocyrtella* and *Cimmentiella* in the lower Cisuralian (probably upper Asselian to lower Artinskian) of Gondwana, the peri-Gondwanan region and the Cimmerian blocks was widely distributed, indicative of the acme of the late Palaeozoic ice ages.

As a result of the amelioration of the palaeoclimate during the late Kungurian and/or the northwards drift of the Cimmerian blocks, brachiopods show a distinct shift from their cold water affinity to mixed or warm water affinity late in the Cisuralian. By contrast, brachiopods in the northern transitional zone are warm water faunas associated with fusulinids in the lower Cisuralian. The Guadalupian brachiopods of the northern transitional zone were clearly mixed, with boreal and palaeoequatorial affinities indicated by the presence of some anti-tropical or boreal genera (e.g., *Gysospirifer, Kaninospirifer, Rhombospirifer, Spiriferella, Yakovlevia*) associated with numerous typical Cathaysian elements, suggesting that the northern transitional zone drifted to a more northerly location during the Guadalupian.

The onset of the end-Permian mass extinctions in the latest Changhsingian is exhibited globally by the occurrence of a dwarf brachiopod assemblage characterized by small sizes and thin shells. Typical representatives are *Paraacrurithyris, Fusichonetes, Paryphella, Spinomarnigifera, Martinia* and numerous lingulids. In addition, some brachiopods with bipolar/bitemperate distributions may be useful for correlation between the Boreal and Gondwanan realms.

### Brachiopods

Brachiopoda is a phylum of marine animals with two valves known from more than 12 000 fossil species in more than 5000 genera. Brachiopods were common shelly benthos during the Permian, mostly as seafloor filter-feeders. They suffered major losses as one of the animal groups hardest hit by the end-Permian extinctions.

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**Other marine biostratigraphy**

Non-cephalopod molluscs, the bivalves and gastropods, were, like the brachiopods, common denizens of Permian seafloors. However, they have only been used in a limited fashion in Permian biostratigraphy.

The most abundant Permian bivalves were epifaunal pteriommorphs; much less common were semi-infaunal to infaunal suspension feeders such as Myophroriiidae, Astartidae, Permophoridae, Megadesmidae and Pholadomyidae (e.g. Nakazawa & Runnegar 1973; Miller 1988, 1989). Bivalves became increasingly important members of marine communities through Permian time and the late Permian was a time of increased generic richness, ecological diversity and cosmopolitanism (Clapham & Bottjer 2007; Mondal & Harries 2016). However, Permian biostratigraphy based on marine bivalves suffers from the problems that beset the brachiopods, especially provincialization and facies control of distributions, so marine bivalves are little used in Permian correlations.

Permian marine gastropods reached their peak diversity during the Guadalupian, but this may reflect a bias due to the extremely prolific assemblages from the Guadalupian of West Texas (Batten 1973). As an example of the limited use of marine gastropods in Permian biostratigraphy, we note that Knight (1940, p. 1128) stated that the euomphaline gastropod genus *Omphalotrochus* ‘makes its first appearance throughout the world at the base of what appear to be the equivalents of the Wolfcamp series in the United States’. However, this includes records of *Omphalotrochus* in the Gzhelian *Uddenites* shale of the Gaptank Formation in West Texas and Gzhelian records in Russia (e.g. Yochelson 1954, 1956; Mazaev 1994). So, although most records of *Omphalotrochus* appear to be lower Permian, the FAD of the genus is below the long accepted base of the Permian and not obviously synchronous globally.

**Non-marine biostratigraphy**

Non-marine Permian biostratigraphy has also been developed, based primarily on palynomorphs, mega-fossil plants, conchostracans, tetrapod (amphibian and reptile) footprints and tetrapod body fossils. Some other non-marine fossil groups (charophytes, ostracods, freshwater bivalves, insects and fishes) have been used for Permian biostratigraphy and are also briefly discussed here.

**Palynomorphs**

Spores and pollen are the microscopic reproductive structures of vascular plants. Their organic walls resist pressure, desiccation and microbial decomposition, so they are often well preserved in sedimentary rocks and Permian 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 non-marine and marine strata. They provide an important method for the cross-correlation of non-marine and marine strata based on shared palynomorph taxa. However, most palynomorphs are only dispersed within a few kilometres or less of the plant that produces them, and any provincialization of the palaeoflora hinders their use in broad-scale correlation. Plants are also environmentally sensitive, so palaeoenvironmental and facies restrictions of extinct plants affect the distribution of their palynomorphs.

As Stephenson (2016) notes, during the Permian the palaeoflora was provincialized into three or more provinces. Thus correlations based on fossil plants and the palynoflora have proved to be difficult between portions of Permian Pangaea that were in relatively close proximity, but in different palaeo-provinces, such as Western Europe and eastern North America. Permian palynostratigraphic schemes have been mainly used to correlate coal- and hydrocarbon-bearing rocks within and between basins, sometimes at high levels of biostratigraphic resolution. Up to now, their main limitations have been the lack of correlation with schemes outside the basins, coalfields and hydrocarbon fields where they occur, and a lack of correlation with the Permian Standard Global Chronostratigraphic Scale (SGCS). This is partly because phytogeographical provinciality from the Guadalupian through Lopingian makes correlation between regional palynostratigraphic schemes difficult. However, local high-resolution palynostratigraphic schemes for different regions are now being linked to each other, either by assemblage level quantitative taxonomic comparison or by the use of single, well-characterized palynological taxa that occur across Permian phytogeographical provinces. Such taxa include *Scutaspores*, *Vittatina*, *Weylandites*, *Lueckisporites virkkiae*, *Otynisporites eotriassicus* and *Converrucosisporites confluens*. These palynological correlations are facilitated and supplemented with radioisotopic dating, magnetostratigraphy, independent faunal correlations and strontium isotope stratigraphy. Thus the future of Permian palynostratigraphy looks promising.

**Megafossil plants**

Megafossil plants have been part of Permian chronostratigraphy and biostratigraphy back to the beginning of the concept of the Permian, due, in part, to the identification of a Permian flora distinct from that of the Carboniferous or the Triassic.
This is a flora of late Palaeozoic aspect, dominated by primitive conifers, peltasperms, true ferns, sphenopsids and cordaites that co-occur with the last lycopsids. However, the Permian floras were very provincialized due to the complex topography and steep climatic gradients that characterized Permian Pangaea. This hinders the development of a global biostratigraphy based on Permian plants.

Cleaf (2016) reviews the use of megafossil plants in Permian biostratigraphy and correlations. He notes that separate biostratigraphic schemes have been developed for Permian macrofloras in the five main phytchoria (palaeokingdoms) of Permian Pangaea, reflecting the general lack of overlap in taxonomic composition between the phytchoria. Two biozones are normally recognized in Europe; in North America three zones, in Cathaysia three or four zones, in Gondwana four zones and in Angara five zones. The stratigraphic resolution is thus far less than for palynology and up to an order of magnitude coarser than the macrofloral biozones of the Pennsylvania. This is probably due (at least in part) to the lack of rigour in the way that the Permian macrofloral zones have been defined. Nevertheless, the existing zones do provide evidence of the overarching trajectory of change in vegetation through the Permian Period, as it responded at all palaeolatitudes to a combination of climate change, large-scale volcanic eruptions and tectonically driven landscape changes. Thus, as is generally true of fossil plants, Permian plant fossils remain excellent indicators of palaeoclimates and palaeoenvironments, but are not robust biostratigraphic tools.

Conchostracans

Conchostracans are bivalved crustaceans that have lived in freshwater lakes and ponds over the last few hundred million years. Their minute, drought-resistant eggs can be dispersed by the wind and this guarantees a broad geographical range to some conchostracan taxa across much of Permian Pangaea. Their habitats ranged from perennial lakes of the Carboniferous and early Permian to seasonal playa lakes and temporary ponds and puddles of the late early Permian through the Triassic, when they could form mass death assemblages. This, together with relatively high speciation rates, make them ideal guide fossils, especially in otherwise non-fossiliferous wet and dry red beds.

Schneider & Scholze (2016) present a review of Permian conchostracan biostratigraphy in Western Europe. A preliminary conchostracan zonation is proposed based on material and data collected from surface outcrops and well cores in Central Europe since the 1980s. This is based on assemblage zones consisting of two or three species instead of species-range zones with one or two forms only. The average temporal resolution of the proposed zones during the interval from the late Bashkirian (Westphalian A) to the Early Triassic (Induan) is approximately 5 myr, but it deteriorates to 15 myr during the late early to middle Permian because of a discontinuous fossil record and sampling biases. Isotopically dated occurrences of conchostracan zone species or co-occurrences of conchostracans, insect zone species and marine index fossils, such as conodonts and fusulinids, are used for correlations with the SGCS. The conchostracan zones are cross-correlated to the SGCS based on selected radioisotopic ages and the co-occurrence of some conchostracan index taxa with marine index fossils. Nevertheless, much work remains to improve Permian conchostracan biostratigraphy, particularly to resolve their generally oversplit taxonomy.

Tetrapod footprints

Fossil footprints of Permian tetrapods, which have been studied since the early 1800s, are common in some Permian non-marine strata and had broad palaeogeographical distributions. Some Permian non-marine strata that lack or nearly lack a tetrapod bone record have an extensive footprint record. Therefore various workers have used Permian tetrapod footprints in biostratigraphy.

Voigt & Lucas (2016) review the use of tetrapod footprints in Permian biostratigraphy. They argue that several characteristic Permian footprint assemblages and ichnotaxa have restricted stratigraphic ranges and thus represent distinct time intervals that they term footprint biochrons (after Lucas 2007). Based on the temporal distribution of the 13 best known Permian tetrapod ichnotaxa, three footprint biochrons are recognized: (1) Dromopus biochron – latest Carboniferous (roughly Gzhelian) to late early Permian (roughly Artinskian), encompassing ichnoassemblages dominated by tracks of temnospondyls, reptiliomorphs, pelycosaurs and early diapsids; (2) Erpetopus biochron – late early Permian (roughly Kungurian) to late middle Permian (roughly Capitanian), including ichnoassemblages dominated by tracks of non-diapsid eureptiles; and (3) Paradoxichnium biochron – late Permian (Wuchiapingian and Changhsingian), encompassing ichnoassemblages dominated by tracks of medium- and large-sized parareptiles, non-diapsid eureptiles and early saurians.

This is a conservative ichnostreamigraphic scheme for Permian tetrapod tracks and should be refined to almost stage-level resolution by future comprehensive analysis, especially of Permian captorhinomorph and therapsid footprints. Other major
tasks to improve Permian tetrapod footprint ichnosтратigraphy include augmenting our knowledge of middle Permian tetrapod footprints and clarification of the palaeoenvironmental factors that control the distribution of tetrapod footprints in space and time.

Tetrapod footprints thus have some use for Permian biostratigraphy and biochronology. However, compared with the tetrapod body fossil record, which has been used to discriminate 11 biochrons, the three footprint-based biochrons provide much less temporal resolution. Nevertheless, in non-marine Permian strata where body fossils are rare, tetrapod footprints will remain important for biostratigraphy and biochronology.

**Tetrapods**

Permian tetrapod (amphibian and reptile) fossils have long been used in non-marine biostratigraphy, with a tradition extending back to at least the 1870s. Lucas (1998) advocated developing a global Permian timescale based on tetrapod evolution and Lucas (2006) presented a comprehensive global Permian tetrapod biochronology that divided the Permian into 11 time intervals (land vertebrate faunachrons) based on tetrapod evolution. Lucas (2017) presents the current status of the Permian tetrapod-based timescale.

The most extensive Permian tetrapod (amphibian and reptile) fossil records from the western USA (New Mexico and Texas) and South Africa define 11 land vertebrate faunachrons (in ascending order): Coyotean, Seymouran, Mitchellcreekian, Redtankian, Littlecrotonian, Kapteinskraalian, Gamkan, Hoedemakeran, Steilkransian, Platbergian and Lootsbergian. These faunachrons provide a biochronological framework with which to assign ages to and correlate Permian tetrapod fossil assemblages. Intercalated marine strata, radioisotopic ages and magnetostратigraphy correlate the Permian land vertebrate faunachrons to the SGCS with varying degrees of precision. Such correlations identify the following significant events in Permian tetrapod evolution: a Coyotean chronofaunal event (persistence of the Coyotean chronofauna for about 10 myr), a series of extinctions, the Redtankian events (Mitchellcreekian–Littlecrotonian), Olson’s gap (the global absence of tetrapod fossils during the late Littlecrotonian), a therapsid event (sudden appearance of therapsid-dominated assemblages during the Kapteinskraalian), the dinoccephalian extinction event (the largest Permian mass extinction of tetrapods at about the end of the Gamkan) and a latest Permian extinction event (late Platbergian to Lootsbergian).

Problems of incompleteness, endemism and taxonomy, and the relative lack of non-biochronological age control, continue to hinder refinement and correlation of a Permian timescale based on tetrapod biochronology. Nevertheless, the global Permian timescale based on tetrapod biochronology is a robust tool for both global and regional age assignment and correlation. Advances in Permian tetrapod biochronology will come from new fossil discoveries, more detailed biostratigraphy and additional alpha taxonomic studies based on sound evolutionary taxonomic principles.

**Other non-marine biostratigraphy**

Some other non-marine Permian fossils have been used in biostratigraphy, including charophytes, ostracods, bivalves and fish. 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 Permian correlations.

Charophytes are the calcified egg cases (gyrogonites) of characean algae and have been documented from some Permian lacustrine deposits (e.g. Feist et al. 2005). However, too little is known of the Permian charophyte record to allow its use in biostratigraphy. The only substantial record is from China (e.g. Wang & Wang 1986) and the biozonation based on it (four Permian assemblages: Feist et al. 2005, table 4) needs to be tested with data from other regions.

Much of the variation in gyrogonite morphology is ecophenotypic, so it is more a function of environmental variation than a consistent evolutionary signal (e.g. Lucas & Johnson 2016). Thus we suspect that the long-ranging charophyte genera now known from the Permian (e.g. *Stellatochara*) will not segregate into temporally successive species useful in biostratigraphy.

Non-marine ostracods are common in various lacustrine deposits of the Permian, ranging from the black shales and limestones of perennial lakes to claystones and micritic limestones of temporary ponds and pools. They can even be common in strata deposited by brackish waters or environments of higher salinity. Mass death assemblages in shales and limestones, sometimes rock-forming, may be linked to ecological factors that prevent the co-occurrence of other inhabitants of the same or similar guild, as well as the occurrence of ostracod-feeding predators.

Nevertheless, the use of non-marine ostracods in Permian biostratigraphy is hampered by two factors. First, freshwater ostracods have a simple shell morphology and the state of preservation (lack of preserved muscle scars, deformation up to complete flattening during sediment compaction) often precludes precise identification. The second problem is their oversplit alpha taxonomy. Nevertheless, in modern semi-arid and arid environments in Africa
and Arabia, the minute eggs of freshwater ostracods are drought resistant. They can thus be easily distributed over hundreds of kilometres by air currents and this may have happened during the Permian. Therefore Permian non-marine ostracods could have promise for biostratigraphy.

Fig. 4. Current Permian timescale of the Subcommission on Permian Stratigraphy.
Non-marine bivalves, including the anthracosiods, palaeomutelids and some myalinids (brackish water), had a worldwide distribution during the Permian. Some biostratigraphic correlations have been based on these bivalves (e.g. Edgar 1984), but their alpha taxonomy seems extremely over-split, as most variation is ecophenotypic, not interspecific, in origin. It seems unlikely that the stratigraphic ranges of all non-marine Permian bivalves are well established. Thus, for example, Lucas & Rinehart (2005) documented *Palaeonodonta* in the lower Permian of North America, whereas the genus is otherwise known from the middle or late Permian of Antarctica, South Africa, Kenya, Russia, Myanmar and Siberia, among other places. This substantial range extension suggests to us that the true distributions in time and space of Permian freshwater bivalves are not well known. This and the taxonomic problems should make us cautious in using non-marine bivalves for Permian biostratigraphy.

Scudder (1879, 1885) first attempted to use insect wings for Permian biostratigraphy, recognizing the common occurrence of genera and species of blattid insects (cockroaches) in North America and Europe. Later, Durden (1969, 1984) proposed blattid zonations of the Pennsylvanian and Permian, but his correlations were problematic because of inadequate taxonomy (Lucas et al. 2013). Schneider (1983) published a revised classification of Pennsylvanian and Permian blattids and from this came the first proposal of spiloblaugniid zones and later of archimylacrid/spiloblaugniod/conchostracan zones for the Early Pennsylvanian (Westphalian A) through to the late early Permian (Artinskian) (Schneider 1982; Schneider & Werneburg 1993, 2006, 2012). This biostratigraphy has been cross-correlated to parts of the SGCS where the cockroach fossils co-occur or are intercalated with marine strata that yield fusulinids and/or conodonts (e.g. Lucas et al. 2013).

Freshwater fish have never provided a robust biostratigraphy in non-marine strata. This is because of the limitations of these fish and their fossils to specific lithofacies and locations, so that their record is heavily affected by facies control and endemism. Permian xenacanth shark teeth have been applied to regional correlations between some European parts of the SGCS where the cockroach fossils / bioevents im Grenzbereich Stephanium/Autunium (höchstes Karbon) des Saar-Nahe-Beckens (SW-Deutschland) und benachbarter Gebiete. Neues Jahrbuch für Geologie und Paläontologie Abhandlungen, 216, 89–152.

**A Permain timescale**

The Permain timescale presented here (Fig. 4) is of the SPS, well reflected by many of the papers in this volume. Issues in the further development of a Permain chronostratigraphic scale include those of stability and priority of nomenclature and concepts, disagreements over changing taxonomy, ammonoid v. fusulinid v. conodont biostratigraphy, differences in the perceived significance of biotic events for chronostratigraphic classification and correlation problems between provinces. Further development of the Permain chronostratigraphic scale should focus on GSSP selection for the remaining, undefined stage bases, the definition and characterization of substages, and further integration of the Permain chronostratigraphic scale with radioisotopic, magnetostratigraphic and chemostratigraphic tools for calibration and correlation.

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**Correction notice:** The catchline of the original version was incorrect.

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