

Non-marine Permian biostratigraphy and biochronology: an introduction

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Abstract: The Permian time scale based on marine rocks and fossils is well defined and of global utility, but non-marine Permian biostratigraphy and chronology is in an early phase of development. Non-marine Permian strata are best known from western Europe and the western United States, but significant records are also known from Russia, South Africa, China and Brazil. Global time terms based on non-marine Permian strata, such as Rotliegend, Zechstein, Autunian, Saxonian and Thuringian, are either inadequately defined or poorly characterized and should only be used as lithostratigraphic terms. Macro- and microfloras have long been important in non-marine Permian correlations, but are subject to limitations based on palaeoprovinciality and facies/climatic controls. Charophytes, conchostracans, ostracodes and freshwater bivalves have a potential use in non-marine Permian biostratigraphy but are limited by their over-split taxonomy and lack of well-established stratigraphic distributions of low-level taxa. Tetrapod footprints provide poor biostratigraphic resolution during the Permian, but tetrapod body fossils and insects provide more detailed biostratigraphic zonations, especially in the Lower Permian. Numerous radioisotopic ages are available from non-marine Permian sections and need to be more precisely correlated to the global time scale. The Middle Permian Illawarra reversal and subsequent magnetic polarity shifts are also of value to correlation. There needs to be a concerted effort to develop non-marine Permian biostratigraphy, to correlate it to radio-isotopic and magnetostratigraphic data, and to cross-correlate it to the marine time scale.

In 1840, British geologist Roderick Murchison (1792–1871) visited Russia as a guest of the Czar. East of Moscow, he examined strata in the Perm region of the western Urals and applied the name ‘Permian System’ to a ‘vast series of beds of marls, schists, limestones, sandstones and conglomerates’ (Murchison 1841, p. 419) that overlie the Carboniferous strata in a great arc that extends from the Volga River in the west to the Ural Mountains in the east, and from the White Sea in the north to Orenburg in the south. Thus was born the Permian System, and, in western Europe, it soon came to be equated to the British New Red Sandstone and Magnesian Limestone, and to the German Rotliegend and Zechstein.

Much of Murchison’s type Permian section in Russia, and a significant portion of its equivalents further west in Europe, encompass strata of non-marine origin. However, by the twentieth-century, stratigraphers agreed that a global time scale (here referred to as the standard global chronostratigraphic scale, or SGCS) needs to be based on marine fossils in marine strata, not on

non-marine rocks and fossils. For this and other reasons outlined here, the development of non-marine Permian biostratigraphy and correlation has lagged behind developments in the marine realm.

The Permian period, as currently conceived, extends from about 251 to 299 Ma and encompasses nine ages (stages) arranged into three epochs (series) (Wardlaw *et al.* 2004) (Fig. 1). Most of this time scale (the Permian SGCS) has been defined by ratified global stratotype sections and points (GSSPs) for the stage boundaries (Henderson 2005). As the work of formally defining the Permian SGCS draws to a close, it is logical to push forward into developing non-marine Permian biostratigraphy and correlation. This volume is part of that push forward, as its articles present new data, analyses and understanding of the chronology of the non-marine Permian. In this introduction, we assess the state of the-art of non-marine Permian biostratigraphy and correlation, and place the articles in this book into that context.

Ma	PER	EPOCH	STAGE	
252	PERMIAN	LATE (Lopingian)	Changhsingian	
			Wuchiapingian	
260		MIDDLE (Guadalupian)	Capitanian <i>----- Illawarra -----</i>	
			Wordian	
270			Roadian	
			Kungurian	
280		EARLY (Cisuralian)	Wolfcampian	Leonardian
				Artinskian
290				Sakmarian
				Asselian
300	PENNSYLVANIAN		Gzhelian	

Fig. 1. The standard global chronostratigraphic scale (SGCS) for the Permian (after Henderson 2005).

The non-marine Permian world

The Pangaeon supercontinent came together (accreted) at the end of the Carboniferous, when Laurasia and Gondwana were sutured along what has been termed the Hercynian megasuture (Fig. 2). Very old mountain ranges mark the collision boundaries of the Pangaeon blocks: the Appalachian Mountains of eastern North America, the Ural Mountains of European Russia and the Variscan (Hercynian) mountain ranges of southern Europe and Mauretanic ranges of North Africa. The Late Carboniferous was a time of vast coal swamps in the tropical latitudes and a steep temperature gradient from icy poles to hot tropics, more similar to today's

world than perhaps at any other time in the Earth's history. In Gondwana, ice ages occurred that pushed glacial ice streams to within 30°S of the palaeo-equator.

Once assembled, at the beginning of the Permian, Pangaea stretched from pole to pole in a single hemisphere (Fig. 2). The ocean of Panthalassa covered the other hemisphere (two-thirds of the earth's surface). Permian Pangaea was a relatively diverse place in terms of climate and topography. Glacial deposits found in South America, Africa, India, Australia and Antarctica are evidence of the continuation of glaciations in southern Gondwana during the Early Permian (Veevers 2004). Along the sutures of Pangaea, huge mountain ranges towered over vast tropical lowlands. During the Mid- and Late Permian, interior areas included dry deserts where dune sands accumulated. Evaporites (particularly gypsum and halite) deposited in the southwestern USA and northern Europe document the evaporation of hot shallow seas and formed the most extensive salt deposits in the geological record. Perhaps the best testimony to the diversity of Permian Pangaea can be seen in its fossil plants, which identify several floral provinces across the vast supercontinent.

The Late Carboniferous (Pennsylvanian) and the Permian are distinguished by a degree of continentality only matched by the last 5 million years of Earth's history. This extensive continentality underlies numerous problems of Permian stratigraphy that range from local geological mapping to global correlations. These problems are well reflected in the recently published SGCS: most of the Pennsylvanian and Permian stages have been adopted relatively recently, compared to the much longer accepted stages of the Devonian, Mississippian and the Triassic (Ogg 2004). This is the result of conditions that are unique to the Phanerozoic.

One of these was the formation and break-up of the Pangaeon supercontinent, which was surrounded by a single ocean (Panthalassa) with only one intervening seaway, the Tethys. Of the two largest components of the supercontinent, Gondwana covered an area of about 73 million km² but was only about 15% covered by epi-continental seas, while Laurasia covered an area of about 65 million km² but was only about 25% covered by epi-continental seas. This exceptionally low sea level was due to the accumulation of water in polar and inland icecaps during the late Palaeozoic glaciations, little to no spreading activity of the mid-oceanic ridges and, possibly, to the elevation of the geoid because of thermal shielding by the huge landmass of Pangaea.

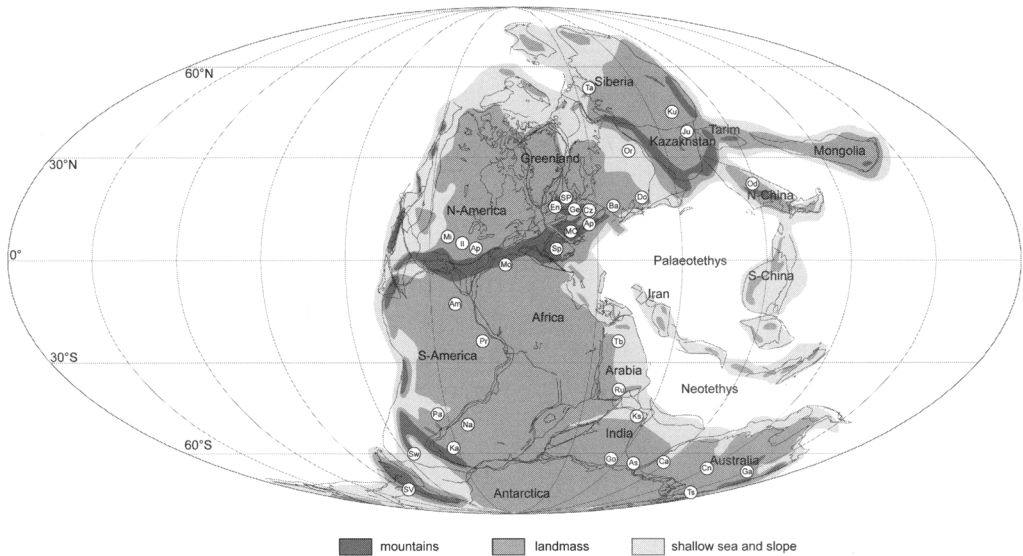


Fig. 2. Map of Pangaea at 270 Ma (modified from Golonka 2000) with the most important continental Permo-Carboniferous basins indicated. **Al**, Alpine basins, e.g. Carnic Alps, Collio Basin, Salvan-Dorénaz Basin; **Am**, Amazon Basin; **Ap**, Appalachian Basin; **As**, Assam-Arakan Basin; **Ba**, Balkan Basins, e.g. Moesian Basin, Resita Basin, Sirina Basin; **Ca**, Carnarvon Basin; **Cn**, Canning Basin; **Cz**, Czech Basins, e.g. Intra-Sudetic Basin, Boskovice Graben, Bohemian basins; **Do**, Donetsk Basin; **En**, localities of Hopeman and Elgin; **Ga**, Galilee Basin; **Ge**, German Basins, e.g. Saar-Nahe Basin, Thuringian Forest Basin, Saale Basin; **Go**, Godavari Valley Basin, Mahanadi Valley Basin; **Il**, Illinois Basin; **Ju**, Junggur Basin; **Ka**, Karoo Basin; **Ks**, Kashmir Basin; **Ku**, Kuznetsk Basin; **MC**, basins of Massif Central and surroundings, e.g. Lodève Basin, Autun Basin, Bourbon l'Archambault Basin, Commentry Basin; **Mi**, Midcontinent Basin; **Mo**, Moroccan Basins, e.g. Chougrane Basin, Khenifra Basin, Tiddas Basin, Souss Basin; **Na**, Namibia region; **Od**, Ordos Basin; **Or**, Orenburg region (Cis-Urals); **Pa**, Paraná Basin; **PB**, Northern and Southern Permian Basins; **Pr**, Parnaíba Basin; **Ru**, Rub Al Khali Basin; **Sp**, Spain Basins, e.g. Puertollano Basin, Cantabrian Mountains; **SV**, South Victoria Land, Trans-Antarctic Mountains; **Sw**, SW South America Basin, e.g. San Rafael Basin, Paganzo Basin, Golondrina Basin; **Ta**, Taimir Basin; **Tb**, Tabuk Basin; **Ts**, Tasmanian Basin.

Diverse tectonic processes, such as the collision of plates, closing of ocean basins, build-up and collapse of orogenic belts, compressional/extensional tectonics and the Late Permian onset of rifting that initiated the break-up of Pangaea, led to a wide variety of Permian basin types, ranging from marine to paralic foreland basins to intramontane and perimontane basins (Fig. 2). Linked to this, diverse tectonomagmatic processes – from synorogenic to post-orogenic magma intrusions, underplating and volcanism to rift-bounded upper mantle basalt extrusions – also influenced basin formation, the rejuvenation of topographic relief and basin reorganization. For example, in Europe, the Mid- to Late Permian cooling of the crust produced the huge southern Permian basin with an areal extent of about 2000×700 km, which was the embryonic stage of the Mesozoic and Cenozoic central European basin.

In this volume, **Roscher & Schneider** discuss the interference of these processes with the transition from the Palaeozoic icehouse to the Mesozoic greenhouse – a multi-stage process of wet and dry phases that created a very broad spectrum of facies types and facies architectures, and an array of evolving environments that triggered biotic evolution. Interrupted by the Permo-Triassic crisis, Mesozoic types of continental biota began to develop during the Permian (e.g. Kerp 1996; DiMichele *et al.* 2001; Kerp *et al.* 2006).

As a consequence, the continental biofacies patterns are as differentiated and complicated as are the lithofacies patterns. Each of the nearly 100 Permian continental basins in Euramerica therefore has its own lithostratigraphic subdivision, which can often only be correlated over several hundreds of square kilometres. Correlations are hampered by the distinctive development of

single basins that lack interbasinal lithological marker horizons or marine intercalations and the sparse and scattered fossil content of many of the non-marine Permian strata.

Non-marine Permian rock record

The non-marine rock record of the Permian System is very diverse and widespread. Long known and best studied are the western European Rotliegend and correlative strata. This is well reflected by several papers in this volume (Arche & López-Gómez; Durand; Roscher & Schneider; Virgili *et al.*) that focus on problems of tectonism, volcanism, sedimentation and ultimately correlation in the non-marine strata of the classical Permian basins in Germany, France, the Czech Republic, Italy and Spain. Also, in this volume, Hmich *et al.* present new stratigraphic and biostratigraphic data on the North African Permian strata.

Since the end of the eighteenth century, in the classical Permian basins of Europe, palaeontological research and sampling by scientists and private collectors focused on the Upper Pennsylvanian and lowermost Permian coal-bearing grey facies. This was driven by economic interest in Rotliegend coals (of poor quality) that were explored and exploited well into the twentieth century. In the French Autun Basin, extensive Upper Permian bituminous black shales have been exploited since the middle of the nineteenth century. Until 2002, open-cast coal-mining in the Bourbon-l'Archambault Basin of the French Massif Central yielded one of the most diverse late Lower Rotliegend or Upper Autunian faunas of lacustrine bituminous black-shale type. In the nineteenth century, the well-known fossiliferous geodes of the Rotliegend Lebach in the Saar-Nahe Basin were exploited for iron ore, and the fish coprolites of the Goldlauter lake horizon in the Thuringian Forest were a source of sulphide ores.

From the approximately 150 years of research history comes a detailed knowledge of the fossil biota of Permian swamp and lake environments. Nevertheless, modern palaeobiological research in combination with advanced sedimentology have recently added much new information on ecosystems, as exemplified by Boy (1998) and Boy & Schindler (2000).

The seemingly barren Permian red beds have not been regarded as of interest for palaeontology, other than tetrapod track sites, such as the Tambach locality of the Thuringian Forest, known since the end of the nineteenth century. In the 1960s, gas exploration in the Rotliegend

dune sandstones began. From this, arose a demand for palaeozoological biostratigraphy of grey to red clastics, poor or barren in plants. New biostratigraphic methods, based on insects, conchostracans, small amphibians and isolated fish remains, were developed (see below). Sediments of restricted lakes, grey and red alluvial plains and playa and sabkha deposits were intensively investigated for the first time. They yielded a thus far unknown fossil content, changing the picture of those environments, which had long been regarded as unfossiliferous in Germany, or 'azoique' in France (e.g. Schneider & Gebhardt 1993). The famous Tambach vertebrate site, with an upland tetrapod fauna of North American affinity, was also discovered at this time (Eberth *et al.* 2000), and arthropod tracks and freshwater jellyfishes of the genus *Medusina* were discovered to be common in floodplain pool and playa fine clastics (e.g. Walter 1983; Gand *et al.* 1996, 2000). For the first time in Europe, Early Permian aistopod-like amphibian remains were discovered in greyish micritic pond-limestones of red alluvial plain deposits with coarse channel fills and intensively rooted calcisols (Schneider & Rössler 1996).

During the last decade, one of the most remarkable discoveries in the western European Permian red beds is the fossil content of the Lodève playa at the southern border of the French Massif Central. Besides the well-known tetrapod tracksite of La Lieude (e.g. Gand *et al.* 2000), a very rich arthropod fauna with mass occurrences of conchostracans and triopsids, as well as a diverse insect fauna, was discovered in decimetre-wide, clayey-silty channel fills (Gand *et al.* 1997a, b; Bethoux *et al.* 2002). Higher in that section, sheetflood deposits containing carbonate nodules of reworked calcisols have yielded skeletal remains of an approximately 3-m-long caseid pelycosaur, similar to *Cotylorhynchus*, as well as the minute vertebral column of an embolomeroan amphibian, both clearly of North American affinity.

In this volume, Hmich *et al.* report on Permian tetrapod bones, the first in Morocco, discovered in reworked calcisols as well as in channel conglomerates, and new Lower to Upper Permian tetrapod tracksites. In contrast to North America and the eastern European platform, grey to red deposits of Permian alluvial environments were not investigated in detail in western Europe and North Africa during the last three decades, because research traditionally focused on coal-bearing sequences. The sediments of Permian alluvial plain environments are therefore a very promising prospect for future research.

According to **Virgili *et al.*** (this volume), in the continental domains of southwestern Europe, from the Carboniferous to Triassic, palaeontological investigations of the macroflora, microflora and tetrapod footprints, as well as radio-isotopic data, essentially indicate the presence of three main 'tectono-stratigraphic sequences,' separated by marked unconformities and gaps of as yet uncertain duration. The most significant geological episode began at about the Early Middle Permian boundary and persisted throughout the Middle Permian (Guadalupian) time. This episode was characterized by specific tectonic, magmatic, thermal and basinal features, which marked the presumed change, suggested by some authors (e.g. Muttoni *et al.* 2003), from a Pangaea 'A' to a Pangaea 'B' configuration.

The ancestral Rocky Mountain foreland of western North America has extensive non-marine Permian deposits, and their biostratigraphic records of tetrapod footprints and body fossils are discussed in this volume by **Hunt & Lucas, Lucas & Hunt,** and **Lucas.** The Ural foreland basin in Russia (Tverdokhlebov *et al.* 2005) and the Karoo foreland basin of southern Africa are also of importance to tetrapod biostratigraphy. In Brazil, the intracratonic Paraná Basin, and the Ordos and Junggur basins of northern China are some of the better-known locations that contain significant non-marine Permian rock and fossil records.

Non-marine Permian time scales

The first attempt to establish time units and correlations based primarily on non-marine Permian rocks was by Jules Marcou (1859), who introduced the term 'Dyas' for the '*nouveau grès rouge en Europe dans l'Amerique du Nord et dans l'Inde.*' At about the same time, the Germans Veltheim (1821–24) and Geinitz (1861) attempted to delineate the red beds of the Rotliegend and to correlate them with the classical Permian of the former Russian department of Perm in the Urals. Geinitz (1869) and Suess (1869) also correlated the Rotliegend of central Europe with some alluvial to lacustrine, plant-bearing dark shales of the upper Val Trompia, in the Southern Alps. The term 'Rotliegend' was then applied to strata in the Southern Alps by German geologists (e.g. Lepsius 1878; Gümbel 1880; Vacek & Hammer 1911; Heritsch 1939).

Several formally proposed subdivisions of Permian time have also been based on non-marine strata. These include:

- (1) Rotliegendes, used by Harland *et al.* (1990) as a series to encompass the Asselian, Sakmarian, Artinskian and Kungurian

Stages (but now abandoned and replaced by Cisuralian);

- (2) Autunian, Saxonian and Thuringian, which form a threefold division of Permian time based largely on French and German non-marine strata;
- (3) Tatarian, based on non-marine Middle–Upper Permian strata in the Russian Urals is a regional stage for the latest Middle Permian and the Upper Permian of the East European platform.

However, no global time scale based on non-marine Permian rocks and fossils is in use.

Thus, the 'parastratigraphic' subdivision into Autunian, Saxonian and Thuringian is neither a suitable chronostratigraphical division of the Permian System nor useful for correlation with non-European domains or with the international scale. This stratigraphic trinity can be compared with the Cisuralian, Guadalupian and Lopingian Series, but, based on current data, their temporal ranges and lack of proper stratotypical definition make the terms 'Autunian', 'Saxonian' and 'Thuringian' unsuitable for use in a global time scale. Despite this, Broutin *et al.* (1999) indicate that significant 'Autunian' floras (such as the mass presence of *Autunia*, *Rhachiphyllum*, *Lodevia*, *Arnhardtia* and *Gracilopterus*) are widespread and well known in many continental basins of Europe. Therefore, even though the temporal boundaries of this fossiliferous succession are not defined in the typical Autun Basin, the floral abundance and its biostratigraphical value cannot be underestimated. Indeed, Broutin *et al.* (1999) suggested that the fossil content of 'Autunian' should be regarded as characteristic of the basal and immediately older time interval (latest Ghzelian to the early Sakmarian) of the continental Permian.

The use of 'Saxonian', due to its chronostratigraphical inconsistency, should be rejected (e.g. Kozur 1986, 1993; Cassinis *et al.* 1992, 1995). In the type area, it seems to include more than six stages, from Sakmarian to basal Dzhulzfian. Thus, 'Saxonian' is too extensive temporally and lacks palaeontological characterization.

'Thuringian' has up to now been used in different countries of Europe to refer to both marine and continental strata, which often bear a number of palaeontological elements that generally pertain to Late Permian time. The type area of this unit, which represents an equivalent of the German Zechstein, corresponds to the Dzhulzfian and early Changshingian (Kozur 1988, 1993). However, the term has been subject to different stratigraphic interpretations, also equating it to the Kazanian and Ufimian.

Since Geinitz (1861), the German Rotliegend, and its literal translations – ‘Cervená Jalovina’ (Czech) or ‘Ėzerwonogo Spagowca’ (Polish) – have been regarded as of Permian age, as has the New Red Sandstone in England. But it is primarily understood as a lithostratigraphic unit. Indeed, ‘Rotes Todes Liegendes’ (or ‘red dead underlayer’: Freiesleben 1795) was a miner’s term for the ore-free continental red beds below the copper ore-bearing marine black shale, the approximately 40-cm thick Kupferschiefer (or ‘Copper slate’).

The Kupferschiefer and its equivalents, marine sandy to conglomeratic clastics as well as limestones and marls (e.g. the Marl Slate of the United Kingdom), mark the base of the second Permian unit: the Zechstein. Again, ‘Zechstein’ is an old miner’s term for ‘firm ground’ – the rock (*Stein*) on which the mine (*Zeche*) for the exploitation of the Kupferschiefer was built. The type area of both terms is the southern foreland of the Harz Mountains (Hercynian Mountains) in Germany at the northern border of the Thuringian basin.

The French term ‘Autunien’, later used as ‘Autunian’ in a chronostratigraphical sense, is comparable to the Rotliegend and is nothing other than a lithostratigraphical term. It was introduced by Mayer-Eymar (1881) as ‘Autunin’ for a sequence of sandstones with characteristic bituminous black shales in the Autun Basin of the French Massif Central. As often discussed (e.g. Kozur 1978; Broutin *et al.* 1999; Schneider 2001), the Autunian has no chronostratigraphical content, and the base and the top have not been biostratigraphically defined (Broutin *et al.* 1999).

The terms ‘Saxonian’ and ‘Thuringian’ were introduced by the French workers Munier-Chalmas & De Lapparent (1893). ‘Saxonian’ should refer to the red sandstones below the marine Zechstein in the Mansfeld area of the southern foreland of the Harz Mountains (former Saxony, or Sachsen, now Sachsen-Anhalt). Those red sandstones have been understood as Upper Rotliegend (Oberrotliegendes). But, by the end of the nineteenth century, it became apparent that they are only partly Rotliegend and that some of these red beds belong to the Mansfeld Subgroup, which is of Late Carboniferous age (see Roscher & Schneider, this volume).

Because of translation problems into French (Oberrotliegendes = Saxonian), the German term ‘Zechstein’ was replaced by ‘Thuringian’ because the Late Permian Zechstein crops out along the borders of the Thuringian basin. Clearly, both terms primarily indicate lithostratigraphical

units. Later attempts to give them a chronostratigraphical meaning were pointless because of the sparse fossil content of the continental red beds of the ‘Saxonian’ and the lack of exact correlation of the restricted-marine ‘Zechstein’ or ‘Thuringian’ to global marine scales (Legler *et al.* 2005; Roscher & Schneider 2005). Both terms are no longer in use in Germany, either as lithostratigraphical or as chronostratigraphical terms.

The term ‘Thuringian’ has often been used in palynostratigraphic publications to indicate microfloras of Late Permian Zechstein affinity. This is very misleading because it has been overlooked that, in the type area of the Zechstein of Lopingian age (the forelands of the Harz and Thuringian Forest Mountains), the youngest palynological records come from Lower Rotliegend (‘Autunian’) grey sediments of Early Permian (Asselian/Sakmarian) age (Schneider 2001; Roscher & Schneider 2005). The Early to Late Permian Upper Rotliegend (‘Saxonian’) red beds in this area are barren of microfloras because of oxidation. Thus, microfloras of ‘Thuringian’ affinity occur long before the Zechstein transgression took place. It follows that the terms ‘Saxonian’ and ‘Thuringian’ should be abandoned as chronostratigraphical units and that ‘Autunian’ should be used in its primary lithostratigraphical sense as ‘Autunin’ or ‘Autunien’, equivalent to the Lower Rotliegend.

Non-marine Permian biostratigraphy

Microfloras and macrofloras

The biostratigraphy of Permian continental deposits has long been based on microfloras (palynomorphs) and macrofloras (e.g. Kozur 1993; Utting & Piasecki 1995). Macrofloras are most valuable as environment indicators and for palaeogeography, as shown in many publications, for example, by Ziegler (1990) in his classical paper ‘*Phytogeographic patterns and continental configurations during the Permian period*’, and by Wang (1996), LePage *et al.* (2003), Berthelin *et al.* (2003) or Cleal & Thomas (2005).

An explosive diversification in the microfloral record is observed during the Late Carboniferous and the Permian, which enables concurrent range zonations based on the first appearances, acmes and last occurrences of different associated forms. Although the environmental influence on macrofloras is reflected in the microflora from local edaphic conditions up to floral provinces as well, regional palynostratigraphical correlations

within the same floral provinces or biomes are possible in the Permian, but correlations between different floral provinces remain speculative. Palynostratigraphy is used in many southwestern European continental deposits, as is shown in this volume by *Virgili et al.* and *Arche & López-Gómez*.

Roscher & Schneider, in this volume, discuss the decreasing marine transgressions during the Pennsylvanian and the aridization during the Late Pennsylvanian and the Permian that generated a change from inter-regionally balanced wet macro- and mesoclimates (with some degree of maritime imprint) to increasingly drier continental climates with stronger seasonality and stronger accentuation of meso- and microclimatic effects. This resulted in a strong edaphic differentiation of the floral associations. The persistence of conservative Carboniferous hydro- to hygrophilous floral elements into Permian (local) wet biotopes and the local appearance of modern typical Permian meso- to xerophilous floral elements in the Carboniferous underlies the well-known problems of Permian floral biostratigraphy (e.g. *Broutin et al.* 1990, 1999; *DiMichele et al.* 1996; *Kerp* 1996).

In this volume, *Rössler* provides an overview of two remarkable Permian petrified forests, those of Chemnitz, Germany, and northern Tocantins, Brazil. These essentially contemporaneous forests represent seasonally influenced, tree-fern-dominated plant communities in the Northern and Southern Hemispheres of Permian Pangaea. The outstanding three-dimensional preservation of particularly large fossil remains, made possible by siliceous permineralization, provides the opportunity to study the gross morphology, anatomy and internal organization of plant tissues in a way not allowed by other preservational states and will force a re-evaluation of the taxonomy and reconstructions of Early Permian floras.

Although the paper by *Rössler's* is the only one in this volume devoted strictly to palaeobotany, many of the other papers (especially those by *Virgili et al.*; *Arche & López-Gómez*, *Durand*, and *Hmich et al.*) rely heavily on fossil plant-based age determinations. The fact is that, despite the caveats and pitfalls, many age determinations in non-marine Permian strata continue to be plant based.

Charophytes

The oogonia of freshwater characean algae (gyrogonites) fossilize and have some utility in the correlation of non-marine strata, particularly in the Cretaceous and Cenozoic. However, the

Permian record of charophytes is very poorly known (*Feist et al.* 2005). 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.

Ostracodes

Non-marine ostracodes are very common in various lacustrine deposits of the Permian, ranging from 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 occurrences 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 ostracode-feeding predators.

The use of non-marine ostracodes in biostratigraphy is hampered by two factors. Firstly, freshwater ostracodes are very simple in terms of morphological features of the shell, and the state of preservation (lack of preserved muscle scars, deformation up to complete flattening during sediment compaction) very often prevents any precise identification. The second factor is their nearly hopelessly over-split alpha taxonomy, which may have been resolved by the taxonomic revisions carried out by *Molostovskaya* (2005). As observed in modern semiarid and arid environments in Africa and Arabia, the minute eggs of freshwater ostracodes are drought resistant. They were easily distributed over hundreds of kilometres by air currents. Therefore, Permian non-marine ostracodes could have promise for biostratigraphy.

Conchostracans

Conchostracans are bivalved crustaceans whose fossils have been employed in some non-marine Permian correlations (e.g. *Martens* 1982; *Schneider et al.* 2005). They have a very high distribution potential because of their minute, drought-resistant and wind-transportable eggs, and they often form mass accumulations in lacustrine lithofacies. Hence, conchostracans are some of the most common animal fossils of the continental Permian.

Nevertheless, the time ranges of many Permian conchostracan species have not been well established, and much alpha taxonomy needs to be resolved (e.g. *Martens* 1983; *Schneider et al.* 2005). If these obstacles can be overcome, then conchostracans may contribute

to regional and, perhaps, global non-marine Permian correlations.

Insects

As early as 1879, Scudder attempted to use insect wings for Permian biostratigraphy. Thus, he recognized the common occurrence of genera and species of blattid insects (cockroaches) in North America and Europe and their potential for 'delicate discriminations of the age of rock deposits' (Scudder 1885). Later, Durden (1969, 1984) proposed blattid zonation for the Pennsylvanian and Permian, but his correlations were doubtful because of inadequate taxonomy. Schneider (1983) published a revised classification of Pennsylvanian and Permian blattids, from which came the first proposal of spiloblattinid zones (Schneider 1982; Schneider & Werneburg 1993) and later of archimylacrid/spiloblattinid/conchostracan zones, for the Early Pennsylvanian (Westphalian A) through the late Early Permian (Artinskian).

In this volume, **Schneider & Werneburg** present an updated insect zonation for the Late Pennsylvanian to Early Permian with a time resolution of 1.5–2 Ma. The zonation is based on the morphogenetic evolution of lineages of time-successive species of three genera of spiloblattinids. All three genera are widely distributed in the palaeo-equatorial zone from Europe to North America. As **Schneider & Werneburg** note, new reports of spiloblattinid zone species in non-marine strata, intercalated with conodont-bearing marine strata in the North American Appalachian, Midcontinent and West Texas basins could be one key to the direct biostratigraphical correlation of continental Permian strata to the SGCS.

Bivalves

During the Carboniferous–Permian, non-marine bivalves, including anthracosids, palaeomutellids, and some myalinids (brackish water), had a worldwide distribution. Records include (but are not limited to): the Middle–Upper Permian Karoo Supergroup of southern Africa and Madagascar; the Permian Mount Glossopteris Formation of the Ohio Mountains, Antarctica; the Upper Carboniferous of Nova Scotia and the Upper Carboniferous to Lower Permian of the eastern United States; the Upper Permian (Tartarian) strata of the Oka–Volga River Basin in Russia; and the Upper Carboniferous Coal Measures of northern France, England and Ireland. Additional assemblages are known from

southern Asia and South America. Some biostratigraphic correlations have been based on these bivalves (e.g. Eagar, 1984), but their alpha taxonomy (taxonomic names of genera and species) seems extremely over-split, as most variation is ecomorphophenotypic, not interspecific, in origin.

Furthermore, it seems unlikely that the stratigraphical ranges of all non-marine Permian bivalves are well established. Thus, for example, Lucas & Rinehart (2005) recently documented *Palaeonodonta* in the Lower Permian of North America, whereas the genus is otherwise known from the Middle or Upper 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 all late Palaeozoic freshwater bivalves are not well known. This and the taxonomic problems should make us very cautious in using non-marine bivalves for Permian biostratigraphy.

Fishes

Fishes have never provided a robust biostratigraphy in non-marine strata. This is because of the limitations of these fishes and their fossils to specific lithofacies and locations, so that their record is dominated by facies-control and endemism. Permian xenacanth shark teeth have been applied to regional correlations between some neighbouring European basins, but their wider use is limited because the migration of fishes is restricted to joint river systems connecting the basins (e.g. Schneider 1996; Schneider *et al.* 2000). But, these fishes do deliver valuable information about basin interconnections and drainage systems (Schneider & Zajic 1994), as well as about ecological changes and events (Boy & Schindler 2000). Thus, the fish zonation of Zajic (2000) is actually a local ecostratigraphy of some Bohemian basins, not a robust biostratigraphy.

In this volume, **Stamberg** reviews the actinopterygian fishes from the continental Westphalian to Lower Permian basins of the Czech Republic and compares them to those of equivalent age in some other European basins. Nine genera of actinopterygians belonging to eight families are known from the Westphalian–Stephanian sediments, and five genera belonging to four families are known from the Lower Permian sediments of the Bohemian Massif. Very close relationships of the actinopterygian fauna between the Bohemian Massif and the basins of the French Massif Central are evident, but the resulting correlations are neither precise nor really extensive.

Tetrapod footprints

Permian tetrapod footprints are known from localities in North America, South America, Europe and Africa, and attempts to use footprints to correlate non-marine Permian strata have a long tradition, especially in Europe (Voigt 2005). This is reflected in the papers by **Gand & Durand**, **Hunt & Lucas** and **Lucas & Hunt** in this volume, which document the distribution of Permian tetrapod footprints and their use in biostratigraphy.

In this volume, **Hunt & Lucas** assign Permian tetrapod footprints to four ichnofacies, the *Chelichnus* ichnofacies from aeolianites and the *Batrachichnus*, *Brontopodus* and *Characichichnos* ichnofacies from water-laid (mostly red bed) strata (Hunt & Lucas 2006). In this volume, **Lucas & Hunt** conclude that Permian track assemblages of the *Chelichnus* ichnofacies are of uniform ichnogeneric composition and low diversity, range in age from Early to Late Permian, and are thus of no biostratigraphical significance.

In contrast, footprints of the *Batrachichnus* and *Brontopodus* ichnofacies represent two biostratigraphically distinct assemblages:

- (1) Early Permian assemblages characterized by *Amphisauropus*, *Batrachichnus*, *Dimetropus*, *Dromopus*, *Hyloidichnus*, *Limnopus* and *Varanopus*;
- (2) Mid- to Late Permian assemblages characterized by *Brontopus*, *Dicynodontipus*, *Lunaepes*, *Pachypes*, *Planipes*, and/or *Rhynchosauroides*.

Few Permian footprint assemblages are demonstrably of Middle Permian (Guadalupian) age, and there is a global gap in the footprint record equivalent to at least Roadian time. Permian tetrapod footprints thus only represent two biostratigraphically distinct assemblages: an Early Permian pelycosaur assemblage and a Mid- to Late Permian therapsid assemblage. Therefore, footprints provide a global Permian biochronology of only two time intervals, much less than the 10 time intervals that can be distinguished with tetrapod body fossils.

Tetrapod body fossils

Permian tetrapod (amphibian and reptile) body fossils have long provided a basis for non-marine biostratigraphy and biochronology (see reviews by Lucas 1998, 2002, 2004). The most extensive Permian tetrapod (amphibian and reptile) fossil records come from the western United States (New Mexico–Texas) and South Africa. In this

volume, **Lucas** uses these records to define 10 land-vertebrate faunachrons ('ages') that encompass Permian time. These faunachrons provide a biochronological framework with which to determine and discuss the age relationships of Permian tetrapod faunas. Their correlation to the SGCS and its numerical calibration is relatively straightforward in the Early Permian, as the Texas Lower Permian red-bed section has marine intercalations that yield fusulinids, conodonts and/or ammonoids that allow for marine ages to be assigned. Correlation of the Mid- to Late Permian tetrapod record with the SGCS is much less certain.

In Europe, biostratigraphical zonations of aquatic or semi-aquatic amphibians were presented by Werneburg (e.g. 1996, 2001, 2003). In this volume, **Werneburg & Schneider** present a revised amphibian zonation (nine amphibian zones) for the European Pennsylvanian and Lower Permian. The index fossils belong to species chronoclines of two or three closely related species. The time resolution of these amphibian zones is about 1.5 to 3.0 Ma, and biostratigraphic correlations based on them are applicable to 16 basins in the Czech Republic, Poland, France, Italy and Germany.

Isotopic ages

Relatively few reliable isotopic ages can be used to calibrate the Permian SGCS. Thus, the numerical calibration is imprecise, being based largely on interpolating between a cluster of radio-isotopic ages near the Carboniferous–Permian boundary, an Artinskian U–Pb age from Russia of 280.3 ± 2.5 , an U–Pb age of the Capitanian base of 265.3 ± 0.2 Ma, and a cluster of ages near the Permo-Triassic boundary (Wardlaw *et al.* 2004) (Fig. 1).

Many more radio-isotopic ages are available in non-marine Permian stratigraphic successions, especially in the German Rotliegend and related strata in France and Italy (e.g. Cadel 1986; Zheng *et al.* 1991–1992; Del Moro *et al.* 1996; Schaltegger & Brack 1999; Cassinis & Ronchi 2001; Deroin *et al.* 2001; Cassinis *et al.* 2002; Pittau *et al.* 2002; Bargossi *et al.* 2004; Roscher & Schneider 2005; Lützner *et al.* 2006). Some of these ages are old K–Ar ages of questionable precision, but recent work is providing more reliable Ar/Ar and U–Pb ages for some igneous rocks intercalated with non-marine Lower Permian strata. These numbers thus provide direct calibration of the non-marine fossil biostratigraphies of the Lower Permian rocks. Fewer Middle and Upper Permian isotopic ages are available in the non-marine succession, but

some are emerging from work on the Karoo Basin of South Africa (Bangert *et al.* 1999; Wanke *et al.* 2000).

These ages hold great promise for yielding a more precise numerical calibration of non-marine Permian biostratigraphy than can be directly achieved for the Permian SGCS. The challenges thus lie in cross-correlating non-marine Permian biostratigraphy to the SGCS so that all the ages can be combined to produce a more precise numerical time scale for the Permian.

Magnetostratigraphy

Most of Permian time has long been considered an interval when there was little or no reversal in the activity of the Earth's magnetic field. Thus, all of Early Permian and some Middle Permian time comprise the latter part of the Carboniferous–Permian reversed polarity superchron (also called the Kiaman superchron). The field began to reverse frequently during the Middle Permian, and this begins the Permo-Triassic mixed superchron. The initiation of the superchron is usually referred to as the Illawarra reversal.

The Illawarra reversal thus has been taken to provide an important datum for intercontinental correlation. Menning (2001) concluded that the Illawarra reversal is Early Capitanian: ~265 Ma on the SGCS. Thus, for example, its presence in the Russian Tatarian has been used to directly correlate the Russian non-marine section to the SGCS.

In this volume, Steiner presents a synthesis of Mid- to Late Permian and Early Triassic magnetostratigraphy, much of it from non-marine sections. From this, she recognizes a polarity pattern for the Mid- and Late Permian of two normal polarity intervals and, just below the Permo-Triassic boundary, a distinctive short-duration reversed-normal-reversed polarity pattern. According to Steiner, the oldest normal polarity in the Middle Permian occurred during the Wordian Stage, established by results from three global sequences. Therefore, the resumption of geomagnetic field reversals after the ~50 Ma-long Carboniferous–Permian reversed-polarity superchron was during the Mid- to Late Wordian, or ~267 Ma. If this is correct, then many accepted correlations based on the Illawarra reversal will have to be revised.

Conclusions

Despite nearly two centuries of study, non-marine Permian biostratigraphy and correlation remain poorly understood. However, a diversity

of biostratigraphical methods are available that need further development. In particular, sound alpha taxonomy and well-established stratigraphical ranges are needed for many fossil groups. A plethora of radio-isotopic ages in non-marine Permian rocks can be directly related to much non-marine Permian biostratigraphy. Furthermore, in Middle–Upper Permian strata, magnetostratigraphy provides another correlation tool. All three datasets for the correlation of non-marine Permian strata – biostratigraphy, radio-isotopic ages and magnetostratigraphy – need to be integrated and cross-correlated to the marine time scale. Only then can a better understanding of Permian earth history on land and sea be achieved.

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