THE INTERNATIONAL PERMIAN TIMESCALE: MARCH 2013 UPDATE

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Abstract—The Subcommission on Permian Stratigraphy is concentrating its efforts to establish the remaining three GSSPs in the Cisuralian as well as refining the Permian timescale for global correlation, including into the terrestrial realm. In this paper, we provide a brief overview on recent progress of Permian timescale development based on new biostratigraphic, geochemical and geochronologic data. The Permian Period was from 298.9 Ma to 252.17 Ma based on the latest U-Pb ages in the southern Urals and South China. The Cisuralian, Guadalupian and Lopingian have durations of 26.6 Myr, 12.5 Myr and 7.63 Myr, respectively.

INTRODUCTION

The international Permian timescale has been significantly improved during the past five years although no new GSSPs have been formally ratified since 2005. The Permian System is composed of three series (Cisuralian, Guadalupian and Lopingian in ascending order) and nine stages, among which significant progress has been made on the GSSPs and GSSP candidates. New data for several stages are now available. Three GSSPs (base-Sakmarian, base-Artinskian and base-Kungurian) remain to be proposed and ratified. We present here a brief summary and an updated timescale (Fig. 1) to show recent advances on each stage of the Permian System. This timescale is updated from Henderson (2005). A more comprehensive paper on the Permian timescale is presented by Henderson et al. (2012a), but some important data have been updated since then. The current chart provides the latest high-precision geochronologic dates for each stage, high-resolution biostratigraphic data based on multiple fossil groups including terrestrial tetrapods (Lucas, 2006), sea-level changes and paleomagnetic reversal zones. The Cisuralian Working Group has formally published the proposal for the candidates for the base-Kungurian GSSP (Henderson et al., 2012b; Chernykh et al., 2012), and the proposals for the base-Sakmarian and base-Artinskian are in preparation. High-resolution conodonts are from Henderson and Mei (2003) and Chernykh (2006) for the Cisuralian; from Glenister et al. (1999), Wardlaw (2000) and Jin et al. (2006a) for the Guadalupian; and from Jin et al. (2006b), Mei and Henderson (2004) and Shen and Mei (2010) for the Lopingian.

CISURALIAN

The base of the Permian System (also the base of the Asselian Stage) was defined by the First Appearance Datum (FAD) of Streptognathodus isolatus Chernykh, Ritter and Wardlaw at Aidaralash Creek, Aktöbe (formerly Aktyubinsk) region, northern Kazakhstan (Davydov et al., 1998). Biostratigraphic data from this GSSP have been rarely updated since it was defined. Geochemical and geochronologic data are not available. However, some progress was made from the Usolka section on the north bank of the Usolka River that was defined as an auxiliary section for the Carboniferous–Permian boundary (CPB) (Davydov et al., 1998; Schmitz and Davydov, 2012). The CPB is recognized in the Usolka section at the first occurrence of Streptognathodus isolatus associated with multiple ash beds, and the radiometric calibration and biostratigraphy for this part of the section has been published (Ramezani et al., 2007). Those radiometric ages were recently confirmed by new dating of ash beds above and below those ash beds dated by Ramezani et al. (2007). Thus, the CPB is interpolated as 298.9±0.15 Ma (Schmitz and Davydov, 2012). In addition, high-resolution carbon isotopic data were analyzed from the Usolka section. A gradually increasing trend in δ13C values from -4.8‰ at the base of the Asselian upward to 4.2‰ by new dating of ash beds above and below those ash beds dated by Ramezani et al. (2007). Thus, the CPB is interpolated as 298.9±0.15 Ma

The base of the Sakmarian was previously considered as the FAD of Sweetognathus merrilli Kozur at the Kondurovsky section in the southern Urals (Chuvashov et al., 2002b). However, subsequent studies indicate that the conodont lineage to define the base-Sakmarian GSSP at the Kondurovsky section proposed by the Cisuralian Working Group (Chuvashov et al., 2002b) was rare or absent in samples processed by different labs. Thus, the Kondurovsky section is no longer being considered, and the Usolka section is now under consideration as the candidate for the base-Sakmarian GSSP. Two alternative possibilities for defining the base of the Sakmarian Stage are under consideration. One is the FAD at 54.3 mab of Sweetognathus merrilli Kozur within the chronomorphocline Sweetognathus expansus–S. merrilli (Chernykh, 2005). However, results from the Apillapampa section in Bolivia, which yields abundant conodonts, interbedded with zircon-rich ash beds, demonstrates that forms comparable to Sweetognathus merrilli were present already in the mid-Asselian (Henderson and Kotlyar, 2009). The second option is the FAD at 51.6 mab of Mesogondolella uralensis Chernykh within the chronomorphocline of M. pseudoatriata–M. arcuata–M. uralensis (Chernykh, 2006). The latter lineage is considered acceptable by the Cisuralian Working Group because a similar lineage has been found from Nevada, SE Alaska and possibly in Arctic Canada (Henderson and Kotlyar, 2009). This lineage has not been confirmed yet in South China, which is an important area for global correlation. The estimated age of the base of the Sakmarian Stage is 295.0 Ma (Schmitz and Davydov, 2012). An excursion with double negative shifts in δ13C value is documented around the Asselian/Sakmarian boundary in both the Usolka and Kondovsky sections, which may have potential to serve as chemostratigraphic markers for intercontinental correlation (Zeng et al., 2012). However, more work in different areas is necessary to confirm this pattern.

The base of the Artinskian Stage is best represented in the Dalny Tulkas section, which was proposed as the GSSP for the base of the Artinskian (Chuvashov et al., 2002a). The base is proposed to be defined by the FAD in Bed 4 of Sweetognathus “whiteti” (Rhodes sensu Chernykh) within the chronomorphocline S. binodosus–S. anceps–S. “whiteti”. Three ash beds in the Dalny Tulkas section closely constrain the age of the base of the Artinskian to 290.1 Ma (Schmitz and Davydov, 2012). The δ13C and δ18O curves in the Dalny Tulkas section are characterized by a rapid
FIGURE 1. Updated Permian timescale. Geochronologic ages are combined from Shen et al. (2011) for the Lopingian; Schmitz and Davydov (2012) for the Cisuralian, Henderson et al. (2012a) for the GLB and Henderson et al. (2012b) for the base of Kungurian. Tetrapod biochronology is after Lucas (2006). Biostratigraphic columns are a work in progress and comments are invited.
and sharp drop around the Sakmarian/Artinskian boundary and a long-term deep depletion stage in the following Artinskian interval, which was interpreted as a diagenetic signature or a result of enhanced organic carbon burial and subsequent isotopic refractionation by microbial chemo-synthetic processes (Zeng et al., 2012). The strontium isotopic composition of seawater at the base of the Artinskian Stage is $^{87}\text{Sr}/^{86}\text{Sr} = 0.70767$ (Chernykh et al., 2012).

The base of the Kungurian Stage was proposed for the Mechetlino section exposed along the right bank of the Yuryuzan River downstream (Chuvashov et al., 2002a). However, subsequent studies indicated that samples collected to test reproducibility of the index conodont species Neostreptognathodus pnevi FAD did not produce any conodonts; the section is also too heavily weathered to carry out any chemostratigraphic analysis. Therefore, the Rockland section in the Pequop Mountains of Nevada, USA, with the same chronomorphochron from Neostreptognathodus pequopensis to N. pnevi was proposed as a potential new candidate for the base-Kungurian GSSP by SP&S (Henderson et al., 2012b).

Meanwhile, a new section called the Mechetlino Quarry section, which is about 600 m east of the previous Mechetlino section, was also proposed as a new candidate for the base-Kungurian GSSP (Chernykh et al., 2012). This section contains fusulinaceans, ammonoids, conodonts, and presumably some layers of volcanic ash beds. Unfortunately, there are no U-Pb ages for late Artinskian to Kungurian strata at both the Mechetlino and Rockland sections. However, strontium isotopic analysis of conodonts yielded reproducible values of $^{87}\text{Sr}/^{86}\text{Sr} = 0.70743$ to 0.70739. Projecting these compositions onto the interpolated seawater curve yields an apparent age for the boundary of 283.5 ± 0.5 Ma (Chernykh et al., 2012). This is much older than the age of 279.3 Ma for the base of Kungurian in GTS 2012 (Henderson et al., 2012a).

**GUADALUPIAN**

The Cisuralian/Guadalupian boundary (CGB) is defined by the FAD of Jinogondolella nankingensis within the conodont chronomorphochron from Mesogondolella idahoensis lamberti to Jinogondolella nankingensis that can be readily distinguished by the appearance of the distinctly characteristic serration on the anterior part of the Jinogondolella platform. However, the correlation between the fusulinacean-based Tethyan and the conodont-based international timescales of the Permian System has become one of the most disputed issues among the Permian community during the past two decades; this uncertainty is reflected in Figure 1. The main problem was derived from the appearance of Murgabian fusulinids including Neoschwagerina simplex in a horizon about 150 m below the first appearance of the serrated conodont Jinogondolella nankingensis at the Luodian section in Guizhou, South China. This point may actually be close to the base of the Roadian if the first occurrence of serrated conodonts is diachronous at the section. The co-occurrence of Neoschwagerina simplex with some Kungurian conodonts has been confirmed recently based on the collection from Hatahoku, Japan (Shen et al., in press). However, preliminary results from SE Pamir suggest that in the Tethyan stratotypes, N. simplex co-occurs with conodonts that straddle the Kungurian-Roadian boundary and range up into the Roadian. Geochronologic constraints for the CGB are interpolated as 272.3 Ma in GTS 2012 (Henderson et al., 2012a). Recently, U-Pb ages from two volcanic ash beds around the CGB at Chaochu, South China were dated as 272.0±5.5 Ma (MSWD=2.6) and 271.5±3.3 Ma (MSWD=1.7) (Zhu et al., in press).

The three Guadalupian GSSPs were defined more than 10 years ago (Glenister et al., 1999), but little has been updated since then. Although they are the earliest GSSPs defined in the Permian, the GSSP papers have not yet been published, and conodonts from the actual GSSP levels have yet to be figured. Furthermore, high-resolution chemostratigraphy for the whole Guadalupian Series is not available. Only one numerical age, of 265.3 Ma from an ash bed, which lies 2 m above the top of the Hegler Member, 20 m below the base of Capitanian Stage, is available (Bowring et al., 1998). The interpolated ages are 265.1 Ma for the base Capitanian Stage and 268.8 Ma for the base of the Wordian (Henderson et al., 2012), but many more control points are needed. The Illawarra Reversal during the late Wordian (ca. 266 Ma) is a mark for time correlation among different regions. This reversal represents a remarkable change in geomagnetism following the long-term stable Kiaman Reversal Superchron (throughout the Late Carboniferous and Early-Middle Permian) and marks the beginning of the Permian–Triassic Mixed Superchron with frequent polarity changes during the Late Permian and Triassic (Embleton et al., 1996; Isozaki, 2009; Jin et al., 1999; Vozarova and Tunyi, 2003). This reversal has not yet been found in South China due to a serious Mesozoic magnetic overprint. Another useful marker in chemostratigraphic correlation of the Late Guadalupian is the late Capitanian minimum of $^{87}\text{Sr}/^{86}\text{Sr}$ ratio (ca. 0.7068–0.7069; ~260.4 Ma), which represents one of the most significant features in Phanerozoic seawater $^{87}\text{Sr}/^{86}\text{Sr}$ history (Kani et al., 2013; Liu et al., 2013; McArthur et al., 2012; Veizer et al., 1999).

Carbon isotope chemostratigraphy around the GLB has been extensively studied in different sections, but the results are controversial. A large negative shift was reported from the late Capitanian Jinogondolella xuanhanensis/J. prexuanhanensis zones in Guizhou, South China (Wignall et al., 2009), but this negative excursion is not confirmed at the Penglaian GSSP section (Chen et al., 2011). A negative excursion with minor magnitude at GLB was reported by Wang et al. (2004) and Jin et al. (2006a), but may have little significance. A significant positive excursion of carbon isotopic values during the late Capitanian was documented as the Kamura event by Isozaki (2007), but the precise horizon with this event based on conodonts is still unclear.

**LOPINGIAN**

The Guadalupian/Lopingian boundary (GLB) is defined by the chronomorphochron from Clarkina postbitteri hongsbiensis to C. postbitteri postbitteri at the Penglaian section in Laibin, Guangxi Province of South China. Conodonts reported from other sections (Lambert et al., 2002, 2010; Nishikane et al., 2011; Xia et al., 2006; Zhang et al., 2007) as representing this chronomorphochron are mostly questionable in terms of taxonomy. This boundary was associated with the Emeishan volcanism and the largest regression during the Phanerozoic. A widespread distinct disconformity is present in most areas around the world. Only a few areas, such as South China, Iran, and SE Pamir possess continuous deposits around the GLB. The age of the GLB is much discussed and still uncertain. Although widespread volcanism was present around the GLB and numerous dating of the Emeishan basalt has been carried out, high-precision ages are still not available. Some new zircon CA–TMS–U–Pb ages were obtained from intrusive rocks of the Panxi region (Inner Zone) of the Emeishan Large Igneous Province, which yielded a wide range of ages between >257 Ma and ~260 Ma (Shellnutt et al., 2012). An age of about 259 Ma is suggested by Shen et al. (2010) and 259.8 Ma is provided in GTS 2012 (Henderson et al., 2012a). A combined study of mineralogy, geochemistry and geochronology on six layers of claystone around the GLB at the Penglaian GSSP section indicate that the Penglaian claystones are not suitable for age determination of the GLB (Zhong et al., 2013).

The Wuchiapingian/Changhsingian boundary (WCB) has been well constrained within the conodont chronomorphochron from Clarkina longicuspidata to C. wangi at the Meishan GSSP section (Jin et al., 2006b). This same conodont succession was also confirmed at the Shangsi section in Sichuan province, South China. High-precision CA–TMS–U–Pb ages are available from both the Meishan and Shangsi sections. The WCB is bracketed by two ash beds at Shangsi and constrained by a few ages above the WCB at the Meishan GSSP section; it is estimated as 254.14 Ma (Shen et al., 2011) and 254.2 Ma (Henderson et al., 2012a).

The Permian–Triassic boundary (PTB) is very well dated because of a concentrated effort to understand the largest mass extinction in Earth
history that occurred immediately below the PTB (Shen et al., 2011). This boundary, defined by the FAD of *Hindeodus parvus*, has been well dated by two ash beds at the Meishan GSSP section. Bed 25 is 252.28±0.08 Ma and Bed 28 is 252.10±0.06 Ma. An interpolated age for the PTB of 252.17±0.06 Ma is suggested from Meishan section data (Shen et al., 2011). The high-precision CA–TIMS U-Pb ages offer far greater resolution at this level than that based on conodont zones.

**MARINE-TERRESTRIAL CORRELATION**

The Permian time scale is based on the marine record, and, although a few problems and issues are outstanding, it is essentially established. The next major direction for SPS research is to build a rich record of terrestrial correlation proxies including insects, fresh water invertebrates, vertebrates, palynology, paleobotany, magnetostratigraphy, chronostratigraphy and especially geochronology. Figure 1 provides a preliminary assessment of appearances of key vertebrate taxa during the Permian (Lucas, 2006). The latter gives a very rough time frame for the continental Permian and its correlation to the marine global scale. Besides the vertebrate zonation of continental deposits, several other tools have been developed for detailed stratigraphic subdivisions and correlations of continental deposits in the different Euramerican non-marine basins. Most detailed and reliable are the insect (spiloblattinid) and amphibian (branchiosaurid) zonations (Schneider, 1982; Wennerburg, 1989; Schneider and Wennerburg, 2006; Wennerburg and Schneider, 2006). But, neither epoch nor stage boundaries are really directly correlated by co-occurring marine and nonmarine zone fossils or reliable isotopic ages thus far (e.g., Menning et al., 2006; Roscher and Schneider, 2005; Lützner et al., 2007).

Recently, most promising for direct marine–non-marine correlations are ongoing investigations in mixed marine-continental Late Pennsylvanian/Early Permian deposits in New Mexico and brand new discoveries of insect zone species in similar deposits of the Donets Basin, which provide for the first time direct links between conodont and foraminifer zones as well as insect zones for the Late Pennsylvanian and earliest Permian (Schneider et al., 2004; Lerner et al., 2009; Lucas et al., 2011, 2013). An updated version of the current state for the Carboniferous/Permian transition is given by Schneider et al. (2013, this volume).

The focus of future work on marine–non-marine correlations should be set for the Cisuralian and Guadalupian mainly on mixed marine-terrestrial deposits on the East European platform and in the North American Midcontinent basins and the East European platform (Sennikov and Golubev, 2006, 2012; Sherbakov, 2008). Most importantly, there needs to be more intensified cooperation by SPS with stratigraphers working in the huge nonmarine basins of Gondwana. The correlation of the Lopingian Series based on marine-terrestrial transitional deposits in South China (Shen et al., 2011) and the vertebrate assemblages in the Middle and Late Permian in the Karoo Basin, South Africa, which is precisely calibrated by a set of new CA–TIMS U-Pb ages (Rubidge et al., 2013), are both excellent examples of how to develop an integrated marine and non-marine time scale.

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