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Editorial

Late Paleozoic deep Gondwana and its peripheries: Stratigraphy, biological events, paleoclimate and paleogeography

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It is important that new tools and data for quantitative reconstruction of past environmental conditions continue to be developed and applied to existing stratigraphic records. New analytic tools and fossil records are now allowing us to put changes in the Earth's landscapes in context with changes in other parameters such as temperature, atmospheric conditions, and the chemical composition of the ocean. The Late Paleozoic features some of the earth's unprecedented physical and biological transitional events of global scale and critical significance. Most notably, these events include:

1) The transition from a united supercontinent Pangea to the breakup and initial dispersal of this supercontinent. To date, there is a growing body of published evidence indicating that the peri-Gondwanan region was extremely active tectonically during the Late Paleozoic, involving tectonic rifting and drifting of Gondwana-derived terranes and, to a lesser extent, amalgamation of some blocks (Shi et al., 1995; Zhou et al., 2002; Metcalfe, 2011; Klootwijk, 2013; Zhang et al., 2013). Those tectonic rifting and drifting events of different blocks had directly led to dramatic paleogeographical and paleobiogeographical changes in the northern peri-Gondwanan region and Paleotethys as indicated by pronounced sequential changes in sedimentary facies and biotas (Shi et al., 1995; Metcalfe, 2011; Zhang et al., 2013), as well as volcanic eruptions in the Permian (Wignall, 2001; Zhou et al., 2002; Kamo et al., 2003; Xu et al., 2004; Li et al., 2011).
2) The transition of the Earth's global climate regime from an icehouse to a greenhouse condition through the Late Paleozoic was equally profound. Advances in modeling in the past 30 years have provided important insights into the future of the Earth's climate and environment, but most research has focused on the climate state of the Earth for the very recent past—younger than 2 million years, when the northern hemisphere ice cap was present. The waning of the ice caps and the rise of atmospheric CO_2 concentrations are rapidly taking the Earth into conditions not experienced for more than 30 million years. Hence the models on which we rely to predict future changes are unlikely to be fully developed for the states of radically different Earth systems. The Late Paleozoic Ice Age (LPIA) marked by widespread glaciation probably began in the Late Devonian or Early Carboniferous and ended in the Early Permian (Cisuralian) when it started to transition into a greenhouse regime (Isbell et al., 2003; Montanez et al., 2007; Fielding et al., 2008; Shi and Waterhouse, 2010; Isbell et al., 2012; Chen et al., 2013). It is interesting to note here the possible parallels between this major global climate regime shift in deep geological time and the transition from icehouse to global warming that the Earth is currently experiencing. This comparison would indicate that deep-time geo-historical records may provide a narrative of the changes in the Earth's past climate, environment and life. The knowledge and a good understanding of the past are clearly important for evaluating the current situation and for understanding future trends of the Earth system (NRC, 2011).
3) A profound change of the global ecosystems and biotas is marked by the earth's most devastating post-Proterozoic mass extinction event at the Permian–Triassic boundary which was also associated with dramatic environmental changes (Shen et al., 2011; Payne and Clapham, 2012; Retallack, 2013).

In this special issue, we intend to bring together a multidisciplinary suite of high-quality papers that 1) document the paleogeographical, paleobiogeographical and paleoclimatic changes across Gondwana and its peripheries during the Late Paleozoic and Early Triassic, and 2) discuss the underlying forces (factors) that may have triggered and regulated these changes. Our primary aim was to address specific changes and their causes at a continental to a global scale. Several general review papers on LPIA, paleoclimatic and biotic changes, paleogeography and tectonic evolution and paleobiogeography are also included (Chen et al., 2013; Klootwijk, 2013; Retallack, 2013; Shen et al., 2013; Zhang et al., 2013).

This special issue is based on extensive communications with geoscientists who have worked on the aspects of Late Paleozoic Gondwana and its peripheries. All studies document the latest progress on tectonic, paleogeographical, geochemical, paleobiogeographical, paleoclimatic and biotic evolutions of deep Gondwana and its peripheries. Some of these invited papers have been presented by their respective authors at two recent international conferences: the XVII International Conference on the Carboniferous and Permian (XIV ICCP) held in July 2011 in Perth, Australia; and the Gondwana 14 international conference held in September, 2011 in Buzios, Brazil.

Geological and oxygen isotopic evidence indicate that the maximum ice volume of LPIA was as great as or greater than that during the Pleistocene glacial maxima (Joachimski et al., 2006). The last time the Earth experienced a global climate regime change from an icehouse to a greenhouse state was in the mid-Permian (Isbell et al., 2003; Fielding et al., 2008). Therefore, studies of LPIA would provide important insights and a possible analog for the current climatic transition. In this special issue, a few studies based on different proxies document paleoclimatic changes in the Late Paleozoic. Chen et al. (2013), for the first time, provide a secular paleotemperature history

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for the entire Permian based on oxygen isotope analyses of conodont apatite from South China, Iran and West Texas, USA. They reported that the transition from an icehouse to a greenhouse of LPIA actually began in the Late Kungurian times based on paleotemperature trend in the tropical area, in contrast to some earlier views in favor of the LPIA terminated in the Middle Sakmarian or Artinskian based on southern and northern high-latitude areas (Isbell et al., 2003; Fielding et al., 2008; Zeng et al., 2012). Significant temperature fluctuations are observed during the Guadalupian–Lopingian transition (Chen et al., 2011), and a trend of climate cooling through and up to the latest Changhsingian as evidenced by paleontological studies in temperate settings such as Tibet, Pakistan etc. (Shen et al., 2006, 2010). Recent stable isotope studies of conodont apatite indicate that sea temperatures at the Permian–Triassic boundary rose by 8–10 °C, suggesting a rapid warming event coinciding the end-Permian mass extinction. This accelerated warming at the end-Permian is increasingly being linked to the massive release of greenhouse gases derived from the Siberian Traps volcanism and related processes (Ryskin, 2003; Shen et al., 2011; Joachimski et al., 2012; Sun et al., 2012).

Stable carbon and oxygen isotope compositions of brachiopod shells are among the most widely adopted geochemical indicators to quantitatively explore Paleozoic climate and environments. However, different oxygen and carbon isotopic values have been reported for the Permian (Korte et al., 2005; Grossman et al., 2008; Zeng et al., 2012). In this issue, Mii et al. (2013) analyzed 120 brachiopod samples for carbon and oxygen isotopes based on Permian brachiopod shells from Western Australia. Their results suggest that an average oxygen isotope values of brachiopod shells from Western Australia do not appear to be tightly correlated to any glacial–interglacial intervals reported (Isbell et al., 2003; Fielding et al., 2008), nor do they provide paleotemperatures consistent with those from southeastern Australia (Mii et al., 2012). This discrepancy is interpreted by the authors (Mii et al., 2013) to be, at least in part, due to different seawater salinities between eastern and Western Australian basins during the Permian.

The paleosols from the Permian–Triassic transition also offer evidence for the relationship between paleoclimate and atmospheric CO_2 levels, leading to the recognition of several intervals characterized by heightened atmospheric CO_2 concentrations. These greenhouse events (intervals) appear to have punctuated the evolution dynamics of plants and reptilian land animals during the Permian–Triassic transition (Retallack, 2013).

The paleoclimatic changes throughout the Permian have been analyzed by Waterhouse and Shi (2013) based on the successive brachiopod and bivalve zones of eastern Australia and New Zealand. They recognized three glacial intervals in the Cisuralian (Early Permian), followed by a cold Roadian interval and a very late Lopingian episode intervened by marked warm intervals. The paleoclimatic history indicated by benthic megafossils are generally consistent with that derived from oxygen isotope analyses of conodont apatite (Chen et al., 2013), but some differences are also apparent probably because of different proxies, paleo-latitudinal positions and/or different resolution in correlation and timescale.

The occurrence of paleowildfire is another proxy related to climatic changes. The estimated high atmospheric oxygen concentration during the Late Carboniferous and Early Permian made vegetation highly flammable, therefore conducive for occurrences of paleowildfires. The scarcity of charcoal remains after the cessation of peat deposition suggests a warm Late Permian. Based on a review of all occurrences of paleowildfire on Gondwana, Jasper et al. (2013) concluded that wildfires occurred in several regions and time-slices during the Permian in Gondwana, corresponded to the transition from a cold to a cool and warm climate interval. Almost all of the known evidences of Permian wildfires on Gondwana come from broadly the same paleolatitudes, which are connected to the occurrence of climatically-controlled peat deposition.

There are numerous direct sedimentary products of LPIA in Gondwana. Koch and Isbell (2013) reported their study of grounding-line fans in the Lower Permian Pagoda Formation in the central Transantarctic Mountains, Antarctica. Such fans were formed due to the expulsion of sediment laden subglacial waters at the grounding-lines of temperate tidewater glaciers (Powell, 1990). Thus, they suggested that numerous small glaciers occurred in South Polar Antarctica during the LPIA rather than a large terrestrial ice sheet centered over the Transantarctic Mountains for up to 90 million years.

Paleogeography, paleobiogeography and tectonic processes, associated paleoenvironmental changes and biotic responses at the interface between Gondwana and Tethys

The Permian was a period with the most distinctive provincialism due to the closure of the seaway between Gondwana and Euramerica and the formation of the supercontinent Pangea. Extensive literature has documented the Permian paleobiogeography and a triple-zoned, paleolatitude-dependent three-realm pattern of the Permian biosphere, including the Boreal, the Paleoequatorial and the Gondwanan realms, has long been recognized. The peri-Gondwanan region was very active during the Late Paleozoic in tectonism marked by many rifting and drifting events. A number of biotic provincial names have previously been proposed for Gondwana, but mostly were at a regional scale and based on qualitative or semi-quantitative analyses. Brachiopods are one of the best-studied fossil groups to recognize the paleobiogeography during the Late Paleozoic. Shen et al. (2013) provided a global analysis and a review on the Cisuralian (Early Permian) paleobiogeography based on a newly-established global database. This study as well as their previous studies for younger Permian stages (Shen and Shi, 2000, 2004; Shen et al., 2009) revealed that a few different provinces in the peri-Gondwanan region had not been previously recognized at a global scale, and that the characteristic two transitional zones [northern and southern transitional zones of Shi et al. (1995)] first developed in the Sakmarian and Kungurian, respectively. They also revealed that a paleolatitude-related thermal gradient was the major controlling determinant for the Cisuralian provincialism and brachiopod distribution. The transition from an icehouse to a greenhouse stage led to a steady increase in brachiopod diversity and provincialism during the Cisuralian and Guadalupian. In addition, Angiolini et al. (2013) also provided a quantitative analysis on the Guadalupian (Middle Permian) brachiopods from the different terranes in the peri-Gondwanan region and Paleotethys. They showed how the evolution of the brachiopod provinces responded to the changing climate and paleogeography boundary conditions across the southern and northern margins of the opening Neotethys Ocean during the Guadalupian.

The Qinghai–Tibet Plateau in China consists of an array of different terranes now sutured together. Understanding the origin and geologic history of these terranes is difficult because of the complicated tectonic history. A comprehensive review on the Late Paleozoic history of these terranes is presented by Zhang et al. (2013) based on a large set of lithostratigraphic, biostratigraphic and paleontoloigcal data. Based on their study, the development of the southern transitional zone and the Middle Permian Cimmerian province is closely linked to and driven by the northward drift of the Cimmerian Continent, superimposed with a gradual global warming in the wake of the Gondwanan deglaciation. They proposed a new paleogeographic reconstruction in that all major peri-Gondwana blocks constituted three different continental slices, rather than one as perceived in some previous literature.

The Sibumasu Terrane in Southeast Asia consists of allochthonous blocks located between Gondwana and Eurasia and its tectonic evolutionary history has long been the subject for hot discussion. Wang et al. (2013) documented, based on the temporal and spatial distributions of solitary rugose coral *Cyathaxonia* faunas, that the Sibumasu