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Late Palaeozoic global changes affecting high-latitude environments and biotas: An introduction

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ABSTRACT

The Late Palaeozoic Ice Age (LPIA), spanning approximately from ~320 Ma (Serpukhovian, late Mississippian) to 290 Ma (mid-Sakmarian, Early Permian), represents the vegetated Earth's largest and most long-lasting regime of severe and multiple glaciations, involving processes and patterns probably comparable to those of the Last Ice Age. Accompanying the LPIA occurred a number of broadly synchronous global environmental and biotic changes. These global changes, as briefly reviewed and summarized in this introductory paper, comprised (but are not limited to) the following: massive continental reorganization in the lead up to the final assembly of Pangea resulting in profound changes in global palaeogeography, palaeoceanography and palaeobiogeogarphy; substantially lowered global atmospheric carbon dioxide concentrations (pCO_2), coupled with an unprecedented increase in atmospheric oxygen concentrations reaching Earth's all-time high in its last 600 million year history; sharp global temperature and sea-level drops (albeit with considerable spatial and temporal variability throughout the ice age); and apparently a prolonged period of global sluggish macro-evolution with both low extinction and origination rates compared to other times. In the aftermath of the LPIA, the world's climate entered into a transitional climate phase through the late Early to Middle Permian before its transformation into a greenhouse state towards the end-Permian. In recent years, considerable amount of data and interpretations have been published concerning the physical evidence in support of the LPIA, its broad timeframe and eustatic and ecosystem responses from the lower latitudes, but relatively less attention has been drawn to the impact of the ice age on late Palaeozoic high-latitude environments and biotas. It is with this mission in mind that we have organized this special issue, with the central focus on late Palaeozoic high latitude regions of both hemispheres, that is, Gondwana and northern Eurasia. Our aim is to gather a set of papers that not only document the physical environmental changes that had occurred in the polar regions of Gondwana and northern Eurasia during the LPIA, but also review on the biotic responses at different taxonomic, ecological and spatial scales to these physical changes in a refined chronological timeframe.

This introductory paper is designed to provide a global context for the special issue, with a brief review of key late Palaeozoic global environmental changes (including: changes in global land-sea configurations, atmospheric chemistry, global climate regimes, global ocean circulation patterns and sea levels) and large-scale biotic (biogeographic and evolutionary) responses, followed by a summary of what we see as unresolved scientific issues and various working hypotheses concerning late Palaeozoic global changes and, in particular, the LPIA, as a possible reference to future research.

1. Introduction

The Late Palaeozoic Ice Age (LPIA), spanning approximately from Serpukhovian (~320 Ma) to mid-Sakmarian (~290 Ma), signifies the vegetated Earth's largest and most long-lasting regime of severe and multiple glaciations, involving processes and patterns probably comparable to those of the Last Ice Age. At the peak of the LPIA, continental ice sheets of Gondwana extended from the south pole to latitudes as low as ~30°S (e.g. Montañez et al., 2007), accompanied by broadly synchronous glacial/interglacial cycles over Gondwana, substantially lowered global atmospheric carbon dioxide concentrations (pCO_2), sharp global temperature and sea-level drops, and apparently a prolonged period of global sluggish macro-evolution with both low extinction and origination rates compared to other times (Fig. 1A–C). In the aftermath of the LPIA, the world climate entered to a transition phase through the late Early and all of the Middle Permian before its transformation into a greenhouse state towards the end-Permian. Whilst broad consensus exists regarding

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the recognition of late Palaeozoic glacial deposits and landforms (e.g. Fielding et al., 2010-this issue; Henry et al., 2010-this issue; and also see Fig. 2 for some of the most spectacular LPIA field evidence), its broad timeframe and eustatic and ecosystem responses from the lower latitudes (e.g. Montañez et al., 2007; DiMichele et al., 2009), considerable differences still prevail concerning a range of issues, notably: (i) the detailed chronology and correlation of the LPIA at high latitudes of both hemispheres; and (ii) the processes and patterns of biotic responses to the LPIA and its icehouse-to-greenhouse transition at high latitudes.

It is with these questions in mind we have organized this special issue, with the central focus on late Palaeozoic high latitude regions of both hemispheres, that is, Gondwana and northern Eurasia (Fig. 3). Our aim is to gather a set of papers that not only document the physical environmental changes that had occurred in the polar regions of Gondwana and northern Eurasia during the LPIA, but also reviews on the biotic responses at different taxonomic, ecological and spatial scales to these physical changes in a refined chronological timeframe. The concept of this special issue arose from two recently held international field workshops organized by one of the IUGS ICS (International Commission on Stratigraphy) SPS (Subcommission on Permian Stratigraphy) international working groups. Both field workshops were designed to examine some of the best exposed upper Palaeozoic glacial and glacially influenced depositional sequences and fossil records of Gondwana (see Fig. 2) in two vastly separate regions. The first of these workshops was held in February 2008 in the southern Sydney Basin, southeastern Australia, attended by 15 geologists from several different countries (Fig. 2A), with a focus on the Lower to Middle Permian glacigene marine sediments and fossil successions in one of the best exposed upper Palaeozoic successions in eastern Gondwana. The second international field workshop was held in the following year (February–March 2009) in western Argentina and Patagonia (Fig. 2B), located in southwestern Gondwana during the late Palaeozoic (Fig. 3), attended by some of the members who had also attended the Australian field workshop. The results of these field workshops and field discussions are reflected in some of the papers included in this special issue, along with a few invited papers closely linked to the theme of the special issue (i.e. papers by Fielding et al., 2010-this issue, Henry et al., 2010-this issue, Reid and James, 2010-this issue — all in this volume).

The theme of this special issue complements two other recently published special issues, edited respectively by Fielding et al. (2008a) and Soreghan and Montanez (2008). All three publications focus on the LPIA, but they have different aims. The works compiled and edited by Fielding et al. (2008a) concentrated on the stratigraphic record, especially sedimentological and biostratigraphic aspects, of the LPIA from both near-field (Gondwana) and far-field (Eurasia) records. In contrast, papers in the volume compiled by Soreghan and Montanez (2008) were restricted to the far-field records of the late Palaeozoic equatorial Pangea. The present PPP special issue is intended to bring together a group of papers that document, compare and interpret high-latitude late Palaeozoic depositional successions, environmental processes and changes (including palaeoclimate change) and biotic responses, covering high latitude regions of both hemispheres (Fig. 3).

To provide a global context for the special issue, in this introductory paper we intend to first summarize key features of late Palaeozoic global changes and large-scale biotic responses. We then proceed with a summary of unresolved scientific issues and various working hypotheses concerning late Palaeozoic global changes and, in particular, the LPIA, as a possible reference to future research.

2. Global changes in the Late Palaeozoic — a summary

The late Palaeozoic interval was a time of significant global changes, some occurred concurrently while others developed in sequential manner. Some of these major global changes are generalized and illustrated in Figs. 1 and 4, and are further briefly summarized below.

2.1. Changes in continental configuration and formation of Pangea

Among all global changes, the most fundamental and also one of the rarest occurrences in Earth history is the formation of supercontinents. Pangea, earth's most recent supercontinent, took its final shape in the Early Carboniferous about 320 Ma and lasted about 120 million years until starting to break up in late Triassic (Gutiérrez-Alonso et al., 2008). The continental assembly process in the lead up to the final formation of Pangea and the ensuing consolidation stage prior to its breakup is believed by some (e.g. Tajika, 2007; Link, 2009) to have played an important role for the origin of the LPIA and other associated continental to global environmental changes (Link, 2009). This is considered so because the formation of Pangea would have substantially increased earth's chemical weathering rate that would have accompanied active and extensive mountain building processes. As enhanced weathering is positively correlated with the drawdown rate of atmospheric CO_2, elevated weathering accompanying the formation of Pangea in turn would have substantially decreased the CO_2 concentrations in the atmosphere and consequently significantly cooled the earth.

Key features of late Palaeozoic palaeogeographical changes, specific to the LPIA and of continental to global scale, are readily decipherable from a comparison of three successive global palaeogeographical reconstruction maps (Fig. 4A–C); they include:

- The coalescence of all major southern continents around the south pole by late Devonian, a phenomenon attributed by some (e.g. Crowell, 1999) to probably have triggered an early and incipient episode of Gondwana glaciation in northern South America.
- The final collision of Gondwana and Laurasia during the Variscan Orogeny in Europe in the Mississippian, which resulted in the closure of the Rheic Ocean (Fig. 4B, C).
- By mid Early Permian (Artinskian), the Urals seaway, which connected the Palaeotethys to the palaeo-Arctic ocean across some 30° in latitude throughout most of the Palaeozoic, also became closed off, resulting in the cut-off of the Palaeotethyan warm-water currents flowing to the palaeo-Arctic.
- The final closure of the Palaeo-Asian Ocean between Sino-Korea and the Mongolian (Amuria) Massif (Fig. 4B) in the middle Permian, which profoundly modified the palaeogeography and palaeoceanography of eastern Palaeotethys and northeastern Pangea (Shi, 2006).
- The opening and continuous widening of the Mongol–Okhotsk ocean in northeast Asia, which facilitated the flow of Palaeo-Arctic cold-water currents into mid-latitude eastern Palaeotethys (present-day east Asia) along the northeast coast of Pangea (Fig. 4D–F).

Fig. 1. (A) Phanerozoic global change curves of atmospheric carbon dioxide partial pressures (pCO_2) (Royer et al., 2004), atmospheric oxygen concentrations (O_2) (Berner and Canfield, 1989; Gans et al., 1999), and GEOCARBIII modelled estimates of mean global temperatures based on reconstructions of atmospheric CO_2 (Came et al., 2007). Red bars at the bottom represent major global warm intervals during which mean global temperatures were as much as 10 °C warmer than today, in contrast to the dark green bars representing comparatively colder intervals (Came et al. 2007). (B) Estimated latitude and time span of major glaciations through the Phanerozoic (from Chumakov, 2002). (C) Phanerozoic generic diversity of marine invertebrate animals and protist groups, plotted for intervals averaging 5.4 million years in duration (Stanley, 2007). (D) Inferred palaeotropical sea surface temperatures (SSTs), best-estimated palaeo-atmospheric pCO_2 and relative global sea level curve (Montañez et al., 2007). The SSTs are reconstructed from brachiopod $\delta^{18}O$ data and reported as temperature anomalies (relative to the present-day tropical mean SST of 17.5 °C) (see Montañez et al., 2007 for details). P1, P2, P3 and P4 represent the four major Permian glacial intervals recognized by Fielding et al. (2008c). LPCDM = Late Palaeozoic Carbon Dioxide Minimum, LPIA = Late Palaeozoic Ice Age, LPOP = Late Palaeozoic Oxygen Pulse.