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Acme and demise of the late Palaeozoic ice age: A view from the southeastern margin of Gondwana

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ABSTRACT

Palaeoenvironmental reconstructions from across the globe indicate that the climatic and oceanographic changes that accompanied the Permian transition from deep icehouse to greenhouse conditions were uneven and asynchronous. Because of a paucity of well-constrained data, environmental changes in Gondwana remain poorly understood relative to tropical Pangaea. In this regard, the Permian System of eastern Australia provides a unique record of this transition along a high-latitude, open marine shelf. Not only was glaciation protracted here relative to other regions of Gondwana, but the record also spans temperate to polar palaeolatitudes, providing an opportunity to examine environmental changes along a latitudinal transect. We integrate proxies for $\delta^{18}O_{seawater}$, palaeotemperature, pCO_2, and depositional environment to assess the evolution of nearshore conditions through the Permian. Glaciation was not continuous, but rather focused into four discrete, glacial epochs (P1–P4), each several million years in length, which alternated with nonglacial intervals of similar duration. During the Asselian–mid-Artinskian (P1–P2 time), uniform conditions along the full extent of the margin were maintained by a cold boundary current coupled with oceanic upwelling. Increased spatiotemporal variability is evident at the end of glacial P2 (mid-Artinskian), perhaps due to tectonic changes that impacted the palaeogeography of the margin. Although glaciers had disappeared by this time elsewhere in Gondwana, eastern Australia saw two additional periods of glaciation, P3 (Roadian–earliest Captianian) and P4 (early Wuchiagingian). Continued, albeit intermittent, glaciation was facilitated by drift toward higher palaeolatitudes, orogenic activity that led to the development of areas of high elevation that could serve as nucleation points for glaciers, and transient drops in atmospheric pCO_2. Variations in meltwater input exerted a strong effect on local $\delta^{18}O_{seawater}$ values, complicating attempts to reconstruct latitudinal gradients in palaeotemperature. Results point to atmospheric CO_2 as the primary driver responsible for the dynamic climate variations evident in the record.

1. Introduction

The Permian saw one of the most extreme climate transitions of the Phanerozoic, from deep icehouse conditions in the Early Permian, which marked the acme of the late Palaeozoic ice age (LPIA), to the onset of a protracted greenhouse state by Late Permian time. Because the transition occurred on a forested Earth characterized by a vast south polar landmass, low atmospheric carbon dioxide concentrations, and sea levels similar to those of the Neogene, this interval is considered by many to provide a valuable analogue for the Cenozoic icehouse and present-day environmental change (Gastaldo et al., 1996; Montañez et al., 2007). The long-held view of the demise of the LPIA involved the decay of a vast, long-lived ice sheet that had covered a large swath of Gondwana since mid-Mississippian time, with permanent deglaciation and warming beginning in the mid-Sakmarian (Veevers and Powell, 1987; Frakes and Francis, 1988; Crowley and Baum, 1991, 1992; Crowell, 1999). With improvements in geochronology and increased attention to the high latitude record deposited in and around glaciated regions, however, a rather different view of this transition has emerged. It is evident that rather than a single continent-wide ice sheet, multiple smaller ice centres were active at different times and places across Gondwana (Isbell et al., 2003, 2012; Fielding et al., 2008a). Moreover, the interval was much more dynamic than previously supposed, with stratigraphic (Fielding et al., 2008b) and proxy records (Montañez et al., 2007) indicating that the LPIA consisted of a series of discrete glacial epochs, each more or less akin to the Quaternary ice age and characterized by lower atmospheric pCO_2 and increased ice volume. Inferences from cyclothems (Wanless and Shepard, 1936; Heckel, 1986) and climate-ice sheet modeling (Horton et al., 2012) suggest that ice centres were modulated by orbital forcing. These glacial epochs alternated with non-glacial intervals of similar duration. Localized ice centres first appeared in South America during latest Devonian and Visean time before spreading to other parts of Gondwana (Isbell

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et al., 2003). Maximum ice extent was reached during the Asselian–mid-Sakmarian, and glaciation likely became bipolar at that time (Fielding et al., 2008a). Subsequent glacial activity, which continued intermittently into Late Permian time, was limited to eastern Australia and possibly Siberia (Frakes et al., 1975; Hyde et al., 2006; Fielding et al., 2008a; Isbell et al., 2012; Montañez and Poulsen, 2013). Climatic and oceanographic changes that accompanied the transition from deep icehouse to greenhouse conditions were uneven and asynchronous. Terrestrial settings in the Euramerican tropics underwent gradual warming and drying (Parrish, 1993; Poulsen et al., 2007; Tabor et al., 2008), perhaps to the point where conditions in some areas became unfavourable for life (Tabor, 2013; Zambito and Benison, 2013). By contrast, evidence for wetter western tropical coasts (Kutzbach and Gallimore, 1989), narrow rainbelts along the northern and southern Palaeotethyan coasts (Parrish, 1993), and the persistence of mire vegetation in south China through the Late Permian (Gastaldo et al., 1996) indicate that some low-latitude regions remained relatively humid despite increasing warmth. Increasing poleward transport of moisture during the Permian has been inferred on the basis of a shift in peat formation from tropical to temperate and subpolar latitudes (Parrish, 1993). The thermal state of the oceans during the Early–Middle Permian remains poorly understood (Montañez and Poulsen, 2013). Studies comparing palaeotemperature proxy data from the low and high palaeolatitudes suggest that Permian meridional temperature gradients were similar to today's (Korte et al., 2008; Mii et al., 2012). However, interpretation of the low-latitude proxy data is complex due to local variations in climate conditions (Chen et al., 2013). Some studies suggest equable tropics that were climatically buffered (Angiolini et al., 2009). Others, however, call for cooler shallow-ocean temperatures that were sensitive to high-latitude forcing (Powell, 2005, 2007; Powell et al., 2009; Waterhouse and Shi, 2010; Giles, 2012). Cooler temperatures may have been maintained by upwelling in the eastern Panthalassan and Palaeotethyan oceans, which intensified during glacial intervals (Winguth et al., 2002; Montañez and Poulsen, 2013). The regional complexity of the Permian icehouse–greenhouse transition should come as no surprise in light of the uneven response of the globe to current climate change (Esau et al., 2012). The Permian world may have been characterized by even stronger regional variability because Pangaea, as a large north-south oriented landmass, would have disrupted zonal circulation patterns (Parrish, 1993) and been subject to extreme continentality and large-scale monsoon circulation (Kutzbach and Gallimore, 1989).

Clearly, full understanding of climate change in the Permian world will require synthesis of many regional data sets. Whereas the low-palaeolatitude regions of Pangaea have been documented by multiple data sets, the high palaeolatitudes are poorly understood due to a relative paucity of well-constrained data. In this regard, the objective of this paper is to integrate a range of geochemical and sedimentological proxies from Permian strata in eastern Australia to reconstruct the evolution of nearshore palaeoceanographic conditions along a high-latitude margin during the acme and waning stages of the late Palaeozoic ice age. Emphasis is placed not only on temporal evolution of palaeoenvironmental conditions, but also on how conditions varied along a palaeolatitudinal transect. Data are derived from Permian glacially influenced marine strata exposed in Queensland (QLD), New South Wales (NSW), and Tasmania (TAS), Australia. These deposits record the complex and multi-phase LPIA over a 2000 km polar to temperate palaeolatitudinal transect along the eastern margin of Australia. The results improve understanding of one of the major climate transitions of the Phanerozoic.

2. Setting

This paper focuses on Permian strata preserved in the Tasmania, Sydney, and Bowen Basins of Australia. For much of the Permian, the Bowen, Gunnedah, and Sydney Basins of QLD and NSW were contiguous, comprising a north-south elongate marine seaway along the southeast Panthalassan margin of Gondwana (Fielding et al., 2001; Korsch et al., 2009). The Tasmania Basin, by contrast, was somewhat more confined (Veevers et al., 1994; Reid et al., in press). Recent plate reconstructions indicate that Australia rotated in a clockwise direction and moved slowly poleward through the Permian (Fig. 1), such that the Tasmania Basin remained south of 60°S, the Sydney Basin migrated from 55°S to just within the polar circle, and the Bowen Basin migrated from c. 45°S in the Early Permian to around 55°S by Late Permian time (Domeier and Torsvik, 2014). Modeling of ocean current patterns indicates that this high-latitude margin (Fig. 2) was influenced by a shallow poleward-flowing, western boundary current underlain by a deeper countercurrent that originated at polar latitudes (Winguth et al., 2002). Prevailing wind systems included winter zonal westerlies and summer longshore northerlies (Gibbs et al., 2002). The combination of offshore-directed winds and Ekman transport is postulated to have driven year-round upwelling of cold, polar-derived deep water (Jones et al., 2006). Assuming that polar deep-water production was most intense during the winter months (Winguth et al., 2002), then upwelling waters would have been particularly cold. Several lines of evidence are consistent with cold, nutrient-rich nearshore waters, including

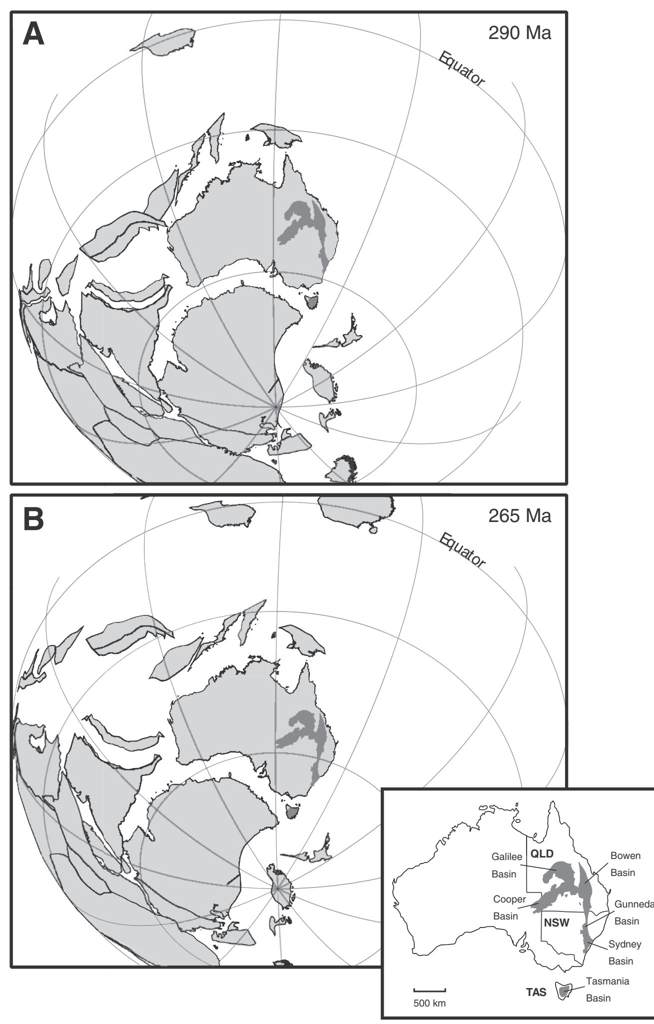

Fig. 1. South-pole focused views showing palaeogeography for two time slices, (A) 290 Ma, Early Permian and (B) 265 Ma, Middle Permian. Maps generated using GPlates 1.3 software and plate tectonic reconstruction data of Domeier and Torsvik (2014). Shaded area in Australian continent denotes the extent of Permian depocentres. Inset map shows distribution of Permian basins and political boundaries for Queensland (QLD), New South Wales (NSW), and Tasmania (TAS).