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GR focus review

Glacial paradoxes during the late Paleozoic ice age: Evaluating the equilibrium line altitude as a control on glaciation

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ABSTRACT

The late Paleozoic ice age (LPIA) consists of multiple glaciations that waxed and waned across Gondwana during the Carboniferous and Permian. Three key intervals are evaluated using the concept of the equilibrium-line altitude (ELA) as a control on glaciation to provide insight into two intervals of paradoxical ice distribution during and following glaciation. The LPIA began in the mid-latitudes during the Viséan in western Argentina with the growth of glaciers in the Protoprecordillera. Glaciation was initiated by uplift of the range above the ELA. In the Bashkirian, deglaciation occurred there while glaciation was beginning at the same latitude in uplands associated with the Paraná Basin in Brazil. Analysis suggests that deglaciation of the Protoprecordillera occurred due to extensional collapse of the range below the ELA during a westward shift in the location of plate subduction. During Late Pennsylvanian–Early Permian peak glaciation for the LPIA, extensive glacimarine deposits indicate that glaciers reached sea level, which corresponds to a major lowering of the ELA due to global cooling. Finally, during the Early to early Late transition out of the LPIA, polar Gondwana was unglaciated. However, three glacial intervals occurred at mid- to high-latitudes in eastern Australia from the Sakmarian to the Capitanian/earliest Wuchiapingian. The magnitude of global cooling during these events is debatable as evidence indicates ice-free conditions and an elevated ELA at the South Pole in Antarctica. This suggests that severe global cooling was not the cause of the final three Australian glaciations, but rather that ELA-related conditions specific to eastern Australia drove these late-phase events. Possible causes for the Australian glaciations include: 1) anomalous cold conditions produced by coastal upwelling, 2) the presence of uplands allowing nucleation of glaciers, 3) fluctuations in $p\mathrm{CO}_2$ levels, and 4) increased precipitation due to the location of the area in the subpolar low pressure belt.

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1. Introduction

The late Paleozoic Ice Age (LPIA) and the ensuing Early to Late Permian icehouse to greenhouse transition were two important intervals during the Phanerozoic as they had a major impact on Earth's physical, chemical, and biological systems (Heckel, 1994, 2008; Falcon-Lang, 2004; Joachimski et al., 2006; Clapham and James, 2008; Grossman et al., 2008; Isbell et al., 2008a; Falcon-Lang and DiMichele, 2010). The LPIA, which lasted for approximately 72 Myr from the Viséan (Mississippian) to the Capitanian/earliest Wuchiapingian (Middle-earliest Late Permian), occurred on a biologically complex Earth characterized by an extensive south polar landmass; low atmospheric partial pressure of CO_2 (pCO_2); and multiple, possibly bipolar, glacial events (Isbell et al., 2003; Fielding et al., 2008a). Because of these features, which also characterize Cenozoic glaciation, the LPIA serves as the most recent and complete analog for modern environmental change associated with global climate change (Gastaldo et al., 1996; Montañez and Soreghan, 2006; Isbell et al., 2008a).

The stratigraphic, geochemical, and tectonic records of the LPIA continue to improve in resolution (e.g., papers in Fielding et al., 2008b; Gulbranson et al., 2010; papers in López-Gamundí and Buatois, 2010) revealing glacial and non-glacial intervals that occurred across Gondwana. To date, these events are roughly correlated with changes in the paleolatitude of Gondwana and to fluctuations in greenhouse gasses (Caputo and Crowell, 1985; Royer et al., 2001; Montañez et al., 2007), whereas shorter-term Earth system fluctuations (e.g. eustasy) are attributed to Milankovitch forced glacial events (Heckel, 1994; Davydov et al., 2010). However, the drivers behind the waxing and waning of each LPIA glacial event, as well as the shorter duration glacial/interglacial cycles, are likely a complex interplay of local, regional and global conditions. These conditions are difficult to quantify under the current state of knowledge, and determining why glaciers were maintained in one area while adjacent areas were ice-free or undergoing de-glaciation, remain problematic. Unresolved problems, which are addressed in this paper, include: 1) identifying the causes for the initiation of glaciation in western Argentina during the Middle Mississippian to Early Pennsylvanian, 2) determining why glaciers disappeared in western Argentina during the Pennsylvanian while glaciers were forming in adjacent areas to the east, 3) identifying causes for the LPIA glacial maximum during the latest Pennsylvanian and Early Permian, and 4) determining the controls on glaciation in eastern Australia during the late Early to early Late Permian while areas located at higher paleolatitudes were ice free. Much work is still necessary to unravel the causes of climatic perturbations and their influence on LPIA glaciation.

The role that the Equilibrium Line Altitude (ELA) played in glaciation and the insights it provides on the formation, waxing and waning, and collapse of the Gondwana glaciers has not been previously investigated. Traditionally, Gondwana glaciation is modeled as a single, massive, ice sheet centered over the paleo-South Pole located in Antarctica and extending outward into the mid-latitudes (e.g., Scotese, 1997; Ziegler et al., 1997; Hyde et al., 1999). Ice is also hypothesized to have formed in high northern latitudes on the East Asian crustal block and in low latitude uplands in North America (Raymond and Metz, 2004; Soreghan et al., 2008, 2009). The size and configuration of the hypothetical Gondwanan ice sheet appears to have been determined by encircling all known glacial deposits on paleogeographic maps. However, such practices are highly inaccurate and would be misleading if conducted on modern deposits due to the occurrence of alpine glaciers and ice caps in low latitude uplands. A single, massive, Gondwanan ice sheet is untenable (cf., Horton and Poulsen, 2009). Such a model does not take into consideration the mass balance required to sustain such an ice sheet (Isbell et al., 2003), nor the fact that the ELA varies in elevation with respect to latitude. The ELA is the theoretical altitude on a glacier that separates areas of annual net accumulation from areas of annual net ablation (Benn and Evans, 2010). Because the ELA determines where glaciers can form, consideration of factors that influence both the local position and the global distribution of the ELA provide insight on the formation and demise of glaciers in time and space (Fujita, 2008). Although it is exceedingly difficult to accurately estimate paleo-elevation, consideration of the ELA concept, comparison of synchronous glaciated vs. non-glaciated areas, and the comparison with modern ELA curves can provide a tool for understanding ancient glacial successions.

This paper summarizes the current state of knowledge on the LPIA and its main environmental drivers, and highlights problems that are unresolved concerning the distribution of glaciers and timing of glaciation across Gondwana. We then present a discussion on the ELA and how it controls glaciation in time and space, and speculate on the role that the ELA had as a driver of glacial and non-glacial intervals during the LPIA in an attempt to better understand Earth's transition from icehouse to greenhouse conditions.

2. Late Paleozoic Ice Age in Gondwana

Traditional models of LPIA glaciation depict a massive ice sheet(s) that waxed and waned continuously across Gondwana for up to 100 million years (Figs. 1A and 2; cf. Veevers and Powell, 1987; Frakes and Francis, 1988; Frakes et al., 1992; Ziegler et al., 1997; Hyde et al., 1999; Blakey, 2008; Buggisch et al., 2011). This concept is prevalent in geologic literature up to the present day. However, recent work has identified evidence of numerous small ice centers that waxed and waned diachronously across Gondwana through multiple glacial intervals of 1–8 million years in duration alternating with non-glacial periods of approximately equal duration (Figs. 1B and 2; Crowell and Frakes, 1970; Caputo and Crowell, 1985; Dickins, 1997; López-Gamundí, 1997; Isbell et al., 2003; Fielding et al., 2008a, 2008c, 2008d; Gulbranson et al., 2010). Although glaciation occurred in northern South America and northern Africa during the Late Devonian and early Mississippian (Caputo and Crowell, 1985; López-Gamundí, 1997; Crowell, 1999; Isbell et al., 2003; Caputo et al., 2008), most authors consider the LPIA to have begun in western South America during the Viséan (Caputo et al., 2008; Pérez Loinaze et al., 2010) and to have concluded in eastern Australia during the Middle to earliest Late Permian (Capitanian/earliest Wuchiapingian; Fielding et al., 2008a, 2008c, 2008d).

Continental drift of Gondwana across the South Pole (Fig. 3) has long been recognized as a major control for the diachronous shifting of glacial centers across the supercontinent during the LPIA (DuToit, 1921; Wegener, 1929; Crowell, 1978; Caputo and Crowell, 1985).