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Atmospheric dust from the Pennsylvanian Copacabana Formation (Bolivia): A high-resolution record of paleoclimate and volcanism from northwestern Gondwana

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ABSTRACT

This study documents the occurrence of atmospheric dust from Pennsylvanian carbonates of the Copacabana Formation, recovered in core (Mobil-Oxy Manuripi X-1) from the Madre de Dios basin (Bolivia), within southern mid-latitudes (~35°S) of western Gondwana. The Copacabana Formation spans Pennsylvanian-Early Permian time, and thus formed coeval with and in relative proximity to ice centers and associated glacial deposits located at southern paleolatitudes in adjoining regions of Gondwana (e.g. the Paraná, Tarija, and Paganzo basins in Brazil, southeastern Bolivia, and Argentina, respectively). In Pennsylvanian time carbonate deposition of the Copacabana Formation occurred on a ramp isolated from fluvial-deltaic influx, and thus siliciclastic material in this system reflects atmospheric input. The study interval comprises a series of upwardly shallowing successions 1–3 m thick ranging from open marine ramp facies to more restricted inner-ramp facies, commonly capped by horizons of microkarsted and/or red mudstone reflecting subaerial exposure of the carbonate ramp. These horizons mark abnormal exposure and are interpreted to record glacial lowstands.

Dust recovered from throughout the study section varies from ~1 to 43 wt% in carbonate facies and is quartzo-feldspathic. Grain size modes range from <1 to 97 μm, with coarser intervals generally corresponding to peak dust content (wt%), and high-frequency sequence (glacial-stage) boundaries. Provenance indicates two discrete sources of atmospheric input–a western volcanic arc source and eastern continental source, recording both westerly (zonal) and easterly (katabatic) wind directions. The western (volcanic) source records zonal westerlies expected at this mid-latitude (~35°S) locality. In contrast, easterly winds suggest the influence of katabatic winds associated with Gondwanan ice centers. The most likely dust-sourcing regions are the periglacial to proglacial regions of the Gondwanan ice sheets. Non-volcanic peaks in dust occur most commonly associated with subaerial exposure surfaces; this, together with mass accumulation rate estimations suggest that atmospheric dust loading peaked during glacial stages.

1. Introduction

Dust deposits form robust paleoclimate archives and are an active climate-forcing agent. Late Cenozoic records of eolian dust from both continental and marine environments comprise high-resolution climate archives (e.g., Rea and Bloomstine, 1986; Porter and Zhisheng, 1995; Kemp, 2001; Scheuvens et al., 2013; Schatz et al., 2015). Dust can be preserved within a variety of environments, including glaciers, lacustrine and marine systems, and as loess deposits (Smalley, 1966, 1997; Pécsi, 1990; Pye, 1995; Muhs and Bettis, 2000, 2003; Muhs et al., 2013). In the Quaternary, for example, the Chinese Loess Plateau constitutes one of the most extensive continental climate archives, as it consists of a succession of loess and paleosols that has been accumulating since ~2.6 Ma, recording variations in atmospheric dustiness through glacial-interglacial phases of the Pleistocene (Kukla and An, 1989; Spassov, 2002; An, 2014; Maher, 2016).

In the Quaternary, continental dust (loess) deposits form climate archives in periglacial loess deposits of high- and mid-latitudes and in peridesert loess deposits of subtropical latitudes (Pécsi, 1990; Pye, 1995; Bettis et al., 2003; Muhs and Bettis, 2003; Muhs et al., 2014). Dust deposits are less known from Earth's deep-time sedimentary

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record, but are well recognized from the Pennsylvanian-Lower Permian record of western equatorial Pangaea (e.g., Soreghan et al., 2002, 2008). Dust can be preserved within carbonate systems otherwise isolated from detrital (fluvio-deltaic) influx, and recovered to assess the geologic record of atmospheric dustiness (Sur et al., 2010a). These dust deposits of the Late Paleozoic ice age (LPIA) present an opportunity to examine spatial and temporal variations of atmospheric dust loading during Earth's most recent pre-Cenozoic icehouse and through glacial-interglacial cycles of that icehouse (Soreghan et al., 2008, 2015; Heavens et al., 2015).

Extending previous research that reported high dustiness in the Pennsylvanian-Permian of western equatorial Pangaea (e.g., Soreghan et al., 2008; Soreghan and Soreghan, 2013; Sur et al., 2010a; Foster et al., 2014), this research examines the atmospheric dust flux to carbonate strata of the Pennsylvanian (upper Bashkirian) Copacabana Formation in the Madre de Dios basin, Bolivia, which formed in the southern mid-latitude region. For the time interval of interest, this carbonate system formed isolated from fluvial-deltaic influx; thus, detrital silicate material recovered from these carbonate strata should reflect atmospheric input.

The primary goal of this study is to assess the atmospheric dustiness and temporal variation in dustiness of the southern mid-latitude region of western Gondwana during the study interval of the lower-middle Pennsylvanian. Specifically, these data document (1) the sources of atmospheric dust based on mineral and chemical composition, (2) the impact of glacial-interglacial cycles on atmospheric dust variability, and (3) the regional dispersal of the non-volcanic dust fraction determined by the dust provenance and paleo-wind patterns. These data shed light on temporal shifts in atmospheric circulation and aridity, and provide input to further constrain climate models of the LPIA.

2. Geological setting

In the Late Cambrian to Early Ordovician, the western Gondwanan margin along the western part of present-day South America developed into an active margin (Sempere, 1995; Jaillard et al., 2000; Grader, 2003; Sempere et al., 2002). The development of this active margin had two contrasting phases from the Carboniferous (359–299 Ma) to Permian (299–254 Ma) interval in that a retroarc foreland basin formed inboard of the arc along the western Gondwanan margin in early Carboniferous time, but evolved to backarc transtension by the late Carboniferous (Jaillard et al., 2000; Grader, 2003; Grader et al., 2003), with arc volcanism persisting from Late Cambrian to Jurassic times (Isaacson and Martinez, 1995; Sempere, 1995; Jaillard et al., 2000).

Paleomagnetic data from the Madre de Dios basin of western Bolivia indicate a paleolatitude of ~36°S for the early Carboniferous (Fig. 1; Díaz-Martínez, 1995; Sempere, 1995; Grader et al., 2008). The paleolatitude of the region varied considerably during this time as this region drifted northward, from ~35°S in the Pennsylvanian to ~19°S by the Late Permian (Tait et al., 2000; Rakotosolofo et al., 2006). A paleolatitude of 28.1°S was calculated from inclination data reported (Rakotosolofo et al., 2006) for the Early Permian (Asselian-Sakmarian) Copacabana Formation exposed in Peru. Thus, the paleolatitude of the studied (older) section in Bolivia is constrained to between 36°S and 28°S, but likely closer to 36°S given the age. The strata of the Madre de Dios basin reflect this shift from high-mid-latitude deposition influenced by the near-field effects of Gondwanan glaciation to low-mid-latitude deposition influenced by carbonate- and eolian-influenced systems (Fig. 2; Diaz Martinez, 1996; Suarez Soruco, 2000; Grader et al., 2003).

Whereas the LPIA was once cast as a prolonged icehouse characterized by essentially continuous and invariant glaciation of relatively constant extent, more recently several authors have suggested that multiple short-lived ice sheets waxed and waned at the 1–8 My timescale throughout high-latitude Gondwana during the LPIA (~335–260 Ma; Isbell et al., 2003, 2012; Fielding et al., 2008; Montañez and Poulsen, 2013; Limarino et al., 2014). Glacial centers that supplied sediment to the Madre de Dios basin comprised the Brazilian Shield to the east, Arequipa Massif to the west, and the Puna Arc to the south (Fig. 3B; Caputo et al., 2008). Limarino et al. (2014) argued that glacial deposits (glacial diamictite, dropstones, and varve deposits) diminished during early Bashkirian (early late Carboniferous) time in the basins along western Gondwana, whereas glaciation persisted into Early Cisuralian (Early Permian) time in the eastern basins including the Paraná, South Paraná, and Chaco Paraná (Fig. 3B).

The Copacabana Formation accumulated in the Madre de Dios basin from Early Pennsylvanian (Bashkirian, ~323 Ma) time through Early Permian (Artinskian, ~279 Ma) time, and consists of pericratonic marine strata (Grader et al., 2003). The Mobil-Oxy Manuripi X-1 core (recovered in 1991) from the northern margin of the Madre de Dios basin includes the Devonian Tomachi-Toregua formations, the Pennsylvanian (Bashkirian-Moscovian) interval of the Copacabana Formation, the

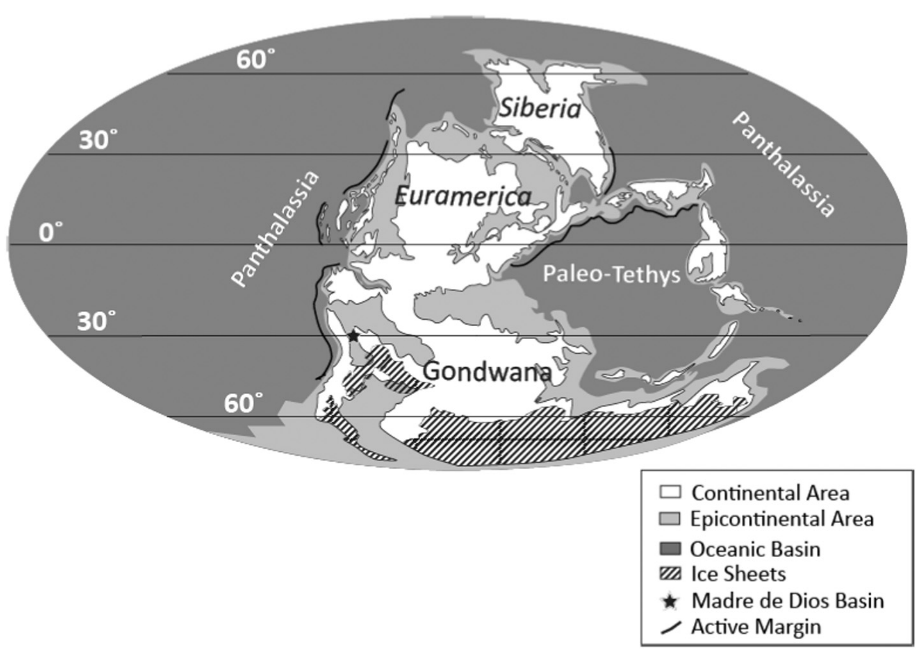

Fig. 1. Paleogeographic map of Gondwana during Late Carboniferous time (323–299 Ma) modified from Blakey (2011) showing the icesheet distributions and the study area.