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New constraints on equatorial temperatures during a Late Neoproterozoic snowball Earth glaciation

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ABSTRACT

Intense glaciation during the end of Cryogenian time (∼635 million years ago) marks the coldest climate state in Earth history – a time when glacial deposits accumulated at low, tropical paleolatitudes. The leading idea to explain these deposits, the snowball Earth hypothesis, predicts globally frozen surface conditions and subfreezing temperatures, with global climate models placing surface temperatures in the tropics between −20 °C and −60 °C. However, precise paleosurface temperatures based upon geologic constraints have remained elusive and the global severity of the glaciation undetermined. Here we make new geologic observations of tropical periglacial, aeolian and fluvial sedimentary structures formed during the end-Cryogenian, Marinoan glaciation in South Australia; these observations allow us to constrain ancient surface temperatures. We find periglacial sand wedges and associated deformation suggest that ground temperatures were sufficiently warm to allow for ductile deformation of a sandy regolith. The wide range of deformation structures likely indicate the presence of a paleoactive layer that penetrated 2–4 m below the ground surface. These observations, paired with a model of ground temperature forced by solar insolation, constrain the local mean annual surface temperature to within a few degrees of freezing. This temperature constraint matches well with our observations of fluvial deposits, which require temperatures sufficiently warm for surface runoff. Although this estimate coincides with one of the coldest near sea-level tropical temperatures in Earth history, if these structures represent peak Marinaon glacial conditions, they do not support the persistent deep freeze of the snowball Earth hypothesis. Rather, surface temperatures near 0 °C allow for regions of seasonal surface melting, atmosphere–ocean coupling and possible tropical refugia for early metazoans. If instead these structures formed during glacial onset or deglaciation, then they have implications for the timescale and character for the transition into or out of a snowball state.

1. Introduction

Observations of globally-distributed glacial sediments deposited at sea-level in low paleolatitudes (Harland, 2007; Hoffman and Schrag, 2002; Williams, 1975) gave rise to claims that Earth's late Neoproterozoic glacial climate must have been radically different from that of Phanerozoic glacial intervals (Hoffman and Schrag, 2002; Hoffman et al., 1998; Kirschvink, 1992; Williams, 1975). The origin and significance of these glaciogenic deposits has been debated for nearly a century (see review in Harland, 2007), but the snowball Earth hypothesis has emerged as a unifying hypothesis to explain the evidence. The snowball Earth model proposes that Cryogenian climatic events drove equatorial temperatures to below −20 °C, temperatures sufficient to freeze Earth's oceans from pole to equator (Hoffman and Schrag, 2002; Kirschvink, 1992). Variants on the snowball Earth model propose that the equatorial regions of Earth's oceans remained open and Earth's surface temperatures, though cold, were not sufficient to freeze the entirety of Earth's surface (Abbot et al., 2011; Crowley et al., 2001; Peltier et al., 2007). Direct geological constraints on surface temperatures during this period are missing, and evidence supporting any one hypothesis has thus far been equivocal.

Although abundant glacial sediments deposited at low latitudes during Cryogenian time provide the primary evidence for a cold

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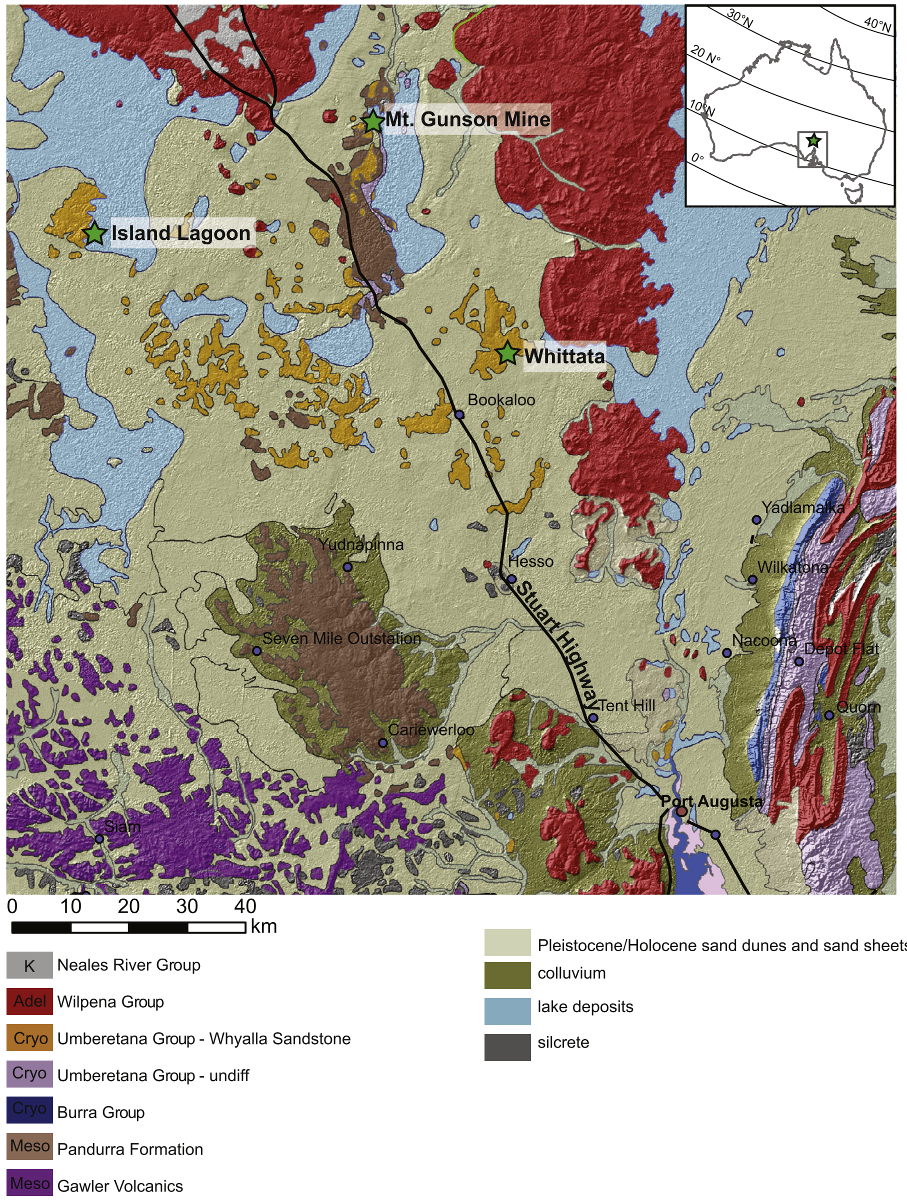

Fig. 1. Generalized geological map of the Stuart Shelf and Adelaide Rift Complex in South Australia. Outcrop localities are labeled. Inset map shows paleolatitude of Australia (Evans and Raub, 2011; Schmidt et al., 2009; Sohl et al., 1999; Sumner et al., 1987).

global climate, significant differences in the environment are expected depending on the temperature of Earth's surface. For example, at the temperatures expected by the end-member model of a snowball Earth, the range of active sedimentary processes during the peak glacial periods would be limited (Allen and Etienne, 2008). Wind-blown sediments may be made unavailable for transport because of ice burial or ice cementation. Temperatures would be too cold for fluvial activity and modification of continental shelf sediments by tidal and wave action would be greatly attenuated (Hoffman and Schrag, 2002). Models that do not require deeply frozen temperatures allow a wider range of sedimentary environments associated with an active hydrologic cycle and open oceans to be active throughout the glaciation and, in certain localities, such sedimentary environments have been highlighted as counter evidence to the presence of a snowball Earth during the Cryogenian (Allen and Etienne, 2008).

Periglacial sand wedges and associated regolith deformation and fluvial deposits found in the Marinoan Whyalla Sandstone in South Australia, are a primary focus of this study (Fig. 1). This suite of sedimentary structures forms under a relatively narrow thermal regime (Mellon, 1997; Pewe, 1959) and can be used to refine equatorial temperature estimates during the Marinoan glaciation. Models and modern observations of sand wedges indicate that wedges form by sediment infilling of thermal contraction cracks, which occur when the ground cools and induces a tensile stress that exceeds the strength of frozen regolith (Maloof et al., 2002; Mellon, 1997; Pewe, 1959). Large seasonal temperature variations found at high latitudes, very cold ground (mean annual temperature $< 0\,^{\circ}\mathrm{C}$), and a dry climate are key characteristics of these models and observations that indicate crack and fill cycles that give rise to vertically laminated, sand-filled wedges, which may be associated with deformed ground (Fig. 2) (Black, 1976; Hallet et al., 2011; Pewe, 1959; Sletten et al., 2003). Deformed ground associated with sand wedge growth occurs because sand fills the open fracture and during a warm phase of the cycle the ground expands; the fracture cannot close and compressive stresses propagate horizontally to deform the ground surrounding the wedge (Hallet et al., 2011).