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Focus paper

Strongly seasonal Proterozoic glacial climate in low palaeolatitudes: Radically different climate system on the pre-Ediacaran Earth

George E. Williams [a,*], Phillip W. Schmidt [b], Grant M. Young [c]

[a] Department of Earth Sciences, University of Adelaide, SA 5005, Australia
[b] CSIRO Mineral Resources Flagship, PO Box 52, North Ryde, NSW 1670, Australia
[c] Department of Earth Sciences, University of Western Ontario, London, Ontario N6A 5B7, Canada

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ABSTRACT

Proterozoic (pre-Ediacaran) glaciations occurred under strongly seasonal climates near sea level in low palaeolatitudes. Metre-scale primary sand wedges in Cryogenian periglacial deposits are identical to those actively forming, through the infilling of seasonal (winter) thermal contraction-cracks in permafrost by windblown sand, in present-day polar regions with a mean monthly air temperature range of 40 °C and mean annual air temperatures of −20 °C or lower. Varve-like rhythmites with dropstones in Proterozoic glacial successions are consistent with an active seasonal freeze–thaw cycle. The seasonal (annual) oscillation of sea level recorded by tidal rhythmites in Cryogenian glacial successions indicates a significant seasonal cycle and extensive open seas. Palaeomagnetic data determined *directly* for Proterozoic glacial deposits and closely associated rocks indicate low palaeolatitudes: Cryogenian deposits in South Australia accumulated at ≤10°, most other Cryogenian deposits at <20° and Palaeoproterozoic deposits at <15° palaeolatitude. Palaeomagnetic data imply that the Proterozoic geomagnetic field approximated a geocentric axial dipole, hence palaeolatitudes represent geographic latitudes. The Cryogenian glacial environment included glacier-free, continental permafrost regions with ground frozen on a kyr time-scale, aeolian sand-sheets, extensive and long-lived open seas, and an active hydrological cycle. This palaeoenvironment conflicts with the 'snowball Earth' and 'slushball Earth' hypotheses, which cannot accommodate large seasonal changes of temperature near the equator. Consequently, their proponents have attempted to refute the evidence for strong seasonality by introducing Popperian 'auxiliary assumptions'. However, non-actualistic arguments that the Cryogenian sand wedges indicate diurnal or weakly seasonal temperature changes are based on misunderstandings of periglacial processes. Modelling of a strongly seasonal climate for a frozen-over Earth is invalidated by the evidence for persistent open seas and glacier-free continental regions during Cryogenian glaciations, and gives a mean monthly air temperature range of only ≤10 °C for ≤10° latitude. By contrast, a strongly seasonal climate in low palaeolatitudes, based on the actualistic interpretation of cryogenic sand wedges and other structures, is consistent with a high obliquity of the ecliptic (>54°) during Proterozoic low-latitude glaciations, whereby the equator would be cooler than the poles, on average, and global seasonality would be greatly amplified.

1. Introduction

Precambrian glaciations are known from the Archaean, Palaeoproterozoic, Cryogenian and Ediacaran, and provide insight into the climate system on the early Earth.

The oldest known glacial deposits (2.9 Ga) occur in South Africa (Young et al., 1998). Early Palaeoproterozoic (2.4–2.3 Ga) glaciations affected North America, Fennoscandia, South Africa and Western Australia (Crowell, 1999; Young, 2014), and late Palaeoproterozoic (1.8 Ga) glaciation occurred in NW Australia (Williams, 2005).

Cryogenian glacial deposits are recognised on all continents, possibly including Antarctica (Stump et al., 1988), attain great thicknesses and cover wide areas (Hambrey and Harland, 1981;

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* Corresponding author. Tel.: +61 (0)8 8313 5843; fax: +61 (0)8 8313 4347.
E-mail address: george.williams@adelaide.edu.au (G.E. Williams).

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Arnaud et al., 2011). In South Australia, which is the de facto 'type region' for Cryogenian glaciations, deposits of the Sturt glaciation (≥660 Ma) are >5 km thick (Preiss et al., 2011) and those of the terminal Cryogenian Elatina glaciation are up to 1500 m thick and cover 200,000 km^2 (Coats and Preiss, 1987; Lemon and Gostin, 1990; Williams et al., 2008, 2011). The presence of tidalites in the glacial successions (Williams, 2000; Williams and Schmidt, 2004) indicates that both these glaciations extended to sea level. The age of the Elatina glaciation has not been determined directly, but is taken as ≥635 Ma based on U–Pb zircon dating of terminal Cryogenian glacial deposits in Namibia (635.5 ± 1.2 Ma; Hoffmann et al., 2004), China (636.3 ± 4.9 Ma; Zhang et al., 2008) and Tasmania (636 ± 0.45 Ma; Calver et al., 2013). Facies of the Elatina glaciation are particularly varied (Fig. 1), ranging from permafrost regolith (Cattle Grid Breccia) and overlying periglacial–aeolian sand sheet (Whyalla Sandstone) on the cratonic Stuart Shelf, with the Adelaide Geosyncline to the east including glaciofluvial sandstones and tidal, deltaic and inner marine-shelf sandstones and diamictites (Elatina Formation), and outer marine-shelf deposits with laminated mudstones–siltstones with dropstones and diamictites indicating the

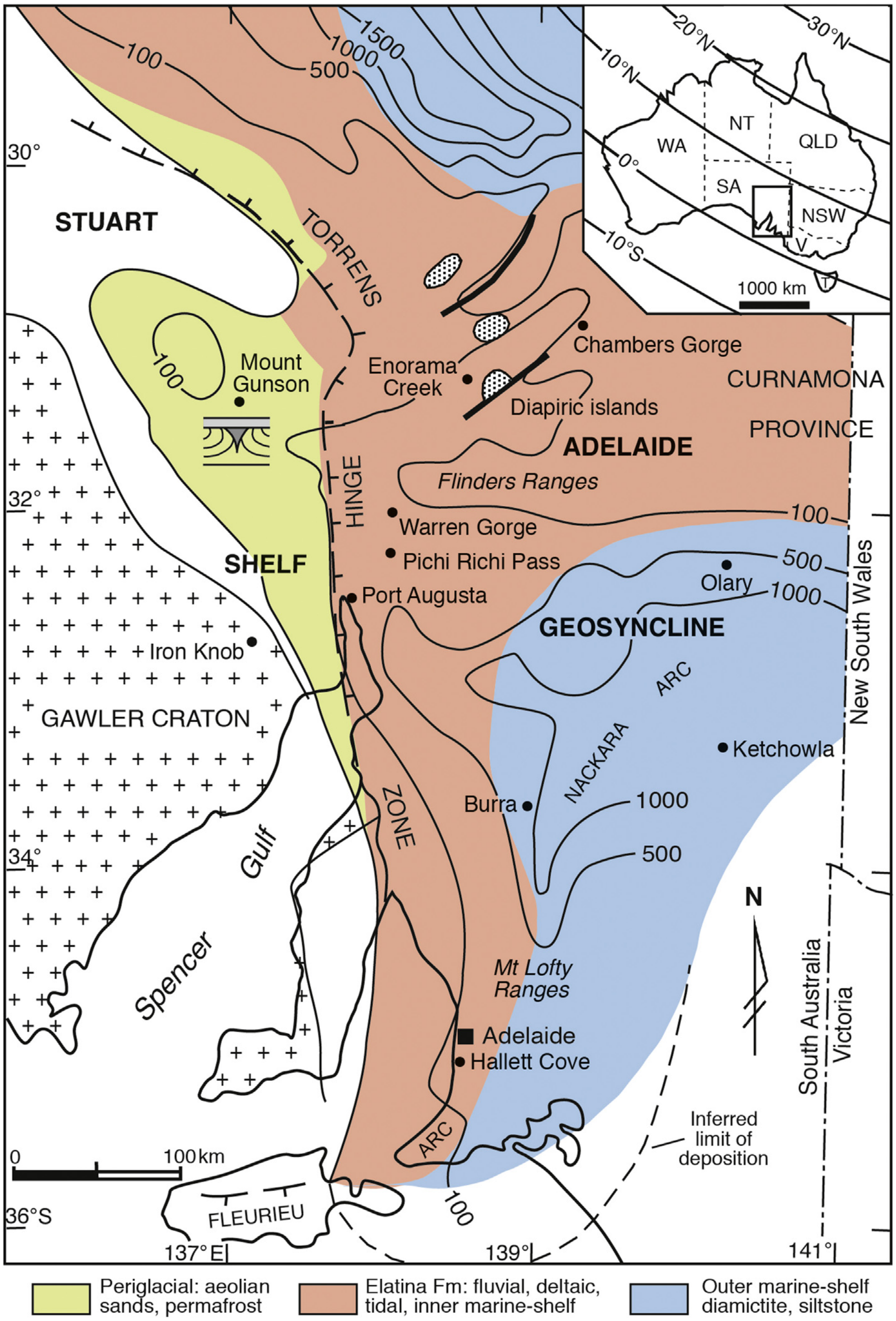

Figure 1. Map of SE South Australia, showing sedimentary settings for the terminal Cryogenian Elatina glaciation. The periglacial–aeolian Whyalla Sandstone on the cratonic Stuart Shelf passes eastwards to glaciofluvial, deltaic, tidal and inner marine-shelf deposits of the Elatina Formation in the Adelaide Geosyncline, which passes further eastwards to outer marine-shelf diamictites and mudstones–siltstones with ice-rafted debris. Isopachs in metres. The Ediacaran GSSP is located in Enorama Creek. The inset shows palaeolatitudes for Australia during the Elatina glaciation (Schmidt et al., 2009). Adapted after Preiss (1993).