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The Neoproterozoic Snowball Earth

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Abstract: Wee' McEarth: The rise and fall of 'Scottishism' in Neoproterzoic global climate

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Extended Abstract

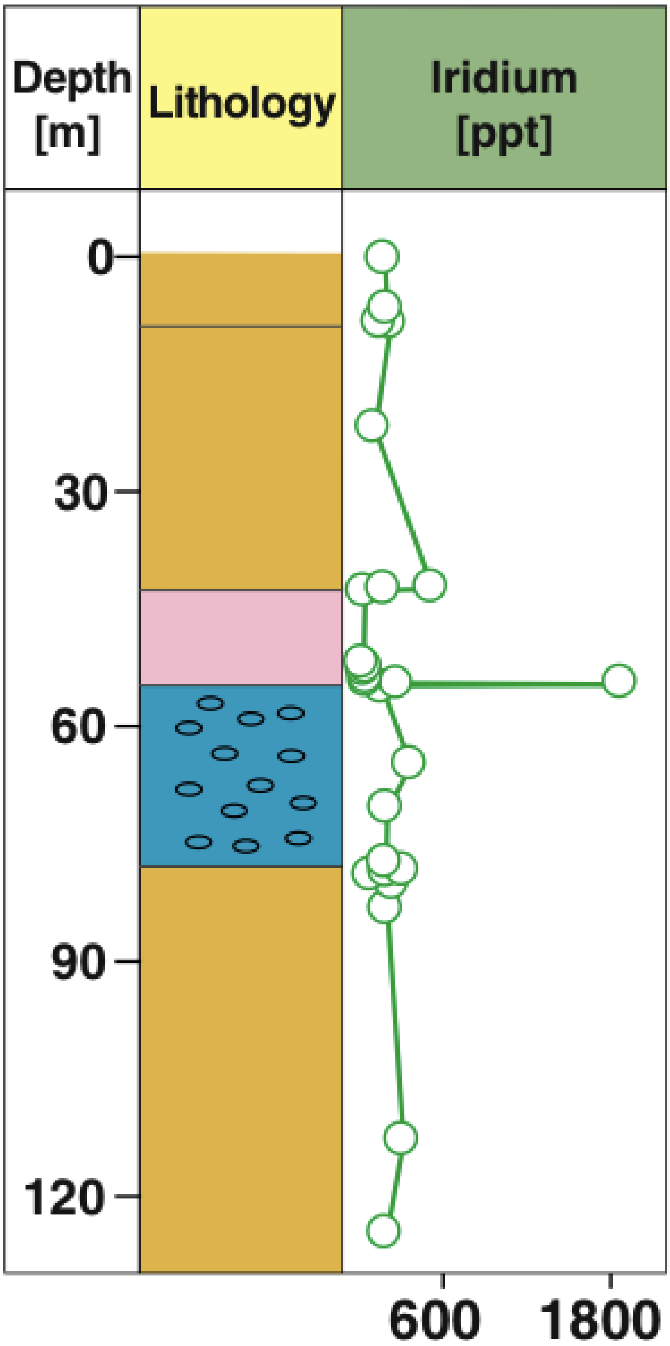
The Flinders Ranges of South Australia host some of the most reliable evidence for Neoproterozoic near-equatorial glaciation (Figure 1 in Hoffman and Schrag, 2002). Widespread Neoproterozoic lowlatitude glaciation was first proposed by Harland (1964), to explain late Neoproterozoic (750-580 Ma) glacio-sedimentary deposits overlain by post-glacial 'cap-carbonate' sequences, which have been identified on every modern-day continent (see Figure 1 and Figure 3 in Hoffman and Schrag, 2002). Lithological and isotopic (C, O, Sr) similarities suggest these deposits may be correlative, and could represent two or more globally synchronous depositional events. Paleomagnetic evidence (Harland, 1964; Embleton and Williams, 1986; Sohl et al., 1999) indicates that many of these deposits formed at low latitudes, implying that ice sheets may have extended almost to the equator at least twice during the Neoproterozoic (Hoffman et al., 1998b). Although this interpretation has been questioned (e.g. Schermerhorn, 1974), and some paleomagnetic evidence against low-latitude glaciation has emerged (Stupavsky et al., 1982; Morris, 1977), Harland (1964) hypothesis has achieved widespread acceptance (see review in Evans, 2000).

Two Neoproterozoic low-latitude glacial events are currently recognised, the Sturtian phase (ca. 700 Ma), and the Marinoan phase (ca. 630 Ma), both accumulated thick (≤6 km) glacial diamictites (Figure 6 in Hoffman and Schrag, 2002), overlain by a thin (<10 m) cap carbonate, typically composed of fine laminated dolostone (e.g. Figure 6 in Hoffman and Schrag, 2002). Marinoan-type cap carbonates are characterised by syn-depositional sedimentary and cementation structures, and very negative $\delta^{13}C$ compositions (ca. -5‰), decreasing upsection (e.g. Figure 8 in Hoffman and Schrag, 2002). Sturtian-type caps also show highly negative $\delta^{13}C$ compositions (ca. -6‰), however unlike the Marinoan type, their $\delta^{13}C$ compositions increase up-section and they do not show evidence of sea floor cementation or formation of sedimentary structures (e.g. Figure 8 in Hoffman and Schrag, 2002). The consistent, distinctive isotopic profiles from Neoproterozoic cap carbonates have been used extensively as a means of globally correlating stratigraphic horizons. However, it is noted that as variations in the C-isotope record may reflect both spatial and temporal changes in seawater composition, and the validity C-isotope chemostratigraphy as a correlative technique has been called into question (Giddings, 2005).

A number of hypotheses have been proposed to explain the apparent evidence for Neoproterozoic low latitude glaciation, including major changes in the earth's obliquity (Williams, 1975), shading of the equator by planetery ice-rings (Sheldon, 1984), and reduced atmospheric CO_2 (Schermerhorn, 1983). One of the most popular ideas, however, is the 'Snowball Earth' hypothesis, originally proposed by (Kirschivnik, 1992), and later extended by (Hoffman et al., 1998b,a). The Snowball Earth hypothesis postulates that glacial episodes were preceded by periods of high organic productivity and burial, marked by positive $\delta^{13}C$ compositions (Figure 8 in Hoffman and Schrag, 2002; Hoffman et al., 1998b,a). It is suggested that a congregation of continental landmass close to the equator increased global albedo and silicate weathering, in turn leading to reduced atmospheric CO_2 (Hoffman et al., 1998b,a). Expansion of the polar ices caps lead to a Snowball state, in which mean global temperatures dropped to ≤-50°C (Hoffman et al., 1998b,a, Figure 7 in Hoffman and Schrag, 2002). Frozen oceans caused the hydrologic cycle to shut down, and dramatically reduced biological activity, together driving down the $\delta^{13}C$ composition of seawater (Hoffman et al., 1998b,a). It is suggested this state may have lasted up to 10 Ma, until volcanic outgassing of CO_2 gradually warmed the atmosphere (Hoffman et al., 1998b,a). Dispersal of ice sheets lead to elevated rates of continental erosion, and re-equilibration of the hydrologic cycle, causing global precipitation of ^{13}C depleted carbonate (Hoffman et al., 1998b,a).

While the existence of low-latitude Neoproterozoic glacial deposits has been fairly well documented, evidence supporting their formation according to the Snowball Earth hypothesis remains in dispute. Some workers have argued that a complete shutdown of the hydrologic cycle would inhibit formation of glaciers, essential for transporting large volumes of glacial sediments (Christie-Blick et al., 1999). These workers prefer a 'Slushball' earth, in which a strong hydrologic cycle was maintained and the oceans were not completely frozen over (Kennedy et al., 1998). They further suggest that trends toward more radiogenic $^{87}Sr/^{86}Sr$ during Marinoan and Sturtian glaciations, and positive $\delta^{13}C$ values obtained from within glacial successions in Australia and Namibia are inconsistent with the Snowball Earth hypothesis (Kennedy, 1996; Kennedy et al., 1998). However, recent studies have identified extreme Ir anomalies at the base of cap carbonates from the Eastern Congo craton (see Figure 1 below and Figure 7 in Hoffman and Schrag, 2002), and argue their data require a protracted Snowball state (cf. Slushball) lasting at least 3 Ma, and possibly as long as 12 Ma (Kerr, 2005; Bodislitsch et al., 2005).

Figure 1. Global temperature and Ir anomalies.



Ir anomaly at the base of cap carbonates deposited at the end of the Marinoan glaciation (Bodislitsch et al., 2005; Kerr, 2005).

An alternative interpretation suggests that perturbations in the carbon cycle were the direct cause (rather than the result of) episodes of low-latitude glaciation glaciation. It is argued that periods of high organic burial could lead to a reduction in atmospheric CO_2, thereby inducing global cooling (e.g. Kaufman et al., 1997). These workers interpret negative $\delta^{13}C$ anomalies during and after glaciation as the result of overturning of a poorly vented, highly stratified ocean (Kaufman et al., 1997). A better understanding of the processes giving rise to perturbations of C, O, and Sr isotopic record in carbonate rocks is required to resolve these issues.

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