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Rapid sea level rise in the aftermath of a Neoproterozoic snowball Earth

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Earth's most severe climate changes occurred during global-scale snowball-Earth glaciations, which profoundly altered Earth's atmosphere, oceans, and biosphere. Extreme rates of glacio-eustatic sea-level rise are a fundamental prediction of the snowball Earth hypothesis, but supporting geologic evidence is lacking. We use paleohydraulic analysis of wave ripples and tidal laminae of the Elatina Formation, Australia — deposited following the Marinoan glaciation ca. 635Ma — to show that water depths of 9–16m remained nearly constant for ~100yrs throughout 27m of sediment accumulation. This accumulation rate was too great to have been accommodated by subsidence, and instead indicates an extraordinarily rapid rate of sea-level rise (0.2–0.27m/yr). Our results substantiate a fundamental prediction of snowball Earth models of rapid deglaciation during the early transition to a super-greenhouse climate.

Close monitoring of the Antarctic ice sheet indicates rapid and significant collapse (1) due in part to anthropogenically induced climate change. Present rates of ice sheet collapse are constrained by observations, but little is known about rates for ancient glaciations. The Late Neoproterozoic snowball Earth events represent an extreme climate change scenario, in which the collapse of global ice sheets during deglaciation are thought to have caused extremely large and rapid sea-level rise (2–4). Complete deglaciation occurring over only 2–10kyr and rapid sea-level rise is inferred from estimates of ice volume and greenhouse conditions (5) with CO₂ of ~400–660 times present atmospheric levels and surface temperatures of ~50°C (2). However, paleomagnetic reversals within cap carbonate beds, which mantle glaciogenic deposits and are part of the glacio-eustatic sea-level rise succession (Fig. 1A), indicate slow deposition over >10⁴ to 10⁶ yrs (6, 7), presenting a major obstacle to the snowball Earth hypothesis. Although slow rise rates may be tied to late-stage thermal expansion of oceans, rather than ice melt (4), geologic evidence of rapid sea-level rise during deglaciation is lacking. Here we show that a siltstone unit that rests below a cap carbonate records the extremely rapid initial sea level rise predicted by the snowball Earth hypothesis.

The Elatina Formation in South Australia contains a unique record of the Marinoan (~635Ma) snowball Earth that includes evidence for ice advance and subsequent deglaciation, including the early postglacial interval, as it is directly overlain by the Nuccaleena cap carbonate (8) (Fig. 1A). Paleomagnetic data constrain deposition of the formation to < 15°

north latitude (9), supporting a low-latitude glaciation consistent with a snowball Earth. Within the deglaciation succession, a ~30m thick, tidal-rhythmite siltstone unit records a complete daily record of sedimentation driven by tidal currents and wave action (10). We use a suite of sedimentary structures in these deposits to test a fundamental prediction of the snowball Earth model, namely, rapid glacio-eustatic rise during deglaciation.

Siltstone of the upper Elatina Formation crops out across ~4500km² of the Adelaide Rift Complex (ARC) and Stuart Shelf of South Australia. It consists of cm-scale packages of ~12 pairs of mm-thick silt and muddy silt laminae (average grain sizes are 61 and 37μm, respectively; 11) that vertically thicken and thin. These lamina pairs were initially considered to be varves formed in a periglacial lake (12), and later to be tidal delta deposits formed by spring-neap cycles (13). The rhythmites are preserved within bedforms (e.g., ripples) that aggrade vertically with few erosional surfaces, and individual bedforms can be continuously tracked vertically across meters of strata (8). Within this facies, several hierarchies of bedforms are preserved.

First-order (i.e., the largest class) bedforms are straight-crested, relatively symmetrical ripples (Fig. 1, B and C) with average heights of $h = 1.8 \pm 0.6\text{cm}$ (1σ), and average crest-to-crest spacings of $\lambda = 33 \pm 11\text{cm}$ (table S1). Locally, cross-lamination shows evidence of convex-up lamination (Fig. 2A), typical of combined-flow ripples (14), and gradual vertical shifts, including reversals, in migration direction (Fig. 2C). Several new observations provide independent evidence that the large ripples were deposited under reversing tidal currents. First, large ripple strata locally contain reactivation

surfaces, which indicate a current reversal that eroded the bedform flank. Second, ripple cross-laminated beds contain isolated, fully preserved ripples, less than 5 mm in height, that rest just below, or on, the larger ripple crests (Fig. 2B). These small ripples are oriented opposite to the dominant ripple cross-lamination and are bounded by the thickest laminae of the tidal bundles, indicating that the strongest reversing currents (i.e., spring tides) produced traction transport against the dominant tide. Finally, in cases, the first-order ripple cross-lamination contains two alternating types of erosional surfaces, half of which dip antithetical to the main cross-lamination and truncate the ripple foresets, whereas the others dip in the dip direction of the large ripples, but at a lower angle (Fig. 2D). The two truncation-surface types alternate upwards along the trace of the preserved climbing ripple crests, and the surfaces are contiguous with mm-thick white laminae that define rhythmite bundle boundaries, which again links the erosion surfaces to spring tides and cyclic lamination to reversing tidal currents.

The troughs of the first-order ripples preserve vertically aggraded second-order bedforms (i.e., smaller bedforms superimposed on the first-order bedforms) that align perpendicular to the first-order ripple crests (Fig. 1B). The second-order bedforms consist of symmetrical to moderately asymmetrical 2D ripples with $h = 0.4 \pm 0.2\text{cm}$ and $\lambda = 6.0 \pm 2.1\text{cm}$ (table S1). Second-order bedforms show locally developed bifurcations typical of straight-crested wave ripples. Their aspect ratio is $h/\lambda = 0.06 \pm 0.02$, and the ripple symmetry index (RSI), which is the ratio of the width of the stoss-to-lee sides, is 1.9 ± 1.6 (table S2), making them consistent with post-vortex anorbital wave ripples (15). Aspect ratios of these bedforms are smaller than wave ripples produced experimentally in sand but are consistent with ripples formed in silty sand beds in the presence of significant suspension of mud (16).

The sedimentological characteristics indicate deposition during both wave and current activity in an ice-free body of water, consistent with the latest- to post-snowball Earth climate. Whereas there is some spatial and stratigraphic variation, the most complete succession shows no systematic vertical changes in the heights and spacings of first or second order ripples throughout at least 16 m of the rhythmite unit (8). The small ripples are oriented NNE-SSW (fig. S1 and table S3), orthogonal to the first-order tidally influenced ripples, and thus wave action that generated the second-order ripples was normal to the tidal currents, consistent with expected equatorial easterlies and NW oriented wind fields inferred from eolian dunes (17).

Wave ripples in sand and silt, whether orbital or anorbital, show a consistent relation between their aspect ratio, h/λ , and the formative wave orbital diameter, d_o (Fig. 3A), which can be used to reconstruct the paleo-water depth. For the Elatina wave ripples, we estimate $d_o = 0.95 \pm 0.15\text{m}$ (11).

Wave generation constraints (11) dictate that for a given average wind speed and $d_o = 0.95 \pm 0.15\text{m}$, water depths varied by less than $\sim 7\text{m}$ (Fig. 3B). A near uniform average daily wind speed is expected due to trade winds, possibly modulated by diurnal katabatic winds (8). A larger change in water depth during deposition requires an unlikely systematic co-variation between depth and wind speed (Fig. 3B), and therefore relative sea level must have risen nearly commensurate with sediment accumulation.

Constraints on absolute water depth require an estimate of the wave period or average wind speed during ripple formation. Oscillatory duct experiments (16) with $d_o = 0.8\text{--}1.0\text{m}$ in silty sand produced ripples of equivalent dimensions to the Elatina with wave periods of $T = 5.5\text{--}7.5\text{s}$. The wave generation model (11) indicates that this combination of wave parameters ($T = 5.5\text{--}7.5\text{s}$ and $d_o = 0.8\text{--}1.1\text{m}$) limits absolute water depths to 9–30 m (Fig. 3B and fig. S2). The deeper end member (30m) requires the unlikely case of reoccurring whole-gale force (25m/s) winds, whereas the lower-bound (9–16m) indicates reasonable average wind speeds of $\sim 16\text{m/s}$, equivalent to speeds previously proposed (8). Burial of the Elatina Formation would have been to $\sim 5\text{--}6\text{km}$ depth (18) with compaction of $\sim 40\%$ (19). Thus, the original (decompacted) deposit thickness of $\sim 27\text{m}$ (11) exceeds our estimated maximum change in water depth ($\sim 7\text{m}$), in addition to the likely absolute water depth (9–16 m; Fig. 3B), which provides two independent constraints that the rate of relative sea-level rise must have closely matched the accumulation rate.

The preservation of tidal laminae in the Elatina Formation provides a means to explain how two scales of superimposed bedforms accrete over 27m with little change in ripple dimensions and inferred water depth. Williams (13) identified 1,580 neap-spring tidal cycles in a 9.39m thick core of the Elatina Formation devoid of truncation surfaces, which he used to constrain depositional time, but did not consider implications for sea-level rise. Alternating thick and thin packages of laminae throughout the core, with each package containing ~ 12 pairs of silt and mud laminae, represent the neap-spring cycles within half a lunar month. Spectral analysis of these packages yielded the number of lunar months per year (13.1 ± 0.1), and $60.3 \pm 0.5\text{yrs}$ for deposition of the 9.39 m thick core (13). The resulting accumulation rate is used to estimate that the decompacted original thickness of $\sim 27\text{m}$ determined for our rippled section was deposited over $\sim 100\text{yrs}$ with an accumulation rate of $\sim 27\text{cm/yr}$ (11), or 20cm/yr if water depth shallowed during deposition by the maximum allowed (7m). This accumulation rate is higher than any previously estimated for a large marine basin over century timescales or longer (20), consistent with high suspended-sediment concentrations during rapid deglaciation of a snowball Earth episode. Given that subsidence over ~ 100

years would be negligible (21), the inferred ~27m of accumulation could only be accomplished through rapid rise of sea level, specifically at 20–27cm/yr.

The rhythmite unit represents a fraction of the total deglaciation deposit, and duration estimates for complete deglaciation, based on ice volumes and greenhouse conditions, are typically 2–10kyr (6kyr average) (5). The total sea-level rise due to melting of Marinoan glaciers has been estimated at ~1,000–1,500m (2, 22), which likely varied spatially due to gravitational effects (23). A glacioeustatic rise of 1.5km over 2–10kyr corresponds to a long-term rise rate of 15–75cm/yr, or 25cm/yr for a 6-kyr deglaciation, which is consistent with our independent short-term geologic constraint of 20–27cm/yr. This rate of sea-level rise is one-hundred-fold greater than present-day rates (24) and five times greater than the highest during Pleistocene deglaciations (25). Sea-level rise of this magnitude is a strong confirmation of a major tenet of the snowball Earth hypothesis, namely rapid deglaciation during the early transition from icehouse to hyper-greenhouse conditions.

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SUPPLEMENTARY MATERIALS

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Materials and Methods

Figs. S1 to S2

Tables S1 to S3

References (30–34)

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Fig. 1. Elatina Formation. (A) Generalized stratigraphic succession of Marinoan glacial and postglacial deposits modified from (2), and study location (star) with paleolatitude lines (26) in South Australia. (B) Planview (bedding plane) outcrop showing larger first-order ripples oriented perpendicular to second order ripples with locally developed bifurcations. (C) Vertically climbing secondary ripples in cross-section. Note mm-scale tidal laminae. Laminae bundle boundaries highlighted by cm-scale spaced darker laminae. Pencil is 14cm long.

Fig. 2. Sedimentary structures of first-order ripples. (A) Stoss-erosional to nearly stoss-preservational first-order ripple cross-stratification with convex-up (CVU) lamination typical of combined-flow ripples. (B) Migrating ripple lamination with bundled tidal laminae. Note small ripple with cross-stratification that dips opposite to the main ripple laminae. (C) Climbing first-order ripple cross-stratification with lower part recording bedform climb to the left, and upper part reversing to the right, similar to cap carbonate strata (27). (D) Close-up of upper part of panel (C). Truncation surfaces that are flat to slightly inclined to the right (T1) become conformable downdip with laminae defining the cross-lamination of the ripple. These surfaces truncate laminae on the stoss side of the ripple that are dipping to the left. Surfaces that are moderately inclined to the left (T2) truncate the main cross-lamination of the ripple. The two truncation-surface types generally alternate along the trace of the ripple crest. Pencil is 14cm long.

Fig. 3. Paleohydraulic reconstructions. (A) Wave ripple geometry (h is ripple height, λ is ripple crest-to-crest spacing) as a function of normalized orbital diameter, d_0 . Sand-bed field data (28) include orbital, suborbital and anorbital ripples. Silt-bed experiments (16) produced ripples with geometries and grainsizes similar to Elatina ripples. Solid line represents Eq. (1) (11). **(B)** Combinations of average wind speed and water depth capable of producing $d_0 = 0.95 \pm 0.15$ m (gray shade) according to a wave generation model (11). Orange shaded region marks where wave ripples are stable (29) for 50-micron silt (11), and the green shaded region corresponds to wave periods, T , of 5.5 – 7.5 s, conditions in which ripples similar the Elatina formed in experiments (16). Reconstruction is based on 75 km fetch inferred from paleogeographic reconstructions (10); varying fetch within a factor of two (38–150 km) has a negligible effect on the water depth.