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Focus paper

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

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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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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

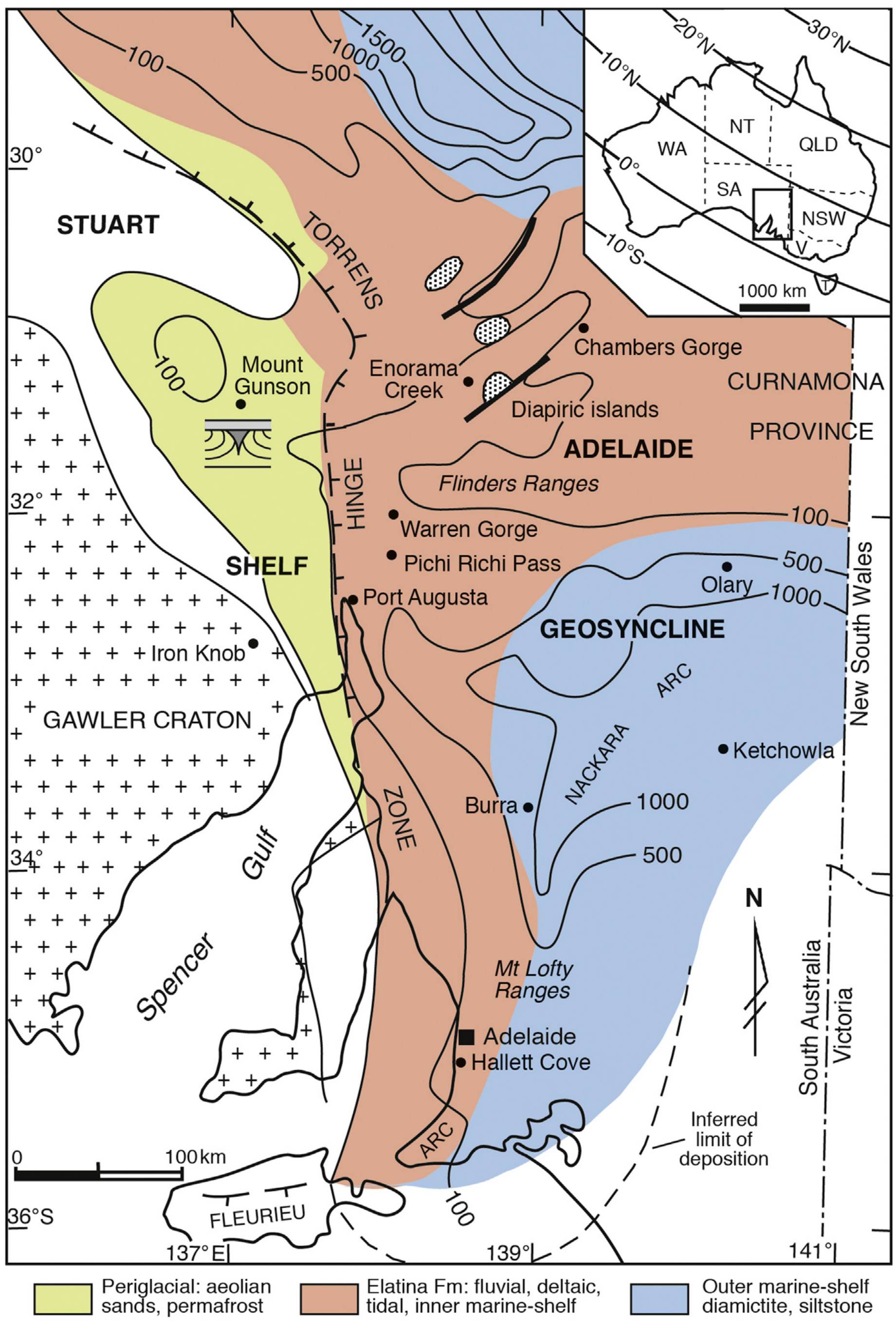

Figure 1. Map of SE South Australia, showing sedimentary settings for the terminal Cryogenian Elatina glaciation. The periglacial–aeolian Whyalla Sandstone on the cratonic Stuart Shelf passes eastwards to glaciofluvial, deltaic, tidal and inner marine-shelf deposits of the Elatina Formation in the Adelaide 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).

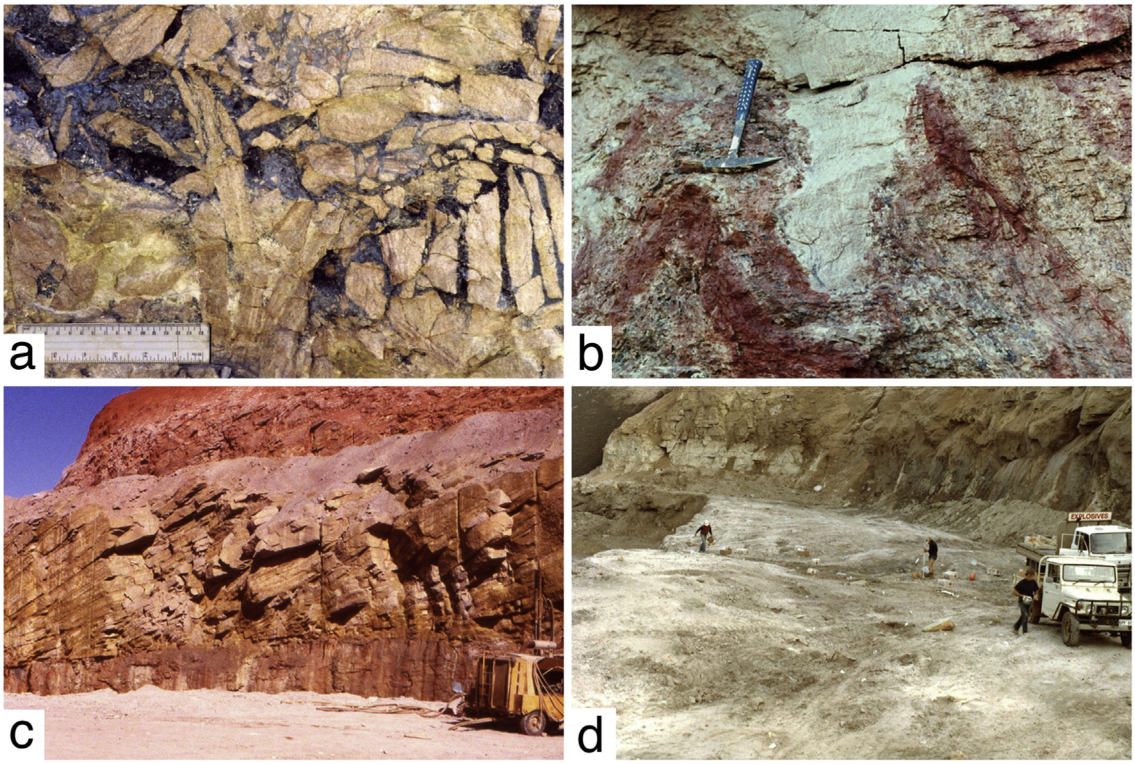

Figure 2. Cattle Grid Breccia and Whyalla Sandstone, Cattle Grid pit. (a) Copper sulfides filling voids in the breccia; scale 15 cm. (b) Anticline in the breccia penetrated by a sand wedge displaying vertical lamination; hammer 33 cm long. From The Australian Geologist (Nos. 117, 2000); published with the permission of the Geological Society of Australia. (c) Periglacial–aeolian Whyalla Sandstone exposed in the Cattle Grid open pit, showing two 7 m-thick cross-bedded sets of medium- to very coarse-grained sandstone above a basal unit of low-angle strata (behind trailer). (d) A mine bench in the Cattle Grid open pit excavated to the top of the Cattle Grid Breccia, showing polygonal hummocks ~10 m across; the depressions outlining the hummocks (by figure at left) mark the position of underlying sand wedges. The vertical face in the background exposes low-angle strata of the Whyalla Sandstone. After Williams and Tonkin (1985); published with the permission of the Geological Society of Australia.

widespread and persistent rainout of ice-rafted debris and several glacial advances and retreats (Coats and Preiss, 1987; Williams et al., 2008, 2011). Both the Whyalla Sandstone and the Elatina Formation are overlain by the early Ediacaran Nuccaleena Formation cap dolostone, demonstrating that both the Cattle Grid Breccia and the Whyalla Sandstone formed during the Elatina glaciation (Coats, 1981; Coats and Preiss, 1987; Preiss, 1993; Preiss et al., 1998; Williams, 1998; Williams et al., 2008). Ediacaran (~635–541 Ma) glaciation is recognised on most continents (Etienne et al., 2008) and its echoes reached southern Australia (Gostin et al., 2010).

A feature of Proterozoic (herein excluding the Ediacaran) glacial deposits is their occurrence in low palaeolatitudes as determined *directly* by the palaeomagnetic study of such deposits and closely associated rocks (see Section 3). Indeed, a high palaeolatitude has not been determined for any pre-Ediacaran glacial deposit. Another persistent feature of Proterozoic glacial successions is the evidence from a variety of facies for a strongly seasonal glacial climate, in particular for large seasonal changes of temperature. Here we bring together and review the compelling evidence for strong seasonality, and identify the shortcomings of arguments put forward by some to account for the paradoxical finding of a strongly seasonal Proterozoic glacial climate in low palaeolatitudes.

2. Geological evidence for strong seasonality

2.1. Proterozoic cryogenic wedges

2.1.1. Cryogenian, South Australia

During the Elatina glaciation, a ridge of flat-lying Mesoproterozoic fluvial arenite, the Pandurra Formation, formed an upwarp in the central part of the Stuart Shelf (Fig. 1). At Mount Gunson, a tabular breccia body up to 20 m thick (average 5 m), termed the Cattle Grid Breccia, developed in situ through ice segregation and frost shattering of the silicified Pandurra Formation (Williams and Tonkin, 1985; Williams, 1986; Williams et al., 2008). Fractures and interclast voids in the Cattle Grid Breccia are lined and filled with copper sulfides (Fig. 2a; Tonkin and Creelman, 1990). Anticlinal structures up to 4 m high and 4 m wide in the breccia (Fig. 2b), some with associated moderate- to high-angle reverse faults, indicate both horizontal and vertical expansion during brecciation.

The Cattle Grid Breccia is overlain by 'low-angle strata' – that is, deposits with initial dip of $\leq 15°$ (Kocurek, 1986) – of quartzose sandstone representing the basal unit of the Whyalla Sandstone. The Whyalla Sandstone is an undeformed periglacial–aeolian sand-sheet deposit (Williams, 1998; Williams et al., 2008, 2011) up to 165 m thick and covering 25,000 km^2 in outcrop and subcrop. It comprises mostly medium- to very coarse-grained, quartzose sandstone with well rounded grains and bimodal texture such as characterise desert environments (Folk, 1968; Binda and Hildred, 1973). Two 7 m-thick cross-bedded sets overlie the basal low-angle strata (Fig. 2c), and display uniquely aeolian inversely-graded subcritically climbing translatent strata and grainfall and grainflow deposits (Williams, 1998). Thin conglomeratic beds at several localities near the base of the Whyalla Sandstone (Williams and Tonkin, 1985; Williams, 1998; Ewing et al., 2014) record local fluvial input. The single, fragmentary striated clast found in the basal beds south of Mount Gunson (Ewing et al., 2014) implies some fluvial reworking of glacial deposits of uncertain age; diamictites of the preceding

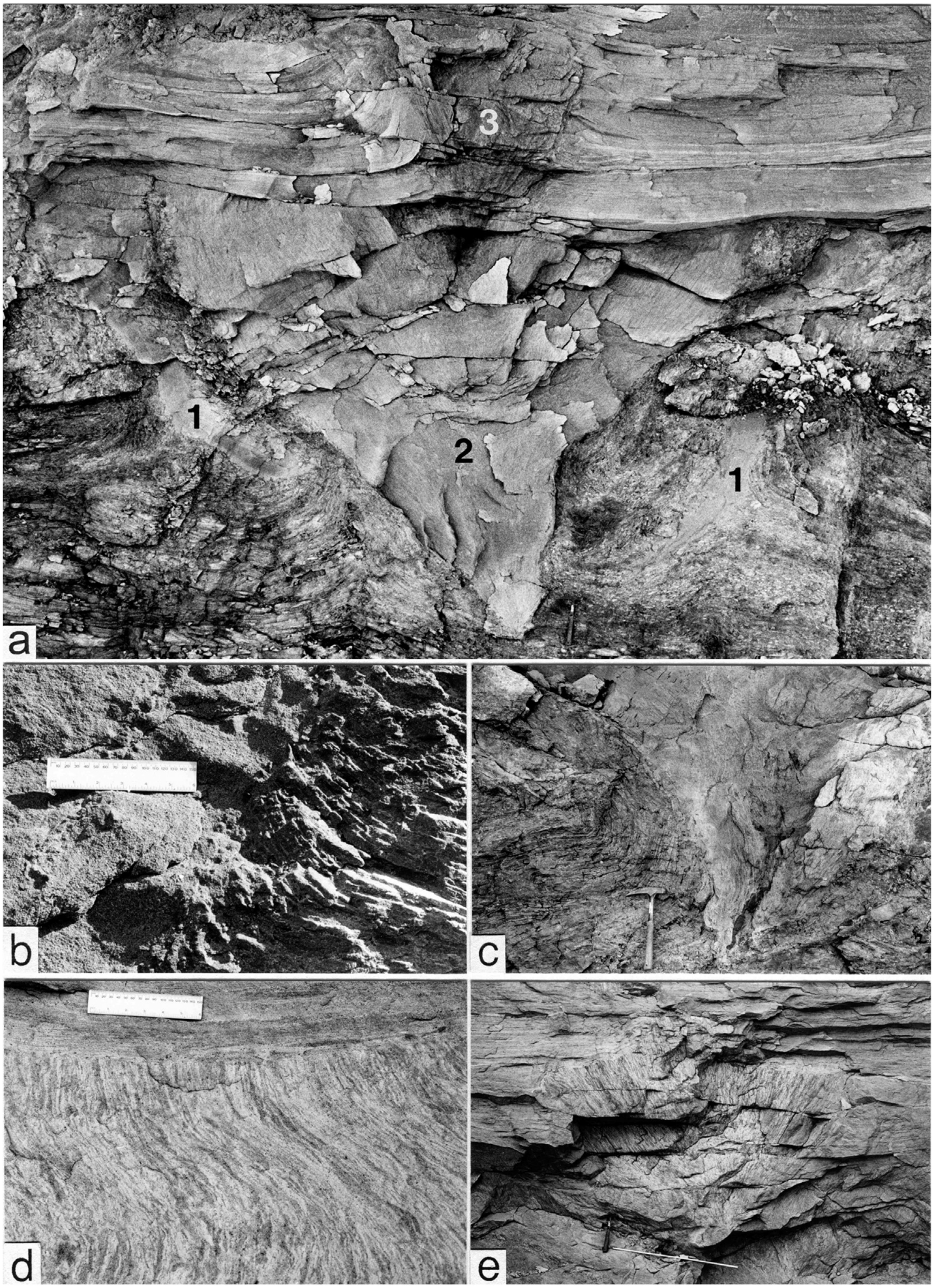

Figure 3. Cryogenian sand wedges exposed in the Cattle Grid open pit, Mount Gunson. (a) Large V-shaped sand wedge (2) 3+ m-deep in the Cattle Grid Breccia and truncated at an erosional surface by low-angle strata of the Whyalla Sandstone. A near-vertical diverging fabric is discernible within the wedge. Two earlier, deformed wedges (1) occur in the breccia. A third-stage wedge (3) is developed within the uppermost part of the large wedge and in the Whyalla Sandstone. Breccia and sandstone are upturned next to the wedges. Hammer 33 cm long. (b) Contact between a sand wedge and in situ breccia, showing upturning of relict bedding in the breccia. Scale 15 cm. (c) Curved base of a sand wedge, and disturbed relict bedding in the adjacent breccia (above hammer). (d) Steeply dipping, flexed laminae near the centre of a sand wedge, truncated by low-angle strata of the Whyalla Sandstone. Scale 15 cm. (e) Sand wedge 1.7 m deep, with conspicuous diverging fabric, developed in an older wedge in the Cattle Grid Breccia and in low-angle strata of the Whyalla Sandstone. Tape 1 m long. After Williams and Tonkin (1985); published with the permission of the Geological Society of Australia.

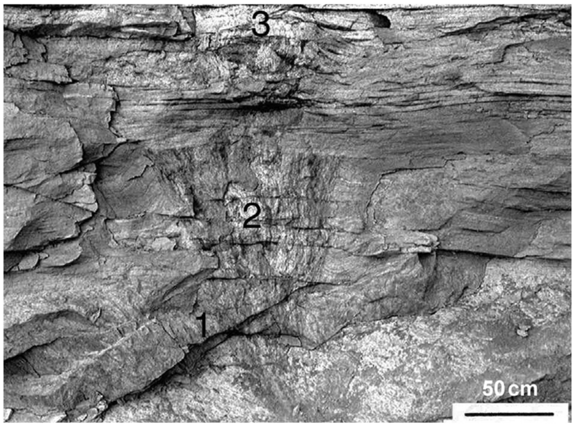

Figure 4. Three sand wedges exposed in vertical section in the Cattle Grid open pit, Mount Gunson. A wedge 1.5 m deep displaying near-vertical lamination (2) has its lower half developed within a wedge in the Cattle Grid Breccia (1) and its upper half in low-angle strata of the Whyalla Sandstone. A small wedge at the top (3) formed in the Whyalla Sandstone and the upper part of the underlying wedge. Strata of the Whyalla Sandstone are upturned next to the wedges. Scale bar 50 cm. Adapted after Williams (1998); published with the permission of the Geological Society of Australia.

Sturt glaciation are known on the Stuart Shelf, but not those of the Elatina glaciation (Coats and Preiss, 1987). Fluvial material was transported into the basin then reworked by aeolian processes, as also occurred with deposition of the Cryogenian aeolian Bakoye 3 Formation in Mali (Deynoux et al., 1989). Such fluvial input of sediment is important for the growth of dunefields (Fitzsimmons, 2007), and implies the existence of an active hydrological cycle during deposition of the Whyalla Sandstone despite overall aridity. The Whyalla Sandstone and the Bakoye 3 Formation are the only known examples of pre-Cenozoic periglacial dunefields (Rodríguez-López et al., 2014).

Exceptionally well-preserved periglacial primary sand-wedges in the Cattle Grid Breccia and Whyalla Sandstone were exposed during copper mining at Mount Gunson from 1974 to 1986. The best exposures in the Cattle Grid open pit (Figs. 2–4, 6) were examined as mining progressed in the 1980s, and in diversity and quality of preservation these periglacial structures are unsurpassed in the pre-Pleistocene record. Unfortunately, backfilling during mining buried the best structures, and those exposures remaining when mining ceased have since been spoiled by acid leaching, which has rendered the structures difficult to discern.

V-shaped wedges of fine- to very coarse-grained quartzose sandstone, which are up to 3+ m-deep and up to 4 m in apparent width, occur at the top of the Cattle Grid Breccia (Figs. 2b and 3a). The wedge sandstone contains rounded quartz grains and shows bimodal texture like that of the Whyalla Sandstone. The wedges display fan-like internal lamination, with laminae near wedge margins paralleling the contact with the breccia. Typically the relict bedding in the breccia is turned upwards next to the wedges (Fig. 3b). Where temporarily exposed before blasting, the surface of the breccia displayed grooves several metres wide and up to 1 m deep that outlined polygons ~10 m across (Fig. 2d). These grooves mark the surface trace of large sand wedges and demonstrate that the wedges have a polygonal arrangement in plan. Two stages of wedge formation are recognised in the breccia (Fig. 3a), the earlier wedges being deformed and displaced from the vertical by the development of the younger wedges.

The wedges in the Cattle Grid Breccia are truncated at an erosional surface beneath the low-angle strata at the base of the Whyalla Sandstone (Fig. 3a,d). The basal unit itself displays at least two levels of V-shaped sand wedges up to 1.5 m deep that typically sit directly above sand wedges in the breccia (Figs. 3a and 4). Bedding in the Whyalla Sandstone is turned upwards next to the wedges.

The structure, dimensions and internal fabric of the wedges at Mount Gunson, and the upturning of ground next to the wedges, are closely comparable with features of primary, V-shaped sand wedges that are widespread and actively forming in the Dry Valleys of Antarctica (Péwé, 1959; Black, 1973, 1982; Bockheim et al., 2007). Additional features shared by the sand wedges in the Cattle Grid Breccia and in Antarctica (Péwé, 1959; Black, 1973) are the development of wedges in bedrock rubble produced by frost action and the presence of multistage, wedge-in-wedge structure.

Wedge-in-wedge structure characterises the wedges at Mount Gunson, where they developed in at least four stages: the first two stages of wedge formation occurred in the Cattle Grid Breccia (Fig. 3a), and two further stages in the basal Whyalla Sandstone (Figs. 3a and 4) that were punctuated by the deposition of aeolian sand. These are syngenetic wedges (Mackay, 1990) resulting from wedge formation alternating with the vertical accretion of host material at the top of the permafrost (Fig. 5).

2.1.2. *Cryogenian, West Africa*

Deynoux (1982) described well preserved periglacial polygonal structures and sand wedges that can be followed for more than 100 km at the top of Cryogenian glacial deposits just below a cap dolostone in the Taoudeni Basin, Mauritania, West Africa. The V-shaped wedges are 2–3 m deep, comprise fine- to coarse-grained bimodal sandstone that is conglomeratic near the top, display a steeply dipping internal lamination that follows the V-shape, and form polygons 6–11 m in diameter. The roundness and sphericity of

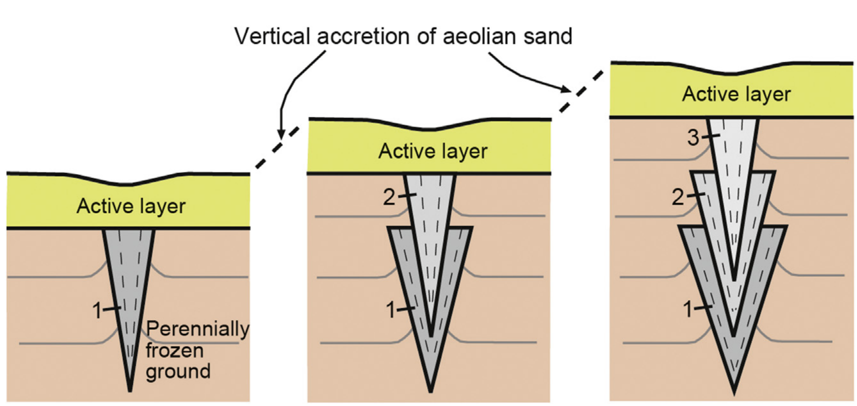

Figure 5. Diagram showing the relationships among perennially frozen ground, the overlying active layer, and the development of multistage, syngenetic sand wedges with the episodic vertical accretion of aeolian sand as seen at Mount Gunson.

the coarse sand grains and the bimodal texture of the wedge sandstone imply an aeolian source. As in South Australia, the Cryogenian glacial succession in West Africa includes extensive periglacial–aeolian deposits (Deynoux et al., 1989), indicating an arid periglacial environment with the ready availability of windblown sand.

2.1.3. Cryogenian, North Atlantic region

Polygonal wedges up to 12 m deep and 50 cm wide penetrate diamictite and granite conglomerate at 27 stratigraphic horizons in the Port Askaig Formation of the Dalradian Supergroup in Scotland (Spencer, 1971, 1975, 1985; Arnaud and Fairchild, 2011). The wedges comprise sandstone with vertical internal fabric and vertically-aligned pebbles, and are interpreted to be cryogenic sand wedges formed by the infilling of periglacial contraction cracks, indicating subaerial permafrost conditions.

A diamictite unit in the Ulvesø Formation, East Greenland, is penetrated by metre-scale, sandy and gravelly wedges inferred to have formed by the infilling of frost contraction cracks in permafrost (Moncrieff and Hambrey, 1990). Partial thawing of the permafrost then occurred, causing the distortion of some wedges and the soft-sediment deformation of the overlying sandstone bed with the development of sandstone load structures.

Sand-filled wedges are common in the dominantly periglacial Wilsonbreen Formation in Svalbard, with some wedges up to 0.6 m wide penetrating diamictite to depths of 3.5 m (Fairchild and Hambrey, 1984; Fairchild et al., 1989; Harland et al., 1993). Internal layering sags downwards at the top of the wedges and parallels their lower margins. Harland et al. (1993, p. 35) regarded these structures as 'analogous to periglacial ice-wedge casts or less likely cold-arid sand wedges', while Fairchild and Hambrey (1984) preferred an ice-wedge cast origin.

2.1.4. Palaeoproterozoic, Australia, Europe, North America

Williams (2005) described a subglacial grooved surface and overlying widespread (130 km × 260 km in outcrop) glaciofluvial conglomerates and sandstones, including ventifacts, that formed during the 1.8 Ga King Leopold glaciation in NW Australia. The grooved surface exhibits vertical sandstone-filled cracks up to 5 cm wide and >20 cm deep outlining irregular polygons several metres across, interpreted as frost-fissure casts formed by thermal contraction-cracking in a frigid, windy periglacial setting.

Kuipers et al. (2013) interpreted a V-shaped, 1.7 m-deep wedge structure developed in 1.9 Ga dacitic metavolcanic sediments in central Sweden to be a periglacial ice-wedge cast. They suggested that the structure may record a glacial interval broadly coeval with the King Leopold glaciation.

The oldest known wedge structures interpreted as cryogenic occur in bedded sandstone and siltstone of the lower Huronian (~2.4 Ga) glaciogenic Ramsay Lake Formation in Ontario, Canada (Young and Long, 1976). The larger of the two structures is about 1.3 m deep and 65 cm wide, has a sharp contact with the host rock, and comprises sandstone with fragments of bedded sandstone near the base and showing faint, concave bedding near the top. The smaller structure is about 30 cm deep and 20 cm wide and filled with structureless sandstone. Young and Long (1976) argued that the structures are the casts of subaerial ice-wedges that formed in permafrost; subsequent warming caused thawing of the permafrost and the filling of the structures from above, with the partial collapse of the larger structure.

2.1.5. Formation and climatic implications of cryogenic wedges

Metre-scale primary sand wedges identical to the Cryogenian wedge structures at Mount Gunson and other localities are widespread and forming in present-day polar periglacial regions with a frigid, *strongly seasonal* climate (Péwé, 1959; Black, 1976, 1982; Washburn, 1980; Karte, 1983; Bockheim et al., 2009). In these polar regions, essentially vertical, planar thermal-contraction cracks (tensile fractures 'resulting from thermal stresses in *frozen ground*'; van Everdingen, 2005, p. 79) up to 10 m deep and 1–10 mm wide, form polygons 10–30 m across in plan in the upper part of permafrost with rapid drops of temperature during repeated severe winters, particularly in localities with thin snow cover. Such thermal-contraction cracks develop in perennially frozen ground *beneath* the active layer (Lachenbruch, 1962; Washburn, 1980), which Washburn (1980, p. 57) defined as the 'layer of ground above the permafrost which thaws in the summer and freezes again in the winter'. CALM (Circumpolar Active Layer Monitoring) likewise defines the active layer as 'The layer of ground that is subject to annual thawing and freezing in areas underlain by permafrost' (van Everdingen, 2005). The active layer is generally thinnest in polar regions, where it may be as little as 15 cm thick (French, 2007). In the Dry Valleys of Antarctica, where sand-wedge polygons are well developed, active layer thickness at 19 localities in the McMurdo Dry Valleys averages 29 cm (Bockheim et al., 2007) and in the Beacon Valley is 20–30 cm (Bockheim et al., 2009). The thinnest active layers (as little as 2–3 cm) occur in the highest mountains of the equatorial zone, where solar radiation changes little annually (Dobinski, 2011). Fig. 5 shows the relationship between perennially frozen ground and the active layer, and the development of syngenetic sand wedges as seen at Mount Gunson. As discussed in Section 4.2, it is important to distinguish perennially frozen ground and the active layer in assessing the palaeoclimatic implications of cryogenic wedges.

Seasonal temperature changes in permafrost in high latitudes may reach depths of 15 m or more and take place entirely below the freezing point (Embleton and King, 1975). In arid permafrost areas the seasonal thermal-contraction cracks in perennially frozen ground may be filled by windblown sand, and the repeated infilling of successive contraction cracks over many years results in the development, *beneath the active layer*, of primary sand wedges typically exhibiting vertical to fan-like lamination. Ice wedges form in perennially frozen ground in humid periglacial areas where water freezes within contraction cracks that form repeatedly over many winters; the resulting ice wedges may be replaced by sediment, commonly showing horizontal layering, upon thawing of the permafrost. Lateral pressure during summer expansion causes the upturning of the host permafrost next to sand- and ice-wedges.

According to Goehring and Morris (2014, p. 41), 'frozen-terrain networks consist of cracks that open and close seasonally …. The polygons observed today usually represent many thousands of years of iterated evolution.' Observations over several decades confirm that cryogenic sand wedges in Antarctica are actively forming under a strongly seasonal climate (Black, 1982). A mean annual rate of horizontal growth of ~1 mm per year determined for certain extant sand wedges and ice wedges (Washburn, 1980; Black, 1982) suggests that the sand wedges at Mount Gunson took ~4 kyr to form (Williams and Tonkin, 1985). Sand wedges up to 2 m deep and >100 ka in age occur in perennially frozen ground in the Beacon Valley, Antarctica (Bockheim et al., 2009). Hence great stability of the ground over long intervals of time is imperative for the growth of wedges, and the required stability can be provided only where the wedges form in perennially frozen ground beneath the active layer.

Climatic conditions for the Dry Valleys of Antarctica, where sand wedges are well developed and actively forming, are summarised in Table 1. Because cryogenic sand wedges form through *physical* processes and now are restricted to regions with a unique climate, they provide insight into glacial palaeoclimates. Applying an actualistic interpretation for the formation of cryogenic sand

Table 1
Climate data for present-day areas with cryogenic sand- and ice-wedge polygons.

Cryogenic structure	Locality	MAAT (°C)	MMAT range (°C)	MAP (mm)	Climate reference
Sand wedges	McMurdo Sound region, Antarctica	−20	−38 to +1.4	100	Keys (1980)
Sand wedges	Taylor Valley, Antarctica	−21.1	−30.2[a] to −7.7[b]		Fountain et al. (1999)
Sand wedges, occasional ice-wedges	High Arctic and Antarctica	<−20	<−35 to <+4	<100	Karte (1983)
Ice wedges	Arctic frost debris zone	<−6	−35 to <+5	100–450	Karte (1983)
Ice wedges	Arctic tundra periglacial zone	−5 to −16	<−20 to <+10	100–500	Karte (1983)

MAAT, mean annual air temperature; MMAT, mean monthly air temperature; MAP, mean annual precipitation. [a]March–September; [b]October–February.

wedges, their presence at Mount Gunson implies that the following features characterised the terminal Cryogenian climate in South Australia (Williams and Tonkin, 1985; Williams, 1986, 1998; Williams et al., 2008, 2011):

- Strongly seasonal climate, with a mean monthly air temperature range of 40 °C (mean monthly air temperatures as low as −35 °C or lower in midwinter and <+4 °C in midsummer). Ground surface temperature responds strongly to air temperature at measurement sites in continental Antarctica (Guglielmin, 2006).
- Mean annual air temperature of −20 °C or lower. The in situ brecciation of bedrock to form the Cattle Grid Breccia attests to frost shattering under a frigid climate.
- Aridity (≤100 mm mean annual precipitation), thin snow cover, and windiness causing the infilling of thermal contraction-cracks with windblown sand. An arid, windy climate is supported by the presence of an extensive aeolian sand sheet (Whyalla Sandstone).

This frigid, strongly seasonal climate existed near sea level within 10° of the palaeoequator (see Section 3).

Deynoux (1982) attributed the Cryogenian periglacial polygonal structures and sand wedges in Mauritania to seasonal contraction cracking during repeated, abrupt and severe falls of temperature in winter and the infilling of the cracks from above by clastic material. A seasonal temperature range comparable with that inferred for the formation of the sand wedges at Mount Gunson is indicated. The ice-wedge casts identified in the Wilsonbreen Formation in Svalbard (Fairchild and Hambrey, 1984; Fairchild et al., 1989) likewise imply a strongly seasonal, frigid climate (Table 1).

In summary, the occurrence of periglacial sand wedges and ice-wedge casts with Cryogenian glacial deposits argues forcibly for a strongly seasonal climate during Cryogenian glaciations. The presence of structures interpreted as ice-wedge casts and frost-fissure casts associated with Palaeoproterozoic glaciogenic deposits (Young and Long, 1976; Williams, 2005) suggests that Palaeoproterozoic glacial climates also were strongly seasonal.

2.1.6. *Thaw-modification structures*

At Mount Gunson, local soft-sediment structures include deformed, curved and inclined sand wedges in places associated with disturbed bedding (Figs. 3c and 6a), wedges with flexed internal laminae (Fig. 3d), diapiric flame structures of Cattle Grid Breccia injected into the lowermost Whyalla Sandstone (Fig. 6b) that Williams (1998) attributed to thawing permafrost, and downward-penetrating involutions of sandstone and breccia (Williams and Tonkin, 1985; Williams, 1986, 1998). The local presence of metre-scale channel-forms and lenticular beds of reworked quartzite clasts near the base of the Whyalla Sandstone attests to the action of running water.

These soft-sediment structures are closely comparable with thaw-modification structures, including curved, folded, inclined and sheared relict sand-wedges, involutions, and load, flame and diapiric structures, that survived permafrost degradation in Arctic Canada (Murton and French, 1993). Hence the permafrost horizon in the Cattle Grid Breccia underwent local degradation, with the formation of thaw-modification structures. This was followed by further wedge formation in the Whyalla Sandstone, indicating fluctuations of climate. Likewise, in other Proterozoic cryogenic horizons, sand- and ice-wedges were formed in permafrost and only later, with thawing of the permafrost, were sand wedges

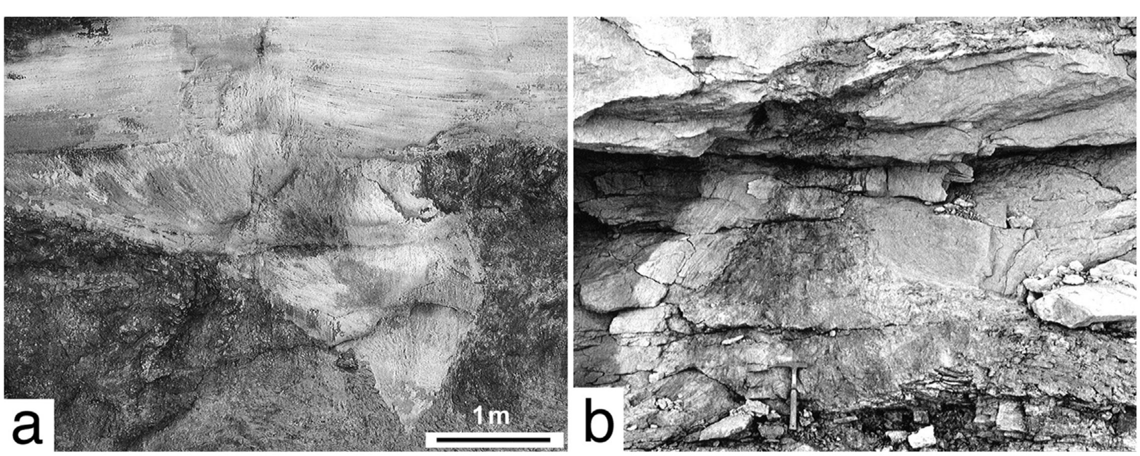

Figure 6. Thaw-modification structures, Cattle Grid open pit, Mount Gunson. (a) Deformed sand wedge 2.5 m deep in the Cattle Grid Breccia, overlain at an erosion surface by low-angle strata of the Whyalla Sandstone. Scale bar 1 m. Photograph by courtesy of David Tonkin. (b) Diapiric flame structure of Cattle Grid Breccia (above hammer) in the basal Whyalla Sandstone. Bedding in the adjacent sandstone locally parallels the margins of the structure. Hammer 33 cm long. After Williams (1998); published with the permission of the Geological Society of Australia.

deformed and truncated and ice wedges replaced by clastic material (e.g. Young and Long, 1976; Moncrieff and Hambrey, 1990).

As discussed in Section 2.1.5, great stability of climate with ground perennially frozen over long intervals of time (kyr timescale) is necessary for wedge formation, whereas thawing and degradation of permafrost with the deformation of wedges and the formation of involutions and slump, load and diapiric structures may occur during much briefer, warmer intervals. For example, Jorgenson et al. (2006) found 'an abrupt, large increase in the extent of permafrost degradation in northern Alaska since 1982, associated with record warm temperatures during 1989–1998', and that 'the recent degradation has mainly occurred to massive wedges of ice that previously had been stable for 1000s of years.' That thawing of the upper part of permafrost can be rapid is also seen in northern Alaska, where terrain disturbance by bulldozing and excavation for camp sites caused thawing of the permafrost and initiated slumping and gravitational flow (Lawson, 1982). Hence, much evidence indicates that the formation of pristine sand- and ice-wedges, and their deformation or replacement through permafrost degradation, are not coeval processes, but develop on quite different time scales and by different mechanisms that characterise mutually exclusive periglacial environments. This principle is of importance in ascertaining the palaeoclimatic significance of the sand wedges at Mount Gunson (see Section 4.2).

2.2. *Proterozoic varves*

A 'varve' may be defined as a sedimentary bed or lamina deposited within one year's time, with a 'glacial varve' normally including a lower, summer layer of relatively coarse-grained, usually sandy or silty, pale coloured sediment derived from meltwater streams, grading up to a thinner winter layer of very fine-grained, commonly clayey, dark sediment deposited from suspension (Neuendorf et al., 2005). Hence glacial varves record a seasonal freeze–thaw cycle. The annual nature of Quaternary varves can be verified by independent dating techniques, but whether some regularly laminated Proterozoic rhythmites comprise varves cannot be proved because of the lack of such techniques. However, numerous geologists have concluded that regularly laminated deposits associated with Proterozoic glacial successions are varve-like or represent varves.

2.2.1. *Cryogenian varves*

Numerous beds of siltstone associated with diamictite in the Port Askaig Formation display regular, even lamination that is continuous laterally (Spencer, 1971). The laminae, which are graded, 1–5 mm thick and very dolomitic locally, were interpreted as varves of possible fresh-water origin. Statistical analysis of a 5.5 m-thick sequence of 2587 lamina-thickness measurements did not reveal any periodicity between 1 and 18 laminae, which implies that the laminae are not diurnal tidal increments. Sandstone wedges penetrate downwards from the tops of several 'varve' units. This close association of wedges and 'varves' points to a strongly seasonal climate during Port Askaig deposition.

Hambrey and Spencer (1987, pp. 37–38) described two 'rhythmite (varvite)' sequences 9.1 and 7.7 m thick from the Ulvesø Formation of the Cryogenian Tillite Group, East Greenland. The sequences comprise 'varve-like' finely laminated siltstones and sandstones, with laminae usually 1–10 mm thick, and contain scattered ice-rafted dropstones up to boulder size. Hambrey and Spencer (1987) regarded the presence of some sand–silt couplets as 'reminiscent of varves', with deposition 'in glaciolacustrine or restricted glaciomarine environments'. Moncrieff and Hambrey (1990, p. 402) concluded on the basis of thickness and grain size that rhythmites in the Ulvesø Formation 'are likely to represent annual cycles'.

Harland et al. (1993, p. 37) illustrated a dropstone-bearing rhythmite facies in the Cryogenian Elbobreen Formation in Svalbard, with silty–sandy carbonate couplets 'suggestive of varves.' Fairchild et al. (1989) recorded carbonate-bearing glaciolacustrine rhythmites in the overlying Wilsonbreen Formation, stating (p. 481) that 'an origin as varves is probable' and concluding that there 'is a close analogy with carbonate–siliciclastic varves in modern and sub-Recent lakes in Taylor Valley, Antarctica.' Fairchild and Kennedy (2007, p. 900) discussed an assemblage of carbonate facies in the Wilsonbreen Formation, 'including limestone and dolomite stromatolites, clastic–carbonate rhythmite couplets, dolocretes and evaporite pseudomorphs, intimately associated with sandstones and diamictites, which compare closely with the modern Antarctic Dry Valleys region.' The presence also of periglacial sand wedges or ice-wedge casts in the Wilsonbreen Formation (Fairchild and Hambrey, 1984; Harland et al., 1993) strengthens the comparison with deposits in the Dry Valleys of Antarctica. A strongly seasonal climate during Wilsonbreen deposition is implied.

Haines et al. (2008) described siltstone and mudstone rhythmites seen in drill core from the Cryogenian glaciogenic Pirrilyungka Formation in the Officer Basin, Western Australia (Fig. 7). They suggested (p. 403) that the rhythmites may represent glacial varves because of 'the extreme regularity of the lamination and rare dropstone fabrics'. The rhythmite does not display cyclicity, although pairs of similar silty, light layers are evident in some places.

Figure 7. Varve-like rhythmite of siltstone (pale bands) and mudstone with dropstone from the Cryogenian Pirrilyungka Formation, Officer Basin, Western Australia. Scale bar 1 cm. Photograph by courtesy of Peter Haines. After Haines et al. (2008); published with the permission of the Geological Society of Australia.

2.2.2. Palaeoproterozoic varves

The upper Huronian (~2.3 Ga; Young, 2014) glaciogenic Gowganda Formation in Canada includes abundant diamictites and locally associated rhythmites. The latter are well exposed at the NE corner of Wells Township, Ontario, where they exhibit laterally persistent, sandy–silty and argillaceous couplets containing dropstones (Fig. 8a) and till pellets (Fig. 8b). The Gowganda rhythmites have been interpreted as, or compared with, glacial varves by numerous geologists (Jackson, 1965; Lindsey, 1969; Mustard and Donaldson, 1987; Young, 2001, 2004, 2013), and Long (1974) compared rhythmites in the correlative Chibougamau Formation, Quebec, with glacial varves. Young (2013, caption for cover photograph) noted the 'striking occurrence of pairs of identical light layers, possibly representing two similar summer seasons in each year', in the Wells Township rhythmites. Pairs of similar light layers are evident in Fig. 8a. Longer periodicities are not visually evident in Wells Township rhythmites, nor were they identified by power spectral analysis of a sequence of couplet thicknesses (Jackson, 1965), which argues against a tidal influence on deposition. The presence of rhythmites comparable with glacial varves is consistent with a seasonal, freeze-thaw climate and an active hydrological cycle during early Palaeoproterozoic glaciation.

2.3. Seasonal oscillation of Cryogenian sea level

Vertically accreted, cyclic tidal rhythmites associated with Cryogenian glacial deposits at Pichi Richi Pass in the Flinders Ranges, South Australia, record a range of synodic tidal cycles and the *non-tidal* seasonal, or annual, oscillation of sea level through periodic change in the thickness of neap–spring (synodic fortnightly) cycles, which is a proxy for tidal height (sea level height) or tidal range (Williams, 1989, 1991, 2000; Williams and Schmidt, 2004). These rhythmites were deposited on an ebb-tidal delta with the drowning of tidal estuaries and inlets through rise of sea level during an interstadial of the Elatina glaciation (Williams et al., 2008) at a palaeolatitude of $\leq 10°$ (see Section 3). Time-series analysis of the 60 year-long Elatina rhythmite record of 1580 neap–spring cycle thickness measurements has illuminated Earth's palaeorotation and the Moon's orbit in late Cryogenian times (Williams, 1989, 2000).

The seasonal oscillation of sea level results mainly from seasonal changes in sea surface temperature and variation in winds and atmospheric pressure, with changes in heat content of the sea accounting for most of the annual sea-level variation between latitudes 45°N and 45°S (Roden, 1963; Pattullo, 1966; Wunsch, 1972; Komar and Enfield, 1987). The conspicuous signal of the seasonal oscillation of sea level occurs throughout the Elatina rhythmite sequence (Fig. 9a) (Williams, 1991, 2000). For comparison, Fig. 9b shows the seasonal oscillation of sea level at Townsville, NE Australia, as indicated by the maximum height of spring tides. Townsville is situated at a low latitude (19°16′) and has synodic tides.

Fig. 9c shows the Fast Fourier Transform (FFT) spectrum for the Elatina record of 1580 neap–spring cycle thicknesses, and Fig. 9d gives the FFT spectrum for a 20-year record of the maximum height of 495 spring tides at Townsville. The seasonal (annual) signal in the Elatina spectrum has approximately 15 times more power than does the seasonal signal in the spectrum for the Townsville data, relative to respective monthly peaks. While differences in local geography may partly account for this contrast, the seasonal signal appears strongly developed in the rhythmite data, which is consistent with the findings of Section 2.1.5 that a significant seasonal cycle existed during the Elatina glaciation.

The essentially noise-free FFT spectrum for the Elatina rhythmites (Fig. 9c) implies minimal fluvial input of sediment to the marine environment at that locality (Williams, 2000), which accords with an arid hinterland as shown by the presence of periglacial sand wedges and an extensive aeolian sand sheet on the Stuart Shelf (Fig. 1). Furthermore, the record of the seasonal oscillation of sea level in the inner marine-shelf Elatina rhythmites indicates that the terminal Cryogenian global ocean was not frozen over during this interstadial, because an ice-cover would have insulated the ocean from seasonal changes of temperature and winds. The presence of conspicuous wave-generated symmetrical and interference ripple marks in the Elatina Formation at Warren Gorge (Williams, 1996, 2004; Williams and Schmidt, 2004; Williams et al., 2008) and elsewhere in the Flinders Ranges (Coats, 1971) confirms that open seas existed at that time. In fact, the widespread and persistent rainout of ice-rafted debris on the outer marine-shelf indicates that open seas and an active hydrological cycle prevailed during the Elatina glaciation (Williams et al., 2008). Open-water conditions, as shown by the presence of wave-generated hummocky cross-stratified sandstones, marked episodes of glacial retreat during the preceding Sturt glaciation in South Australia (Busfield and Le Heron, 2014). Numerous other studies similarly indicate that open seas and an active hydrological cycle existed during Cryogenian glacial epochs (e.g. Kennedy et al., 2001; Condon et al., 2002; Etienne et al., 2008; Arnaud et al., 2011 and references therein).

3. Palaeolatitude of Proterozoic glacial successions

As summarised in Fig. 10, a persistent feature of Proterozoic glaciations is their occurrence in low palaeolatitudes as determined

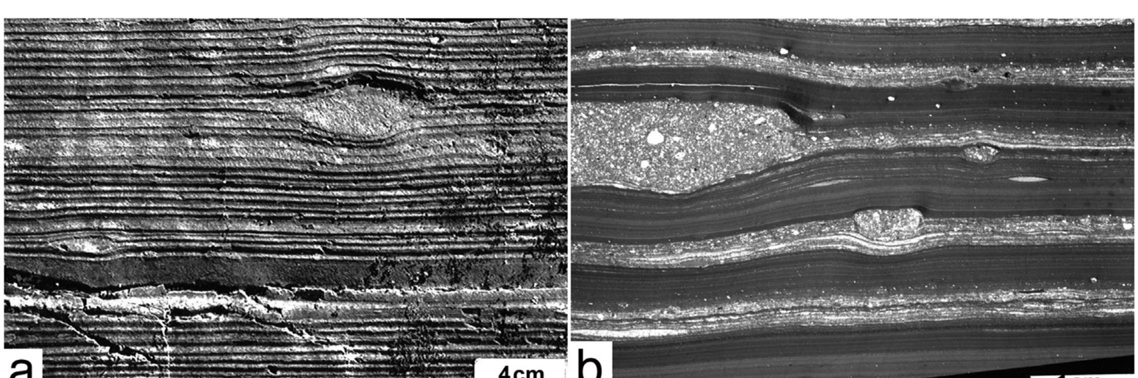

Figure 8. Varve-like rhythmites from the Palaeoproterozoic Gowganda Formation, NE corner of Wells Township, Ontario, Canada. (a) Field section, showing rhythmites with dropstones. Scale 4 cm. (b) Thin section (plane light), showing pale bands of fine sand- and silt-grade with till pellets, alternating with dark argillaceous layers. Scale bar 1 cm.

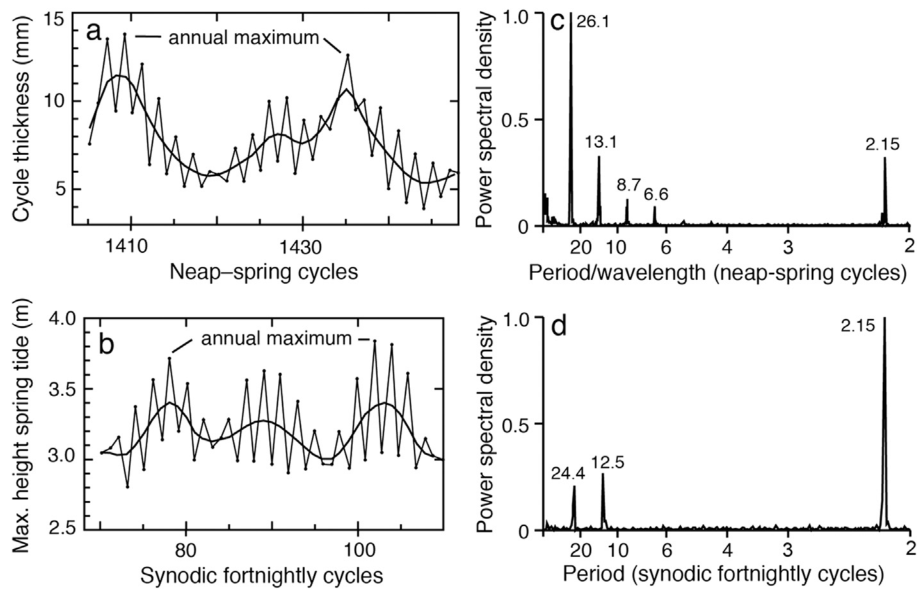

Figure 9. (a) Neap–spring cycle thickness for 1.6 years of the Cryogenian Elatina 60 year-long synodic tidal rhythmite record, Adelaide Geosyncline, compared with (b) maximum height of the synodic fortnightly tide at Townsville, NE Australia, for 1.6 years from 19 October 1968 to 3 June 1970 (data from the Beach Protection Authority, Queensland Department of Transport), showing the non-tidal seasonal (annual) oscillation of sea level and the sawtooth pattern of the 'monthly inequality' of spring-tidal height resulting from the eccentric lunar orbit. Cycle numbers increase up the stratigraphic sequence, and with time. (c) FFT spectrum for the Elatina record of 1580 neap–spring cycle thicknesses, with annual, semiannual and monthly peaks at 26.1, 13.1 and 2.15 cycles, respectively. (d) FFT spectrum for maximum height of 495 spring tides at Townsville from 1 January 1966 to 31 December 1985, with annual, semiannual and monthly peaks at 24.4, 12.5 and 2.15 fortnightly cycles, respectively. Adapted after Williams (1989) and Williams and Schmidt (2004).

directly by the palaeomagnetic study of unmetamorphosed glacial deposits and closely associated rocks (Eriksson et al., 2013; Schmidt, 2014). High-palaeolatitude pre-Ediacaran glaciation has not been identified.

McWilliams and McElhinny (1980) reported on a reconnaissance palaeomagnetic study of the Neoproterozoic succession in the Adelaide Geosyncline and inferred low palaeolatitudes for the Cryogenian glaciations. The low palaeolatitude of Cryogenian glaciation was first firmly established for the Elatina glaciation (Schmidt et al., 1991; Schmidt and Williams, 1995; Sohl et al., 1999). These studies yielded high-quality palaeomagnetic data for red beds from the Elatina Formation, with positive fold tests executed on syn-sedimentary slump folds (*not* ripples, which cannot yield a positive fold test; Williams, 1996; Williams et al., 2008) and on tectonic folds, indicating the early acquisition of magnetisation and that glaciation took place within 10° of the palaeoequator. This finding helped stimulate research worldwide on Cryogenian glacial deposits. Combined data for the Elatina Formation from two independent laboratories, with minor correction for inclination shallowing caused by compaction (Schmidt et al., 2009; Schmidt and Williams, 2013), satisfy all the palaeomagnetic reliability criteria of Van der Voo (1990) and provide the benchmark for Cryogenian near-equatorial ($\leq$10°) glaciation. The entire Cryogenian succession in southern Australia, including those of the Elatina and Sturt glaciations and the interglacial interval, were deposited when the region lay in low palaeolatitudes (Williams and Schmidt, 2015). Studies of Cryogenian glacial deposits on other continents have consistently yielded near-equatorial to low palaeolatitudes, with most results <20° and no reliable result >40° palaeolatitude (Evans and Raub, 2011).

The late Palaeoproterozoic King Leopold glaciation in NW Australia occurred near sea level at a palaeolatitude of 8 $\pm$ 2° (Schmidt and Williams, 2008). The early Palaeoproterozoic Huronian glaciations in North America at the southern margin of the Archaean

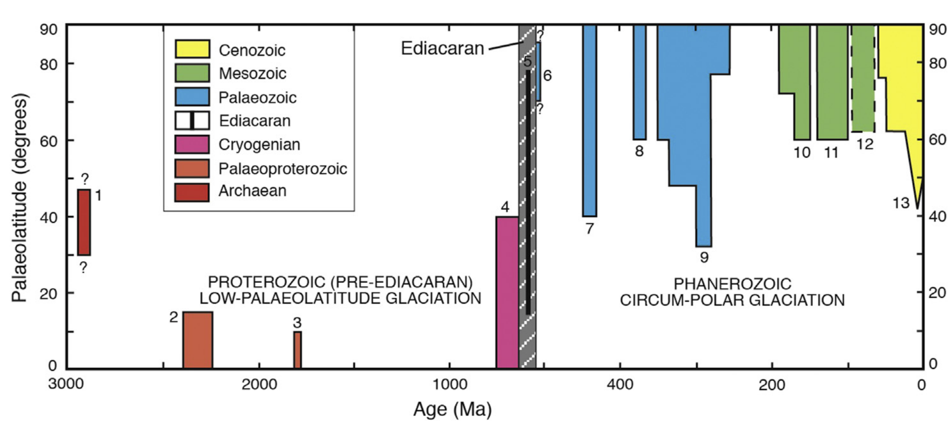

Figure 10. Palaeolatitudinal extent of glacial deposits for (1) Archaean, (2) early Palaeoproterozoic, (3) late Palaeoproterozoic, (4) Cryogenian, (5) Ediacaran (see text), (6) Cambrian (Landing and MacGabhann, 2010). Palaeoequatorward extent of ice-rafted deposits for (7) late Ordovician–early Silurian, (8) late Devonian, (9) early Carboniferous–late Permian, (10–12) early Jurassic–late Cretaceous, (13) Cenozoic (Frakes and Francis, 1988). Note change of time-scale at 500 Ma. Adapted after Eriksson et al. (2013).

Superior craton (Young et al., 2001; Young, 2014) occurred during drift of the region across the palaeoequator between 2.4 and 2.3 Ga (Fig. 11) as indicated by dated igneous primary poles or 'key poles' for Palaeoproterozoic dykes and sills that intrude the craton (Bindeman et al., 2010; Buchan, 2013). Stable shallow magnetisations carried by the Gowganda Formation and the conformably overlying Lorrain Formation accord with a low palaeolatitude for the Gowganda glaciation (Williams and Schmidt, 1997; Schmidt and Williams, 1999). Palaeomagnetic data for 2.2 Ga lavas in South Africa suggest the underlying glaciogenic Makganyene Formation accumulated at 11 ± 5° palaeolatitude (Evans et al., 1997).

The palaeolatitude of the Archaean (~2.9 Ga) Pongola Supergroup in South Africa, which includes the oldest known glacial deposits (Young et al., 1998), is uncertain. Nhleko (2003) determined mid-palaeolatitudes (normal polarity = −47.8°, reversed = 42.8°) for the glacial deposits, whereas Strik et al. (2007) found an apparent mean palaeolatitude of ~30° for the Pongola Supergroup. As the Pongola Supergroup has been metamorphosed to greenschist facies and subjected to several tectonothermal events and major intrusions (Burke et al., 1985; Strik et al., 2007), possible overprinting cannot be precluded and hence these palaeomagnetic results must be interpreted with caution.

In contrast to the palaeolatitudes of Proterozoic glacial deposits, those of Ediacaran glacial deposits are ambiguous and seemingly span a wide range (Evans and Raub, 2011; Eriksson et al., 2013). To add to the complexity, intense weathering may have occurred at high palaeolatitudes in Baltica during the Ediacaran (Liivamägi et al., 2014, 2015). Phanerozoic glaciations are consistently circum-polar (Fig. 10).

Palaeomagnetic data imply that the geomagnetic field approximated a geocentric axial dipole (GAD) during the Proterozoic (Schmidt, 2001; Smirnov and Tarduno, 2004; Veikkolainen et al., 2014b) and probably for all of recorded geological time (McElhinny, 2004). Hence palaeolatitudes represent geographic latitudes. Veikkolainen et al. (2014a) identified nearly 1000 high-latitude palaeomagnetic poles from the Precambrian geomagnetic database, although no data are available concerning the high-palaeolatitude environment during Proterozoic glaciation.

In summary, after more than half a century of palaeomagnetic studies of Proterozoic glacial deposits, the enigma persists of Proterozoic glaciations near sea level in low palaeolatitudes. These glaciations occurred under strongly seasonal climates with an active hydrological cycle.

4. Proterozoic glaciation and Earth's climate system

4.1. Hypotheses for Proterozoic low-latitude glaciation

Two opposing hypotheses in explanation of Proterozoic low-palaeolatitude glaciation – 'snowball Earth' and high obliquity – present contrasting scenarios for the climate system on the Proterozoic Earth. Our aim is to ascertain whether these hypotheses can accommodate the diverse evidence for a strongly seasonal glacial climate in low palaeolatitudes.

According to the snowball Earth hypothesis, global glaciation during the Cryogenian, caused by runaway ice–albedo feedback, was marked by ~3 km-thick synchronous ice-sheets on all continents, with equatorial temperatures below −20 °C, the oceans covered by a continuous shell of ice hundreds of metres thick from pole to pole, and a shut-down of the hydrological cycle (Hoffman et al., 1998; Hoffman and Schrag, 2002; Domack and Hoffman, 2011). Modelling by Baum and Crowley (2001) estimated a mean global temperature of −50 °C and mean surface temperatures of −80 to −110 °C in high latitudes. The global freeze-over lasted for up to 30 million years, with synchronous glaciation and deglaciation. The idea of a partly frozen-over 'slushball Earth', with low-latitude glaciation and open seas (Schrag and Hoffman, 2001; Crowley et al., 2001; Hoffman and Li, 2009), is a modification of the snowball Earth hypothesis and recalls earlier concepts of 'global glaciation' (Eyles, 2004).

The obliquity of the ecliptic, the angle between Earth's spin-axis and orbit normal or Earth's axial tilt (present-day value 23.5°, ranging between 22° and 24° over a cycle of 41 kyr), controls the strength of the global seasonal cycle and the sign of climatic zonation. The high obliquity hypothesis postulates a pre-Ediacaran obliquity >54°, whereby low to moderate latitudes (≤40°) receive less solar radiation per year than high latitudes (Milankovitch, 1930; Williams, 1975, 1993, 2008; Oglesby and Ogg, 1998; Jenkins, 2000, 2001, 2003, 2004; Donnadieu et al., 2002). Modelling shows that for an obliquity of 70°, sea ice forms at the equator and spreads to all latitudes <45° (Jenkins, 2004), and glaciers can form near sea-level in latitudes <40° with obliquities of 60–90° (Donnadieu et al., 2002). In high latitudes, however, the limited snow that forms during the arid winter melts during the very hot summer. A high obliquity alone would not have been the primary cause of glaciation, but would have influenced the latitudinal distribution of glaciers. Thus, under unexceptional icehouse

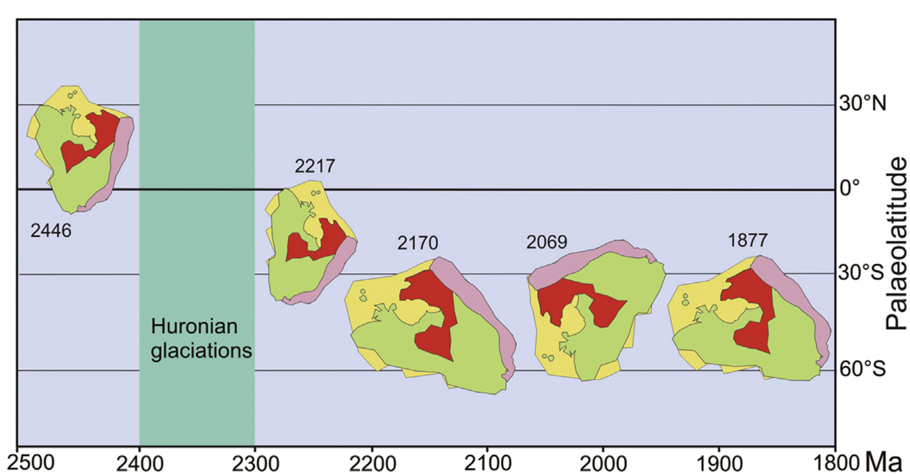

Figure 11. Palaeolatitudes (Mercator projection) and orientations for Palaeoproterozoic North America vs. time, as indicated by dated igneous primary palaeomagnetic poles for dykes and sills (Buchan, 2013) that intrude the Archaean Superior craton (red). The early Palaeoproterozoic Huronian glaciations (~2400–2300 Ma; Young, 2014) at the southern margin of the Superior craton occurred during drift across the palaeoequator.

conditions, low latitudes would be glaciated preferentially, with accompanying strongly seasonal climate, active hydrological cycle and open seas. Glaciation and deglaciation could be either synchronous or diachronous.

The snowball Earth and high-obliquity hypotheses are not without their difficulties. Much sedimentological, stratigraphic and geochemical data conflict with the requirements and predictions of a snowball Earth (e.g. Kennedy et al., 2001; Williams and Schmidt, 2004; Allen and Etienne, 2008; Williams, 2008; Sansjofre et al., 2011; Busfield and Le Heron, 2014). As discussed in Section 3, high-palaeolatitude pre-Ediacaran glaciation has not been determined, and the character of numerous Cryogenian glacial successions indicates glacier-free continental regions, times of extensive open seas, and an active hydrological cycle. Indeed, Etienne et al. (2008, p. 343) concluded that Cryogenian glacial facies 'are typical of sedimentary sequences deposited along glaciated continental margins throughout Earth history.' The major difficulty facing the high-obliquity hypothesis lies in celestial mechanics. While an early high obliquity is a plausible, perhaps likely, outcome of a single giant impact with the proto-Earth at ~4.5 Ga that may have produced the Moon (Hartmann and Vail, 1986; Agnor et al., 1999; Stevenson and Halliday, 2014), no mechanism has been identified to reduce a high (>54°) obliquity during the Ediacaran–early Palaeozoic to permit Phanerozoic circum-polar glaciation.

4.2. Strong seasonality with a snowball/slushball Earth

The diverse geological evidence from several continents that Proterozoic glacial climates in low palaeolatitudes were strongly seasonal presents a major difficulty for the snowball Earth and slushball Earth hypotheses. Accordingly, their proponents have striven to refute the evidence for strong seasonality by introducing what Popper (1963) termed 'auxiliary assumptions'.

As discussed above, much evidence based on actualistic interpretations indicates that metre-scale periglacial sand wedges formed near sea level at a palaeolatitude of ≤10° under a strongly seasonal climate during the terminal Cryogenian Elatina glaciation in South Australia. However, Maloof et al. (2002) used numerical modelling to argue that the 3+ m-deep sand wedges at Mount Gunson were caused by diurnal fluctuations of temperature during a snowball Earth event (low mean annual temperature). This non-actualistic idea is ruled out for several reasons. Embleton and King (1975, p. 31) found that in polar regions diurnal temperature changes in permafrost 'may affect the upper layer to a depth of perhaps 1 m at the most'. Moreover, active layers as little as 2–3 cm thick in the highest mountains of the equatorial zone (Dobinski, 2011) attest to the feeble effect of temperature changes on surface materials in that zone. Not surprisingly, cryogenic wedges are absent in Pleistocene and present-day permafrost horizons at high elevations near the equator (Hastenrath, 1973, 1981), where temperature fluctuations are mainly diurnal, despite the mean annual air temperature remaining below 0 °C for several millennia during Pleistocene stades (Bonnefille et al., 1990; Clapperton, 1993). Ewing et al. (2014) conceded that the model of Maloof et al. (2002) cannot account for the cryogenic sand wedges at Mount Gunson.

Pierrehumbert et al. (2011, p. 441) stated 'The overarching feature of the Snowball climate is that the replacement of the ocean with a globally thick ice cover eliminates the ocean's thermal inertia. The low thermal inertia of the Snowball surface results in an extreme seasonal cycle.' This conclusion is based on modelling by Pierrehumbert (2005) with the ocean globally covered by sea ice at least 5 m thick and by sea-glacier ice in tropical regions. The hypothesis fails because it employs a scenario that is not applicable to the Cryogenian Earth. The Cryogenian ocean during glaciations was *not* frozen-over with a globally-thick ice cover, with much evidence indicating times of extensive, long-lived open seas, an active hydrological cycle, and glacier-free continental regions. Moreover, the seasonal (summer/winter) mean monthly air temperature range of only ≤10 °C for ≤10° latitude, as modelled by Pierrehumbert (2005), is much smaller than the mean monthly air temperature range of 40 °C within 10° of the Cryogenian palaeoequator as indicated by the presence there of metre-scale sand wedges. Additionally, the sand wedges at Mount Gunson did not form during an alleged snowball Earth with kilometre-thick grounded ice-sheets on all continents, as such ice sheets would have insulated the ground from seasonal changes of air temperature. Hence for several reasons the modelling of Pierrehumbert (2005) and Pierrehumbert et al. (2011) cannot account for the large seasonal changes of air and ground temperature required to produce the Cryogenian periglacial sand wedges near the palaeoequator.

Hoffman and Li (2009) attempted to downplay the significance of periglacial sand wedges at a low palaeolatitude during Neoproterozoic 'pan-glacial' (both snowball and slushball Earth) states by claiming that six of eight known occurrences of Cryogenian periglacial polygonal sand-wedges formed at palaeolatitudes >30°. However, their palaeolatitudes are not indicated by direct palaeomagnetic data for glaciogenic deposits, but were estimated from a continental assembly of Rodinia (Li et al., 2008), the configuration of which is uncertain (e.g. Meert and Torsvik, 2003; Pisarevsky et al., 2003). Only palaeolatitudes determined *directly* by the palaeomagnetic study of Neoproterozoic glacial deposits and closely associated rocks should be considered. Such palaeomagnetic data indicate that Cryogenian glacial successions formed in near-equatorial and low palaeolatitudes.

Because the presence of periglacial sand wedges up to 3+ m deep near the palaeoequator poses a major difficulty for both the snowball Earth and slushball Earth hypotheses, Ewing et al. (2014) presented a non-actualistic interpretation of the sand wedges at Mount Gunson. The best examples of numerous large, polygonal sand wedges and other structures in the Cattle Grid pit (Figs. 2–4, 6) were not exposed for examination by Ewing and colleagues, whose observations at Mount Gunson were largely confined to the much smaller NE and NW pits. Ewing et al. (2014) thought that the sand wedges at Mount Gunson formed within an active layer 2–4 m thick, *coeval* with soft-sediment deformation structures such as involutions and diapirs. They concluded that the mean annual surface temperature was then within a few degrees of freezing and that the seasonal temperature range during wedge formation was comparable with that in present-day low latitudes. However, as discussed in Sections 2.1.5 and 2.1.6, the slow growth of undeformed, metre-scale wedges over thousands of years in perennially frozen ground *beneath* the active layer, and the formation of thaw-modification structures such as deformed wedges, involutions and diapirs caused by regional or local environmental change, are mutually exclusive processes that proceed on greatly different time-scales. The curved wedges interpreted as undeformed structures (Ewing et al., 2014, their figs. 3 and 4d) are in fact deformed wedges associated with disturbed bedding and diapiric structures, which are typical of thaw modification of permafrost *after* wedge formation (Murton and French, 1993). The conclusions of Ewing et al. (2014) are further invalidated by the absence of cryogenic wedges at high elevations near the present-day equator (see above). *Neither diurnal nor seasonal temperature variability as in present-day low latitudes could produce metre-scale cryogenic sand wedges such as those at Mount Gunson.*

Benn et al. (2015) also attempted to discount the climatic significance of periglacial features in Cryogenian deposits. Finding that millimetre-scale carbonate–siliciclastic rhythmites from the Wilsonbreen Formation in Svalbard indicate seasonal cycles of photosynthesis, they concluded (pp. 704–705) that the 'environment seems to have been closely similar to that of the present-day McMurdo Dry Valleys in Antarctica, a*lthough with less extreme seasonality owing to its low latitude*' (our italics). This is another example of preconceived theory overriding actualistic geological interpretation.

It is concluded that neither the snowball Earth hypothesis nor its variant, a slushball Earth, can accommodate the geological evidence for large seasonal changes of temperature in low palaeolatitudes during Cryogenian glaciation.

4.3. *Strong seasonality with a high obliquity*

A strongly seasonal glacial climate in low latitudes is a pillar of the high-obliquity hypothesis for Proterozoic (pre-Ediacaran) low-latitude glaciation (Williams, 1975, 1993, 2008). Modelling shows that for obliquities of 60–90°, continental temperatures could range from 80 °C in summer to −70 °C in winter, with a seasonal (mean monthly) temperature range of 40 °C at the equator for an obliquity of 90° (Donnadieu et al., 2002). According to Jenkins (2000), with an obliquity of 65° seasonal temperature ranges would exceed 50 °C for continental regions at 30° latitude and 10 °C for the ocean. Importantly, a high obliquity would cause only moderate seasonal changes in ocean temperatures, in contrast to the large seasonal changes in temperature over continents, because of the higher heat capacity of the ocean compared to that of land masses. Hence, while evidence for large seasonal changes of temperature could be expected in the continental geological record with a high obliquity, indications of strong seasonality may not be prominent in the marine record.

As reviewed above, a strongly seasonal Proterozoic glacial climate in low palaeolatitudes is best exemplified by an actualistic interpretation of Cryogenian metre-scale periglacial sand wedges in South Australia, which implies a mean monthly air temperature range of 40 °C (Table 1; Williams and Tonkin, 1985; Williams, 1993, 2008; Williams et al., 2008). The presence of metre-scale sand wedges and ice-wedge casts in other Cryogenian and Palaeoproterozoic glacial successions likewise indicates a mean monthly air temperature range of 40 °C. A continental climate with large seasonal changes of temperature in low latitudes is consistent with the high-obliquity hypothesis for Proterozoic low-latitude glaciation. Hoffman and Li (2009, p. 165) acknowledged that 'Because seasonality close to the equator is weak with small orbital obliquity, the existence of the Elatina sand-wedges provides empirical support for the hypothesis that preferential low-latitude glaciation in the Neoproterozoic was a response to a large orbital obliquity at that time.' Furthermore, the tendency for some Proterozoic varve-like rhythmites to display pairs of similar light layers may record two similar summer seasons per year as for high-obliquity conditions (Young, 2013; see Section 2.2.2), as anticipated by Williams (1975).

Intriguingly, the Curiosity rover on Mars has provided pictures of finely laminated lacustrine sediments that Grotzinger et al. (2015) thought are similar to glacial varves. These varve-like sediments occur at latitude 4.6°S and are estimated to have been deposited between 3.8–3.6 and 3.3–3.1 Ga. The obliquity of Mars at that time is poorly constrained, but Laskar et al. (2004) found the probability is 89.3% that Mars' obliquity reached more than 60° in the past 3 Ga, with the most probable (mean) obliquity over the past 4 Ga being 41.8°. Furthermore, glacier-like landforms in low and middle latitudes on Mars are interpreted as recording episodic glacial activity at times of high obliquity (e.g. Forget et al., 2006; Milkovich et al., 2006; Mège and Bourgeois, 2011). Hence strong seasonality and glaciation in low latitudes may have occurred at times of high obliquity for both Earth and Mars.

5. Conclusions

The finding that the Proterozoic glacial climate was strongly seasonal is based on the actualistic interpretation of Proterozoic glacial deposits.

- Cryogenian primary sand wedges are identical to those in present-day polar periglacial regions with a mean monthly air temperature range of 40 °C and mean annual air temperatures of −20 °C or lower.
- Varve-like rhythmites indicate an active freeze–thaw cycle.
- The seasonal (annual) oscillation of sea level recorded by Cryogenian tidal rhythmites indicates a significant seasonal cycle during Cryogenian glaciation.

The Cryogenian glacial environment included glacier-free continental regions with permafrost and aeolian sand-sheets, extensive and long-lived open seas as indicated by the presence of the seasonal oscillation of sea level, marine deposits with wave-generated ripple marks and hummocky cross-stratification, and an active hydrological cycle permitting fluvial activity and the persistent and widespread rainout of ice-rafted debris.

After more than 50 years of palaeomagnetic study of Proterozoic glacial deposits, most results are between 0 and 20° palaeolatitude and no high palaeolatitude glacial deposit has been identified, although the high-palaeolatitude environment during Proterozoic glaciation is unknown. Much data indicate that a GAD prevailed during the Proterozoic, hence palaeolatitudes represent geographic latitudes.

The evidence for large seasonal changes of temperature in low palaeolatitudes presents a major difficulty for the snowball Earth and slushball Earth hypotheses. Non-actualistic arguments by Maloof et al. (2002) and Ewing et al. (2014) that the Cryogenian sand wedges at Mount Gunson do not indicate a strongly seasonal palaeoclimate are invalidated by the results of many decades of research in polar periglacial regions. Benn et al. (2015) thought, incongruously, that the Cryogenian climate in Svalbard was 'closely similar' to the climate of the McMurdo Dry Valleys in Antarctica, but lacked the strong seasonality characterising that region. The model of Pierrehumbert et al. (2005, 2011) employed a global scenario inappropriate for Cryogenian glaciation and consequently failed to model the inferred Cryogenian seasonal temperature range of 40 °C at ≤10° palaeolatitude. Such attempts by scientists to explain away a conflicting observation or anomaly have been criticised by philosophers of science. Popper (1963, p. 37) argued that upholding a theory 'by introducing *ad hoc* some auxiliary assumption', as exemplified above, 'is always possible, but it rescues the theory from refutation only at the price of destroying, or at least lowering, its scientific status'. Kuhn (1970, p. 78) found that scientists may, when faced by anomaly, 'devise numerous articulations and *ad hoc* modifications of their theory in order to eliminate any apparent conflict.' He concluded that anomalies may 'help to permit the emergence of a new and different analysis of science within which they are no longer a source of trouble.'

A strongly seasonal climate in low palaeolatitudes, based on an actualistic interpretation of cryogenic sand wedges and other structures, is an integral part of the high-obliquity hypothesis for Proterozoic low-latitude glaciation. A high (>54°) obliquity for the early Earth is a plausible result of a single giant impact that may have produced the Moon. Proposed mechanisms to change a postulated high obliquity at the end of the Cryogenian to an obliquity approaching the present-day value by the early Palaeozoic are discussed by Williams (2008) and will be further examined elsewhere.

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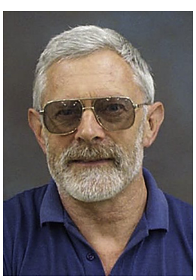

George Williams holds an MSc from the University of Melbourne and a PhD from the Sedimentology Research Laboratory, University of Reading, for work on the Proterozoic Torridonian sandstone of NW Scotland. His career has been divided between industry and research based at the University of Adelaide, focusing on Neoproterozoic and Palaeoproterozoic glacial sedimentology, palaeoclimatology and palaeomagnetism, tidal rhythmites and the dynamics of the Precambrian Earth–Moon system, and the geological and environmental consequences of the Ediacaran Acraman impact in South Australia. He received a DSc from the University of Reading in 1998, and is a Fellow of the Geological Society of America, the Geological Society of Australia, and the Australian Academy of Science.

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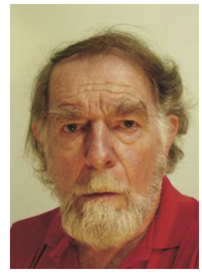

Grant Young was raised on the small Isle of Bute in western Scotland where abundant rock exposures stimulated an early interest in geology. Following studies at the University of Glasgow, emigration to Canada and introduction to the Huronian Supergroup led to a lifelong interest in Precambrian rocks, ancient glaciations and Earth's evolution. Attempts to elucidate the distribution of Palaeoproterozoic glaciations in North America were followed by studies of Neoproterozoic platform deposits in the Canadian Arctic. This led to work on similar rocks in the northern Cordillera, including Sturtian glacial deposits and eventually to their counterparts in the Flinders Ranges of South Australia and beyond. In recent years the circle has been completed with field investigations in various parts of Scotland where the seed of geological curiosity was planted.