Chapter 70

The Elatina glaciation (late Cryogenian), South Australia

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Abstract: Deposits of the late Cryogenian Elatina glaciation constitute the Yerelina Subgroup in the Adelaide Geosyncline region, South Australia. They have a maximum thickness of c. 1500 m, cover 200 000 km², and include the following facies: basal boulder diamictite with penetrative glaciotectonites affecting preglacial beds; widespread massive and stratified diamictites containing faceted and striated clasts, some derived from nearby emergent diapiric islands and others of extrabasinal provenance; laminated siltstone and mudstone with dropstones; tidalites and widespread glacioluvial, deltaic to marine-shelf sandstones; a regolith of frost-shattered quartzite breccia up to 20 m thick that contains primary sand wedges 3 m deep and other large-scale periglacial forms; and an aeolian sand sheet covering 25 000 km² and containing primary sand wedges near its base. These deposits mark a spectrum of settings ranging from permafrost regolith and periglacial aeolian on the cratonic platform (Stuart Shelf) in the present west, through glacioluvial, marginal-marine and inner marine-shelf in the central parts of the Adelaide Geosyncline, to outer marine-shelf in sub-basins in the present SE and north.

The Elatina glaciation has not been dated directly, and only maximum and minimum age limits of c. 640 and 580 Ma, respectively, are indicated. Palaeomagnetic data for red beds from the Elatina Formation (Fm.) and associated strata indicate deposition of the Yerelina Subgroup within 10° of the palaeoequator. The Yerelina Subgroup is unconformably to disconformably overlain by the dolomitic Nuccaleena Fm., which in most places is the lowest unit of the Wilpena Group and marks Early Ediacaran marine transgression.

Supplementary material: Photographs are available at http://www.geolsoc.org.uk/SUP18481.

This chapter discusses the extensive (200 000 km²) glaciogenic facies associated with the late Cryogenian Elatina glaciation of the Marinoan Epoch in the Adelaide Geosyncline region, South Australia (Fig. 70.1), and their palaeomagnetism and palaeoenvironments. Preiss et al. (2011) discuss the preceding Cryogenian (Sturtian age) glacial succession in South Australia and the lithostratigraphy of the Adelaide Geosyncline.

The Marinoan Epoch as defined in South Australia encompasses both the late Cryogenian and the Ediacaran (Preiss 1987; Williams et al. 2008). The term ‘Elatina glaciation’ was proposed by Mawson (1949) following his discovery of diamictite containing faceted and striated clasts in Elatina Creek in the central Flinders Ranges. The diamictite belongs to the Elatina Fm. (Preiss 1987; Lemon & Gostin 1990), which has its type section near Enoroma Creek (Fig. 70.1). We use Mawson’s terminology for the late Cryogenian glaciation in South Australia.

The Elatina glaciation is of global importance for several reasons: (i) its diverse and excellently preserved glacial and periglacial facies represent a de facto type region for late Cryogenian glaciation in general; (ii) the Elatina Fm. has yielded the most robust palaeomagnetic data for any Cryogenian glaciogenic succession; and (iii) the recently established Ediacaran System and Period (Knoll et al. 2004, 2006; Preiss 2005) has its Global Stratotype Section and Point (GSSP) placed near the base of the Nuccaleena Fm. overlying the Elatina Fm. in the central Flinders Ranges (Fig. 70.1).

Structural framework

The Adelaide Geosyncline (Preiss 1987) was initiated by rifting of a Precambrian craton, the post-rifting parts of which are now represented by the Gawler Craton in the west and the Curnamona Province in the NE (Fig. 70.1). Feeder dykes for volcanic rocks near the base of the sedimentary succession have been dated at 867 ± 47 and 802 ± 35 Ma (Zhao & McCulloch 1993; Zhao et al. 1994) and 827 ± 6 Ma (Wingate et al. 1998). The early stages of development of the Adelaide Geosyncline were marked by a succession of major rift cycles, but rifting was less important during the later stages including the late Cryogenian (Preiss 1987, 2000). No volcanism is known in the region during the Elatina glaciation.

The Neoproterozoic–early Palaeozoic succession in the Adelaide Geosyncline was deformed by the Delamerian Orogeny at 514–490 Ma (Drexel & Preiss 1995; Foden et al. 2006). The folded strata of the Delamerian Orogen now form the Flinders Ranges in the north and Mount Lofty Ranges in the Adelaide area in the south. Preiss (2000) identified the following major subdivisions of the Adelaide Geosyncline region based on Delamerian tectonic style (Fig. 70.1):

- Cratonic platforms of the Stuart Shelf and the Curnamona Province, with thin, little deformed Neoproterozoic and Cambrian cover;
- Torrens Hinge Zone of gentle folding;
- Central Flinders Zone of broad dome and basin structures;
- North Flinders Zone of arcuate, open to tight folds;
- Nackara Arc of long, arcuate, relatively upright folds;
- Fleurieu Arc marked by thrusting and tight folding.

Stratigraphy

The Neoproterozoic stratigraphy of the Adelaide Geosyncline region is discussed by Coats & Preiss (1987), Preiss (1993, 2000) and Preiss et al. (1998). The Yerelina Subgroup at the top of the Cryogenian Umberatana Group embraces all the glaciogenic formations of the Elatina glaciation (Preiss et al. 1998).

The Elatina glaciation is recorded by a wide range of facies, including permafrost regolith and periglacial–aeolian sandstone on the Stuart Shelf, and sandstone, mudstone, siltstone and diamictite of interpreted glacioluvial, deltalic, marginal marine and marine shelf environments to the east, north and SE (Fig. 70.1). Proposed correlations within the Yerelina Subgroup, its possible division into three sequences, and a suggested relative sea-level curve are shown in Figure 70.2. Measured sections and fence

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diagrams showing various facies of the subgroup and their suggested correlations are provided by Coats & Preiss (1987) and Lemon & Gostin (1990). The Yerelina Subgroup is unconformably to disconformably overlain by the Ediacaran Wilpena Group.

**Glaciogenic deposits and associated strata**

The thickest deposits and most complete successions of the Yerelina Subgroup occur in the North Flinders Zone and the Nackara Arc (Fig. 70.1).

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**North Flinders Zone**

Deposition in the North Flinders Zone commenced, possibly following an erosional break, with the 1070-m-thick Fortress Hill Fm., which comprises laminated siltstone with gritty lenses and scattered dropstones, some faceted, marking the onset of glacial deposition (Coats & Preiss 1987; Preiss *et al.* 1998). Clast lithologies include granite, quartzite, limestone, oolitic limestone and dolostone. The Fortress Hill Fm. is typical of the dominantly fine-grained units of the Yerelina Subgroup that are interpreted by Preiss (1992) as outer marine-shelf deposits.
The Fortress Hill Fm. is sharply overlain by sandstone and conglomerate at the base of the Mount Curtis Tillite (90 m) that may record a lowering of relative sea level and mark a sequence boundary (Preiss et al. 1998). (Use of ‘Tillite’ in the formal lithostratigraphic terminology of Cryogenian diamictite units in South Australia reflects early practice and does not imply any specific glacial environment.) The Mount Curtis Tillite is a sparse diamictite with erratics of pebble to boulder size, some faceted and striated, in massive and laminated, grey-green dolomitic siltstone. Clast lithologies are mostly quartzite, limestone and dolostone, but also include granite and porphyry (Coats & Preiss 1987). Granite boulders attain 3 × 8 m. The Mount Curtis Tillite is overlain by the medium-grained, feldspathic Balparana Sandstone (130 m), which contains interbeds and lenses of calcareous siltstone and pebble conglomerate. The Balparana Sandstone is disconformably overlain by the Wilpena Group. The main source for the glaciogenic deposits may have been the Curnamona Province to the present east (Fig. 70.1) and possibly the now-buried Mulloolina Ridge immediately north of the North Flinders Zone (Preiss 1987).

**Nackara Arc**

The glaciogenic succession in the Nackara Arc is up to 1500 m thick and has some similarity to that in the North Flinders Zone (Coats & Preiss 1987; Preiss 1992; Preiss et al. 1998). The lowermost, laminated siltstone facies of the Fortress Hill Fm. shows progressively greater amounts of scattered, ice-rafterd granules and pebbles. The shallow-water Gumbowie Arkose (45–90 m) disconformably overlies these early deposits at a possible sequence boundary and is conformably succeeded by the Pepuarta Tillite (120–197 m), which is a sparse diamictite with scattered, ice-rafted granules and pebbles. The Pepuarta Tillite is overlain by the laminated to cross-laminated, calcareous, pale grey Ketchowla Siltstone (271 m) (Preiss 1992). The Ketchowla Siltstone contains scattered ice-rafterd granules, pebbles and boulders up to 1 m across, and is ascribed by Preiss (1992) to outer marine-shelf deposition under generally waning glacial conditions. It is overlain disconformably by the Nuccaleena Fm., with any Ketchowla Siltstone deposited in the North Flinders Zone having been completely removed by erosion at this sequence boundary (Preiss 2000).

The widespread Grampus Quartzite (60 m) disconformably overlies the Pepuarta Tillite, possibly at a sequence boundary and is conformably succeeded by the Pepuarta Tillite, possibly at a sequence boundary. The Pepuarta Tillite and the correlative Mount Curtis Tillite mark the glacial maximum of the Elatina glaciation (Preiss et al. 1998).

**Central Flinders Zone**

Deposition of the relatively thin (30–130 m), inner marine-shelf, glaciofluvial and deltaic facies of the Elatina Fm. in the Central Flinders Zone (Lemon & Gostin 1990) commenced about the time of the glacial maximum. The Elatina Fm. attests to punctuated glacial retreat, although the entire formation accumulated under glacial conditions. Its reddish hue results from the presence of ultra-fine hematitic pigmentation, which makes the formation ideal for palaeomagnetic study. Regionally, the pre-Elatina surface has a relief of >450 m but shows little relief at outcrop apart from local karst solution features. In its type area the Elatina Fm. unconformably overlies the Trezona Fm. and the Yalitipena Fm. of the Upalina Subgroup (Lemon & Gostin 1990; Lemon & Reid 1998).

The Elatina Fm. around the emergent Enorama Diapir (Fig. 70.1) is c. 100 m thick and includes the following facies:

1. Boulder conglomerate and basal diamictite (≤ 5 m) containing boulders of granite gneiss and other extrabasinal clasts in a muddy and sandy matrix that includes some material from the underlying beds. At Trezona Bore and Bulls Gap 5–12 km north of Enorama Creek, the top 1–3 m of the then poorly lithified, preglacial Yaltipena Formation are truncated and deformed (Lemon & Gostin 1990; Lemon & Reid 1998; Williams et al. 2008). Locally, boulders of granite gneiss have been forced into the top of the Yaltipena Fm. These features are classifiable as penetrative, Type A glaciectonites (Evans et al. 2006).

2. Cross-bedded, coarse-grained sandstone (c. 5 m) interpreted as fluvial channel deposits (Lemon & Gostin 1990). This unit is correlative with trough cross-bedded, labile coarse-grained sandstone at the base of the Elatina Fm. in Pichi Richi Pass.

3. Placer-bedded, muddy and silty sandstone, overlain by sandstone beds ≤ 1 m thick showing large ball-and-pillow structures ascribed by Lemon & Gostin (1990) to collapse of the sand bodies into the underlying muds.

4. White, pink to red brown, poorly sorted feldspathic sandstone (20–40 m) that is regionally extensive and in many places rests on the basal unconformity. The sandstone has indistinct bedding with slumped trough cross-bedded sets ≤ 1 m thick and small water-escape structures, and contains thin discontinuous granule layers and rare pebbles to...
boulders. The bimodal nature of the sandstone, expressed as a
dominance of coarse silt to fine sand and very coarse sand to
granule fractions, suggests aeolian winnowing in the source
area. Lemon & Gostin (1990) concluded the sandstone was
rapidly deposited in a subaqueous environment with almost
continuous slumping and dewatering. Eyles & Gannum
(2007) identified hummocky cross-bedding in sandstone
5–10 km north of Enorama Creek, which they interpreted
as indicating a storm-influenced shore-face setting.
(5) Laminated reddish grey siltstone and red mudstone with rare
dropstones that pass laterally into diamicite with sparse
clasts, suggesting deposition from floating ice and a return
to glacial conditions.
(6) Diamicite partly reworked by shallow-marine currents as
marked by the presence of lag gravel layers capped by
ripple cross-laminated sandstone within otherwise massive
units, in the upper third of the Elatina Fm. west of the
Enorama Diapir.
(7) A diamicite (Supplementary material, Photo 3) with numer-
ous striated clasts that underlies the Nuccaleena Fm., indicat-
ating that a glacial influence persisted to the end of deposition
of the Nuccaleena Fm. (Lemon & Gostin 1990).
(8) The Elatina Fm. east of the line of diapiric islands is c. 120 m
thick and has a thin basal conglomerate over lain by massive
diamicite carrying boulders of extrabasinal origin (Lemon &
Gostin 1990). This is succeeded by c. 50 m of pink sandstone
with indistinct bedding, followed by ripple cross-laminated
fine-grained sandstone with rare limestones. A subaqueous,
possibly marine shelf, environment is suggested. Further
east in the Chambers Gorge area, a cross-bedded sandstone
facies up to 200 m thick may mark a delta at the western
margin of the Curnamona Province (Cosets & Preiss 1987).
Halite casts occur in purple fine-grained sandstones of the
Elatina Fm. in this area (Cosets 1973).

Near the western margin of the Adelaide Geosyncline, the Elatina
Fm. includes tidal rhythmites of siltstone and fine-grained
sandstone that formed on a series of ebb-tidal deltas (Williams
1989, 1991, 2000). The rhythmites locally display gravity-slide
fold structures (wavelength typically 30–50 cm, height 3–5 cm)
and wave-generated ripple marks (wavelength 3–5 cm, height
<1.5 cm), best seen at Warren Gorge where the unit is c. 18 m
thick (Williams 1996). Tidal rhythmites are well formed at a
more distal setting in Pichi Richi Pass, although exposure is
limited. Detailed study of cores from three diamond drill holes
through the rhythmites in Pichi Richi Pass, supplemented by data
for rhythms near Hallett Cove, has provided a self-consistent
palaeotidal data set spanning 60 years (continuous log 9.4 m
long comprising 1580 successive fortnightly neap–spring cycles;
Williams 1991) that records information on the Earth’s palaeo-
rotation and the Moon’s orbit in the late Cryogenian: data
include 13.1 ± 0.1 lunar months/year, 400 ± 7 solar days/year,
21.9 ± 0.4 hours/solar day, and a mean Earth–Moon distance
of 96.5 ± 0.5% of the present distance (Williams 1989, 1991,
2000). The rhythmites also record the non-tidal, annual
oscillation of sea level (Williams 2004; Williams & Schmidt
2004; Williams et al. 2008), which is a response mostly to seasonal
changes in water temperature as well as variation in winds
and atmospheric pressure (Rodent 1963; Pattullo 1966; Wunsch
1972; Komar & Enfield 1987). The rhythmites were deposited
during a high stand of sea level during temporary glacial retreat
(Williams et al. 2008). Comparable tidal rhythmites are known
from modern glaciomarine settings (Smith et al. 1990; Covin
et al. 1999).

The extensive sandstone (facies 4) of the Elatina Fm. may
equate with the Gumbowie Arkose and Grampus Quartzite
(Fig. 70.2). Diamicite units near the base and at the top of the
Elatina Fm. may correlate with the Pepuarta Tillite–Mount
Curtis Tillite and the Ketchowla Silstone, respectively.

Numerous clasts in the Elatina Fm. diamicites are faceted
and striated, with striations paralleling the long axes of clasts,
and linear series of chattermarks are seen on some boulders.
About 40% of the larger clasts are extrabasinal in origin, compris-
ing granite gneiss, red porphyritic daleite, schist, metaquartzite,
vein quartz and iron-formation. Smaller clasts of pebble and
cobble size are dominated by dolerite and vesicular basalt,
and also include dolostone and heavy-mineral band sandstone.
Faceted and striated basalt clasts that are abundant in the diamicite
at the top of the Elatina Fm. in the Central Flinders Zone are
ascribed to the glacial erosion of rafts of identical volcanic rocks
up to 1 km across in the emergent diapiric islands in the area
(Mawson 1949; Coats & Preiss 1987; Lemon & Gostin 1990).
Hence grounded glaciers persisted on these islands to the end of
Elatina deposition. Some of the extrabasinal clasts may have
been derived from the Curnamona Province, and Lemon &
Gostin (1990) matched other clasts with basement rocks in the
Iron Knob area of the Gawler Craton. Derivation directly from
the west of the Central Flinders Zone is unlikely, however,
because the presence on the Stuart Shelf of a preglacial palaeo-
alsos, a late Cryogenian permafrost regolith and an overlying per-
iglacian. Grain sand sheet indicates that the craton to the west
was free of glaciers throughout the late Cryogenian (Williams
et al. 2008).

Hallett Cove area

In the Hallett Cove area of the southern Adelaide Geosyncline
(Fig. 70.1), sandstone of the preglacial Wilmington Fm. at the
top of the Upalinnna Subgroup is overlain with an erosional
contact by the Reynella Siltstone Member of the Elatina Fm.,
which is exposed in a 120-m-thick coastal section at Marino
Rocks 2.5 km north of Hallett Cove (Cosets & Preiss 1987).
The section comprises four facies:

(1) A lowermost, massive, dark red silstone that contains rare
granules and angular dolostone fragments.
(2) Siltstone and fine-grained sandstone, including tidalites
displaying herringbone cross-bedding, flaser bedding and
tidal rhythms (Williams 1989, 1991, 2000; Williams
et al. 2008). Authigenic carbonates form sub-vertical chim-
neys 1–2 m in diameter and branching pipes (Kennedy
et al. 2008).
(3) Calcareous and dolomitic sandstone and siltstone containing
angular, granule- to pebble-sized intraclasts of limestone and
dolostone. Tepee-like structures and dolostone interbeds
withstromatolitic laminae are also present (Dyson & von
der Borch 1986). Accisural crystal pseudomorphs in some
beds may record evaporite minerals.
(4) Massive, granule-bearing silstone at the top of the section.
The Reynella Siltstone Member at Marino Rocks displays
no conclusive evidence of glaciation, but 7 km to the SSW, the
member includes a silstone with a probable dropstone (Cosets
& Preiss 1987).

Stuart Shelf

Periglacial facies that locally overlie the Cryogenian interglacial
Tapiyle Hill Fm. and are directly followed by the Nuccaleena
Fm. occur on the Stuart Shelf west of the Adelaide Geosyncline
(Fig. 70.1). These stratigraphic relationships show that the perigl-
cial facies are broadly correlative with the Elatina Fm. and other
formations of the Yerelina Subgroup (Cosets 1981; Cosets
& Preiss 1987; Preiss 1993; Preiss et al. 1998). The Nuccaleena
Fm. marks marine transgression over most of the Stuart Shelf
(Forbes & Preiss 1987), indicating that the late Cryogenian peri-
glacial facies formed near sea level.
**Permafrost regolith.** A breccia regolith up to 20 m thick, termed the Cattle Grid Breccia, that developed on an inlier of flat-lying, silicified sandstone of the Mesoproterozoic Pandurra Formation near Mount Gunson, is interpreted to have formed by in situ frost shattering (Williams & Tonkin 1985; Williams 1986, 1994). The Cattle Grid Breccia is similar to breccias of modern, periglacial block fields (White 1976; Washburn 1980) and in situ brecciated bedrock extending to depths of 11+ m below the ground surface associated with former and present permafrost horizons in SE England, Spitsbergen and the Canadian Arctic (Murton 1996).

The Cattle Grid Breccia displays two generations of sand wedges up to 3 m or more deep and 2–3 m wide that show steeply-dipping laminae of coarse-grained sandstone and outline polygons 10–30 m in diameter. Relict bedding in the Cattle Grid Breccia is upturned adjacent to the wedges. These sand wedges are comparable in dimensions, structure and internal fabric with V-shaped primary sand wedges forming today in rubble produced by frost action on bedrock in the dry valleys of Antarctica (Péwé 1959; Washburn 1980). Additional metre-scale periglacial forms displayed by the Cattle Grid Breccia include antichains, tepee-like structures, L-shaped mounds, frost-hooded boulder caps, periglacial breccia injections, and inversions or sags (Williams & Tonkin 1985; Williams 1986). The in situ Cattle Grid Breccia is capped by a layer of reworked breccia up to 2 m thick, interpreted as an active layer (Washburn 1980).

**Periglacial aeolianite.** The Whyalla Sandstone conformably overlies the Cattle Grid Breccia and covers 25 000 km2 in outcrop and subcrop (Coats & Preiss 1987; Preiss 1993; Williams 1998). The flat-lying formation is up to 165 m thick and comprises mainly medium- to very coarse-grained, well-rounded, commonly bimodal quartzose sandstone that shows regional SSE-ward fining. Low angle strata form the dominant stratification type, with cross-bed sets up to 7 m thick occurring mainly in the central area. The basal few metres of the formation display two generations of primary sand wedges up to 1.5 m deep, periglacial inversions and diapiric injections (Williams & Tonkin 1985; Williams 1998). Red gritty siltstones are intercalated locally. The presence of subcritically climbing translatent strata and grainflow and grainfall deposits in the sandstone facies confirms a predominantly aeolian sand-sheet environment, with the attitude of cross-bedding indicating winds directed towards the present SE (Williams 1998).

**Boundary relations with underlying and overlying non-glacial units.**

The Fortress Hill Fm. overlies the Upalinna Subgroup, at least locally with an erosional contact at the base of Marinoan sequence set M2.1 (Fig. 70.2; Preiss et al. 1998). In the Adelaide–Hallett Cove region, the Central Flinders Zone and the western region of the Nackara Arc, the Elatina Fm. unconformably overlies the Upalinna Subgroup. This sequence boundary may equate with that at the base of the Gumbowie Arkose in the eastern part of the Nackara Arc, marking the base of Marinoan sequence set M2.2.

The contact between the Yerelina Subgroup and the overlying Wilpena Group is a disconformity to low-angle unconformity marking a sequence boundary (Fig. 70.2; Coats & Blissett 1971; Preiss et al. 1998; Preiss 2000; Knoll et al. 2006). Erosion at this sequence boundary is most pronounced in the North Flinders Zone, where in several areas it cuts down through the Balparana Sandstone, Mount Curtis Tillite and Fortress Hill Fm. (Coats et al. 1969, 1973; Ambrose 1973; Preiss 2000), implying up to 1500 m of erosion prior to deposition of the Wilpena Group. The erosion may indicate post-glacial isostatic rebound of adjoining cratons, particularly the Curnamona Province in the NE, and an appreciable time-gap between the end of the Elatina glaciation and Nuclaeaena deposition (Schmidt et al. 2009).

In most places in the Adelaide Geosyncline and on the Stuart Shelf the Yerelina Subgroup is overlain by the Nuclaeaena Fm., which is a persistent marker in the region (Coats & Preiss 1987; Forbes & Preiss 1987; Preiss 2000). The Nuclaeaena Fm. is typified by a laminated, pink, buff and cream micritic dolostone unit, with interbedded dolostone, sandstone and mudstone occurring locally at the base. The dolostone unit is several metres thick near the western margin of the Adelaide Geosyncline and on the Stuart Shelf, and 5–17 m thick in the Central Flinders Zone. At Hallett Cove in the south, however, the Reynella Siltstone Member of the Elatina Fm. is sharply overlain by the pale red and grey Seafall Sandstone; the post-Cove member is the Wilpena Group, and the principal dolostone unit of the Nuclaeaena Fm. lies c. 70 m stratigraphically above the Elatina Fm. (Forbes & Preiss 1987). The Seafall Sandstone attains a thickness of 340 m elsewhere in the southwestern Adelaide Geosyncline and intertongues regionally with the Nuclaeaena Fm. and overlying Brachina Fm. (Forbes & Preiss 1987; Preiss 1993). The Ediacaran GSSP in Enorama Creek in the Central Flinders Zone appears to be placed within the transitional dolostones below prominent dolostone beds of the Nuclaeaena Fm. and above a 0.2–0.3 m-thick bed of pale red sandstone that disconformably overlies the Elatina Fm. This sandstone bed may be a local manifestation of the Seafall Sandstone (Williams et al. 2008).

**Chem stratigraphy.**

The characteristic Δ13CVPDB profile of the dolostone unit of the Nuclaeaena Formation in the Adelaide Geosyncline decreases upwards from −1%e to −2.5%e at its base to −3.5%e at its top (Calver 2000; McKirdy et al. 2005; Knoll et al. 2006). In its topmost and absolute values, the post-Cove member is the Wilpena Group, those of basal Ediacaran dolostones elsewhere (Kennedy et al. 1998; Halverson et al. 2004). Authigenic carbonate cements in facies 2 of the Reynella Siltstone Member at Hallett Cove yielded Δ18OVCDP values from −25‰ to +12‰ and Δ13CVPDB values from −10‰ to +10‰ (Kennedy et al. 2008).

**Palaeolatitude and palaeogeography.**

Detailed palaeomagnetic studies have been conducted on red beds from the folded Elatina Fm. in the Central Flinders Zone and unfolded equivalent strata on the Stuart Shelf (Embleton & Williams 1986; Schmidt et al. 1991; Schmidt & Williams 1995; Sohl et al. 1999). Embleton & Williams (1986) determined a stable, high-temperature (c. 680 °C) magnetization carried by hematite (mean declination D = 191.9°, mean inclination I = −9.6°, δø5 = 3.4°; inferred palaeolatitude = c. 5°) for six sites in exposed tidal rhythmites in Pichi Richi Pass. Their accompanying study of drill cores of the rhythmites also yielded shallow inclinations with respect to bedding, likewise suggesting a low palaeolatitude, with the spread of declinations resulting from uncertainty in bedding attitudes in the cores. Three positive fold tests were executed on small folds (wavelengths 30–50 cm) that formed by soft-sediment gravity sliding of the tidal rhythmites; the truncation and delicate scouring of some fold crests show that the folds formed during deposition (Williams 1996; Williams et al. 2008). Sumner et al. (1987) reported a positive fold test but did not provide a magnetic direction. Two detailed soft-sediment fold tests (Schmidt et al. 1991; Schmidt & Williams 1995) found that directions of remanence for the tightest clustering occurred for 66–67% unfolding, at 99% level of confidence. The two detailed fold tests showed that the magnetization was acquired essentially coeval with deposition and is mostly a detrital remanent
magnetization (DRM). The positive fold tests confirmed that the structures are folds and not ripples. These soft-sediment fold tests did not, however, confirm a low palaeolatitude. Because the studies in Pichi Richi Pass sampled the geomagnetic field for <100 years, there were growing objections that the data provided just a virtual geomagnetic pole, that is, a snapshot of the geomagnetic field, and could indicate a geomagnetic excursion or transition. Confirmation of a low palaeolatitude came only when Schmidt & Williams (1995) studied the full succession of the Elatina Fm. in the Central Flinders Zone and obtained a stable, high-temperature component carried by hematite (dip-corrected $D = 197.3^\circ$, $I = -5.3^\circ$, $\alpha95 = 7.4^\circ$) and interpreted as an early chemical remanent magnetization (CRM). This magnetic direction is concordant with directions obtained previously for the Elatina rhythms and implied a palaeolatitude of 2.7 ± 3.7°. The presence of sequential magnetic reversals for the Elatina Fm. in the Central Flinders Zone (Schmidt & Williams 1995; Sohl et al. 1999) and a positive tectonic fold-test (Sohl et al. 1999) are consistent with early magnetization.

Combined data for 205 samples from the Elatina Fm. (Schmidt & Williams 1995; Sohl et al. 1999; Geological Society of America Data Repository item) yielded a direction of $D = 208.3^\circ$ and $I = -12.9^\circ$ ($\alpha95 = 4.2^\circ$), indicating a palaeopole at 43.7°S, 359.3°E ($dp = 21.1^\circ$, $dm = 4.2^\circ$) and a palaeolatitude of 6.5 ± 2.2°. The following observations indicate only minor compaction-related inclination shallowing (Williams 2008; Williams et al. 2008): (i) the typical shallow inclination of the Elatina palaeomagnetic remanence obtained for samples of different lithologies (fine-, medium- and coarse-grained sandstone, with mudstone and muddy diamictite being avoided); (ii) the comparable inclinations determined for samples from flat-lying strata in the condensed succession on the cratonic platform and from folded strata in basinal successions; and (iii) the low anisotropy of magnetic susceptibility (mean <4% for 65 samples), which indicates only slight magnetic foliation (Enkin et al. 2003). The findings are supported by a palaeolatitude of 8.4 ± 6.2°–5.7° determined for the immediately preglacial Yaltipena Fm. (Sohl et al. 1999) and by the low palaeolatitudes (≤10°) determined for late Cryogenian glaciogenic deposits in the Officer Basin, Western Australia (Psarsenovsky et al. 2001, 2007). Schmidt et al. (2009) provide further palaeomagnetic and rock magnetic data and sedimentological evidence for late Neoproterozoic successions in southern Australia that demonstrate that the effects of inclination shallowing for the Elatina Fm. are minor. The Elatina data together satisfy all the palaeomagnetic reliability criteria of Van der Voo (1990), and indicate that the magnetization of the Elatina Fm. was acquired close to the time of deposition and that the Elatina glaciation took place at a palaeolatitude of ≤10°.

Geochronological constraints

The Elatina glaciation has not been accurately dated, and only broad age limits can be given. A U–Pb age of 657 ± 17 Ma was obtained for a zircon grain of uncertain provenance from the Marino Arkose Member of the underlying Upalina Subgroup (Preiss 2000). Re–Os dating gave an age of 643.0 ± 2.4 Ma for black shale from the Tindelpina Shale Member at the base of the Tapley Hill Fm., which overlies glacial deposits of Sturtian age in the Adelaide Geosyncline (Kendall et al. 2006). Zoned igneous zircon from a tuffaceous layer near the top of the Sturtian-age glaciogenic succession gave a SHRIMP U–Pb age of c. 658 Ma (Fanning & Link 2006). Mahan et al. (2007) reported a Th–U–total Pb age of 680 ± 23 Ma for euhedral laths of monazite, interpreted as authigenic, from the Enorama Shale of the Upalina Subgroup. These data, although in part contradictory, provide maximum age constraints for the Elatina glaciation.

Suggested ages for the Elatina glaciation of 635 ± 1.2 Ma (Hoffmann et al. 2004) and near 580 Ma (Calver et al. 2004) are based on U–Pb zircon dating of volcanic rocks associated with the Ghabuf Fm. in Namibia and diamictites in Tasmania, respectively, that were thought to be coeval with the Elatina glaciation. Zhou et al. (2004) gave a maximum age of 663 ± 4 Ma and Condon et al. (2005) a minimum age of 635.2 ± 0.6 Ma for the Nantuog glaciation in China, which they equated with the Elatina glaciation. Zhang et al. (2008) reported a SHRIMP U–Pb zircon age of 636 ± 4.9 Ma for a tuff near the base of the Nantuog Fm. Whether Cryogenian glaciations correlate worldwide is unclear, however, and the Tasmanian diamictites may be related to Ediacaran glaciation identified on several continents and dated at c. 580 Ma in Newfoundland (Bowring et al. 2003).

The above findings provide only maximum and minimum age limits of c. 640 and 580 Ma, respectively, for the Elatina glaciation. Accepting ages of 643 Ma for the Tindelpina Shale Member and 635 Ma for the Elatina glaciation requires high rates of sedimentation for the >4 km of interglacial strata in the Central Flinders Zone. Alternatively, either the Re–Os shale ages could be too young or the Elatina glaciation could be younger than 635 Ma.

Discussion

The late Cryogenian Elatina glaciation in South Australia, which occurred at some undetermined time between c. 640 and 580 Ma, is recorded by a wide range of terrestrial and marine facies: permafrost regolith displaying large-scale cryogenic structures; a periglacial–aeolian sand sheet; littoral and neritic deposits including tidalites and evaporites; continental and inner marine-shelf sandstones; boulder diamictite with associated glacioclastites; inner marine-shelf diamictite; and outer marine-shelf diamictite and laminated mudstone–siltstone with ice-rafted dropstones. This varied succession throws light on the late Cryogenian depositional environments and climate near sea level in South Australia.

Penetrative glacioclastites affecting the preglacial Yaltipena Fm. beneath the Elatina Fm. in the Central Flinders Zone indicate scouring by ice near sea level, but whether the ice was grounded (Lemon & Gostin 1990) or floating (Eyles & Gammon 2007) is uncertain. The presence of faceted and striated clasts of basalt in diamictite at the top of the Elatina Fm. in the same area indicates that grounded glaciers persisted on diapiric islands to the end of Elatina deposition. The regionally extensive sandstones of the Elatina Fm. (Coats & Preiss 1987; Lemon & Gostin 1990) suggest glaciofluvial and deltaic settings near the margins of the Adelaide Geosyncline passing basinwards to a marine-shelf environment.

The widespread occurrence of glaciomarine diamictites and fine-grained laminated facies with dropstones in the Pepurata Tillite and Mount Curtis Tillite implies the calving of icebergs into open seas and the rainout of ice-rafted debris during the glacial maximum. Extensive and persistent open seas continued during deposition of the Elatina Fm., as indicated by wave-generated ripple marks and the signature of the annual oscillation of sea level displayed by the Elatina rhyhmites (Williams 2008; Williams et al. 2008). These observations are not compatible with a frozen-over ocean like that advocated by Hoffman & Schrag (2002).

More than a century of research on periglacial geomorphology and processes indicates that large-scale primary sand wedges like those at Mount Gunson record a strongly seasonal periglacial climate (Péwé 1959; Black 1976; Washburn 1980; Karte 1983). In polar regions, thermal contraction cracks 1–10 mm wide and up to 10 m deep, which outline polygons 10–30 m across, develop in the upper part of permafrost with rapid drops of temperature during repeated severe winters. In arid periglacial areas the contraction cracks are filled by windblown sand and the resulting
sand wedges show near-vertical lamination. Lateral pressure during summer expansion causes upturning of adjacent permafrost. The claim of Maloof et al. (2002), based on numerical models, that diurnal fluctuations of temperature produced the 3+ m deep late Cryogenian sand wedges at Mount Gunson is refuted by (i) the shallow (<1 m) influence of diurnal temperature changes on permafrost in modern polar regions (Embleton & King 1975) and (ii) the lack of periglacial wedges at high elevations near the equator, where the mean annual air temperature (MAAT) remained below 0 °C for intervals of several millennia during the Pleistocene and temperature fluctuations are mainly diurnal (Hastenrath 1973, 1981; Williams & Schmidt 2004).

Applying an actualistic interpretation of periglacial forms and their climatic significance (Washburn 1980; Karte 1983), the suite of large-scale cryogenic structures in the Cattle Grid Breccia and Whyalla Sandstone implies that the following features characterized the late Cryogenian environment near sea level in South Australia (Karte 1983; Williams & Tonkin 1985; Williams 1986, 1994, 1998; Williams et al. 2008):

- rigid climate (MAAT of −12 to −20 °C or lower), producing a thick (<10 to 20 m) permafrost regolith of frost-shattered bedrock;
- strong seasonality (seasonal temperature range as great as 40 °C, with mean monthly temperatures of −35 °C or lower in midwinter and up to +4 °C in midsummer), indicated by 3+ m-deep primary sand wedges and adjacent upturned permafrost regolith arranged in polygons 10–30 m across;
- aridity (<100 mm mean annual precipitation), limited snow cover, and windiness causing the infilling of thermal contraction-cracks with windblown sand;
- summer temperatures above freezing to produce a 2-m-thick active layer of reworked breccia above the in situ Cattle Grid Breccia;
- climate cycles on a ka timescale, producing several generations of sand wedges alternating with episodes of destabilization and erosion of the upper part of the permafrost.

The implication that the mean annual air temperature rose above freezing both annually and through long-term temperature changes is consistent with observations indicating long-lived and extensive open seas during the Elatina glaciation. Aridity on the Stuart Shelf accords with the presence of casts and pseudomorphs of evaporites in the Elatina Fm.

High quality palaeomagnetic data indicate that this frigid, strongly seasonal, arid climate, under which permafrost, ice-scouring of periglacial beds, and grounded glaciers on emergent diapiric islands all occurred near sea level, existed within 10° of the palaeoequator. Cross-bedding attitudes for the periglacial–aeolian Whyalla Sandstone record palaeo-westerly to palaeo-northwesterly surface winds near the palaeoequator (Fig. 70.1, inset), employing the geographic polarity indicated for late Neoproterozoic Australia (Li et al. 2008). The lack of evidence for elevated topography and late Cryogenian glaciation on the Gawler Craton in the palaeo-west and palaeo-NW (Coats & Preiss 1987; Preiss 1993; Williams et al. 2008) implies that the palaeowind data record a regional palaeowind direction rather than katabatic winds blowing off mountains or an ice sheet. This palaeowind direction is the reverse of the zonal easterlies in low latitudes today.

McKirdy et al. (2005) and Gammon (2006) found that over 90% of the Nuccaleena carbonate comprises dolomicrospar with a radical geochemical zonation which, they argued, formed via early diagenetic organogenic dolomitization mediated by sulphate-reducing bacteria. They concluded that it is unlikely the published δ13C(CO2) profiles of the Nuccaleena Fm. record the C-isotopic composition of post-glacial seawater. Kennedy et al. (2008) interpreted the δ18O(PDB) and δ13C(PDB) values for authigenic carbonate cements in facies 2 of the Reynella Siltstone Member as indicating methane hydrate destabilization that terminated the Elatina glaciation and triggered deposition of the Nuccaleena Formation. However, facies 2 occurs well below the top of the member and has disconformable to unconformable contact with the Sealff Sandstone. Hence the data of Kennedy et al. (2008) evidently record events during the Elatina glaciation, like the episodic destabilization of permafrost on the Stuart Shelf.

Zhang et al. (2008) found an extensive (>500 km) claystone between the late Cryogenian, glaciogenic Nantu Fm, and its overlying Doushantuo cap carbonate in South China, which they interpreted (p. 293) as indicating ‘a time lag between the end of the Nantuo deglaciation and cap carbonate precipitation’. Their conclusion is consistent with the stratigraphic evidence given here for a time-gap between the end of the Elatina glaciation and deposition of the Nuccaleena Fm. The robustness of the Elatina palaeomagnetic data and the presence of a time gap between Elatina and Nuccaleena deposition indicate that palaeomagnetic data for the Nuccaleena Formation (Schmidt et al. 2009; Evans & Raub 2011) cannot be applied to the Elatina Fm.

In conclusion, much geological and palaeomagnetic data indicate an enigmatic late Cryogenian glacial environment in South Australia (Washburn et al. 2008). Research in progress aims to provide an accurate age for the Elatina glaciation to test proposed correlations with late Cryogenian glaciogenic successions elsewhere. Photographs of this succession are available in the online companion atlas at http://neoproterozoic-glaciations.weebly.com.

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