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Bolla Bollana boulder beds: a Neoproterozoic trough mouth fan in South Australia?

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Abstract
The Bolla Bollana Formation is an exceptionally thick (~1500 m), rift-related sedimentary succession cropping out in the northern Flinders Ranges, South Australia, which was deposited during the Sturtian (mid Cryogenian) glaciation. Lithofacies analysis reveals three distinct facies associations which chart changing depositional styles on an ice-sourced subaqueous fan system. The diamictite facies association is dominant, and comprises both massive and stratified varieties with a range of clast compositions and textures, arranged into thick beds (1- 20 m), representing stacked, ice-proximal glaciogenic debris flow (GDF) deposits. A channel belt facies association, most commonly consisting of normally-graded conglomerates and sandstones, displays scour and fill structure of ~10 m width and 1-3 m depth: these strata are interpreted as channelised turbidites. Rare mud-filled channels in this facies association bear glacially striated lonestones. Finally, a sheet heterolithics facies association contains a range of conglomerates through sandstones to silty shales arranged into clear, normally graded cycles from the lamina to bed scale. These record a variety of non-channelised turbidites, probably occupying distal and/or interchannel locations on the subaqueous fan. Coarsening and thickening-up cycles, capped by dolomicrites or mudstones, are indicative of lobe build out and abandonment, potentially as a result of ice lobe advance and stagnation. Dropstones, recognised by downwarped and punctured laminae beneath pebbles to boulders in shale, or in delicate climbing ripple cross-laminated siltstones, are clearly indicative of ice rafting. The co-occurrence of ice-rafted debris and striated lonestones strongly support a glaciogenic sediment source for the diamictites. Comparison to Pleistocene analogues enables an interpretation as a trough mouth fan, most probably deposited leeward of a palaeo-ice stream. Beyond emphasising the highly dynamic nature of Sturtian ice sheets, these interpretations testify to the oldest trough-mouth fan recorded to date.

Keywords: Sturtian; Neoproterozoic; Glaciation; snowball Earth; trough mouth fan; ice stream; Flinders Ranges

INTRODUCTION

The northern Flinders Ranges of South Australia exposes an extremely thick succession of diamictites that were deposited during the Sturt glaciation (Young and Gostin, 1991; Preiss et al., 2011) at ~715 Ma (Macdonald *et al.*, 2010). In Arkaroola (**Fig. 1**), these deposits were first described by Mawson (1941, 1949), and interpreted as terrestrial glacial deposits. By contrast, glaciomarine interpretations were offered by Young and Gostin (1991) by the recognition of dropstone fabrics. The deposits are highly contentious and significant to debates focussed on the intensity and extent of Cryogenian glaciations (e.g. Fairchild and Kennedy, 2007; Etienne et al., 2007; Allen and Etienne, 2008), particularly as South Australia can be regarded as a type area for the "Sturtian" pan-glacial event (Hoffman and Schrag, 2002).

For some, scepticism surrounds the interpretation of many Cryogenian diamictite-bearing successions, such as those in the Flinders Ranges. A mechanism of diachronous rift shoulder glaciation, during the fragmentation of Rodinia, was proposed by Eyles and Januszczak (2004). In that model, debris flows were fluxed into rift basins. In Namibia, for example, it was proposed that some diamictites were deposited by non-glacially influenced gravity flow deposits (Eyles & Januszczak, 2007), amplifying Schermerhorn's earlier non-glacial interpretations (Schermerhorn and Stanton, 1963; Schermerhorn, 1974). Such studies have hence stimulated questions about the clarity of the glacial signature in Neoproterozoic sedimentary successions. Recent examples worldwide, however, highlight the diverse range of reliable glaciogenic proxies preserved, despite tectonically active basin configurations (e.g. Arnaud, 2012; Busfield and Le Heron, in press; Le Heron et al., 2011, 2012; Uhlein et al. 2011). These studies provide substantive evidence for glacial processes during the Neoproterozoic, irrespective of the scale of interpreted ice sheets (cf. Allen and Etienne, 2008).

In this paper, a detailed facies analysis of the Bolla Bollana Formation in the northern Flinders Ranges (**Fig. 1, 2**) is undertaken, presenting data from three outstanding exposures. The succession is part of a classic diamictite succession which has not been subjected to detailed investigation for over 20 years. The data were collected as part of a six week field campaign in August 2012.

STUDY AREA AND STRATIGRAPHY

In the Arkaroola district of the northern Flinders Ranges, the lowermost of two Neoproterozoic diamictite-bearing intervals is exposed. These rocks belong to the Yudnamutana Subgroup (**Fig. 3**). A threefold subdivision of this subgroup is recognised: the Fitton Formation occurs at the base, the Bolla Bollana Formation in the middle, and the Lyndhurst Formation is the uppermost unit (**Fig. 3**). The Bolla Bollana Formation was first examined in the Arkaroola district by Mawson (1941, 1949). This pioneering work offered a terrestrial glacial origin for the diamictites. The formation itself was defined by Coats (in Thomson et al., 1964) as a subgreywacke tillite of massive character with intercalated quartzite and siltstone. Young and Gostin (1988, 1989, 1990, 1991) studied the Sturtian succession within the North Flinders Basin (NFB), a sub-basin within the Adelaide Fold Belt that Preiss (1987, 1998, 2000) argued was likely disconnected from depocentres in the central and southern Flinders Ranges. Each paper presented a series of sedimentary logs, and facies descriptions, recognising a comparable stratigraphic subdivision across the area. The dramatic increase in knowledge of sedimentary processes at tidewater ice margins since the time of Mawson motivated Young and Gostin (1989, 1991) to re-interpret the Bolla

Bollana Formation as glaciomarine. Regional mapping (Coats, 1973) demonstrates that the Bolla Bollana Formation is extensive in the eastern part of the Copley Sheet, and is particularly well exposed to the east and south of Arkaroola (**Fig. 1**). Summarising the regional stratigraphy, Young and Gostin (1991) published a map showing how sediment dispersal, surmised from a variety of palaeocurrent indicators, testifies to the interplay of extensional tectonics, forming graben-like minibasins, and palaeohighs (**Fig. 2**).

The Bolla Bollana Formation trends toward massive in character in the south of the NFB, becoming stratified in the north. To explain this, Young and Gostin (1988) suggested that ice-rafted debris (IRD) deposition was predominant in the south, with reworking processes more important northward. No unequivocal glacially striated surfaces are reported in Cryogenian successions of Australia, with the exception of those in Western Australia (Corkeron, 2007). However, the "cast of striations" is reported to occur "on the underside of basal Sturt silty mudstones near Merinjina Well" (Young and Gostin, 1991). These were interpreted as tectonic by Daily *et al.* (1973), and glaciogenic by others (Preiss, 1987; Young and Gostin, 1991; Preiss *et al.*, 2011).

In our present paper, detailed facies descriptions and interpretations are provided from three new sections at Stubb's Waterhole, Tillite Gorge, and Weetootla Gorge. None of these sections were investigated by Young and Gostin (1991), yet they yield exceptionally high quality exposure. The sections are ideally situated in a region subject to only low grade metamorphism during the Early Palaeozoic Delamerian Orogeny (Preiss, 1987), whereas mid-amphibolite facies affect correlative sediments in the Adelaide region. Our objectives are (1) to highlight a clear glaciogenic source for the Bolla Bollana Formation, (2) to reject a rift-only origin for diamictites, and (3) to present a new depositional model for the sequence as a trough-mouth fan succession.

FACIES ANALYSIS

The thickness of the Yudnamutana Subgroup in the North Flinders Basin is estimated to reach 6000 m in the Yudnamutana Trough (Young and Gostin, 1991), approximately 30 km NW of the study area. Herein, we focus on exceptionally well-preserved, high quality sections rather than attempting a complete stratigraphic traverse. Each of the three facies associations described and interpreted below occur in multiple locations in the Arkaroola district. We recognise a diamictite facies association, a channel belt facies association, and a sheet heterolithics facies association. Below, data from three detailed logged sections are presented (**Fig. 4**).

Diamictite facies association

Description

This facies association is highly heterogeneous and in terms of volume dominates the Bolla Bollana Formation (**Fig. 5** A). Uninterrupted accumulations >90 m thick are common (e.g. Tillite Gorge: **Fig. 4** B; **Fig. 5** A). Diamictites are sandy throughout, including both clast-poor and clast-rich varieties (*sensu* Moncrieff, 1989), with pebble to predominantly boulder sized clasts. Bed thickness varies considerably between 1-15 m (thus reaching megabed dimensions *sensu* Marjanac, 1996) (**Fig. 5** B). With some exceptions, most bed contacts are parallel to one another with minimal evidence for erosive contacts.

Both massive and well stratified diamictites occur as end-members of a continuum; most beds exhibit at least some diffuse stratification. In some cases, pronounced variations in clast content (20-60%) occur in successive beds (e.g. **Fig. 4** A, 15-25 m; **Fig. 5** C). In thick beds, upward transitions from stratified through massive facies occur, accompanied by an increase in clast size and content (**Fig. 4** B, 43-73 m). In stratified clast-poor diamictites, isolated clasts of pebble to boulder size downwarp and pierce underlying laminations; overlying laminae are unaffected (**Fig. 5** D). Sand lenses, or lens-shaped clast-free zones in the diamictite, occur both at the bottom and top of some beds. Throughout the facies association, clasts are typically equant, and sub-rounded to sub-angular. The base of the thickest observed bed in the Tillite Gorge section (**Fig. 4** B, 43 m) shows a highly undulose contact(**Fig. 5** E). Clasts with polished surfaces and crosscutting striations locally occur (**Fig. 5** F).

Interpretation

The diamictite facies association is interpreted largely as a suite of glaciogenic debris flows (GDFs) deposited in a subaqueous setting. The organisation of the diamictites into clearly defined beds indicates repeated emplacement of flows. The typical absence of erosive contacts is attributed to hydroplaning at the head of the flow, thereby lubricating the base of the flow and protecting the underlying bed from cannibalisation (e.g. Laberg and Vorren, 2000). The upsection increase in clast abundance and size is consistent with kinetic sieving within the flow, to generate inverse grading (Talling *et al.*, 2012). The downwarping of laminae beneath pebbles in the stratified clast-poor diamictites (**Fig. 5** D) are interpreted as impact structures produced by falling dropstones. Whilst clasts sinking into water saturated sediment can produce dropstone-like texture in a debris flow, such clasts typically behave similarly to tectonic augen, with concomitant shearing of adjacent laminae as the flow evolves (Hart and Roberts, 1994). Thus, in addition to downslope mass flow, evidence for subaqueous sedimentation and ice-rafted debris accumulation is preserved. Given the compositional similarity of strata both below and above the undulose bed contacts, (**Fig. 5 E**) it is likely that this feature developed through differential compaction rather than through erosion. The presence of clasts with crosscutting striations (**Fig. 5** F) strongly supports glacial derivation. Specifically, the crosscutting striations indicate rotation of the clasts, either in basal ice, at the ice-bed interface, or within the deforming bed beneath an ice mass (Benn and Evans, 2010, p. 361). The exceptional preservation of striations supports incorporation into the GDFs via ice-rafting, thereby protecting clast surfaces from the erosion processes anticipated during downslope re-mobilisation.

Channel belt facies association

Description

A variety of scour and fill structures, measuring 5-14 m wide, and 2-3.5 m depth, are a key feature of this facies association (**Fig. 4** B, 95-113 m; **Fig. 6** A, B). The scours crosscut, with multiple generations apparent over a few metres (**Fig. 6** A, B). Lithologies include pebble to granule conglomerates, sandstones and siltstones, together with subordinate sandy diamictites. Some of the scours are mud-filled and re-incised by an overlying channel (**Fig. 6** C). The base of most beds is irregular (**Fig. 6**

D). Normally-graded bedding is typical, with transitions from granule conglomerate through planar-bedded sandstone well expressed in Tillite Gorge as R1 through S3 turbidite divisions of Lowe (1982) (e.g. **Fig. 4** B, 99-103 m; **Fig. 7**A). Soft-sediment deformation structures in sandstone include recumbent folds (**Fig. 7** B), curvilinear grooves on the upper surfaces of sandstone beds (**Fig. 7** C) and flame structures. This suite of deformation structures is concentrated at a discrete stratigraphic interval ("shear zone" at 25 m, log B, Fig. 4). Sandy diamictites form sheet-like beds of 0.3-1 m, and contain sub-rounded to rounded clasts with striated faces (**Fig. 7** D). Siltstones occur both within channel structures, and as sheet-like lithosomes traceable for several tens of metres. In both cases, siltstones are poorly stratified, yet bear rare clasts of pebble to boulder size; these pierce and downwarp underlying laminations, with overlying laminations unaffected (**Fig. 7** E, F).

Interpretation

The scour and fill structures are interpreted as channels cut by turbidity currents and filled with turbidites. The coarse calibre of some of the channel fills, and the characteristic R1 through S3 turbidite motif (Lowe, 1982), implies a relatively proximal location on the fan (Reading and Richards, 1994). The particularly coarse-calibre (gravelly) material at the base of some channels is suggestive of a lag deposit (Alpak et al., 2013). By comparison, the finer-grained channel fills are interpreted to record lower energy deposition in either a slightly more distal location on the fan or alternatively a finer-grained sediment source. Specifically, silt-plugged channels may suggest that the channels are filled by low density turbidites (Talling et al., 2012). These deposits represent off-axis / channel margin facies (Camacho *et al.*, 2002) or coarse-grained sediment bypass (Talling et al., 2012), and probably record deposition of these turbidites more distal to the sediment source than their coarser-grained counterparts.

The suite of soft-sediment deformation structures is compatible with rapid subaqueous deposition: recumbent folds can be indicative of gravitational instability and downslope slumping (Maltman, 1994), whereas flame structures are probably examples of Rayleigh-Taylor instabilities generated at a grain-size / bed interface (Allen, 1984; Collinson and Thompson, 1987). Numerical modelling of flame structures indicates that their genesis is promoted when relatively low viscosity, Newtonian fluids (the sand layer) rest on underlying clays (Harrison and Maltman, 2003). These conditions may be satisfied by rapid sedimentation or liquefaction. The curvilinear grooves on the upper surface of beds are interpreted as intra-bed slip planes, akin to hydroplastic slickensides (Petit and Laville, 1987) produced by the shearing of soft sediment in response to downslope movement. Shanmugam *et al.* (1995) described similar features from the Cretaceous and Palaeogene of the North Sea. A later tectonic origin can be dismissed on account of their local occurrence, curvilinear geometry, absence of asperities, and lack of mineralisation (c.f. Petit and Laville, 1987).

The presence of “impact structures” (curvature, deflection and puncturing of underlying laminations: Bennett *et al*., 1996) beneath lonestones clearly points to ice-rafted debris (IRD) (e.g. Eyles et al., 2007). Moreover, the presence of polished and striated clast surfaces also indicates a clear glacial derivation. Despite the absence of impact structures in the sheet-like siltstones, the presence of lonestones may likewise indicate rafting from icebergs, or alternatively sub-ice shelf deposition (Benn and

Evans, 2010). By analogy to comparable facies in the diamictite facies association, the diamictites in the channel belt facies association are also interpreted as the product of glaciogenic debris flows.

Sheet heterolithics facies association

Description

These deposits include a heterogeneous collection of lithologies ranging from granule conglomerates and diamictites, sandstones, siltstones, shales and dolostones. At outcrop, these lithologies are well differentiated, forming tabular beds that can be traced for tens to hundreds of metres along strike. Decimetre to metre-scale fining upward cycles is typical, with well-expressed examples in Weetootla Gorge (**Fig. 4** C, 23-75 m; **Fig. 8** A). Fining upward cycles commence with sharp-based and locally scoured surfaces, overlain by granule-lags or massive sandstones (**Fig. 8** B), becoming parallel laminated upsection. Supercritical climbing ripple cross-laminated sandstones and siltstones (**Fig. 8** C) are typical in the upper part of many fining upward cycles (e.g. 56 m, 68 m, 85 m, 100 m at Weetootla Gorge: **Fig. 4** C). The crests of the ripple-cross laminae show an aggradational to weakly progradational character (**Fig**. 8 **C**). Rarely, the fining upward intervals are interrupted by clast-poor, sandy diamictites which do not exceed 1 m in thickness (**Fig**. 8 D). Siltstone and shale occur at the top of the fining upward cycles (**Fig. 8** E). Lonestones with impact structures occur in most facies, including the cross-laminated sandstone (e.g. 102 m, Tillite Gorge: **Fig. 4** B; **Fig. 8** B, arrowed clast) and in shale beds (**Fig. 8** E). The metre-scale fining upward cycles are themselves organised into multi-metre thick coarsening and fining upward motifs. At three intervals (25 m, 37 m, 66.5 m at

Weetootla Gorge: **Fig. 4** C) we observed buff coloured, delicately parallel laminated, mud-grade dolostones (**Fig. 8** F).

Interpretation

This facies association is interpreted to represent deposition in an inter-channel part of a subaqueous fan system, where the well-expressed, metre-scale fining upward cycles are interpreted to record repeated emplacement of turbidity flows. A basal scour and lag, succeeded by a massive then parallel laminated sandstone interval, succeeded by climbing ripple cross-lamination, is a motif common to all models of turbidite genesis (c.f. Bouma, 1962; Lowe, 1982; Mutti, 1996; Talling *et al*., 2012). Whilst the tabular geometry of the cycles is compatible with deposition as high-density turbidites (i.e. divisions T_A, T_{B-2} and T_{B-3} in the modified Bouma nomenclature: Talling *et al*., 2012) The occurrence of lonestones with impact structures, interpreted as dropstones, in ripple cross-laminated siltstones is strong evidence for glacial influence. The supercritical styles of ripple cross-lamination testify to high rates of sediment delivery, and tractive velocities of <0.6 m s^{-1} m (e.g. Bridge and Demicco, 2008). The occurrence of large clasts within these facies is at odds with the low velocities required for the formation of ripple cross-lamination, which are thus interpreted as ice-rafted debris. Furthermore, turbidity flows typically demonstrate low yield strength and cannot support clasts through buoyancy within the flow (Shanmugam, 2002). Although Lowe (1982) suggested that sand-dominated traction carpets in dense sandy turbidites were capable of periodically bouncing clasts as suspension load, these inferred processes have not been observed in turbidity currents (Talling *et al*., 2012). The co-occurrence of thin sandy diamictites, interpreted as the dilute distal fronts of glaciogenic debris flows, strengthens the interpretation of a glacial influence on sedimentation.

The organisation of the Bouma cycles into both coarsening and fining upward motifs at the multi-metre scale is respectively suggested to record the buildout and abandonment of subaqueous fan lobes, in a similar manner to other glacially sourced subaqueous fan systems (Le Heron et al., 2008). The delicately laminated dolostones at the top of some fining-upward cycles remains cryptic. They do not occur in finer-grained, turbidite-dominated systems of the central Flinders Ranges (e.g. Busfield and Le Heron, in review; Le Heron et al., 2011), which likely indicates that the dolostones are of local significance. They are presently suggested to record chemical or biological precipitation during or following lobe abandonment, although the precise mechanisms of precipitation requires further study. Their lonestone-free textures merit one further consideration, however. If subaqueous sedimentation rates of IRD were similar everywhere on the fan system at a given time, comparable deposits should form simulatenously. Given the absence of lonestones in the dolostones, intervals of IRD-free conditions might be proposed, thus suggesting that these might be associated with lower rates of deposition and therefore no floating ice.

STACKING PATTERNS

The vertical stacking motif of facies associations is an important consideration in a glacially-sourced sedimentary system and may allow the dynamics of former ice sheets to be elucidated. At Stubb’s Waterhole, the diamictite facies association predominates but those strata are intercalated with ~5 m thick developments of the sheet heterolithics facies association. A considerably thicker example of that facies association is found interbedded with the diamictite facies association at Weetootla Gorge (23- 75 m: **Fig. 4** C). Given the differences in thickness at both localities, it is proposed that the Stubb's Waterhole occurrence may represent the margins of a turbidite lobe system (e.g. Prélat et al., 2010), whereas the Weetootla Gorge examples are more compatible with the core of a turbidite lobe system. Note, however, that our data do not represent a complete traverse through the formation in either case. Interstratification of the diamictite facies association and the channel belt facies association, at the tens of metres scale at Tillite Gorge testifies to the likely synchronous co-development of turbidite channel belts and GDF deposits. This implies that each sub-environment, recognised in the form of the three facies associations, co-existed during deposition of the Bolla Bollana Formation.

In the Arkaroola area, the Bolla Bollana Formation maps as a continuous stratigraphic unit around the north-eastern extremity of the Gammon Ranges. Preiss *et al.* (1993, 1998, 2000, 2011), interpret the North Flinders Basin as a region that experienced extension synchronous with glaciation by Sturtian ice sheets. Progressive thickness increases to the north are explained by the development of en echelon half graben (Preiss et al., 2011). Crustal extension, during the fragmentation of Rodinia, which accounted for the generation of substantive accommodation space, was also considered to be important by Young and Gostin (1988, 1989, 1990, 1991). However, the location of many of these faults remains unclear: the 1:250,000 sheet (Copley: Coats, 1973) reveals no faults specifically causing abrupt thickness changes in the Bolla Bollana Formation.

We argue that the substantial thickness and sedimentary architecture of the Bolla Bollana Formation can be explained by ice sheet dynamics alone. The diamictite facies association records glaciogenic debris flows (GDFs) with secondary ice-rafting in the proximal part of a subaqueous basin (**Fig. 9**). The presence of facetted, polished and striated clasts in the Bolla Bollana Formation strongly implies direct glacial derivation. This is because cannibalised or reworked (second generation) debris flows tend to erode and smooth clast surfaces (Le Heron *et al*., 2013). The glaciogenic debris flows likely became diluted basinward, developing into turbulent underflows, which built up a series of lobes and channel belts (i.e. channel belt facies association) on a large subaqueous fan (**Fig. 9**). The sheet heterolithics facies association represents lobe deposits (e.g. Prélat *et al*., 2010) in the inter-channel part of a subaqueous fan system. These lobes were influenced by local ice rafting as a secondary sediment source (**Fig. 9**). Abandonment of the lobes locally resulted in some highly unusual laminated dolostone deposits. These superficially resemble "cap dolostone" deposits (e.g. Rose and Maloof, 2010). As noted earlier, given their probable stratigraphic context as lobe abandonment facies it is unlikely that they have any wider significance. The lack of evidence for IRD in these specific facies- a texture which might be expected to appear more prominently once sediment supply is arrested- is also puzzling.

A NEOPROTEROZOIC TROUGH-MOUTH FAN?

It is suggested that the Bolla Bollana Formation is a trough mouth fan (TMF) (**Fig. 9**) deposited seaward of a comparatively small palaeo-ice stream. This interpretation is fully consistent with 1) clear evidence for glacial processes in every facies association of the Bolla Bollana Formation, 2) the substantial thickness of the succession which compares closely to stacked mass flow deposits of the Bear Island Fan (Taylor *et al*., 2002; Ó Cofaigh *et al*., 2003), and 3) the stratigraphic motif and nature of the facies associations preserved.

Evidence for glaciation throughout the Bolla Bollana Formation is pervasive and includes dropstone textures (in turbidites, as well as hemipelagic muds), together with facetted, polished and striated clasts throughout the succession. Boreholes sunk in the Uummannaq Fan (western Greenland) illustrate 300 m thick successions of diamicton that are sharply overlain by mud (Ó Cofaigh *et al*., 2012). These are closely comparable to stacked examples of the diamictite facies association in Tillite Gorge. Intercalated debrites, turbidites, and ice-rafted debris commonly occur together in depositional models of Pleistocene TMFs (Ó Cofaigh *et al*., 2012).

In both the northern and southern hemispheres, trough mouth fans (TMFs) were deposited during Pleistocene glaciations and consist of thick accumulations of glaciogenic detritus (Escutia *et al*., 2000; Taylor *et al*., 2002). In this process, fast-flowing ice streams excavate the subglacial substrate and deposit diamictite at the ice front, perched landward of the slope break. In Pleistocene examples, rapid sedimentation of water saturated tills led to unstable slope angles and hence intermittent failure (Dowdeswell *et al.*, 2002). This in turn led to the generation of GDFs derived from collapsing tills (Taylor *et al.*, 2002). In the southern hemisphere, the Wilkes Land continental margin was fed by stacked GDFs, which evolved downslope into turbidites, building up a multi-kilometre thick pile of channelized proglacial detritus (Escutia *et al.*, 2000).

Regional mapping (Coats, 1973) shows that the Bolla Bollana Formation crops out over at least 1800 km^2. Assuming a conservative thickness of 1 km in the Arkaroola district, the Bolla Bollana Formation represents approximately 1800 km^3 of glaciogenic sediment: impressive, yet substantially less volumetric than the modern Bear Island Fan (ca. 340,000 km^3) (Dowdeswell *et al.*, 2002 and refs therein). Part of the reason for this comparatively small volume may lie in the partitioning of the basin by syn-depositional faults (Preiss *et al.*, 2011). From both stratigraphic and facies perspectives, there is good reason to view the North Flinders Basin as a sub-basin disconnected from the central Flinders Ranges further to the south (Preiss *et al.*, 2011). Differences between Pleistocene TMF models and our interpretation (**Fig. 9**) include the absence of bioturbation and a lower volume of mud in the Bolla Bollana TMF deposit (c.f. Ó Cofaigh et al., 2002; 2003; 2012). In subaqueous fans, increase in mud content improves the run-out efficiency of turbidites and increases fan size (Reading and Richards, 1994). Another obvious difference is the presence of dolostones in the Bolla Bolla Formation: such dolostones are absent in Pleistocene TMFs. They are, however, almost ubiquitous in the Cryogenian record, typically occurring immediately above the diamictite successions as cap carbonates (e.g. Shields, 2005)..

The gentle regional dip of the Bolla Bollana Formation (**Fig. 5** A) precludes mapping of individual debrite megabeds, yet Quaternary analogues may allow some insight into possible maximum lateral dimensions. Debrites on the Bear Island Fan are elongate lobes with individual run-out distances of > 40 km (Laberg and Vorren, 2000; Ó Cofaigh *et al.*, 2003). They commence at ~1 km below sea level, extending to approximately 2.5 km depth. The up-dip termination of the debrite lobes approximates the palaeo-ice margin (**Fig. 9**). In addition to the generation of GDFs, the accumulation of thick piles of detritus on trough-mouth fans lends them prone to gravitational collapse (Dowdeswell *et al*., 2002). Thus, many of the extensional faults and graben structures in the NFB may represent seaward partial collapse of the fan.

Young and Gostin (1989) provided detailed descriptions and interpretations of comparable successions further north, in the Yudnamutana homestead and surrounds. There, a subaqueous fan system, dominated by boulder-bearing debrites with subordinate turbidites, was envisaged (Young and Gostin, 1989). This interpretation is fully compatible with our own and underscores that an identical range of sub-environments are recognised around the Bolla Bollana outcrop belt (**Fig. 9**). It is clear that the Bolla Bollana Formation contains excellent evidence for glacial sedimentary processes, reinforcing the original work of Mawson (1941, 1949), and making it difficult to argue for a rift-source alone as has been suggested for similar Neoproterozoic diamictite successions (e.g. Eyles and Januszczak, 2004).

The connection between the Bolla Bollana depocentre and other sub-basins in the central Flinders Ranges is obscure. Rifting is an attractive mechanism to account for the different stratigraphic units preserved in the North Flinders Basin and depocentres further south such as Baratta and Holowilena (Preiss, 2000). It should be stressed, however, that not all sub-basins in the Flinders Ranges preserve clear evidence for rifting. The Holowilena succession, for example, contains delicately interbedded siltstones, diamictites, sandstones, and IRD-bearing shale (Busfield and Le Heron, in review; Le Heron, 2012). Internally, that succession contains disconformities and not angular relationships between bedsets (Le Heron, 2012) which might be expected where undeformed sediments onlap rotated hangingwall strata. Nonetheless, correlative successions at Oladdie Creek and Hillpara Creek, in the central Flinders Ranges, reveal dramatic thickness changes along strike. These testify to an irregular underlying palaeotopography, which is likely attributed to the combined influence of pre- and early syn-depositional rift activity and subglacial downcutting (Busfield and Le Heron, in review).

The Bolla Bollana Formation provides a unique window into the sedimentary architecture of a trough-mouth fan (TMF). The interpretation of a TMF is doubly significant. Firstly, the authors are not aware of any previously described TMFs of pre-Pleistocene age, and thus the first documentation is provided herein. Secondly, the Bolla Bollana is the only known outcrop example thus far described of such a fan. It is probably the case that the generally large scale of these fans (O'Cofaigh, 2012) has precluded their outcrop-scale interpretation in ancient strata. Whilst volumetrically less significant in the fan systems than GDFs, the Bolla Bollana succession also reveals the common occurrence of turbidite intervals, amplifying the importance of turbidity currents in TMF models (Escutia *et al*., 2000).The occurrence of correlative turbidite and debrite-dominated successions is also well reported from subsurface boreholes elsewhere in southern and central Australia (e.g. Blinman 2 borehole, central Flinders Ranges; Nicholson 2 borehole, ca. 500 km NW of Arkaroola; Vines 1 borehole, Officer Basin) (Eyles *et al*., 2007). A clear, glacial influence is reported from those sections on account of striated and outsized clasts in laminated facies (Eyles et al., 2007), although it remains unclear how these underflow-dominated successions relate laterally to one another. In light of our interpretations, it is possible that these deposits represent an amalgam of overlapping TMFs, line-sourced detritus, or somewhat more disconnected fan systems.

In the context of a Neoproterozoic snowball Earth model, Hoffman (2005) argued that palaeo-ice streaming- which he inferred on the basis of irregular topography within the Ghaub glacial succession of Namibia, and the occurrence of a large wedge of grainstone sediment- was “not incompatible with a frozen ocean”. Etienne *et al*. (2007) and Allen and Etienne (2008), meanwhile, pointed out that the highly dynamic nature of tidewater ice sheets directly challenged this view. In particular, the issue of resupply of snow in the accumulation zone of ablating ice sheets- given the presumed arrested hydrological cycle- remains problematic.

Some 120 km to the south of Arkaroola, exceptionally exposed, age equivalent successions at Holowilena, Oladdie and Hillpara Creeks, in the central Flinders Ranges (Busfield and Le Heron, in review; Le Heron et al. 2011) reveal a highly comparable stratigraphic subdivision in a series of tectonically partitioned basins. These sections identify a clear non-glacial interval within the Wilyerpa Formation, which yields spectacularly preserved hummocky cross strata (HCS), indicative of sea-ice free conditions (Le Heron *et al*., 2011), followed by a glacial re-advance. Young and Gostin (1991) likewise identified a second major re-advance in the Sturtian, represented by accumulation of the Bolla Bollana Formation. These considerations suggest the Bolla Bollana Formation may correlate with the re-advance succession in the central and southern Flinders Ranges and, if so, suggests deposition of the TMF at Arkaroola in seas which were at least periodically unfrozen.

CONCLUSIONS

The Bolla Bollana Formation is a spectacularly exposed glaciogenic succession of Sturtian age in the Arkaroola district. This formation was first investigated by Mawson (1941, 1949) but subsequently little work has been undertaken at the Tillite Gorge, Stubb's Waterhole or Weetootla Gorge locations. Detailed sedimentary logging at these locations, therefore, allows a detailed sedimentary model to be developed as follows:

- Three facies associations are recognised in the Bolla Bollana Formation. These are a diamictite facies association (glaciogenic debris flows with subordinate ice-rafted debris), a channel belt facies association (channelized turbidites with subordinate IRD) and a sheet heterolithics facies association (non-channelised turbidites and subordinate IRD). A strong glacial influence on sedimentation is inferred, reinforcing previous interpretations of Young and Gostin (1991). A rift-related source for the diamictites is rejected.
- A depositional model based on detailed observations and interpretations from all three facies associations proposes that the Bolla Bollana Formation was deposited as a trough-mouth fan, seaward of the terminus of a small ice stream. Rapid ice flux promoted high erosion rates and sediment delivery. At the ice margin, GDF deposited multi-storey stacks of diamictite, many deposited as megabeds. Slope failure and / or dilution of these flows basinward ignited turbidites, which cut channel geometries onto the proximal and medial parts of the fan. Non-channelised turbidites demonstrate well organised multi-metre coarsening and fining upward motifs, interpreted to record build out and abandonment of fan lobes. Laminated dolostones are an

unusual fan-lobe abandonment facies and bear superficial resemblance to post-glacial “cap dolostones” elsewhere.

- Previous models of tectonic compartmentalisation a result of rifting post- 750 Ma (e.g. Preiss, 2000; Young and Gostin, 1991; Eyles and Januzczak, 2004) may help in explaining dramatic regional differences in facies and internal Sturtian stratigraphy. In the Bolla Bollana Formation, however, it is suggested that a tectonic mechanism is not required by reference to Cenozoic trough-mouth fan systems where substantive diamictite accumulations occur.

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Figure captions

Figure 1: Geological sketch map of the Arkaroola region (modified and simplified after Coats, 1973). Note the location of the Tillite Gorge, Stubb’s Waterhole and Weetootla Gorge sections which are shown on figure 4.

Figure 2: Northern Flinders Basin map, reproduced from Young and Gostin (1991). The palaeocurrent data, shown here schematically, derive from a variety of sources (flute casts, ripple cross laminae) and have been used to infer the development of syn-glacial horst and graben topography (Young and Gostin, 1991). The outline of various sub-basins are shown with a solid line, with stippling marking the internal margins of these sub-basins.

Figure 3: Stratigraphy of the Neoproterozoic of the Arkaroola area, with subdivisions of the Sturt glacial succession based on Young and Gostin (1989). The internal lithostratigraphy of the Sturt glacial succession varies dramatically even over the comparatively small region of the northern Flinders Ranges (c.f. Young and Gostin, 1988, 1989, 1990, 1991). In the Arkaroola district, a threefold division is recognised with the Fitton Formation at the base, the Bolla Bollana Formation in the middle, and the Lyndhurst Formation as the uppermost unit within the Yudnamutana Subgroup. This paper specifically examines the Bolla Bollana Formation.

Figure 4: Detailed sedimentary logs through the Bolla Bollana Formation in the Arkaroola district (see Fig. 1 for location of sections). Each is a partial section through the exposure at each locality rather than a complete section. A: Stubb's Waterhole. B: Tillite Gorge. C: Weetootla Gorge. Note that in the case of the diamictites, the grain size in each of the logs refers to grain size of the matrix: maximum clast size, where possible was also measured. These latter data are shown to the right of the logs.

Figure 5: Representative photographs of facies within the diamictite facies association. A: Outcrop perspective of the Tillite Gorge locality, showing thickly bedded diamictites dipping toward the right of the photograph. B: Base of a diamictite megabed (42-67 m, Fig. 4 B) with geologist for scale. C: Clast-poor diamictite overlain by clast-rich diamictite, with geological hammer for scale placed at the boundary. D: Impact structure beneath gneiss pebble in well-stratified diamictite. Rounded clasts are quite typical. E: Undulose contact at the base of a diamictite megabed. Note that this undulose character probably records differential compaction. Scale bar: 1 m. F: Face of a polished and striated sandstone boulder, showing crosscutting striation orientations.

Figure 6: A and B: Panoramic photo and corresponding sketch of stacked channel geometries in the channel belt facies association. Note also the downlapping strata of the diamictite facies association directly above. C: Low angle channel incision cutting down towards the left of the photograph (marked by solid white line), clearly truncating recessive siltstones, themselves infilling a channel scour. D: Low amplitude scour at the base of a sandstone bed: evidence for erosionally-based beds even where clear channel geometries are not observed.

Figure 7: A: Typical fining upward sequence, interpreted as a turbidite bed. In this example, pebble to cobble-grade clasts beneath the hammer pass upward over 10 cm into granular conglomerates, and finally well differentiated, moderately to well-sorted sandstone above the hammer handle. B: Recumbent fold in a turbidite. C: Curvilinear grooves on a sandstone surface, interpreted to record intrastratal shear in sandstones. The absence of asperities or quartz/ calcite mineralisation discounts a tectonic origin. D: Striated lonestone within siltstone: a putative dropstone emplaced toward the top of a Bouma sequence. E and F: Two examples of dropstones with clear impact structures in laminated siltstone intervals.

Figure 8: Representative photographs of facies within the sheet heterolithics facies association. A: Repetitively stacked, decimetric Bouma cycles. Note coin for scale. B: Lonestones to the left of the coin within fine-grained, climbing ripple cross-laminated sandstone. C: Detail of photo B showing prograding crest (from right to left) of a

climbing ripple. Note that tractive velocities predicted within the field of ripple formation (e.g. Bridge and Demicco, 2008) are insufficient to transport pebble-sized clasts. Thus, a dropstone origin is deduced. D: Lonestone with deflected laminations above the clast: possibly as a result of compaction. Field of view 7 cm. E: Quartzite dropstone, with impact structure (truncation and piercing of shale laminae) beneath the coin. Laminated dolostone (25 m, Fig. 4 C).

Figure 9: Simple depositional model for the Bolla Bollana Formation. We interpret a glaciomarine basin, a general setting consistent with previous work (e.g. Coats, 1981; Young and Gostin, 1989, 1991). Glaciogenic debris flows fed the basin, evolving into turbidites down depositional dip. Channel belts and inter-channel areas recording slightly finer grained turbidites are recognised. Phases of fan-lobe buildout and abandonment are recognised, with these processes likely a result of autocyclic switching of channel belts and sediment supply rather than basin-scale ice dynamics. The scale of the sedimentary system, and clear evidence for a strong glacial influence on sedimentation in all facies associations, suggests that the Bolla Bollana deposit is a trough-mouth fan deposit, with huge volumes of glaciogenic debris supplied to a subaqueous setting. This is the first such interpretation from the Neoproterozoic record.

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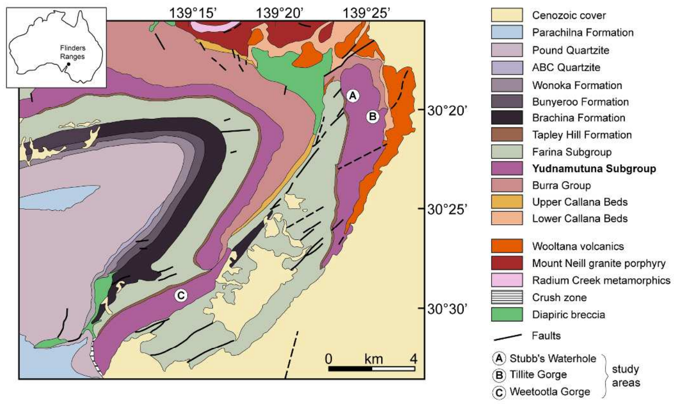

Figure 1: Geological sketch map of the Arkaroola region (modified and simplified after Coats, 1973). Note the location of the Tillite Gorge, Stubb's Waterhole and Weetootla Gorge sections which are shown on figure 4.

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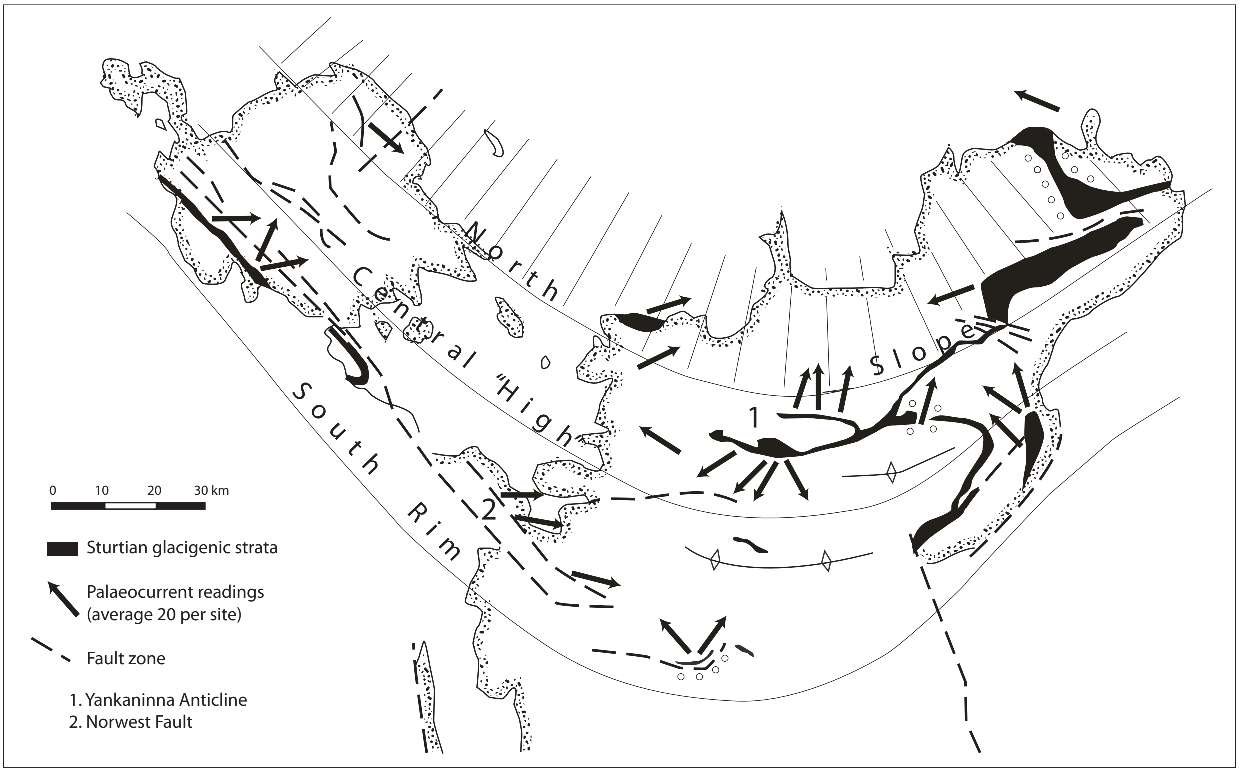
North
Central "High"
Slope
South Rim
1
2
0 10 20 30 km
Sturtian glacigenic strata
Palaeocurrent readings
(average 20 per site)
Fault zone
1. Yankaninna Anticline
2. Norwest Fault

Figure 2

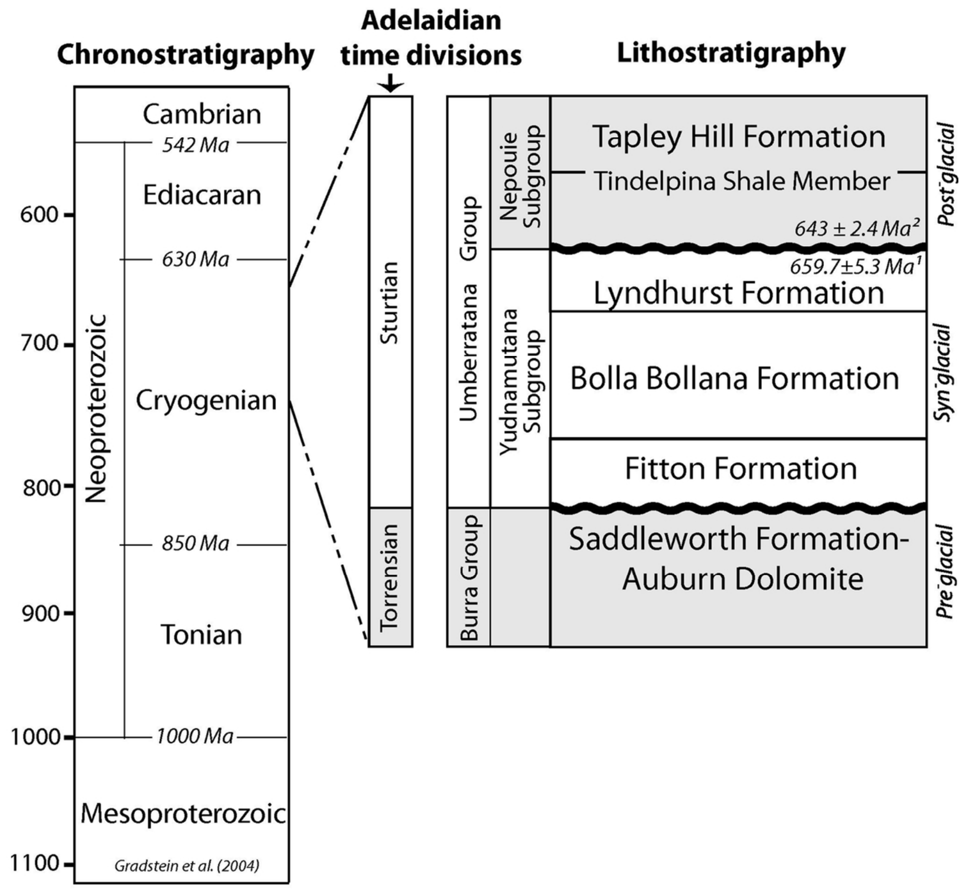

Figure 3: Stratigraphy of the Neoproterozoic of the Arkaroola area, with subdivisions of the Sturt glacial succession based on Young and Gostin (1989). The internal lithostratigraphy of the Sturt glacial succession varies dramatically even over the comparatively small region of the northern Flinders Ranges (c.f. Young and Gostin, 1988, 1989, 1990, 1991). In the Arkaroola district, a threefold division is recognised with the Fitton Formation at the base, the Bolla Bollana Formation in the middle, and the Lyndhurst Formation as the uppermost unit within the Yudnamutana Subgroup. This paper specifically examines the Bolla Bollana Formation.
108x135mm (300 x 300 DPI)

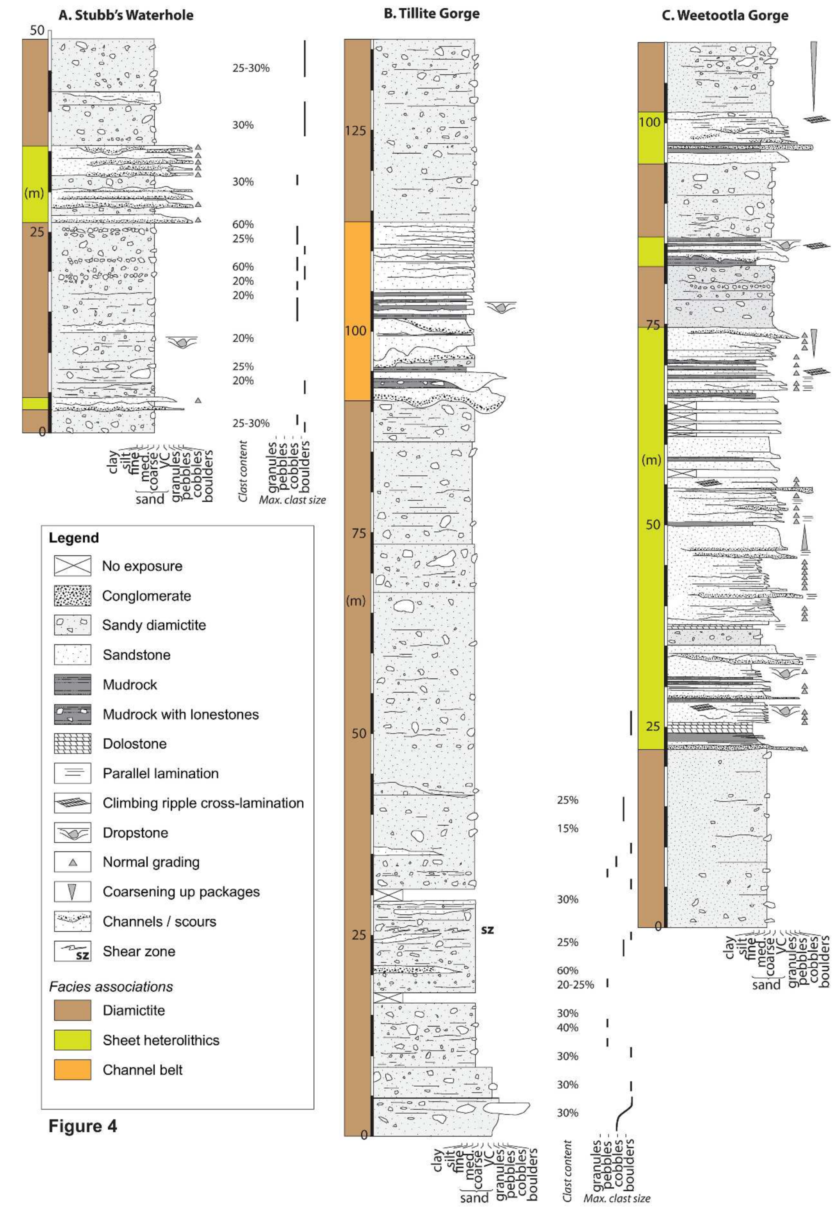

Figure 4: Detailed sedimentary logs through the Bolla Bollana Formation in the Arkaroola district (see Fig. 1 for location of sections). A: Stubb's Waterhole. B: Tillite Gorge. C: Weetootla Gorge. Note that in the case of the diamictites, the grain size in each of the logs refers to grain size of the matrix: maximum clast size, where possible was also measured. These latter data are shown to the right of the logs.
285x422mm (300 x 300 DPI)

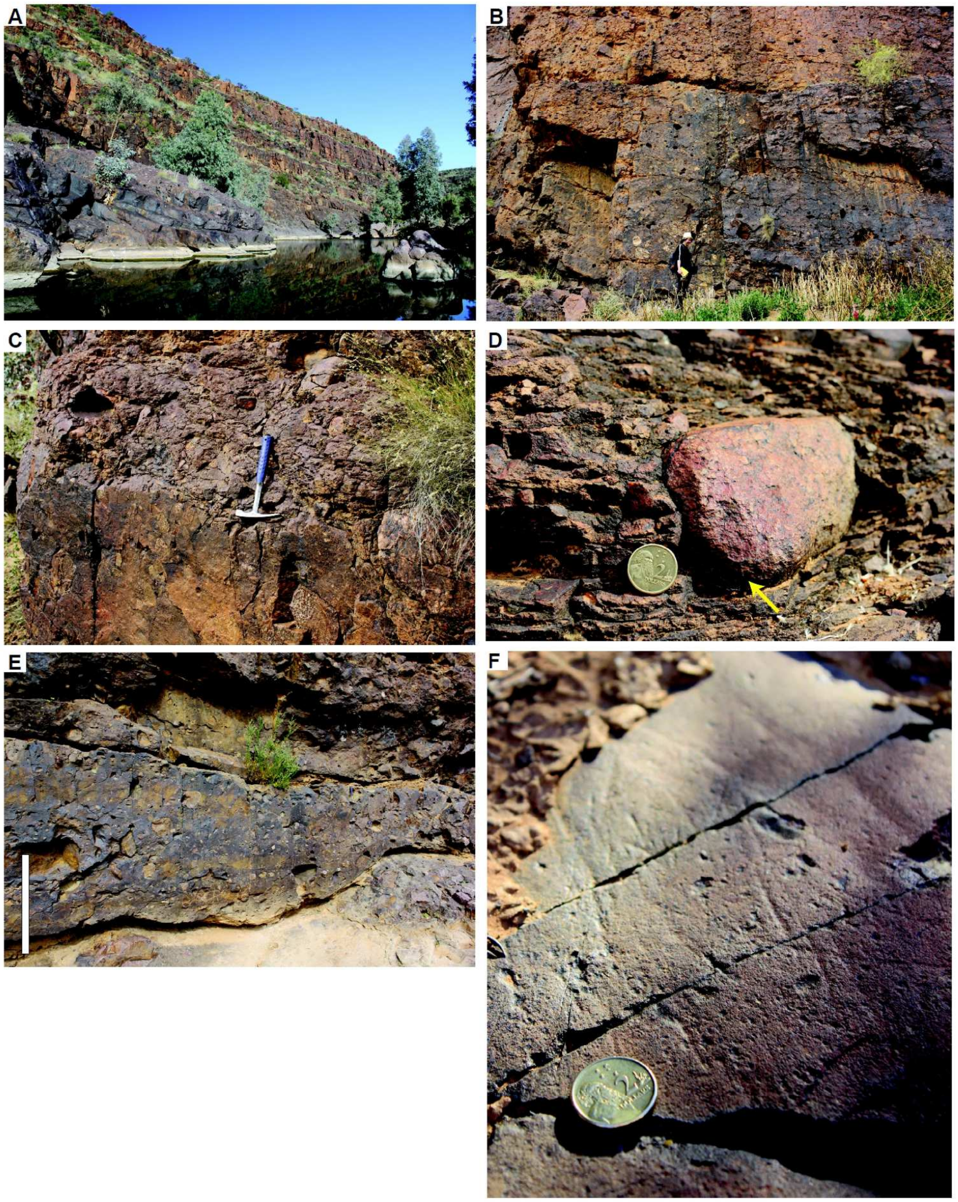

Figure 5: Representative photographs of facies within the diamictite facies association. A: Outcrop perspective of the Tillite Gorge locality, showing thickly bedded diamictites dipping toward the right of the photograph. B: Base of a diamictite megabed (42-67 m, Fig. 4 B) with geologist for scale. C: Clast-poor diamictite overlain by clast-rich diamictite, with geological hammer for scale placed at the boundary. D: Impact structure beneath gneiss pebble in well-stratified diamictite. Rounded clasts are quite typical. E: Undulose contact at the base of a diamictite megabed. Note that this undulose character likely records erosion or differential compaction. Scale bar: 1 m. F: Face of a polished and striated sandstone boulder, showing crosscutting striation orientations.
228x286mm (300 x 300 DPI)

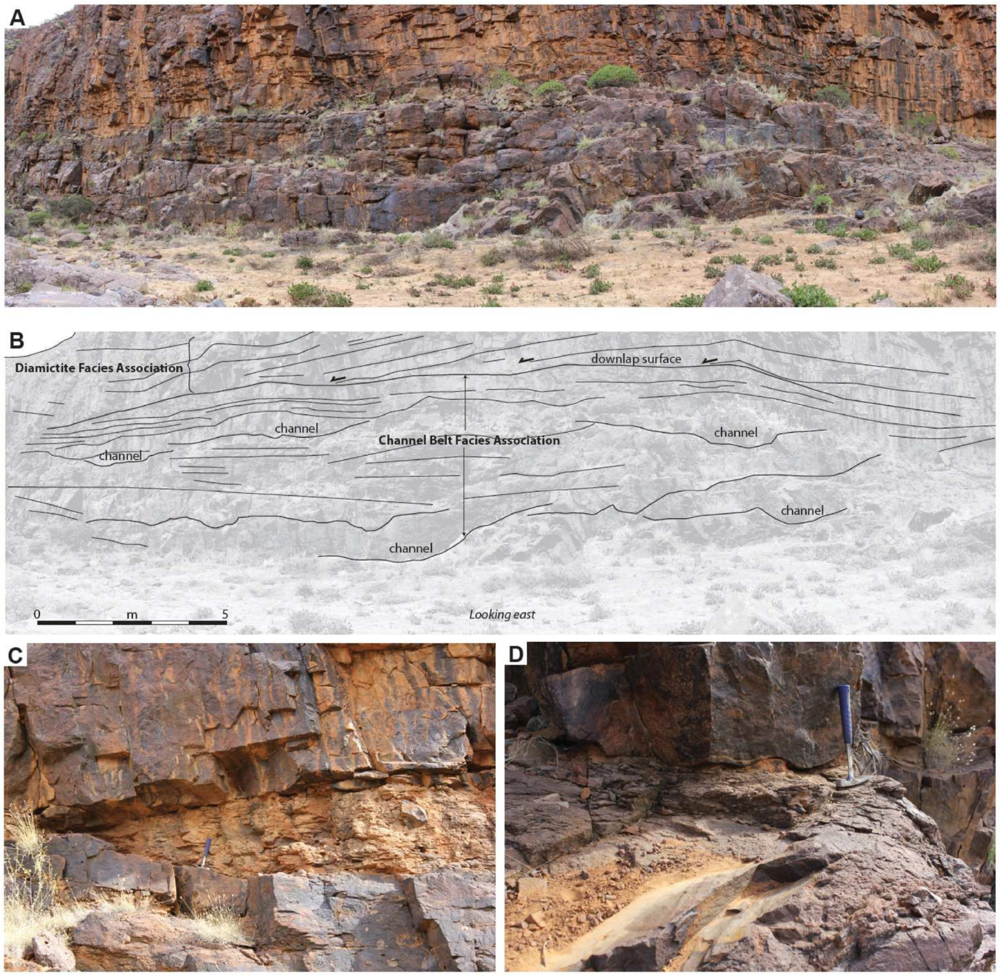

Figure 6: A and B: Panoramic photo and corresponding sketch of stacked channel geometries in the channel belt facies association. Note also the downlapping strata of the diamictite facies association directly above. C: Low angle channel incision cutting down towards the left of the photograph (marked by solid white line), clearly truncating recessive siltstones, themselves infilling a channel scour. D: Low amplitude scour at the base of a sandstone bed: evidence for erosionally-based beds even where clear channel geometries are not observed.

187x182mm (300 x 300 DPI)

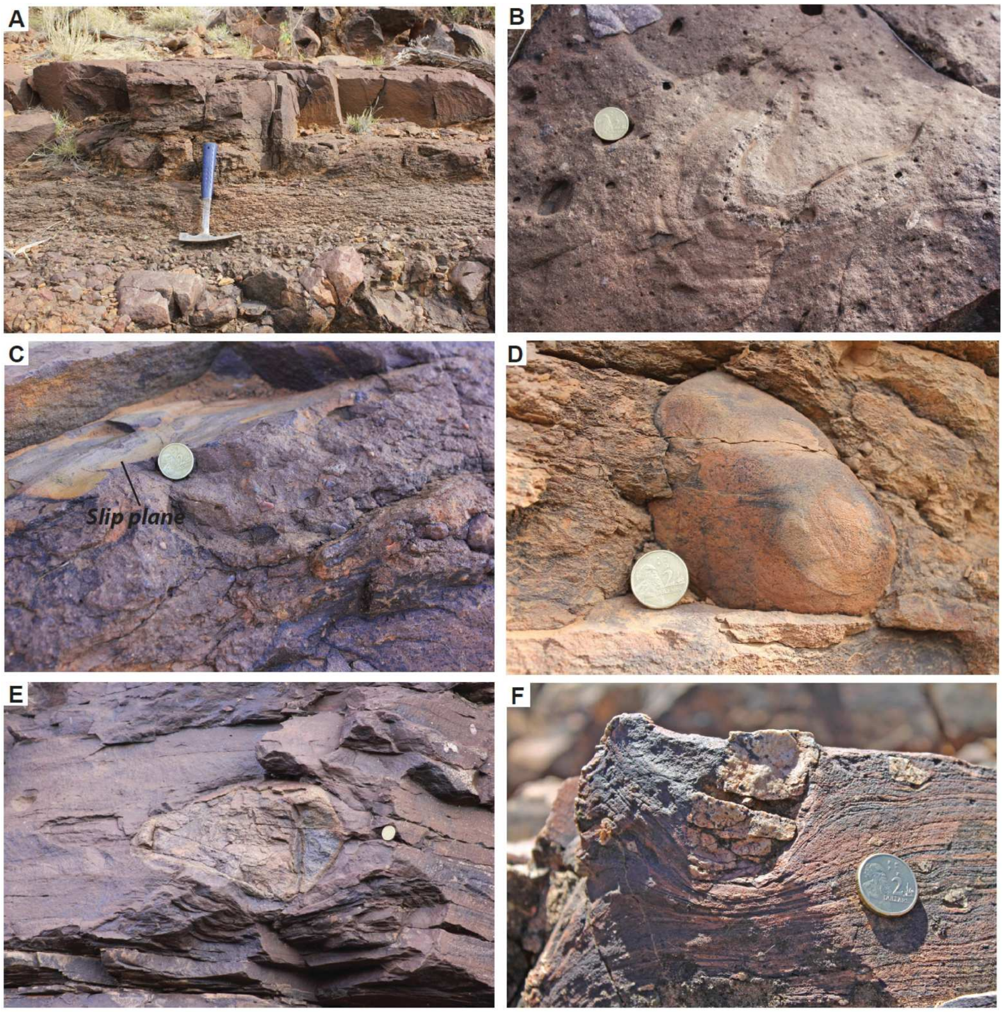

Figure 7: A: Typical fining upward sequence, interpreted as a turbidite bed. In this example, pebble to cobble-grade clasts beneath the hammer pass upward over 10 cm into granular conglomerates, and finally well differentiated, moderately to well-sorted sandstone above the hammer handle. B: Recumbent fold in a turbidite. C: Curvilinear grooves on a sandstone surface, interpreted to record intrastratal shear possibly as a result of compaction, in sandstones. The absence of asperities or quartz/ calcite mineralisation discounts a tectonic origin. D: Striated lonestone within siltstone: a putative dropstone emplaced toward the top of a Bouma sequence. E and F: Two examples of dropstones with clear impact structures in laminated siltstone intervals.
183x185mm (300 x 300 DPI)

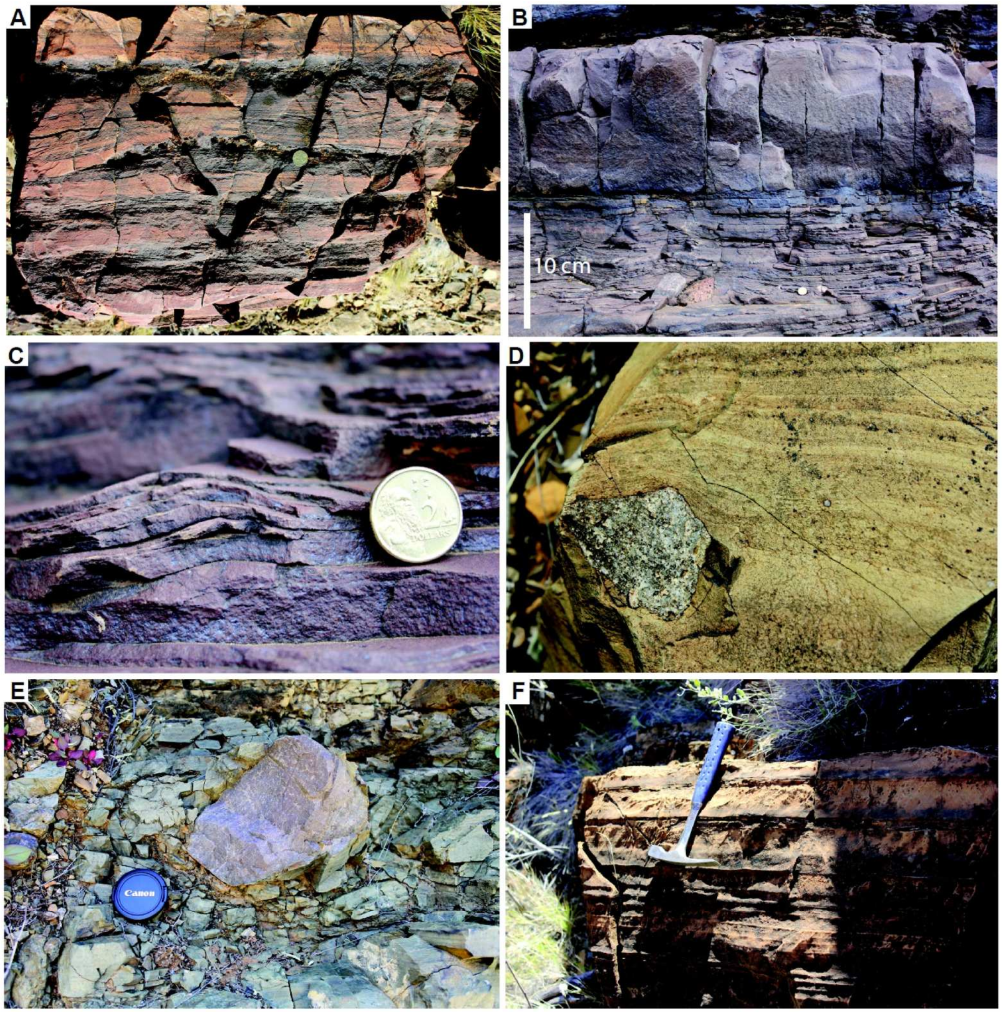

Figure 8: Representative photographs of facies within the sheet heterolithics facies association. A: Repetitively stacked, decimetric Bouma cycles. Note coin for scale. B: Lonestones to the left of the coin within fine-grained, climbing ripple cross-laminated sandstone. C: Detail of photo B showing prograding crest (from right to left) of a climbing ripple. Note that tractive velocities predicted within the field of ripple formation (e.g. Bridge and Demicco, 2008) are insufficient to transport pebble-sized clasts. Thus, a dropstone origin is deduced. D: Lonestone with deflected laminations above the clast: possibly as a result of compaction. Field of view 7 cm. E: Quartzite dropstone, with impact structure (truncation and piercing of shale laminae) beneath the coin. Laminated dolostone (25 m, Fig. 4 C).
197x198mm (300 x 300 DPI)

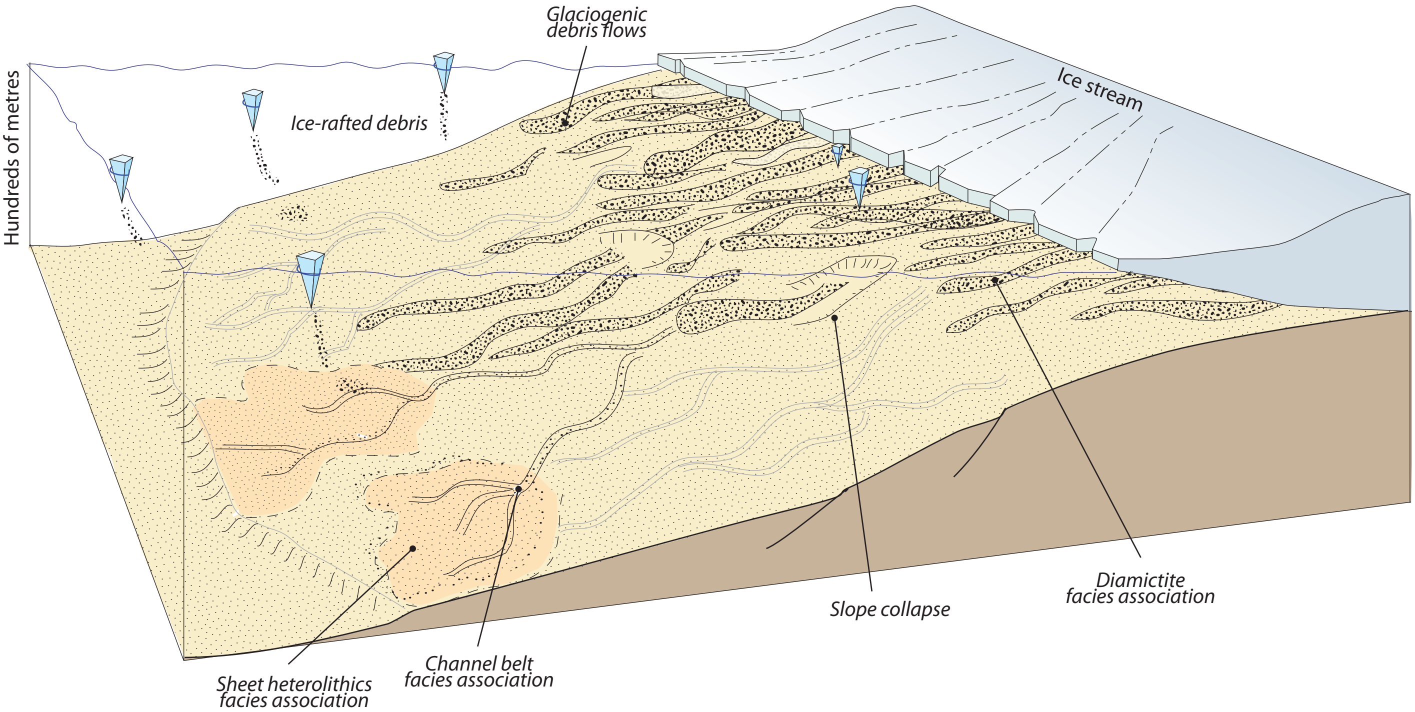
Glaciogenic
debris flows
Ice stream
Ice-rafted debris
Hundreds of metres
Diamictite
facies association
Slope collapse
Channel belt
facies association
Sheet heterolithics
facies association

Figure 9