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An interglacial on snowball Earth? Dynamic ice behaviour revealed in the Chuos Formation, Namibia

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ABSTRACT

The Sturtian is the oldest (ca 716 Ma) of three pan-global glaciations in the Cryogenian. At Omutirapo, in northern Namibia, a 2 km wide, 400 m deep palaeovalley is filled by glaciogenic strata of the Chuos Formation, which represents the Sturtian glacial record. Sedimentary logging of an exceptionally high-quality exposure permits detailed stratigraphic descriptions and interpretations, allowing two glacial cycles to be identified. At the base of the exposed succession, strong evidence supporting glaciation includes diamictites, ice-rafted dropstones and intensely sheared zones of interpreted subglacial origin. These facies collectively represent ice-proximal to ice-rafted deposits. Upsection, dropstone-free mudstones in the middle of the succession, and the absence of diamictites, imply sedimentation free from glacial influence. However, the reappearance of glacial deposits above indicates a phase of Sturtian glacial re-advance. Comparison with age-equivalent strata in South Australia, where evidence for sea-ice free sedimentation has been established previously, suggests that a Sturtian interglacial may have been extensive, implying global-scale waxing and waning of ice sheets during a Cryogenian glacial event.

Keywords Cryogenian, glacial, Namibia, Neoproterozoic, Sturtian.

INTRODUCTION

The snowball Earth hypothesis proposes a global cover of ice at multiple times during the Cryogenian (850 to 630 Ma) period of the Neoproterozoic (Hoffman et al., 1998; Hoffman & Schrag, 2002). The hypothesis has received support from climate modellers owing to the mathematically attractive solution of accumulating ice masses in the warm subtropics (Pollard & Kasting, 2005; Boyle et al., 2007). Another interpretation is that pockets of open ocean persisted, and the term ‘slushball’ is often used to describe this scenario. However, the ‘slushball’ models assume that there were low evaporation rates in the tropics and opaque tropical sea ice: two assumptions that are at odds with contemporary understanding of climate (Pollard & Kasting, 2005).

A wealth of sedimentological data including ice-rafted debris (IRD; Condon et al., 2002), thick diamictite successions recording a substantial sediment flux from dynamic ice sheets (Leather et al., 2002), wave-rippled surfaces intercalated with diamictites (Allen & Etienne, 2008) and hummocky cross-stratification (HCS) in glacio-marine sequences (Le Heron et al., 2011a) is in strong support of either small pockets, or large zones, of open water as first proposed in the ‘slushball’ interpretation of Hyde et al. (2000). Indeed, based on such empirical data, it is clear that ice sheets were very dynamic (Allen & Etienne, 2008). The present study presents strong evidence for substantive wasting then re-growth of ice sheets during the ca 715 Ma ‘Sturtian’ glaciation of Namibia. A high-quality sedimentological dataset is presented from the Chuos
Formation of northern Namibia (Fig. 1) from a hitherto little described but spectacularly exposed succession at Omutirapo (Fig. 2). By comparing the Namibian deposits with age-equivalent Australian counterparts, non-glacial deposits are highlighted within Sturtian successions, pointing to interglacial conditions. Based on these new sedimentological data, it is inferred here that Sturtian ice sheets waxed, waned and re-advanced, with multiple glacial cycles potentially recorded in this severe glacial event.

GEOLOGICAL BACKGROUND

The Neoproterozoic Otavi Group in northern Namibia preserves two diamictite-rich successions (Fig. 3), each overlain by a deglacial cap carbonate (Hoffmann & Prave, 1996), considered in turn to record intense glaciation and rapid climatic recovery (Hoffman et al., 1998). U–Pb ages from the underlying Nauuwport volcanics place the maximum age of the older diamictite succession (Chuos Formation: Fig. 3) at...
747 ± 2 Ma (Hoffman et al., 1996), and the younger Ghaub Formation (Fig. 3) diamicite is constrained to 635.5 ± 1.2 Ma through U–Pb dating of interbedded volcanic ash beds (Hoffmann et al., 2004). Most recent research has focused on this younger interval, with studies advocating either palaeo-ice stream activity or dynamic floating ice margin systems (Domack & Hoffman, 2011) or, conversely, rejecting the glacial hypothesis in favour of a mass flow origin (Eyles & Januszczak, 2007). The older glaciogenic succession, however, remains comparatively neglected, as exposure quality is lower than its younger counterpart.

Based on studies in the central zone of the Damara orogen (Fig. 1), Gevers (1931) first contended that the massive nature of diamicrites in the Chuos, their areal extent and local occurrence of varves, supported a glacial interpretation. Martin et al. (1985) and Porada (1983), meanwhile, discarded this long-held view and interpreted the central Damaran successions as non-glacial gravity flow deposits. In support, the latter author cited: (i) local clast derivation; (ii) proximity to syn-sedimentary faults; and (iii) intercalated quartzites, interpreted as turbidite pulses.

Eyles & Januszczak (2007) developed similar arguments to Martin et al. (1985) and Porada (1983) to side against the glacial hypothesis for the Chuos as well as the second, younger, Cryogenian glacial succession (the Ghaub Formation). For the Chuos, these workers note that the Omurirapo section lies at the immediate juncture between the Congo Craton and the Damara Belt, which was cited to explain syntectonic mass flows (the diamicrites). The problem with this argument, however, is one of timing. Separation of the Congo and Kalahari cratons, which might conceivably produce slopes to yield mass-flows, occurred long before Chuos deposition, with alluvial fanglomerates of the Nosib Group recording the rift phase (Hoffman & Halverson, 2008; Miller, 2008). Thus, the rift to drift transition, and accompanying passive-margin development, is represented by Otavi Group sedimentation (Fig. 3) (Miller, 2008). Compressional deformation, producing slopes to generate further mass flows and to juxtapose the Damara Belt with the Congo Craton, occurred much later when molasse of the Mulden Group was deposited (Miller, 2008).

The present study presents new data, including logged sections totalling ca 1000 m from four traverses, which demonstrate a strong glacial influence on sedimentation. The data permit detailed insight into the dynamics of older Cryogenian ice sheets (716.5 Ma, Sturtian: Macdonald et al., 2010a). Furthermore, clear evidence for non-glaciogenic sedimentation within the middle of the succession, pointing to intra-Sturtian ice-free conditions, is presented.

**STUDY AREA**

In the Khowarib Fold Belt, the Chuos Formation wedges from ca 80 to 347 m in a north-east/south-
west direction along a 3 km long continuous cliff section to form a palaeovalley geometry, exposed ca 15 km north-east of the village of Warmquelle (Fig. 4). Evidence for a palaeovalley at Omutirapo is three-fold: (i) progressive incision and truncation of the Ombombo Subgroup occurs beneath the Chuos in a south-westerly direction; (ii) dramatic thickness changes in the Chuos are apparent from detailed sedimentary sections; and (iii) clear onlap relationships of the Chuos onto the Ombombo Subgroup can be demonstrated (Figs 4 and 5). The diamictite assemblage rests unconformably upon a mixed succession of clastic and carbonate formations of the Ombombo Subgroup (Fig. 3), shows significant lateral thickness variations, and is disconformably overlain by stratified and stromatolitic dolostones of the Rasthof Formation (Hoffman & Halverson, 2008) (Fig. 4). Northward thickening of the formations of the Ombombo Subgroup beneath the sub-Chuos unconformity allows approximately east/west striking growth faults to be inferred (Hoffman & Halverson, 2008). Furthermore, the region (Khowarib Fold Belt) is ideally situated in the least deformed northern margin of the Damara-Kaoko orogenic belt, subject only to sub-greenschist facies metamorphism (Miller, 2008), and thereby permitting detailed facies analysis with minimal tectonic overprint. This interpretation lies in contrast to many earlier studies of the older Cryogenian sequence (e.g. Gevers, 1931; Martin, 1965; Henry et al., 1986; Badenhorst, 1988), undertaken in the highly deformed central Damara Zone to the south (Fig. 1).

Detailed sedimentary logging enables a correlation panel to be presented throughout the Chuos Formation that illustrates the internal architecture (Fig. 5). The correlation adopts the base-Rasthof Formation disconformity as a datum, emphasizing the degree of downcutting beneath the Chuos Formation at the base of the palaeovalley, and complete truncation of the Okakuyu Formation (top Ombombo Subgroup) to the south-west. The basal succession of the Chuos Formation is not preserved at the north-easternmost (thinnest) part of the exposure (Fig. 5, Log 4), but comprises a sandy diamictite in thicker sections of the Chuos Formation (Fig. 5, Logs 1 to 3).

Fig. 4. Panoramic photograph, with accompanying sketch overlay/interpretation, of the Omutirapo palaeovalley. Note the pronounced downcutting at the base of the Chuos Formation, representing the base of the palaeovalley, onlap geometries in the palaeovalley fill and the location of measured sections presented on Fig. 5. Palaeovalley closure is towards the south-west.
Fig. 5. Logged sections, facies and interpreted stratal architecture of the fill to the Omutirapo palaeovalley. Note the clear evidence for non-glacial facies (dropstone free shales, shown in green shading) in each of the measured sections.

FACIES ANALYSIS

Within the Omutirapo palaeovalley, five facies associations are recognized, namely: (i) massive and graded diamictites; (ii) pebbly cross-stratified sandstones; (iii) sheared diamictites; (iv) limestones bearing shale; and (v) clast-free shale.

Massive and graded diamictite facies association

Description
Two distinct constituent facies comprise the massive and graded facies association, both of which make multiple stratigraphic appearances in the Chuos Formation. The first of these is a clast-rich, sandy diamictite, typically brown-orange in colour, which is well-developed at the very base of the Chuos Formation (Fig. 6A and B). Clasts in this facies range from boulder to tree size, are sub-angular to rounded, typically equant and show no preferred orientation. Erratic lithologies include orange-yellow dolostone (particularly near the contact with the underlying Ombombo Subgroup) quartzite, andesite, amygdaloidal basalt, vein quartz, greenschist-facies pelites, leucogranite and sandstone. Locally, clasts are striated (Fig. 6C): these are restricted to the basal 10 m of the Chuos Formation. Bed thicknesses range from 0.3 to 2 m. At the outcrop scale, the massive diamictite facies association is organized into ca 10 m deep, ca 25 m wide channels and interchannel overspills (Fig. 6D). The second facies comprises two end members: a normally graded clast-poor sandy diamictite, and better differentiated, normally graded sandstone (Fig. 6E). These sub-facies are intercalated on the decimetre scale: ‘floating’ 2 cm diameter clasts are common to both. Graded intervals are on the lamination scale (0.7 to 1.5 cm), flat-based to slightly irregular, and repetitively stacked (Fig. 6F). These normally graded laminations form beds up to 0.75 m thick and are a comparatively minor component of the massive and graded diamictite facies association.

Interpretation
The massive diamictites are interpreted as a series of subaqueous glaciogenic debris flow (GDF) deposits, with the graded diamictites and sandstones interpreted as subordinate underflow deposits. Texturally, the massive diamictites are comparable with ‘plug flow’ deposits released from meltwater point sources on a grounding line fan (Powell, 1990). Flows hug the sea bed before becoming buoyant and detached, thus transforming into an underflow (Powell, 1990). In this context, equant clasts and lack of internal structure in bedding are expected. The organization of the GDF deposits into channel and interchannel areas, together with their thicknesses, is comparable with many Quaternary examples such as those found offshore Newfoundland (Tripsanas & Piper, 2008).

It is notable that the very substantial topography on the Ombombo Subgroup records stepwise incision to progressively deeper stratigraphic levels towards the south-west (Fig. 4), through a series of siliciclastic, and then carbonate, deposits (Fig. 5). The large number of non-sedimentary clasts implies that these are not derived locally. The stratigraphic concentration of striated clasts in the basal 10 m of the Chuos Formation is also noteworthy. No striated clasts were described by Eyles & Januszczak (2007): “despite observation of many hundreds of metres of thickness”, including Omutirapo. Otherwise identical occurrences of the massive and graded diamictite facies association further upsection (Fig. 5) imply that subsequent debris flows may have completely eradicated striations on clast surfaces.

The ‘floating clasts’ in the graded diamictites are explained adequately by the Postma et al. (1988) model. In this model, larger clasts are supported on a pseudo-laminar inertia flow layer and are moved downslope in response to shear stresses in the overlying turbulent part of the flow.
flow. Thus, the large clasts in this facies association are not interpreted as dropstones; rather, a within-flow sorting mechanism is envisaged to explain this texture. This interpretation is favoured owing to the lack of deformation/impact structures beneath the clasts typically associated with dropstones. Based on evidence from the pebbly cross-stratified sandstone facies association (see below), it is possible to infer that the basement clasts may have been sourced from the east (i.e. from the Congo Craton). In the Chuos of the central Damara Belt, Henry et al. (1986) contended that the presence of extrabasinal clasts, together with dropstone textures, were two of the strongest pieces of evidence for a glacial influence on deposition. At Omutirapo, parallels can be drawn between the massive and graded diamictites at the base of the palaeovalley with ice-proximal sediments in subglacially cut ‘tunnel valley’ networks (>1 km wide meltwater channels) where matrix-supported conglomerates and diamictites pass laterally and vertically into better differentiated underflow deposits or turbidites (e.g. Lang et al., 2012). This possibility is given full consideration later, in the context of palaeovalley genesis and fill.

Pebby cross-stratified sandstone facies association

Description
These deposits comprise red-coloured, clast-supported pebble conglomerates and sandstones in beds of 0.5 to 2 m thickness. Conglomerate beds are normally graded. Pebbles typically are moderately rounded to rounded, and a north-east dipping imbrication fabric of discoid quartz clasts (Fig. 6G) can be demonstrated locally. Low-angle cross-stratification is also developed. Owing to the poor exposure of this facies association, it was not possible to obtain palaeoflow measurements, although low-angle (<15°) planar foresets dip towards the south-west (Fig. 6G). The conglomerate and sandstone intervals are well-differentiated. At a centimetre-scale, coarse-grained and fine-grained sandstones alternate (Fig. 6G). The laminae exhibit both normal and reverse grading. In a typical exposure of this facies association, three or four stacked beds occur; these show an overall upward diminution in clast size in the conglomerates.

Interpretation
The pebbly cross-stratified sandstone facies association is interpreted as a series of jet efflux deposits released in proximity to a subglacial conduit. In ice-proximal settings, over a distance of several kilometres, a zone of flow establishment (characterized by debrites) typically passes into a zone of flow transition (clast-supported, cross-stratified gravels) and distally/downcurrent to upper flow regime conditions (antidune-bearing sands) (Hornung et al., 2007). Thus, in this way, the clast-supported, cross-stratified, imbricated pebble conglomerates are interpreted to represent a gravelly bedform deposited in the zone of flow establishment. The imbricate clasts, together with the south-west dipping low-angle planar foresets, imply sediment transport to the south-west. Thus, in the pebbly cross-stratified sandstone facies association, sediments are interpreted to have been sourced from a meltwater conduit to the north-east.

In the interbedded sandstones, the distinction between coarsening-upward and fining-upward laminae within these beds may suggest that these structures formed through the ‘burst/sweep process’ (Cheel & Middleton, 1986). In this process, fining upward laminae originate through the gravitational fall out of grains that have been carried upward into suspension by a current ‘burst’, whereas coarsening upward laminae evolve in response to dispersive pressures operating near the base of the boundary layer due to the passage or ‘sweep’ of high-speed fluid near the base of the bed (Cheel & Middleton, 1986). These processes are typical of a rapid current, upper flow regime (Ashley, 1990), potentially the downcurrent equivalents of the cross-stratified conglomerates (Hornung et al., 2007). Note that the alternating fine-grained and coarser-grained sand laminae could superficially be mistaken for varvites, a preferred interpretation of Gevers (1931) from the Chuos of the Damara Belt.

Sheared diamictite facies association

Description
Multiple horizons in the Chuos Formation exhibit diamictites that are stratified, deformed and attenuated. Continuously stratified sections of clast-poor diamictite occur over several metres, with clear separation of more argillaceous and more arenaceous layers (Fig. 7A). A slaty cleavage is observed (Fig. 7B), particularly in the finer-grained layers, which cross-cuts the soft-sediment deformation structures described below. By contrast with the massive and graded diamictite facies association, attenuated and elongate clasts
are common, and these are locally injected and fractured by bedding parallel sandstone sheets (Fig. 7C). Rotational deformation structures are commonplace, with an abundance of galaxy structures (Phillips, 2006; Phillips et al., 2011) and necking structures observed at the macro-scale (Fig. 7D and E). These structures indicate a top to the south-west sense of rotation. Dispersion tails are also commonly observed adjacent to highly attenuated siltstone clasts (Fig. 7F). No clasts were observed to protrude from an underlying bed into an overlying bed. Finally, pervasive lineations are developed in sandy diamictite intervals where prolate/rod geometries are conspicuous and trend approximately north-east/south-west. Within each stratigraphic occurrence (Fig. 5), the intensity of deformation in each shear zone usually increases upsection.

**Interpretation**

Layering in sheared diamictites is attributable to stratification of primary sedimentary origin, and pervasive attenuation of, for example, soft-sediment clasts and rootless folds (e.g. Roberts & Hart, 2005). At Omutirapo, clearly developed stratification within the sheared diamictite facies association is interpreted as primary subaqueous in origin. The multiple occurrences of sheared diamictite throughout the succession are interpreted to record subglacial deformation beneath an oscillating ice margin for the following reasons. The cross-cutting cleavage at a high angle to bedding and deformation structures demonstrates that the latter are soft-sediment in nature, and hence a tectonogenetic origin for the shear zones can be rejected. Thus, two interpretations remain: (i) shearing within a mass flow; or (ii) subglacial deformation. It should be emphasized that, in most analyses of Quaternary deformation structures, microscale observations normally inform interpretations (e.g. van der Meer, 1993; Phillips, 2006; Phillips et al., 2011), yet the following necessarily derives from macroscopic features.

Clast fracture and injection (sedimentary dykes and sills) are common in debrites (Menzies & Zaniewski, 2003) but they also occur subglacially (Le Heron & Etienne, 2005). The presence of galaxy structures, necking structures and dispersion tails (Phillips, 2006) implies the attenuation of soft (non-consolidated) clasts. Turbate/galaxy structures can record clast rotation during simple shear of subglacial sediment, but may also occur in mass flows provided that turbulence can develop (Phillips, 2006). Thus, the top to the south-west sense of shear in the galaxy structures could equally be interpreted as glacial advance or downslope instability in this direction.

Fortunately, the other features permit less equivocal interpretations. Firstly, the observed dispersion tails are ubiquitous in subglacial shear zones but rare in debrites (van der Meer, 1993; Hart & Roberts, 1994; Menzies et al., 1997; Lachniet et al., 2001; Evans & Benn, 2004). Secondly, protruding clasts typically occur on the exposed surface of debrites, which in the rock record pierce overlying beds (Arnaud, 2012): none are observed in this facies association. Thirdly, pervasive lineations, directly comparable with those developed in Omutirapo, occur in the Late Ordovician glacial record of Libya, where they are capped by soft-sediment-striated surfaces of subglacial origin (Le Heron et al., 2005). These features have not been described in debrites. Finally, the upward increase in deformation intensity in each occurrence of the sheared diamictite facies association is compatible with a subglacial glaciectonic shear zone. An upward increase in deformation within Quaternary glaciectonites is observed in many cases because strain is greatest near the ice–bed interface (e.g. Hart & Roberts, 1994; McCarroll & Rijsdijk, 2003; Arnaud, 2008, 2012; Weaver & Arnaud, 2011), although it is recognized that, in some instances, deformation may be partitioned at multiple levels. By contrast, in a debris flow, deformation intensity typically is greatest at the base (Nardin et al., 1979; Lowe, 1982; Mulder & Alexander, 2001).

Overall, the intensity of deformation contrasts vividly with the total absence of deformation in the debris flows and subordinate underflow deposits of the massive and graded diamictite facies association, which also appear recurrently throughout the Chuos Formation (Fig. 5). The repeated occurrence of subglacial shear zones in the stratigraphy of the Chuos Formation may suggest, by analogy to Cenozoic glaciomarine sequences of the south-west Ross Sea, Antarctica (Hambrey et al., 2002), repeated grounding of a periodically buoyant tidewater ice sheet.

**Lonestone-bearing shale facies association**

**Description**

Green, brown and grey lonestone-bearing shale, in successions up to 70 m thick (Fig. 5, Log 3, 50 to 120 m), is represented in multiple stratigraphic occurrences at Omutirapo. Two end-member facies are recognized, viz. pure shale and silty shale that are intercalated on the centimetre scale; in both, lonestones are of granule to cobble-size,
and include the same lithologies as the massive and graded diamictite facies association. Clasts are of the same range of lithologies found in the massive and graded diamictite facies association. These clasts range from angular to sub-rounded; their lower contacts typically depress and punctuate shale laminae to form an impact structure (Fig. 8A and B). Laminae are deformed/deflected to a much lesser extent above than below the clasts (Fig. 8A and B).

**Interpretation**

The lonestone-bearing shale facies association is interpreted as paraglacial hemipelagic muds interrupted by IRD. The observation that the greatest deflection (and locally puncturing) of laminae occurs beneath clasts rather than above them strongly implies that these are released through iceberg meltout (Condon et al., 2002; Leather et al., 2002; Le Heron et al., 2011b). Alternatively, given the south-west-oriented palaeoslope clearly recognized beneath the Chuos Formation, these deposits could record deposits from shorefast ice (e.g. Halverson et al., 2004). The absence of shear textures/deformation structures in the lonestone-bearing shale facies association allows debris-flow rafting of large clasts to be discounted. These interpretations are incompatible with the overall conclusions of Eyles & Januszczak (2007), which did not recognize dropstones, and which, in shale, chart a very strong case for a glacial influence.

**Clast-free shale facies association**

**Description**

Light green to brown shale, devoid of clasts, occurs in each of the logged sections, representing the medial part of the palaeovalley fill at Omuntirapo (Fig. 5). Unlike argillaceous deposits in the lonestone-bearing shale facies association, the clast-free shale does not include a silty-shale end member. Owing to the recessive character of shale, this facies is only intermittently exposed (Fig. 8C to E).

**Interpretation**

Unlike each of the facies associations described above, the clast-free shale facies is unique in lacking evidence for glacial processes, or processes associated with glacial activity. The homogenous nature of these deposits makes them difficult to interpret but the absence of siltstone discounts sedimentation via very distal underflows. Therefore, a hemipelagic fallout interpretation is preferred. The absence of either HCS or wave ripples precludes water depth estimation. Thus, greatest emphasis is placed on the wider context of these clast-free facies, set against the stratigraphic evolution of the Chuos Formation below.

**STRATIGRAPHIC ARCHITECTURE AND ICE SHEET DYNAMICS**

The preceding analysis has established a strong glacial influence on sedimentation in the Chuos Formation of northern Namibia that can be summarized as subglacial deformation (sheared diamictite), glaciogenic debris flows interspersed with underflows (massive and graded diamictite), ice-proximal jet efflux deposits (pebbly cross-stratified sandstone), IRD (lonestone-bearing shale) and non-glacial, hemipelagic fallout (clast-free shale). A schematic depositional model showing the interpreted inter-relationships of the facies associations during ice sheet re-advance is shown in Fig. 9. Below, the vertical and lateral stacking patterns of facies at Omuntirapo are considered to infer ice sheet advance and retreat cycles. On the basis of the present data, the 1000 m thickness quoted in Eyles & Januszczak (2007) for the Omuntirapo section is clearly an over-estimation (Fig. 4).

There are several possible interpretations of palaeovalley genesis. Growth sequences in the Ombombo suggest that an east/west growth fault controlled the location of the palaeovalley (Hoffman & Halverson, 2008). The palaeovalley may represent: (i) a large incision of fluvial or

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**Fig. 7.** The sheared diamictite facies association. (A) General view of the well-bedded aspect of these deposits, with hammer for scale circled (30 cm long). (B) Fold structures in a buff coloured sandy diamictite layer encased within dark-grey muddy diamictite. Note that the fold structures are cut by a cleavage, demonstrating that the fold structures formed in a pre-tectonic phase, thus affecting unconsolidated sediments. (C) Sandstone sheet cross-cutting an attenuated dolostone clast, thus interpreted as a sandstone injectite. Namibian 50 c coin for scale (24 mm diameter). (D) Evidence of rotational deformation – a galaxy structure (Phillips, 2006; Phillips et al., 2011) identified by the ‘wings’ on the perimeter of the clast, indicating that it was unconsolidated during deformation, and a necking structure indicated pre-boudinage extension of the clast ‘wing’. (E) Detail of the galaxy structure developed in (D). (F) Highly attenuated green siltstone clasts with dispersion tails. Field of view is ca 10 cm wide. (G) and (H) Photograph and sketch of pervasive lineations, with characteristic prolate geometries, in a sandy part of a sheared diamictite.

submarine origin; (ii) an ice-carved incision (i.e. part of a sub-ice stream, cross-shelf trough: e.g. Andreasson et al., 2004); or (iii) a tunnel valley (subglacial meltwater incision cut under elevated hydrostatic pressures: O’Cofaigh, 1996). The depth of the incision (ca 267 m) is an order of magnitude greater than lowstand fluvial incised valleys (e.g. Allen & Posamentier, 1993; Thomas & Anderson, 1994), but compares closely with deep tunnel valleys described from the Late Ordovician of Algeria (Lang et al., 2012). Although folding/deformation beneath the Ombombo-Chuos contact is not observed (unlike many tunnel valley incisions: O’Cofaigh, 1996), the GDF deposits (massive and graded diamictite facies association) imply ice-proximal sedimentation

**Fig. 8.** (A) and (B) Examples of lonestones of pink quartzite punctuating, with impact structures, green shale: the lonestone-bearing shale facies association. These deposits are interpreted as ice-rafter debris (IRD). Hammer for scale is 30 cm long. (C) Basal outcrop of the clast-free shale facies association, showing fairly continuous exposure of grey shale. (D) and (E) General view and close-up of the upper part of the clast-free shale facies association in the middle part of the palaeovalley. The interval figured in (C) and (D)/(E) corresponds to the base and top of the ‘dropstone-free interval’ in Fig. 5.
comparable with that developed in the early stages of tunnel valley fill (Lang et al., 2012). Thus, the Omutirapo structure is tentatively interpreted as a tunnel valley incision.

In accordance with sequence stratigraphic methodologies developed for ancient glacial sequences (e.g. Ghienne et al., 2007), coarsening versus fining upward motifs in the Omutirapo palaeovalley fill may allow ice sheet advance/retreat cycles to be inferred. The basal series shows little to no vertical grain-size variation upward (massive and graded diamictite: an aggradational stacking pattern). In the thickest logged sections, the sheared diamictite facies association (‘Shear Zones’: Logs 1 and 2; Fig. 5) is well-developed. These intervals are more numerous towards the south-west (Log 1, 10 to 40 m; Fig. 5). The aggradational, basal series is capped by a conglomerate/sandy diamictite in each logged section, and this passes upward into the lonestone-bearing shale facies association that represents the base of a generally retrogradational medial series (Fig. 5). These latter deposits are characterized by dramatic lateral and vertical facies variations. These features include: (i) fining-up cycles of conglomerate through cross-bedded sandstone (Log 1, 120 m and 130 m; Fig. 5); (ii) diamictite channels, with evidence of channel–channel truncation (Log 1, 140 m and Log 2, 72 m; Fig. 5); and (iii) onlap relationships against the basal fill (Figs 4 and 5, between Logs 2 and 3). The massive and graded diamictite facies association is intercalated with the lonestone-bearing shale facies association in this part of the Chuos Formation (for example, Log 3, 90 to 100 m; Fig. 5).

Towards the top of the retrogradational, medial series, diamictites and dropstone-bearing intervals pass upward into green shales that are devoid of lonestones (i.e. the clast-free shale facies association) (Fig. 9). The dropstone-free zone can be recognized in each of the logged sections and correlated between them (Fig. 5). Upward, above the dropstone-free interval, a coarsening upward (thus progradational) succession is observed in each of the sections, locally culminating in a sheared diamictite (Log 4, 73 m; Fig. 5). The coarsening upward package consists
of increasingly numerous dropstones in siltstone and shale, transitional into silty sandstone and occasionally diamictites. This latter succession is sharply truncated by either an occurrence of the massive and graded diamictite facies association (Log 1, 280 m; Fig. 5) or the pebbly cross-stratified sandstone facies association (Log 4, 94 m; Fig. 5). This diamictite thus rests on an intra-Chuos disconformity that can be correlated between each of the logs (Fig. 5).

Above the intra-Chuos disconformity, the final, uppermost part of the succession comprises silty and sandy diamictites broadly organized into a fining-up (hence retrogradational) package. The finer-grained intervals in the uppermost part of the Chuos are recessive and intermittently exposed, and thus non-exposure characterizes the transition into the Rasthof Formation in two instances (Logs 1 and 2; Fig. 5). The overlying Rasthof Formation, which rests in sharp contact on the Chuos where observed, is divisible into two main facies: (i) laminated limestones; and (ii) stromatolitic limestones (Log 3, 220 to 238 m; Fig. 5).

At Omutirapo, the interpretation by the present authors of the stratigraphic evolution of the Chuos Formation is as follows. Striated cobbles, in the basal part of the palaeovalley, imply an ice-contact setting. The organization of some diamictites into channels (Fig. 6D) is consistent with abundant meltwater availability in this setting, or perhaps gravity-induced re-mobilization of glacial sediments (Eyles & Januszczak, 2007) at the steep palaeovalley margins. Some occurrences of the sheared diamictite facies association are restricted and cannot be traced along strike (cf. Logs 1 and 2; Fig. 5), implying that they formed during restricted re-advance across the palaeovalley and/or local grounding of a floating ice margin. The occurrence of this facies association within an aggradational stacking pattern supports the interpretation of a stable ice margin. Together, the massive and graded diamictites and the pebbly cross-stratified sandstone facies association represent ice-contact fan sedimentation at a subaqueous ice margin (Fig. 9). In this model, the textural differences in these facies associations relates to the position of the jet efflux conduit, prevailing hydraulic conditions on the sediment surface and sediment composition (e.g. Hornung et al., 2007). The conglomerate/sandy diamictite that caps the basal succession represents such an ice-contact fan deposit.

The upward transition into limestone-bearing mudrocks in the medial series of the palaeovalley, in tandem with onlap relationships demonstrable on the panoramic photograph (Fig. 4) and the retrogradational stacking pattern, are interpreted as the signature of ice-front recession. Given that the thick diamictite channels (for example, Log 1, 145 to 228 m; Fig. 5) are immediately followed by deposits of the limestone-bearing shale facies association (IRD), it is suggested that the rapid ice sheet retreat ensued. This stacking pattern is compatible with sequence-stratigraphic models specifically developed for ice sheets rapidly retreating from palaeovalleys (Ghiennie et al., 2007). Given the context of ice sheet retreat, the dropstone-free zone potentially implies IRD-free seas, and thus interglacial conditions. A maximum flooding surface is thus placed within the dropstone-free zone, which is tentatively interpreted to record an interglacial sea-level maximum (Figs 5 and 9).

Resumption of progradation within the Omutirapo palaeovalley – including the progressive re-appearance of IRD-bearing siltstones and shales, and increase in volume of diamictite – is interpreted as the transition from interglacial conditions to a glacial re-advance scenario. An occurrence of the sheared diamictite towards the top of this progradational package is compatible with renewed ice sheet grounding and subglacial deformation (Fig. 9). Thus, the unconformity that truncates this package is tentatively interpreted as a subglacial erosion surface (Fig. 5). This stratigraphic motif compares with the ‘sequence boundaries’ recognized by Fielding et al. (2000) from the Conozoic glaciomarine succession of the south-west Ross Sea, Antarctica, which were suggested by Hambrey et al. (2002) to record periodic ice-sheet grounding at a tidewater margin. The fining-upward diamictite package above (for example, Log 1, 278 to 357 m; Fig. 5) is interpreted as a grounding line moraine: its lateral extent across the palaeovalley stands in contrast to the diamictite channels beneath. The retrogradational nature of this uppermost unit is compatible with ice sheet recession. Thus, although the contact with the overlying Rasthof Formation is sharp where observed (Logs 2 and 4; Fig. 5), terminal ice sheet recession appears to have been more gradual than initial retreat at the onset of the interglacial phase. This observation can simply be explained by an ice front retreating over a topographically subdued shelf (Ghiennie et al., 2007). This behaviour is to be expected given glacial re-advance over a palaeovalley already largely filled with sediment.
DISCUSSION AND CONCLUSIONS

The above analysis has demonstrated that the Omutirapo palaeovalley fill contains a clear glacial retreat–re-advance–retreat signature (Fig. 9). The well-developed, dropstone-free interval is herein suggested to represent interglacial sedimentation, in which a maximum flooding surface is recognized, representing an interglacial sea-level high. The snowball Earth hypothesis recognizes three putative glacial episodes: the Sturtian, Marinoan and Gaskiers events (Hoffman & Schrag, 2002). If it were assumed that, on the basis of geochemical signatures, the Sturtian glaciation was isochronous and global (ca 716.5 Ma: Macdonald et al., 2010b), rather than one of several diachronous ice house events (Allen & Etienne, 2008), internal correlation might be possible between diamictite-prone successions of Sturtian age on different continents. It should be emphasized that, in Namibia, the outcrop quality of Omutirapo is exceptional and that the Chuos is patchy elsewhere (Hoffman & Halverson, 2008). The Omutirapo succession is also exceptionally thick in comparison with neighbouring sections (Hoffman & Halverson, 2008) implying that substantial accommodation space during deposition protected interglacial deposits from cannibalization by re-advancing ice sheets. This implication is also supported by the observation here that the interpreted subglacial erosion surface at the top of the palaeovalley is essentially a disconformity (Fig. 5) and not a deeply channelled discontinuity. Furthermore, at Omutirapo, onlap geometries are clearly expressed throughout (Fig. 4), clearly demonstrating excellent stratal preservation. The present authors envisage a tidewater ice margin that, in addition to a major retreat–re-advance cycle, was subject to periodic oscillations. Buoyancy, perhaps as a result of tidal effects, resulted in repeated floating and grounding of the ice margin; this would account for the mismatch in the number of subglacial shear zones across the palaeovalley (Figs 5 and 9).

Under the snowball Earth model, the Chuos Formation correlates perfectly with the Sturt Tillite and its lateral equivalents in South Australia (Hoffman & Schrag, 2002). During the Sturtian glaciation at ca 716.5 Ma (Macdonald et al., 2010b), northern Namibia and South Australia lay at opposite ends of the Rodinia supercontinent (Collins & Pisarevsky, 2005). Le Heron et al. (2011a,b) provided detailed descriptions of these strata at the Holowilena South homestead in the central Flinders Ranges. At Holowilena, the Sturtian succession comprises the Pualco Tillite (glaciogenic debris flows), overlain by the Holowilena Ironstone (glacioturbidites); these pass up into pebbly diamictite of the lowermost Wilyerp Formation (glaciogenic debris flows), succeeded by hummocky cross-stratification-bearing sandstones and siltstones (storm deposits). These latter deposits are capped by a ca 2 km thick ice-rafter debris-rich unit, deposited during ice sheet re-advance, in which hummocky cross-stratification is lacking. Storm waves are required to generate hummocky cross-stratification, thus implying sea-ice free conditions prior to glacial re-advance (Le Heron et al., 2011a). The hummocky cross-stratification-bearing interval appears ca 2 km below the Tindelpina Shale member of the Tapleys Hill Formation, which records post-glacial flooding and non-glacial hemipelagic shale and underflow deposition. In South Australia, a significant phase of rifting preceded glaciation, and diamictite-rich successions were deposited in local ‘troughs’, grabens and palaeo-lows (Le Heron, 2012 and references therein). On this basis, correlation between the dropstone-free interval of the Chuos Formation with interglacial, hummocky cross-stratified sandstones of the Yudnamutana Subgroup in Holowilena, South Australia (Le Heron et al., 2011a) may be proposed.

In any glacial succession, cannibalization of earlier glacial cycles by successive advances can never be fully discounted. However, considering the high accommodation space settings of Omutirapo (Fig. 9) and Holowilena, and hence preservation potential, it can be argued that these regions provide an excellent opportunity to identify intra-Sturtian global events. Considering evidence from Omutirapo (the clast-free shale facies association) and Australia (the hummocky cross-stratification-bearing interval in the middle of the Wilyerp Formation) in tandem identifies clear non-glacial facies in the middle of each succession. Existing chronostratigraphic frameworks for the Cryogenian glaciations (Macdonald et al., 2010b) are permissible of a global-scale interglacial, although the concept of major ice-free interglacial periods during the supposedly global ice cover may be difficult to reconcile with current interpretations of snowball Earth (Hoffman & Schrag, 2002).

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