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Syntectonic subaqueous mass flows of the Neoproterozoic Otavi Group, Namibia: where is the evidence of global glaciation?

Nick Eyles* and Nicole Januszczak†

**Department of Geology, University of Toronto at Scarborough, Scarborough, ON, Canada M1C 1A4*
†De Beers Canada Exploration Inc., Toronto, ON, Canada M4H 1P1

ABSTRACT

The thick ($>$ 1 km) Neoproterozoic Otavi Group of Namibia accumulated after *ca*. 760 Ma along $>$ 700 km of the faulted margin of the Congo Craton. The margin shows a north to south, downbasin transition from a shallow-water carbonate shelf (Otavi Platform) to offshore deepwater slope (Outjo Basin). Within the latter, the Abenab and Tsumeb Subgroups contain large volumes of poorly sorted breccias, conglomerates and diamictites composed principally of locally derived carbonate. Diamictite facies were reported in the 1930s as tillites left by an ice sheet (although the absence of striated clasts and other key glacial indicators was viewed as problematic). Later workers rejected a glacial origin concluding that Outjo basin facies were deposited as parts of prograding submarine wedges built by mass flows during active rifting. Recently, the Snowball Earth hypothesis has returned to the earlier glacial interpretation; arguing that these strata represent a record of extraordinary late Neoproterozoic glacial and interglacial climates when global temperatures fluctuated by up to 100 °C. Facies analysis of breccias, diamictites, conglomerates and sandstone strata of the Otavi Group identifies them as genetically related, subaqueously deposited sediment gravity flows. They lack diagnostic indicators of any one specific climate in source areas. These facies were all deposited in deepwater at the foot of landslide-prone scarp blocks where debris flows and turbidity currents moved large volumes of coarse, freshly broken carbonate debris produced by faulting. Breccias, diamictites, conglomerates and sandstones occur in composite fining- and thinning-upward bundles that are directly analogous to those reported from many other faulted margins in the Phanerozoic stratigraphic record. These rocks provide no clear sedimentological signature of a glacial source or catastrophic Snowball Earth-type temperature fluctuations. Instead, they point to a dominant tectonic control on sedimentation related to faulting along the margin of the Congo Craton.

INTRODUCTION AND PURPOSE OF THIS PAPER

The purpose of this paper is to focus the attention of sedimentologists and climate modellers on a thick (up to 1 km) Neoproterozoic succession (Otavi Group) in Namibia, southwest Africa (Figs 1 and 2). These strata contain prominent poorly sorted breccias, diamictites and conglomerates that when first reported in the 1930s were interpreted as glacial deposits although the absence of key glacial indicators such as striated clasts was recognized (Gevers, 1931). The considerable thickness and assumed regional extent of these facies were seen as evidence of an extensive ice sheet inviting direct correlation with other supposed glacial deposits across much of southwest Africa. This prompted Gevers (1931) to invoke 'globally engulfing glaciations', although later work by Schermerhorn (1974), Porada & Wittig (1983a, b) and Martin *et al.* (1985) demonstrated a non-glacial origin for these deposits. Recent work has once again revisited a glacial interpretation and these strata are now once more considered as motifs of one or more episodes of global Neoproterozoic cooling and warming events ('Snowball Earth'; Hoffman *et al.*, 1998; Halverson *et al.*, 2005).

Our principal objective in this paper is to evaluate competing interpretations of strata exposed at specific outcrops of the Otavi Group identified as recording extreme Snowball Earth climate events. We present detailed facies descriptions of deposits labelled previously by Hoffman *et al.* (1998) as 'preglacial', 'glacial' and 'postglacial'. We find, by comparison with analogous Phanerozoic deposits described elsewhere, that these deposits have no unique diagnostic palaeoclimatological signature. We argue that these facies are sediment gravity flows generated tectonically during faulting of the Congo Craton margin. The

Correspondence: Nick Eyles, Department of Geology, University of Toronto at Scarborough, 1265 Military Trail, Scarborough, ON, Canada M1C 1A4. E-mail: eyles@utsc.utoronto.ca

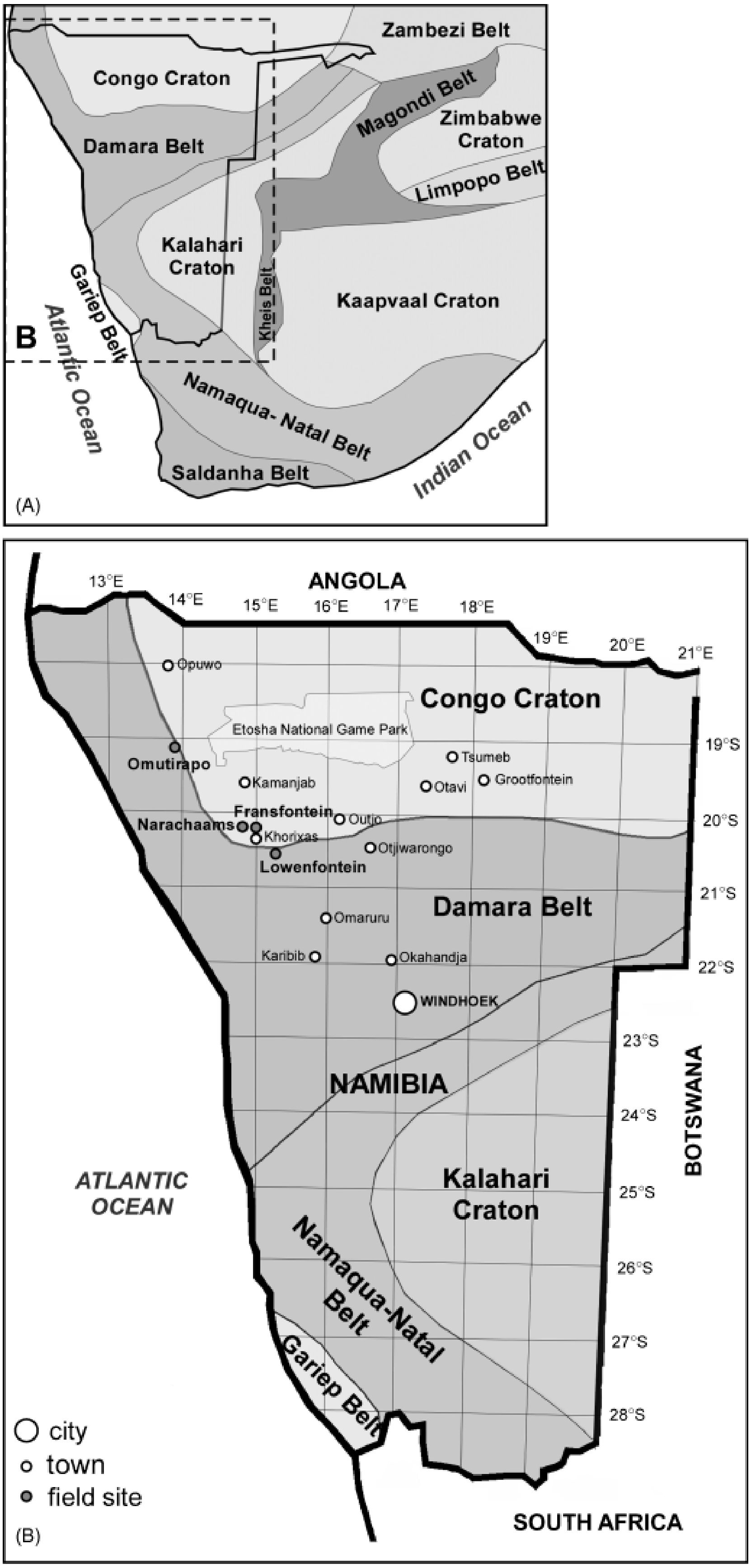

Fig. 1. (A, B) Location of study area in Namibia; this study is based primarily on outcrops exposed at Fransfontein (Fig. 3) and Narachaams (Fig. 4).

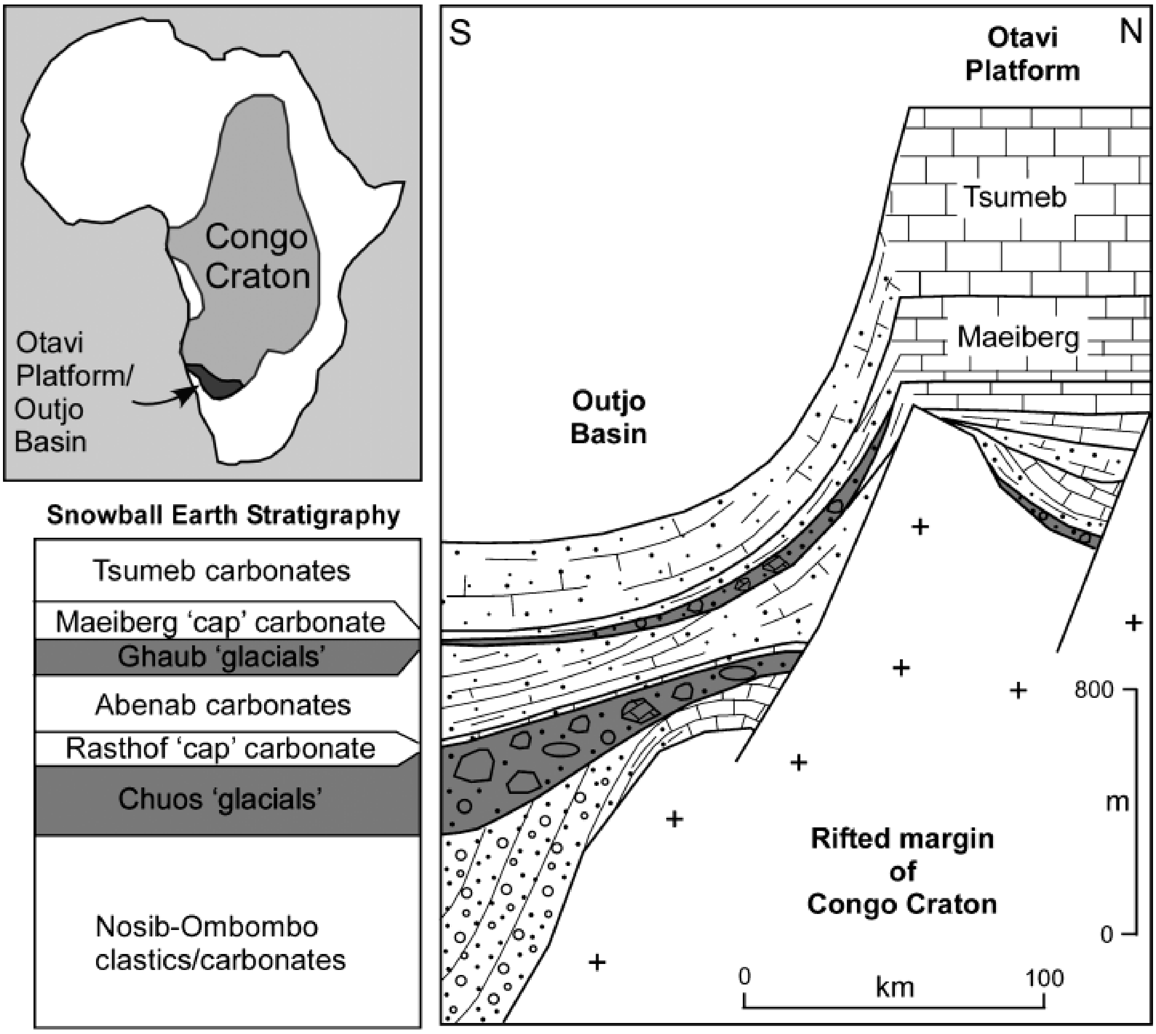

Fig. 2. Regional stratigraphy across the platform and basin of the Otavi Group according to Hoffman & Prave (1996) based on assumed glacigenic origin and regional extent of diamictites as global stratigraphic markers. This scheme is employed here to refer to specific stratigraphic units of these workers as identified in study area; see text for limitations of this stratigraphic scheme.

wider implications of our data and the palaeoenvironmental interpretations drawn from them are then discussed.

AGE AND EXISTING STRATIGRAPHIC NOMENCLATURE

Rocks of the Otavi Group are widely exposed across northwestern Namibia within the 700-km-long Damara Pan-African Fold Belt between the Congo Craton in the north and the Kalahari Craton in the south (Figs 1 and 2). A thick (> 1 km) succession of deep-water basinal facies ('Outjo Basin') forms a southward-thickening wedge banked against the rifted margin of the Congo Craton (Fig. 2). Thick (up to 3.5 km) carbonate-dominated shelfal facies occur up-dip on the adjacent Otavi Platform and contain bioherms and aragonite fan reefs (Hoffman & Schrag, 2002). Figure 2, with some modification, is from Hoffman & Prave (1996) and we cannot emphasize too strongly that it is a schematic representation of the regional stratigraphy. All previous workers agree that the basin stratigraphy is complex as a consequence of the extensional tectonic setting and the presence of numerous sub basins that evolved and filled diachronously (Miller, 1983a, b; Martin *et al.*, 1985). Hoffman & Prave (1996) distilled this complexity into two simple climatostratigraphic couplets consisting of a 'glacial tillite' overlain by 'interglacial cap carbonate' (i.e. Chous and Rasthof formations and the Ghaub-Maieberg formations). In fact, it has long been appreciated by process sedimentologists that a simple lithostratigraphic correlation of the same facies types is not feasible because of local intrabasinal controls on sedimentation during regional extension (see Martin *et al.* 1985). We retain Fig. 2 here because of the need to refer to specific outcrops of depositional units used by Hoffman *et al.* (1998).

The Otavi Group is only broadly bracketed in age between *ca.* 760 and 600 Ma (Hoffman & Prave, 1996; Hoffman *et al.*, 2004; Halverson *et al.*, 2005, p. 1183). Halverson *et al.* (2005) interpreted the Chous Formation as representative of a Sturtian-age glaciation and the Ghaub Formation as a younger Marinoan event tentatively dated to *ca.*

635 Ma and placed at the base of the newly defined Ediacaran period (Gaucher *et al.*, 2005). The two-fold climatostratigraphic division of Hoffman & Prave (1996) is based on the assumed global climatic significance of individual sedimentation units, which in their view can then be correlated across the entire margin of the Congo Craton. This is based on the traditional Australian stratigraphic practice of two principal Neoproterozoic glaciations but its extension to other Neoproterozoic basins is now regarded as suspect (Kendall *et al.*, 2006; Eyles *et al.*, in press).

METHODS AND LOCATIONS

Facies analysis was focussed principally on outcrops of the Ghaub Formation at Fransfontein and Narachaams, with additional observations of Chuos Formation strata at Lowenfontein and Omutirapo (Figs 1 and 2). In constructing lithofacies profiles (Figs 3–5), particular attention was given to sedimentary facies that underlie, rest on or are interbedded with supposed Ghaub and Chuos 'glacial' diamictites. These observations were augmented by consideration of provenance and lithology, palaeocurrent data, along-strike variability, the nature of bedding contacts, and post-depositional deformation structures. Some facies experienced metamorphic stretching and clast elongation (e.g. Fig. 6B) but otherwise primary depositional structures and clast orientation are well preserved.

DESCRIPTION OF OUTCROPS AND FACIES

A thickness of approximately 150 m of the Abenab Subgroup, Ghaub Formation and Maiberg Formation rocks is well exposed in the steep sidewalls of a valley cut through the Fransfontein Ridge (west and east sides of the Fransfontein Gap; Figs 3, 5B, 6 and 7). Outcrops of the same-named units were also examined at Narachaams (Figs 4, 5A, 8, 9 and 10). Chuos strata rest unconformably on carbonates of the Ombombo Subgroup (Fig. 2) and are at least 400 m thick at Lowenfontein increasing to more than 1000 m thick at Omutirapo where they were deposited against a tilted fault scarp of Ombombo Subgroup carbonate. At all these locations, outcrops consist of clast- and matrix-supported breccias, diamictites, conglomerates and sandstones. These facies are systematically described and interpreted below.

Breccia facies (B)

The term *breccia* (facies B) refers to very poorly sorted to non-sorted, coarse-grained facies composed of angular, often shard-like clasts of limestone and dolostone. Clasts vary in size from a few centimetres to rafts several metres in diameter and show a very poorly defined imbrication recording southward-directed palaeocurrents. Breccias are a highly conspicuous facies type within the supposed 'glacial' Ghaub and Chuos formations but are also typical of the underlying 'preglacial' strata where they form rusty brown to yellow-coloured units many tens of metres thick (Figs 5, 8 and 11). Distinction of breccia subtypes in the field is not straightforward because individual sedimentation units often show chaotic internal lateral and vertical transitions from clast to matrix-support. Breccia facies are typically clast-supported (facies Bc) and are either massive (Bcm) or crudely stratified (Bcs). Less common matrix-supported facies (Bmm) show clasts enveloped by a ferruginized carbonate sandstone matrix. Some beds show a distinct upward gradation from breccia to poorly sorted sandstone that supports isolated breccia clasts (Facies Bg; Fig. 5A).

The thickness of individual breccia beds ranges from 30 to 100 m (Fig. 8) with lenticular cross-sections (Fig. 8B). In general, thicker beds contain larger clasts, a relationship that holds for bed thicknesses up to approximately 10 m. Bed bases are locally erosive with evidence of local scouring, but are dominantly conformable. Breccia facies are conformably interbedded with and are overlain by massive and graded conglomerates and sandstones comprising composite, fining upward sedimentation units, recording an upward diminution in the supply of coarse debris (Figs 5 and 11). Intraformational normal faulting and sedimentary dikes are present throughout breccia deposits.

Interpretation

Carbonate breccias are a highly distinctive facies type and accumulate as debrites at the foot of steep slopes such as fault scarps and at the unstable edges of carbonate platforms (e.g. Surlyk, 1978, 2003; James, 1981; Hiscott & James, 1985; Yarnold & Lombard, 1989; Coniglio & Dix, 1992; Ghibaudo, 1992; Nemec & Kazanci, 1999; Gawthorpe & Leeder, 2000; Ineson & Surlyk, 2000). Clast-supported and matrix-supported facies are deposited *en mass* by high-density, non-turbulent debris flows and rock falls capable of freighting large clasts (Ghibaudo, 1992). The presence of normally graded beds of sandstone (interpreted as turbidites) within breccias, along with the occurrence of graded breccia facies (Bg), is key contextual evidence of a subaqueous setting. Overall, however, the general lack of well-developed grading in breccias indicates that turbulence was suppressed and clasts were transported by grain-to-grain collisions typical of coarse-grained cohesionless debris flows lacking a cohesive mud matrix. A relationship between maximum clast size and bed thickness indicates increased competence of thicker flows to support larger clasts (e.g. Nemec *et al.*, 1984). A tapered cross-sectional geometry (Fig. 8B) may reflect a primary depositional geometry in the form of lobate flows that are the thickest along their central axis and thin toward their lateral margins. Thicker beds (10–100 m) most likely formed by the amalgamation of multiple flows rather than representing a single sedimentation event through exceptional mass flow events could also be recorded. The presence of composite fining-upward sedimentation units of breccias that are overlain by

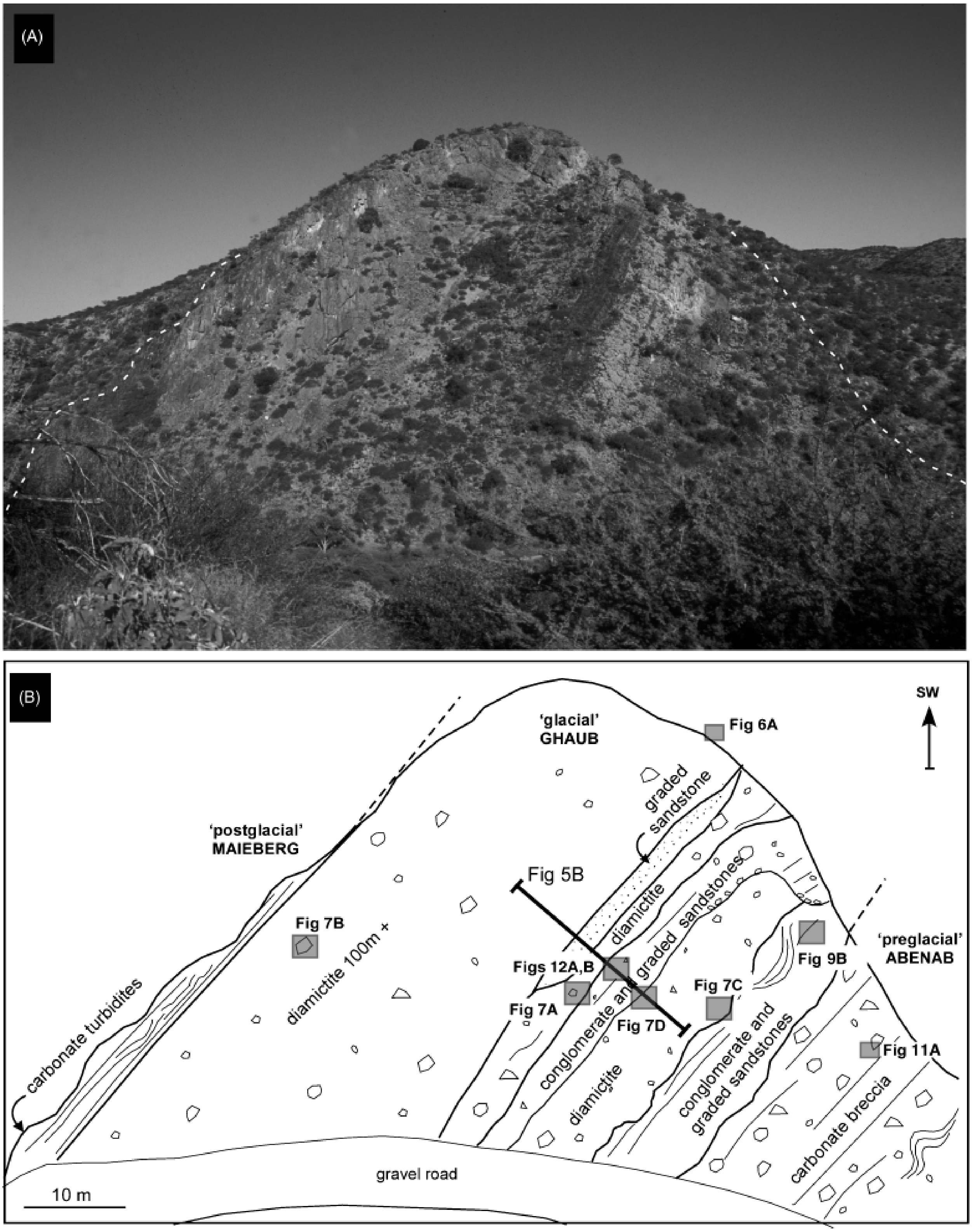

Fig. 3. (A) Outcrop on west side of Fransfontein Gap (see Fig. 1 for location). (B) Existing climatostratigraphy after Hoffman & Prave (1996) and sites of detailed measured sections (Fig. 5B) through Ghaub and Abenab formations.

graded and massive conglomerate and sandstone (Figs 5 and 11) likely records the progressive diminution in the supply of coarse debris during a single but protracted episode of mass wasting (Surlyk, 1978).

Conglomerate and sandstone facies (G, S)

These facies are here considered together because they form intimately interbedded packages (Figs 5, 9, 10 and

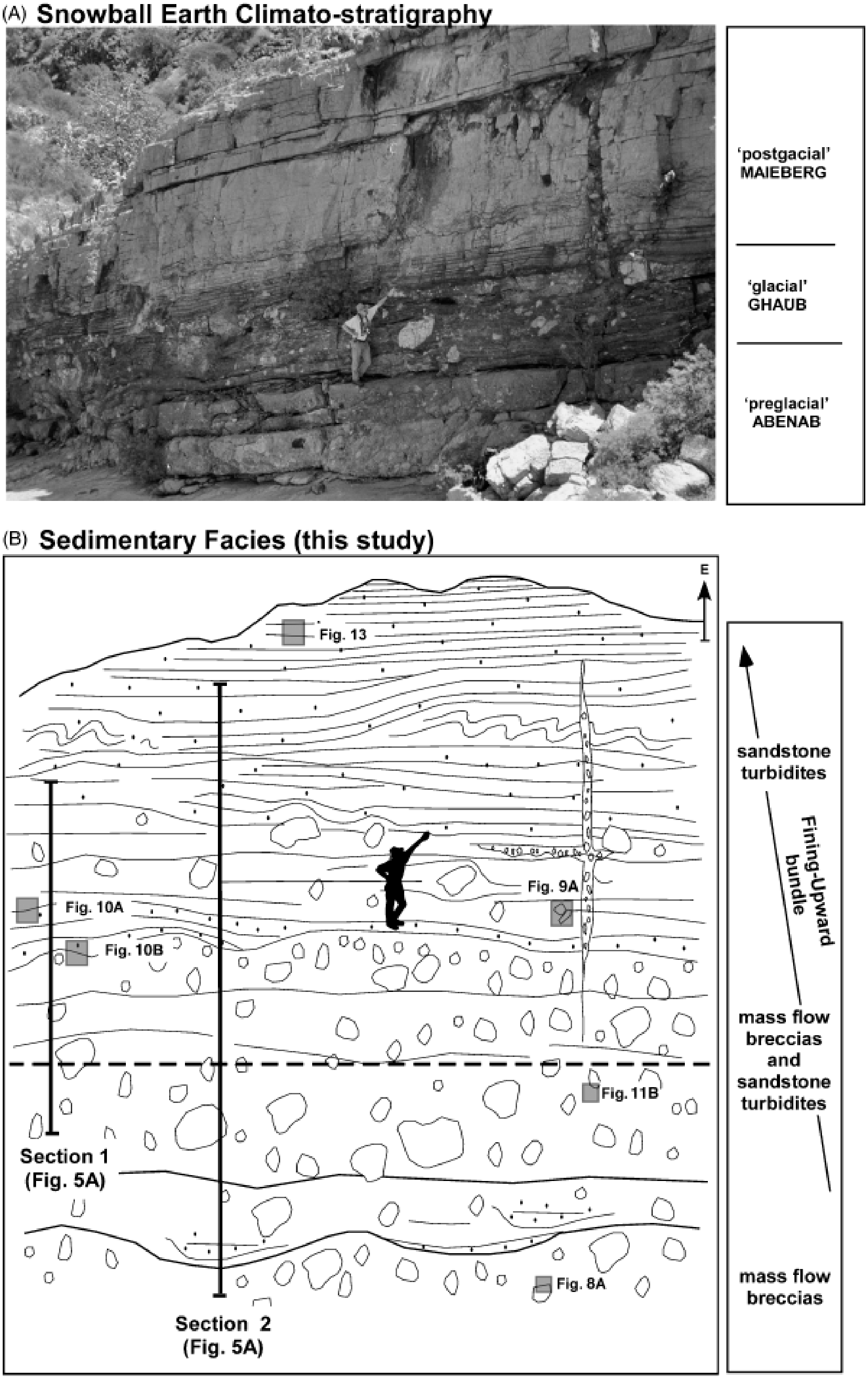

Fig. 4. Outcrop (A) and facies panel (B) at Narachaams (see Fig. 1) with location of measured sections (Fig. 5A) and photographs. Person is approximately 2 m high. In the climatostratigraphy of Hoffman & Schrag (2002), the preglacial Abenab Formation is overlain by a glacial Ghaub Formation that was interpreted as ice rafted, with the overlying Maieberg Formation as postglacial cap carbonates. These are arbitrary sub divisions of a thick fining upward mass flow bundle (shown by arrow). The dashed line on facies panel identifies lower boundary of photograph.

12). Massive conglomerates (Gm) show a wide variety of clast shapes, a gritty sand matrix and good clast imbrication indicating southward-directed palaeocurrents (Figs. 9B and 12B). A crudely developed inverse to normal 'coarse tail' grading (Gg; Fig. 12B) occurs where clasts first increase in size upward and then diminish in size toward

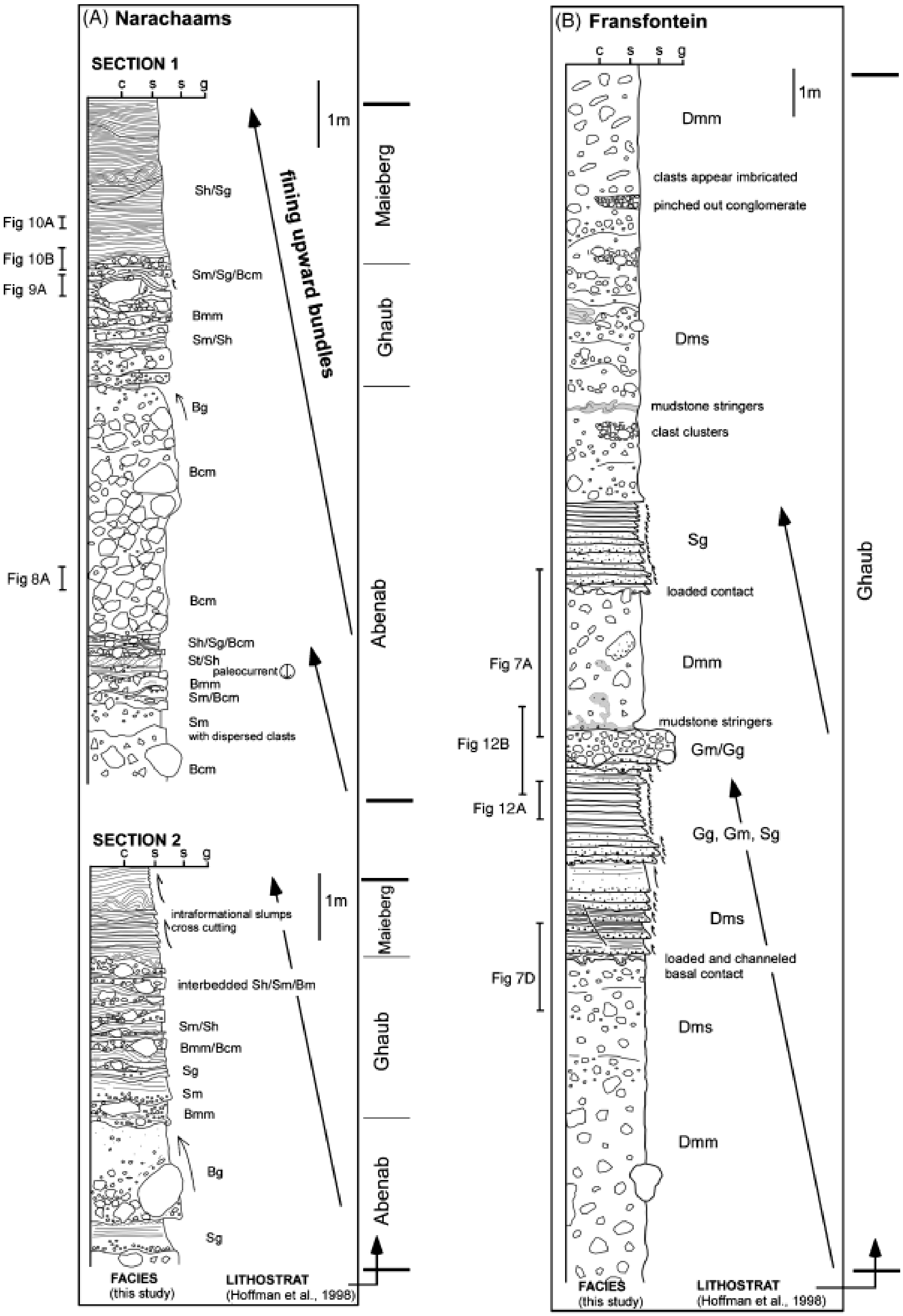

Fig. 5. Detailed sedimentological measured sections of outcrops at Narachaams (A) and on west side of Fransfontein Gap (B). See Figs 3 and 4 for locations. Arrows indicate fining-upward bundles of mass flow facies. Note in (A) that climatostratigraphic subdivisions (Abenab, Ghaub, Maieberg formations) arbitrarily divide these bundles. Facies: B, breccia; Bcm, clast-supported massive; Bcs, clast-supported stratified; Bmm, matrix-supported massive breccia. D, diamictite; Dcm, clast-supported massive; Dmm; matrix-supported, massive; Gm, massive conglomerate; Gg, graded; S, sandstone; Sg, graded sandstone; Sm, massive; Sh, horizontally laminated; St, trough cross-bedded.

bed tops. These facies are interbedded with horizontally bedded successions of normally graded and massive gritty sandstones (Sg, Sm). Locally these facies contain interbeds of conglomerate and many isolated clasts were clearly derived by gravitational settling from overlying conglomerate beds (Fig. 12A and B). At Narachaams (Figs 4, 5A and 9A), the unit interpreted as the glacial Ghaub Formation by Hoffman *et al.* (1998) consists of thin breccia beds conformably inter-bedded with numerous thin-bedded graded and massive sandstones with sporadic 'outsized' carbonate clasts that show a crude imbrication (Fig. 9A). These clasts have the same lithology and shape as those

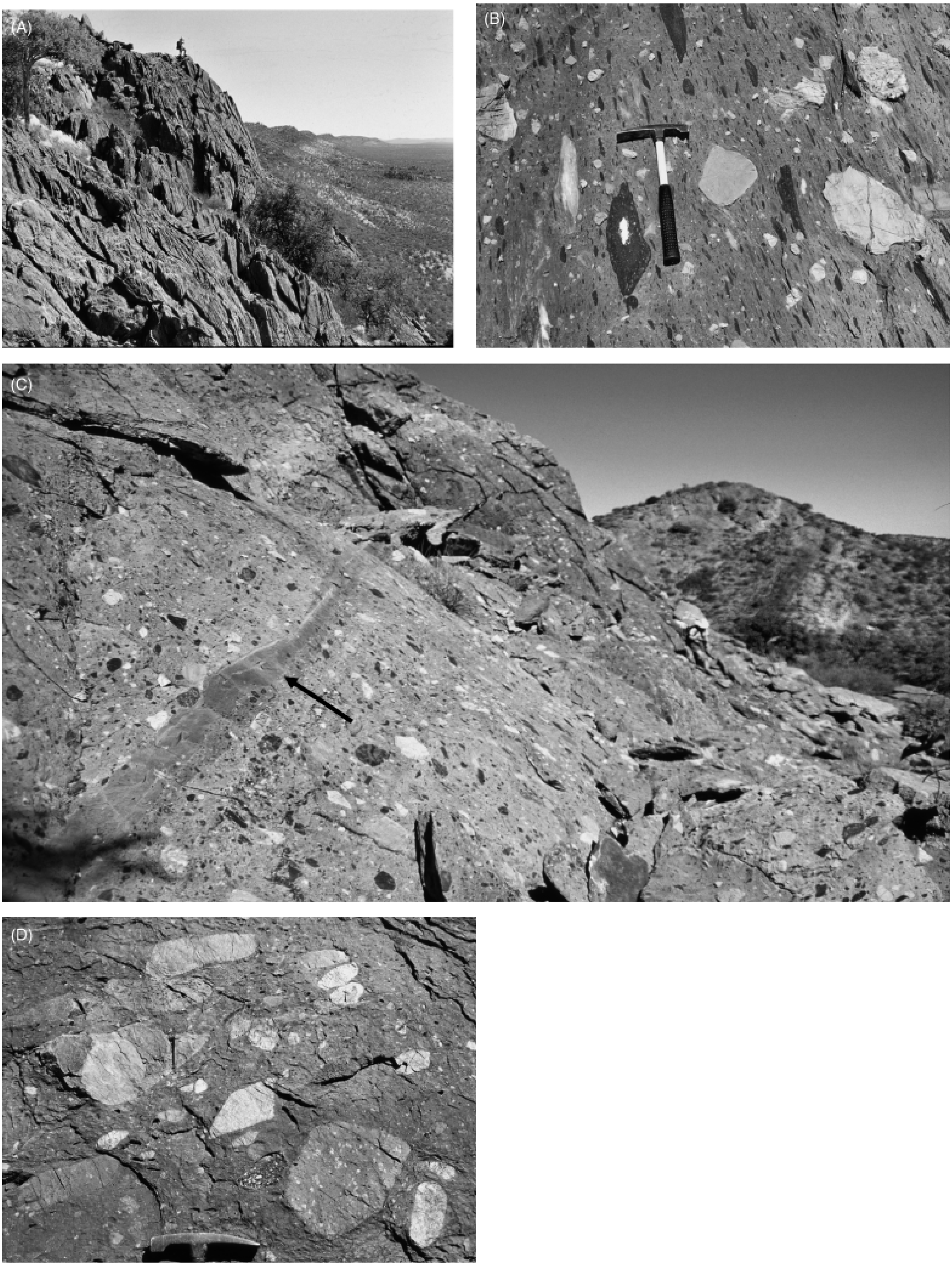

Fig. 6. Diamictite facies II. (A) 100-m-thick composite Ghaub diamictite (facies Dmm) on east side of Fransfontein Gap with figure for scale. (B) Stretched metamorphosed clasts in diamictite; deformation is local and primary clast orientations are in general, well preserved. (C) Thin mudstone interbed (arrowed) within diamictite unit shown in (A) records interval of pelagic mud deposition between debris flow events. Figure at right for scale. (D) Massive Chuos diamictite at Lowenfontein with subhorizontal carbonate and basaltic clasts in a ferruginous sandy carbonate matrix.

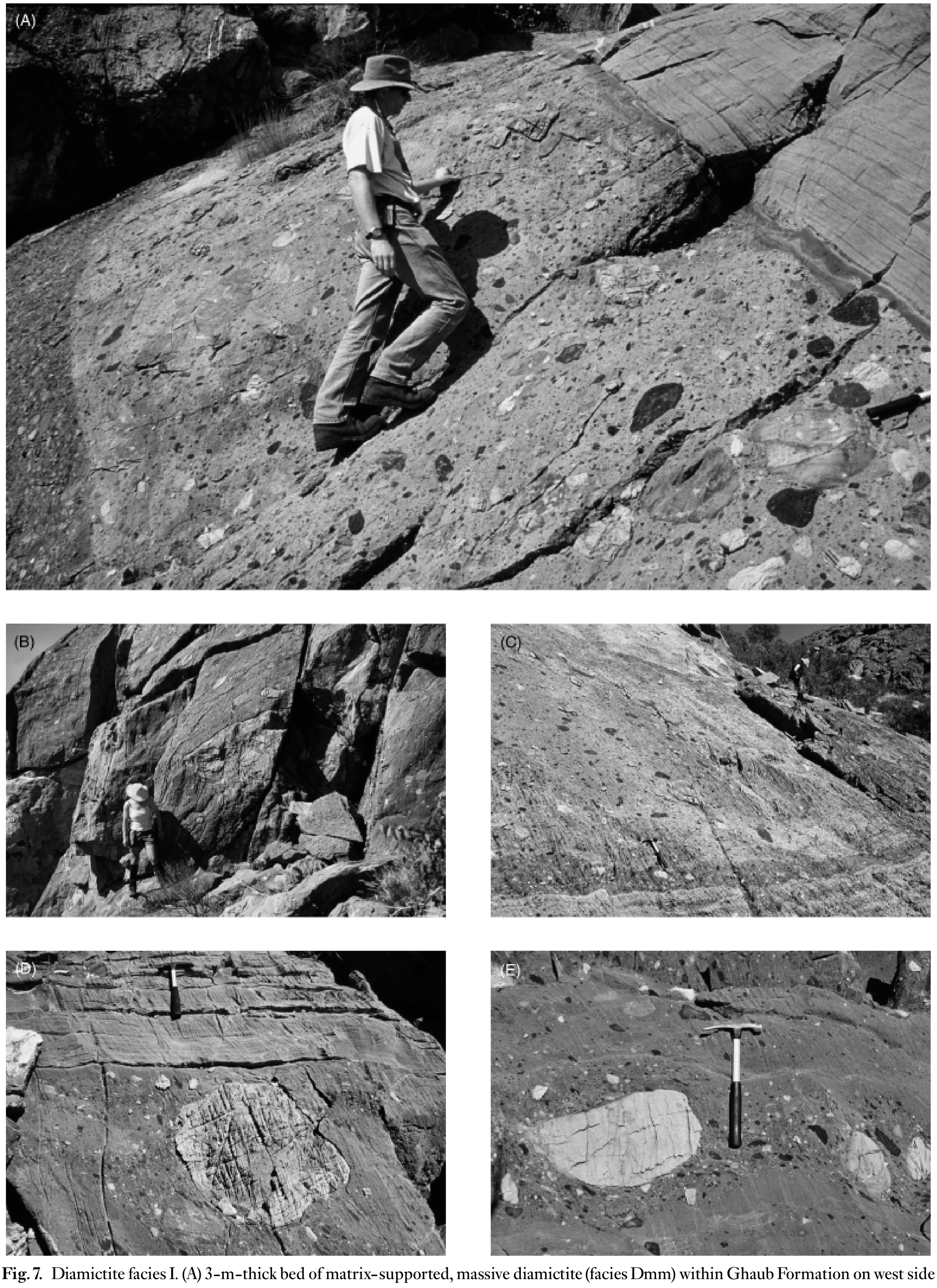

Fig. 7. Diamictite facies I. (A) 3-m-thick bed of matrix-supported, massive diamictite (facies Dmm) within Ghaub Formation on west side of Fransfontein Gap resting on conglomerate below and conformably overlain by thin-bedded, graded sandstone turbidites (facies Sg: Fig. 5B). (B) Large angular block of carbonate within Ghaub diamictite at Fransfontein. (C) 15-m-thick bed of massive diamictite in Ghaub Formation, Fransfontein. (D) Top of same diamictite bed as in (C) above with overlying thin-bedded and laminated-graded sandstones (Fig. 3). (E) Stratified diamictite facies (Dms) of the Ghaub Formation at Fransfontein produced by superimposition of debrites.

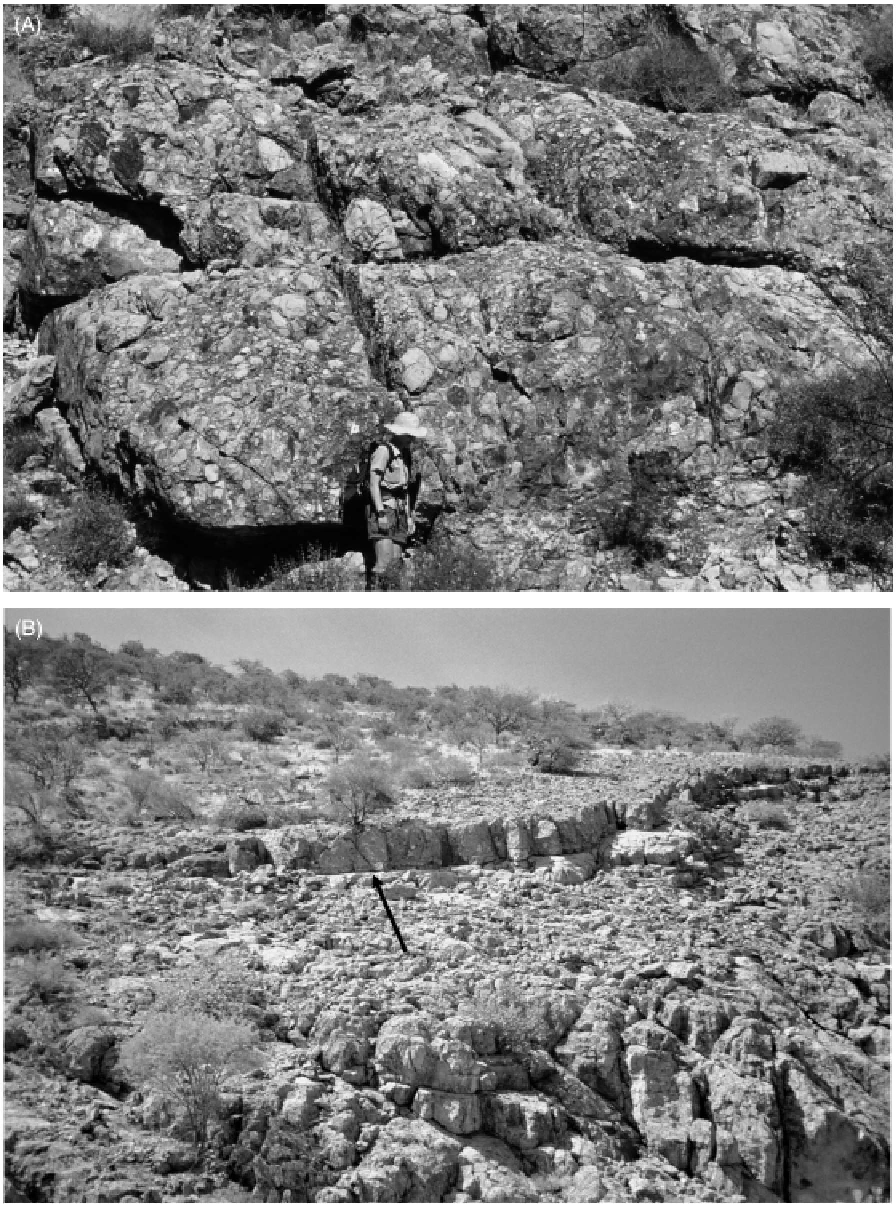

Fig. 8. Breccia facies II. (A) Mid-section of composite massive breccia bed more than 100 m thick within Abenab Formation at Narachaams (Fig. 4). (B) Prominent 10-m-thick breccia bed (base is arrowed) within same thick (100 m+) composite Abenab breccia unit at Narachaams. This bed is approximately 300 m wide and tapers laterally identifying a lobate debrite.

in underlying breccias. Graded and massive sandstones range in thickness from less than a centimetre (parallel-laminated facies; Fig. 10A) to a metre (thick-bedded facies) and represent partial Bouma sequences. The orientation of small, starved ripples (Fig. 10A) indicate southward-directed palaeocurrents. A broadly channeled geometry is evident at Fransfontein (Fig. 3) and facies are commonly deformed by slump structures; a large sedimentary dike is present at Narachaams (Fig. 4). As described above, beds of conglomerate, thin breccias and sandstone facies commonly occur as composite bundles where successive beds show a thinning-upward and fining-upward character (indicated by arrows on Figs 4, 5A and B).

Interpretation

Porada & Wittig (1983a, b) described the sandstone facies of the Outjo Basin as graded 'calcareous turbidites' and rejected the earlier interpretation of these facies as 'glacio-lacustrine varves' (Gevers, 1931). We fully agree with their interpretation based on the presence of well-developed normal grading shown by angular grains of detrital carbonate (Fig. 13). These facies were again simply labelled as 'varves' by Hoffman & Schrag (2000) despite the detailed work of Porada & Wittig (1983a, b).

In Fig. 5A and B, stacked bundles of fining- and thinning-upward units of breccia-conglomerate-sandstone are typical of mass flows that transport progressively finer grained sediment as a consequence of a diminishing supply of coarse material (Surlyk, 1978, 1984; Leppard & Gawthorpe, 2006). These bundles likely record single but complex sedimentation events. The overall fining-upward character of these bundles likely represents exhaustion of the upslope supply of coarse debris during episodic faulting and downslope failure. It is apparent that existing lithostratigraphic divisions ('preglacial' Abenab, 'glacial'

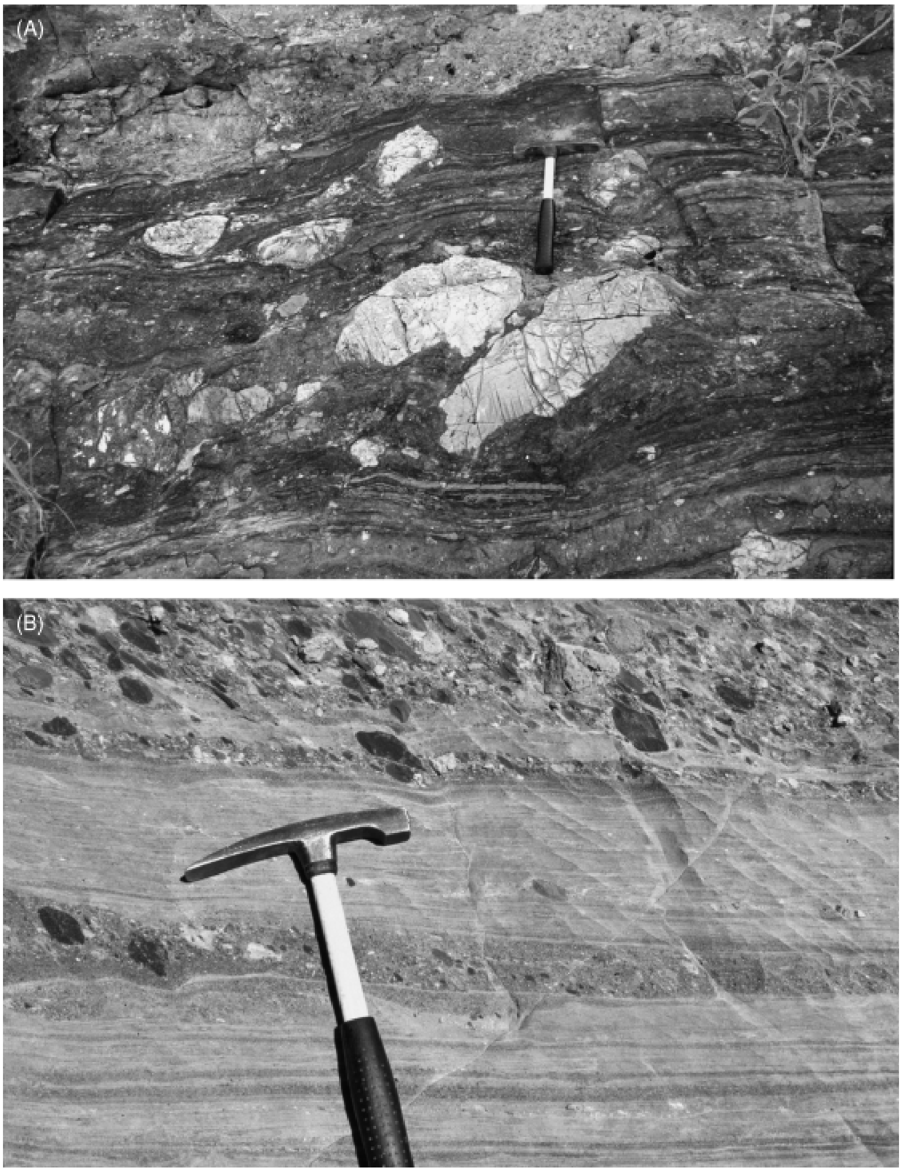

Fig. 9. Conglomerate/sandstone facies I. (A) Ghaub Formation at Narachaams (see Fig. 4) composed of complex stringers of conglomerate (facies Gm), interbedded with thin beds of graded (Sg) and massive (Sm) sandstone turbidites and breccias (B) with outsized carbonate clasts. Note imbrication of clasts indicating southward direction of flow. (B) Imbricated conglomerates (Gm, Gg) and sandstones (Sg) of the Ghaub Formation at Fransfontein (Fig. 3).

Ghaub and 'interglacial' Maieberg formations) are arbitrary subdivisions of genetically related mass flow 'bundles' (Figs 4 and 5A; see Discussion).

The large floating boulders ('lonestones') that occur in graded and massive sandstone facies of the 'Ghaub' at Narachaams (Figs 4, 5A and 9A) were given specific climatic significance by Hoffman *et al.* (1998) as a record of ice rafting ('dropstones'). Martin *et al.* (1985, p. 185) had earlier discussed the origin of so-called ice-rafted boulders and rejected a glacial origin. They argued instead that large clasts of carbonate had been freighted short distances by mass flows on the basis of their local derivation, the unambiguous mass flow origin of enveloping facies and the broader environmental setting involving deposition below unstable fault scarps. Hoffman (1983, p. 49) illustrated large outsized blocks of angular, locally derived carbonate supported by a stratified gritty sand matrix from the Swakop Group and similarly interpreted these facies as subaqueous, deepwater debris flows that had freighted outsized clasts. He stressed their syntectonic setting and pointed out that these had been previously 'misidentified as tillites'. The extreme angularity of clasts (Fig. 9A) indicates little transport distance from their source. No far-travelled lithologies can be identified among the floating lonestones in these Namibian outcrops and there is a conspicuous absence of evidence for a glacial source in the form of the classic glacially shaped 'bullet' clasts. Indeed, the outsized clasts in sandstones at Narachaams are no different in lithology and shape from those within the breccias of the Abenab Formation below (Figs 4 and 5A) from which we infer a very local source.

Locally derived lonestones (lithoclasts; Leppard & Gawthorpe, 2006) are commonly produced on unstable slopes by the partial sorting of coarse, poorly sorted debris leaving larger clasts as lags, or by the tumbling downslope of large semi-buoyant boulders ('outrunner clasts') from scarps into finer facies at the base of the slope. They are extremely common in gravity flow deposits of all ages and

Fig. 10. Sandstone facies. (A) Graded sandstones of the Maieberg Formation at Narachaams (Fig. 4); note presence of starved ripples (arrowed). (B) Graded sandstone facies (Sg) of Maieberg Formation at Narachaams resting on breccia below. The same sandstone facies occur as interbeds throughout diamictites of the Ghaub Formation (Figs 7, 9 and 12).

settings (Surlyk, 1984; Postma *et al.*, 1988; Bahamonde *et al.*, 2004; Eyles & Januszczak, 2004; Lutz *et al.*, 2006) and it is this mechanism that we favour for the outsized clasts at Narachaams (Figs 5A and 9A).

Graded sandstone turbidites of the upper part of the succession at Narachaams that lack outsized clasts (Maieberg Formation; Fig. 4) have been portrayed as postglacial 'cap carbonates'. They are argued to have been produced by the direct precipitation of carbonate from ocean waters oversaturated in carbonate (Hoffman & Schrag, 2002). Such an origin is precluded by their being composed of angular clastic particles (Fig. 13) and by the widespread presence of exactly the same facies within underlying strata (Figs 4 and 5A).

Diamictite facies (D)

Diamictite is a non-genetic descriptive term for poorly sorted, lithified mixtures of matrix and clasts. It is emphasized that such facies are produced in a wide range of depositional environments and they are not uniquely diagnostic of any one setting (Eyles et al., 1983). The term diamictite is used here in preference to terms such as 'matrix-supported breccia' or 'matrix-supported conglomerate' (e.g. Surlyk, 1978) because the Namibian facies contain mixtures of freshly broken, angular carbonate clasts (~70% of clasts) together with sub-rounded clasts (Figs 6 and 7) and thus strictly fall outside either category based on clast shape.

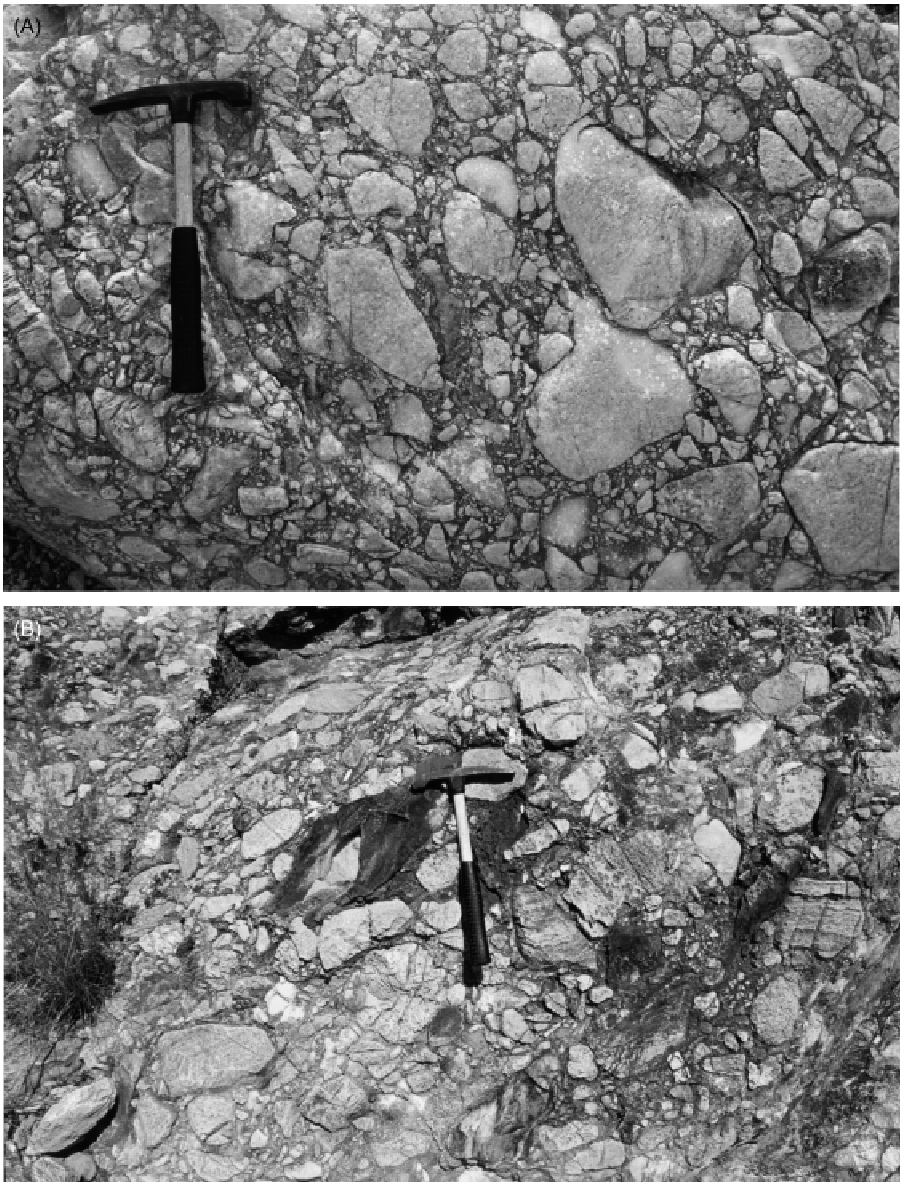

Fig. 11. Breccia facies I. (A) Clast-supported massive carbonate breccia facies (Bcm) at Fransfontein (Abenab Formation; Fig. 3). (B) Same breccia facies in Abenab Formation at Narachaams (Fig. 4) with complex transitions to matrix support (facies Bmm). Note weak clast imbrication in both examples.

Massive, matrix-supported diamictites (Dmm) predominate but stratified, matrix-supported facies (Dms) also occur where thinner beds of massive facies have been superimposed to form crudely bedded deposits. Throughout, clasts are supported by a gritty, often grey-coloured matrix of silty sand. At Narachaams and Fransfontein, clasts within diamictites are composed of varicoloured dolostone, limestones and a distinctive black chert exclusively derived from the underlying Abenab Subgroup. At Lowenfontein, local carbonate lithologies also dominate, but basement lithologies, especially basalt and granite clasts, are present. Clast orientation in diamictites appears to be unordered. No striated or glacially shaped clasts have been identified despite observation of many hundreds of metres of thickness, extensive areas of bedding planes and large zones of broken rubble where numerous clasts are freed from their matrix. This is in agreement with previous workers who were unable to identify definite evidence of a glacial source of sediment (Gevers, 1931; Martin *et al.*, 1985).

Diamictite beds are lenticular in cross-section similar to breccia facies, with thicknesses that range from 20 to 100 m. These thicker units are likely composite depositional units arising from the superimposition of successive beds. Amalgamation of one bed to another is recorded by thin (<25 cm) interbed horizons of deformed mudstone. They are laterally impersistent along strike as a result of local erosion and incorporation into the overlying bed. Irregular 'flame shaped' intrusions of mudstone extend into the basal diamictite where it rests on interbedded mudstone; isolated mudstone clasts commonly armoured by small clasts are also found in the basal parts of diamictite. Diamictites are interbedded with conglomerate and sandstone turbidites (Figs 7C and 12B) and commonly show evidence of gravitational soft-sediment loading at bed tops where overlain by these facies (Fig. 5B). Large rafts of carbonate are common (Fig. 7B) with larger clasts often protruding from bed tops, draped by finer grained facies. Martin et al (1985, p. 182) noted that thicker beds contain

Fig. 12. Conglomerate/sandstone facies II. (A) Multiple crudely graded conglomerates interbedded with graded sandstone facies: Ghaub Formation at Fransfontein (Fig. 3). (B) Erosionally based massive (Gm) to crudely graded (Gg) conglomerate bed below diamictite: Ghaub Formation, Fransfontein. Note considerable variation in clast shape and imbrication.

larger clasts and this is supported by our observations as similarly noted above in regard to breccia facies.

Interpretation

Diamictite facies occur in many environments; hence, when taken out of the context provided by underlying and overlying facies, their interpretation is not straightforward. Nonetheless, there are sufficient clues available in Namibia to identify a precise depositional mechanism and setting. Of primary importance is the conformable interbedding of diamictites with breccias, conglomerates and sandstones deposited in water by sediment gravity flows. This is strong contextual evidence for a subaqueous origin for diamictites in an environment dominated by gravity-driven mass wasting. The presence of intraformational mudstone, often incorporated or gravitationally intruded into diamictite bases, is additional confirmation of a subaqueous setting. Consequently, diamictites are interpreted as debrites deposited by cohesive debris flows. Diamictites share characteristics of both matrix-supported breccias (with angular clasts) and matrix-supported conglomerates (rounded clasts). The presence of both rounded and angular clasts in diamictites can be explained by mixing of unconsolidated breccia, gravel, sand and mud during downslope slumping of heterogenous sediments (e.g.

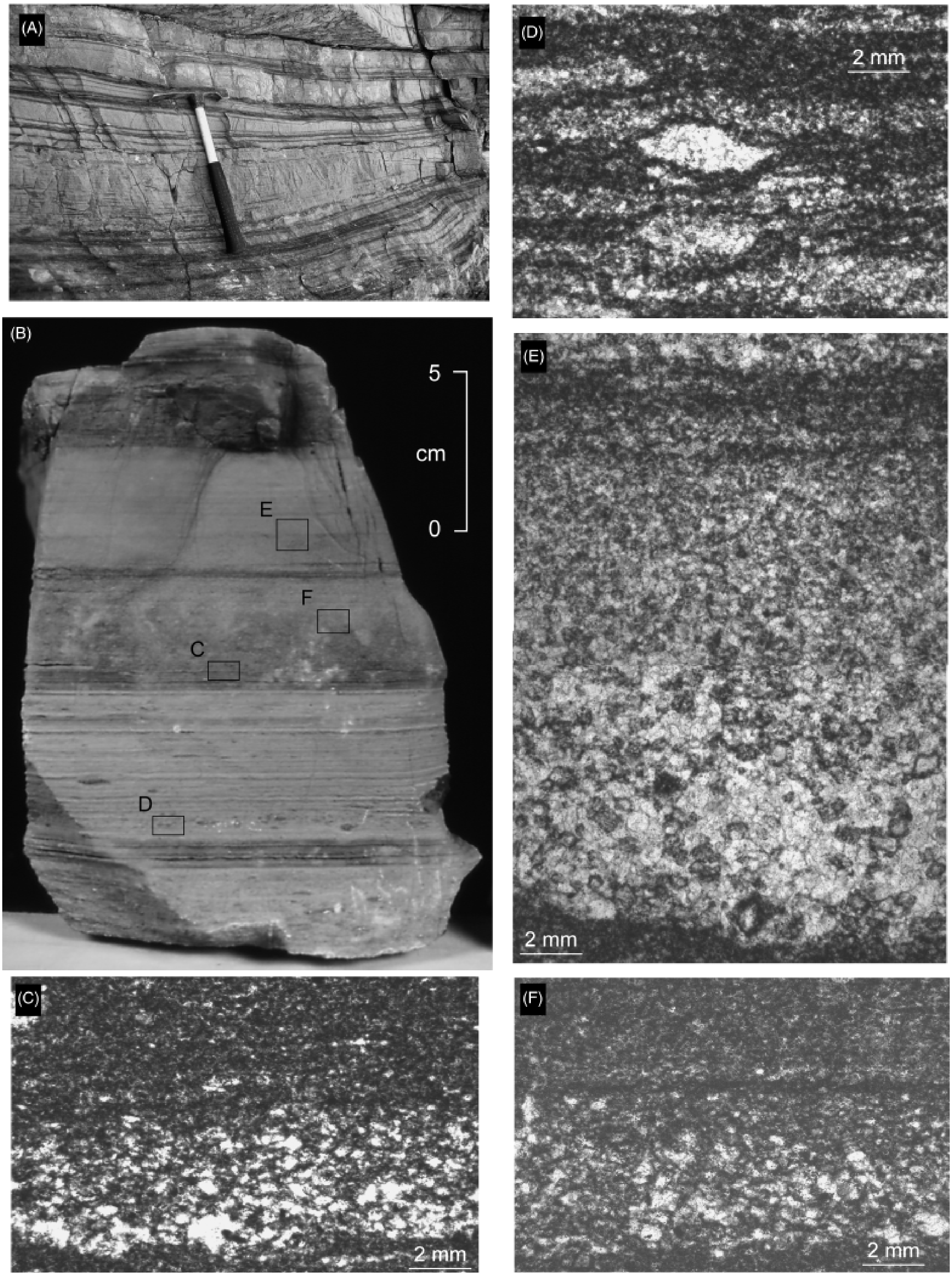

Fig. 13. Outcrop (A) and sawn block (B) with thin-section microphotographs (C–F) of graded sandstone turbidites (facies Sg). Where these facies rest directly on diamictites or breccia facies such as at Narachaams (Fig. 11A and B) they have been described as 'cap carbonates' resulting from carbonate precipitation in a brutally hot interglacial climate (Hoffman & Schrag, 2002). Where these facies are interbedded with diamictites (Figs 7A and 9B) they are described by these same workers as 'varves' (e.g. Fig. 11).

Crowell, 1957; Nemec *et al*., 1984; Eyles & Eyles, 2000). Gravitational loading structures on bed tops (Fig. 5B) suggest soft material properties consistent with underwater debris flows. Schermerhorn (1974) specifically introduced the term *mixtite* for diamictite facies such as those in Namibia, which he argued had been generated by the mixing of coarse and fine sediments during mass flow. In our opinion, this is a very useful genetic term for the Namibian diamictite facies described here. Repeated mixing of heterogenous sediment was likely a common process as unstable slopes underwent repeated episodes of downslope failure. Different sediments at the tops of slopes (or even in mid-slope) were slurried and churned during downslope flow as if in a concrete mixer (Crowell, 1957; Eyles, 1987; Eyles & Eyles, 2000). The presence of rounded clasts within diamictites and conglomerates suggests that fluvial or littoral sediments were reworked and mixed downslope (e.g. Surlyk, 1978). Incorporation of matrix material into coarse-grained flows is a common process on subaqueous fans (Nemec *et al*., 1984; Walker, 1992).

Mudstone interbeds preserved locally between debrites likely record breaks in deposition between successive flow events. This sediment accumulated either by pelagic fallout of fines expelled from the top of the debrite itself or from separate muddy gravity flows. Associated flame structures record the gravitational loading of debris flows into unconsolidated muds. The incorporation of mud into subsequent flows may have increased matrix content and overall cohesiveness. It is likely that flows experienced repeated episodes of downslope movement resulting in progressive homogenization of different sediment types to produce matrix-supported diamictites.

TECTONIC AND DEPOSITIONAL SETTING

The facies analysis presented here identifies breccias, diamictites, conglomerates and sandstones as a genetically related family of sub-aqueously deposited sediment gravity flows. These record non-turbulent debris flow (massive breccias, diamictite) and turbulent flow (graded facies). The dominance of unsorted massive facies and their very considerable thickness indicate a slope setting very close to a substantial source of freshly broken carbonate rock. The presence of rounded clasts and mud suggests an additional fluvial or shallow marine sediment source upslope. A glacial source cannot be ruled out but no diagnostic indicators (striated, shaped clasts) are evident (Gevers, 1931). Our interpretation is perfectly consistent with the regional synrift submarine fan depositional setting proposed by Porada & Wittig (1983a, b), Martin *et al*. (1985) and Frimmel *et al*. (2002) based on regional investigations. Large volumes of reworked clastic carbonate were produced when the Congo Craton underwent extension and was faulted into numerous sub-basins (see Porada & Wittig, 1983b). The presence of basement lithologies in the Chuos is indicative of basement exposure in horst sidewalls during extension and faulting (e.g. Surlyk, 1978; Miller, 1983a, b) rather than a far travelled glacial source. We found no indicators of shallow water (i.e. facies deposited above wave base) and the entire succession most likely accumulated in relatively deepwater in a base-of-slope setting on the margins of fault blocks along the outer edge of the Otavi Platform. Continued tectonic movement and ongoing subsidence controlled by faulting are indicated by common intraformational normal faults, sedimentary dikes, by the abundance of reworked carbonate detritus and by intraformational unconformities (Fig. 3). It is possible that the stacked bundles of breccia/diamictite–conglomerate–sandstone (Fig. 5) record individual faulting events and associated slope failure such as large rock falls accompanying large earthquakes during extension.

The resedimented Otavi Group facies described herein are no different from those reported from submarine syntectonic wedges at the base of active fault scarps (see Gawthorpe *et al*., 1990, 2003; Gawthorpe & Leeder, 2000). The work of Surlyk (1978, 1984) is especially relevant here. He described coarse-grained sediment gravity flow deposits of the Jurassic–Cretaceous Wollaston Forland Group in east Greenland that were deposited in coalescing submarine fans. A directly comparable depositional setting is reflected in the broader geometry and known geodynamic setting of the Otavi Group that comprises a basinward thickening wedge banked against the rifted Congo Craton (Fig. 2). This is in keeping with the overall plate-tectonic setting involving the southward-directed rifting of the Congo Craton margin. Johnson *et al*. (2005) established that a major pulse of rifting across south central Africa was initiated between *ca*. 800 Ma and at *ca*. 750 Ma, consistent with recent age estimates of the base of the Otavi Group (*ca*. 760 Ma: Halverson *et al*., 2005). The broader palaeogeographic and palaeolatitudinal setting of southern Africa at this time, specifically its position within any one Rodinian assembly, is uncertain (Tohver *et al*., 2006).

DISCUSSION

The overall tectono-depositional setting favoured for the Otavi Group diamictites and breccias integrates our observations reported here with the regional work of previous authors. The depositional setting likely consisted of coalesced submarine fans at the foot of tilted fault blocks with each fan containing a local record of sediment gravity flow events unique to that sub-basin. Existing lithostratigraphic divisions based on an assumed global climatic significance (pre-glacial 'Abenab', glacial 'Chuos', 'Ghaub', and post-glacial 'Maieberg' formations) are arbitrary, climate model-based subdivisions of genetically related mass flow bundles.

Glacial vs. non-glacial origin

Gevers (1931) interpreted rocks he named Chuos Tillite as 'basal moraine' left by a glacier. De Kock & Gevers (1933) regarded this glaciation as short lived in keeping with the then prevalent notion that such events were anomalous 'climatic accidents'. This carried the added assumption that deposits were a precise chronostratigraphic marker throughout southern and central Africa, a scheme that was greatly influential (Martin, 1965a, b; Kröner & Rankama, 1972) and adopted as a method of correlating Neoproterozic rocks worldwide (Ojakangas, 1988). Le Roex (1941, p. 218) summarized this view succinctly: 'if the presumed correlation is correct we are faced with isolated glacial deposits very widely separated from one another, indicating old ice movements on a gigantic scale'. Mawson (1949) spoke of a worldwide glaciation extending to the equator (Eyles, 2004, p. 161). Nonetheless, Gevers (1931, p. 5) had some doubts and was troubled by the great thickness of the Chuos Tillite (compared with modern or Quaternary tills) and by his inability to recognize any glacially striated clasts despite extensive outcrops. In retrospect, his interpretations were hampered by a lack of any understanding of depositional environments in which poorly sorted sediments could be deposited by processes other than by glacial action. There was no awareness, for example, of the importance of sediment gravity flow, which had to await the work of Kuenen (1951) and Crowell (1957). Gevers (1931) invoked a glacial origin because of the presumed regional extent of the deposit that he thought could only have been deposited under an extensive ice sheet.

Schermerhorn (1974, pp. 777–778) used emerging information regarding the sedimentary products of mass flows in areas of active tectonics (e.g. Crowell, 1957) to rule out a direct glacial origin not only for the Namibian deposits but also for other poorly sorted deposits in Zaire and Angola correlated by De Kock & Gevers (1933). Porada & Wittig (1983b, p. 26) rejected Gevers' (1931) interpretation of tillites and varves in the Chous, emphasizing their origin as turbidity current and debris flow deposits in an evolving rift basin. Others reached the same conclusion (Frets, 1969; Guj, 1974; Hedberg, 1976; Miller 1983a, b) though some did not despite being unable to recognize specific features diagnostic of a glacial origin other than a supposed 'blanket-like nature', 'lack of sorting, massive bedding and abundant matrix' (Miller, 1981, p. 6, 1983a, b, p. 502; Downing, 1983; Hoffman, 1983). None of these characteristics is uniquely diagnostic of a glacial origin and we are reminded of the similar debate regarding the so-called 'Mawson Tillite' of Antarctica (see Borns & Hall, 1969; Reubi *et al.*, 2005). Schermerhorn's (1974) re-evaluation of the Namibian strata prompted a detailed study by H. Martin, formerly a strong proponent of a glacial origin (Martin, 1965a, b), but later, he concluded that diamictite strata were indeed deposited by synrift submarine mass flows in an active rift basin with no evidence of extensive glaciation (Martin *et al.*, 1985). These conclusions are highly relevant to our study viz: (1) the deposits show no features indicative of any one climatic setting; (2) sediment gravity flow processes were dominant; (3) turbidites are interbedded with diamictites; (4) diamictites are not confined to any one formation (e.g. 'Chuos', 'Ghaub') but are present repeatedly at different stratigraphic levels and were therefore deposited at different times from one part of the basin to another and (5) reworked clastic carbonate sediments are interbedded throughout.

Relevance for Neoproterozic climate models

Marked variation in the rates of fault displacement from one part of a rift basin to another gives rise to a wide range of facies types and stacking patterns in contemporary strata (Ravnas & Steel, 1998; Allen & Densmore, 2000; Gawthorpe & Leeder, 2000). Porada & Wittig (1983b, p. 28) concluded in regard to the turbidite and mass flow successions of the Damara Orogen: 'correlation of sections is not possible due to the lack of chronostratigraphic markers and the complex facies relationships of the diachronous units'. Porada & Wittig (1983b, p. 34) specifically stated that the 'Chuos Formation can no longer be accepted as a chronostratigraphic marker horizon'. Nonetheless, Hoffman & Prave (1996, p. 81) imposed their climato- and chronostratigraphic framework on the Outjo Basin consisting of two regionally extensive glacial horizons (Chuos, Ghaub formations) and postglacial cap carbonates (Rasthof and Maieberg formations, respectively; Fig. 2). This simplified division of a complex basin fill was not founded on modern sedimentary basin analysis integrating facies analyses with tectonic and other data (see e.g. Fig. 3 in Hoffman & Prave, 1996). Nonetheless, the glacial/interglacial interpretation was then transmuted into evidence for 'late Neoproterozoic climate shocks without parallel in the Phanerozoic' during two glaciations (Sturtian and Marinoan; Hoffman & Schrag, 2002, p. 129). The 'glacial/postglacial couplet' model is now extrapolated far beyond Namibia involving synchronous glaciations and interglaciations of global extent (Snowball Earth; Halverson *et al.*, 2005) echoing the earlier worldwide glaciation of Gevers (1931), Le Roex (1941) and Mawson (1949).

A model of marine sedimentation below a grounded ice shelf has most recently been presented for the deposits at Fransfontein in recognition of the subaqueous origin of these facies (Hoffman, 2005). Facies descriptions are not provided in support of a glacial origin and, instead, reliance is placed on the recognition of supposed ice-rafted dropstone clasts (Hoffman & Prave, 1996, p. 78) together with the presence of thin mudstone horizons within till (diamictites of our study) supposedly deposited in 'meltwater puddles beneath grounded ice' (Hoffman, 2005, p. 569). The recognition of meltwater is a major retreat from previous assertions that the entire hydrological cycle was shut down by extreme cold ($-50\,^{\circ}$C) but the model still hinges on a supposed glacial source of sediment. The absence of striated and glacially shaped clasts in diamictites is recognized as problematic (Hoffman & Schrag 1999, p. 1087; Hoffman, 2005) and is explained by catastrophic globe-wide freezing of a tropical shallow-water platform where debris is incorporated within the ice sheet by repeated freezing-on of water to the ice base. Diamictites were later released passively without experiencing any abrasion (as a melt out tillite) when debris-laden ice downwasted *in situ* at the end of the glaciation when global temperatures abruptly rose from −50 to +50 °C (Hoffman *et al.*, 1998; Hoffman & Schrag, 2002). Some alpine glaciers (but not ice sheets) do indeed transport large volumes of poorly sorted breccia on their surface in the form of supraglacial debris derived from rock falls from bounding cliffs and mountainsides. Such facies, however, are always deposited in association with other indisputable glacial deposits such as tills bearing large numbers of glacially shaped and striated clasts (Boulton, 1978; Eyles, 1979). Strangely, little mention is made in the Snowball Earth literature of the presence and very considerable thicknesses of the breccia facies that occur repeatedly throughout the Otavi Group within the Abenab 'preglacial' and Ghaub 'glacial' rocks. These are a striking lithostratigraphic component and a key diagnostic indicator of the overall basinal setting and a strong tectonic control on facies types possibly involving seismic shaking, fault movement and the collapse of steep fault scarps.

SUMMARY AND CONCLUSIONS

We conducted sedimentological investigations of specific outcrops in Namibia identified by Hoffman *et al.* (1998) and Hoffman & Schrag (2002) as recording global glaciations and interglaciations involving extreme, catastrophic temperature fluctuations. These rocks had been previously interpreted as synrift mass flows lacking any specific climate significance (Frets, 1969; Guj, 1974; Schermerhorn, 1974; Hedberg, 1976; Downing, 1983; Miller, 1983a, b; Porada & Wittig, 1983a, b; Martin *et al.*, 1985). Facies descriptions reported here do not support a glacial-interglacial model. These strata have a subaqueous, non-glacial mass flow origin and were deposited coincident with rifting during breakup of the Congo craton. No unique climatic significance in terms of either cold or warm climates can be identified from these subaqueously deposited facies, which are directly comparable to numerous subaqueous slope deposits reported elsewhere throughout the Phanerozoic record. If glaciers were present, they played an indirect, imperceptible role in transporting and delivering sediment to the basin belying their putative significance as records of globally cold climatic catastrophes. According to Hoffman (2005, p. 565), 'the carbonate-glacial association so well developed in Namibia lies at the core of the Cryogenian climatic paradox'. Our study provides a direct sedimentological test of this assertion and concludes that these strata can be explained without recourse to extreme climatic events. It is our conclusion that these rocks provide no clear sedimentologic evidence of catastrophic Snowball Earth-type glaciations and interglaciations but point to a dominant tectonic control on subaqueous mass flow sedimentation most likely related to repeated episodes of faulting and slope failure.

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