A misfit Cryogenian diamictite in the Vrede domes, Northern Damara Zone, Namibia: Chuos (Sturtian) or Ghaub (Marinoan) Formation? Moraine or Palaeovalley?

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Abstract: A wedge-shaped mass of glacigenic diamicite up to 220 m thick is exposed in the southwestern part of the more southerly of two structural domes on Vrede Farm, in the northwestern corner of the Northern Zone of the Damara Belt. The clasts and matrix of the diamictite are sourced mainly from the crystalline basement, which is characteristic of the older Cryogenian (Sturtian) Chuos Formation. The Chuos glaciation coincided with crustal stretching and uplift of basement blocks, while the younger Cryogenian (Marinoan) Ghaub glaciation occurred during passive-margin subsidence. The Ghaub glaciation generated diamictite derived nearly exclusively from carbonate rocks of the directly underlying Abenab Subgroup. However, the apex of the wedge of diamictite at Vrede is directly overlain by the basal Ediacaran Keilberg 'cap dolostone' Member of the Karibib Formation. Accordingly, the diamictite was assigned to the Ghaub Formation, despite its 'misfit' composition. To test this assignment, we measured 20 closely-spaced stratigraphic sections around the Vrede domes, including 15 sections in the southern dome, where we 'walked out' the thin (<4.3 m) Rasthof Formation, the lithologically-distinctive post-Chuos 'cap carbonate.' We show unequivocally that the wedge of diamictite stratigraphically underlies the Rasthof 'cap carbonate' and is therefore Chuos (Sturtian) in age, consistent with its composition. The apex of the wedge is truncated by the sub-Ghaub erosion surface, which is overlain by 0-5.5 m of carbonate diamictite (Ghaub Formation) and the Keilberg 'cap dolostone' Member. The wedge of diamictite has an aspect ratio of 0.15 and did not fill a palaeovalley because no incision is observed in the underlying Ugab Subgroup. We conclude that it originated as a moraine-like buildup, presumably at a stable ice margin or grounding line, and was ultimately buried by basinal argillaceous sediments of the Narachaams Member during the nonglacial interlude between the Sturtian and Marinoan glaciations. It was erosionally decapitated during the Ghaub glaciation by an ice sheet that left little diamictite in the Vrede domes area. Our work illustrates the importance of measuring multiple, closely-spaced, stratigraphic sections for the interpretation of Cryogenian glacial stratigraphy.

Key Words: Neoproterozoic; Sturtian glaciation; diamictite; moraine.

To cite this article: Hoffman, P.F. Bellefroid, E.J. Crockford, P.W. de Moor, A. Halverson, G.P. Hodgin, E.B. Hodgskiss, M.S.W. Holtzman, B.K. Jasechko, G.R. Johnson, B.W. & Lamothe, K.G. 2016. A misfit Cryogenian diamictite in the Vrede domes, Northern Damara Zone, Namibia: Chuos (Sturtian) or Ghaub (Marinoan) Formation? Moraine or Palaeovalley? *Communications of the Geological Survey of Namibi*a, **17**, 1-16.

Submitted 24 March 2016

Introduction

Vrede domes (Maloof, 2000) comprise a pair of doubly-plunging anticlines located in the northwest corner of the allochthonous Northern Zone of the Pan-African Damara Belt (Miller, 1983, 2008) of Namibia (Fig. 1, 2). The domes form topographically prominent inliers (Fig. 3, 4) of Swakop/Otavi Group carbonate and coarse-grained clastic rocks that dip steeply outward beneath semipelitic schist, carbonate-clast debrite and conglomerate of the synorogenic, middle Ediacaran, Kuiseb Formation (Frets, 1969; Maloof, 2000; Schreiber, 2006). Maloof (2000) interpreted the domes as interference folds, produced by successive orthogonal crustal-thickening events in the Kaoko (east-west shortening) and Damara (north-south shortening) belts, at the junction of which the domes are situated. The domes are 1.5 km wide and 5.0 km in combined length, and lie at the foot of the Early Cretaceous Etendeka volcanic escarpment on the west bank of the Huab River. They are accessible by 4WD vehicle from the track from the north through Vrede Farm and from the south via the track between the farms Bethanis and De Riet.

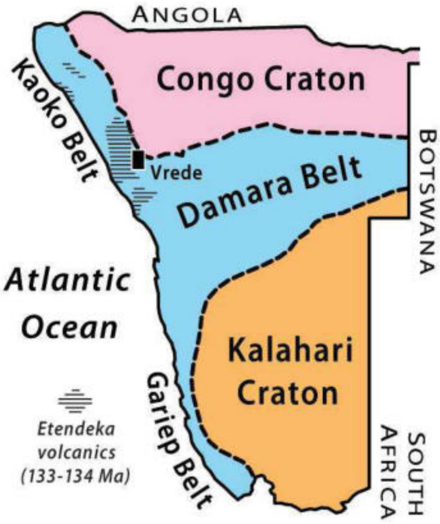

Figure 1: Location of the Vrede domes area (black rectangle) at the junction of the Northern Zone of the Damara Belt and the Eastern Zone of the Kaoko Belt.

Maloof (2000) recognized the presence in both domes of two Cryogenian glaciations, represented by glacial-paraglacial diamictites of the Chuos (Sturtian) and Ghaub (Marinoan) formations, and their respective cap-carbonate sequences, the Rasthof and basal Karibib (Keilberg Member) formations. Maloof (2000) also recognized an older diamictite of uncertain origin and limited extent in the core of the south dome. He showed that the Rasthof Formation, although less than 4.4 m thick in the domes, is key to distinguishing the two Cryogenian diamictites. However, the Rasthof Formation is absent at the southern closure of the south dome (Fig. 3, 4), where a southwestward-thickening wedge of polymictic boulder diamictite (fine-grained matrix-supported conglomerate) up to 220 m thick appears. The wedge includes massive and stratified diamictites, as well as subordinate sorted conglomerate and clast-free siltstone. The predominance of crystalline basement debris is characteristic of the Chuos Formation. In contrast, the Ghaub Formation is dominated by carbonate-clast diamictite. Regionally, the consistent lithologic contrast in diamictites reflects the tectonic transition from crustal stretching during the Chuos glaciation to passive-margin thermal subsidence during the Ghaub glaciation (Hoffman & Halverson, 2008). Yet, the basement-dominated diamictite wedge in the south dome is directly overlain by the Karibib Formation, including a well-developed Keilberg Member, which is the basal Ediacaran cap dolostone regionally affiliated with the younger Ghaub glaciation (Hoffmann & Prave, 1996; Hoffman & Halverson, 2008; Hoffman, 2011). Accordingly, the Chuos-like diamictite body in the south dome was provisionally assigned to the Ghaub Formation (Maloof, 2000; Schreiber, 2006; Hoffman & Halverson, 2008) despite its atypical derivation and composition.

As the stratigraphy in the domes exhibits considerable local variability, we mapped and measured 20 sections over a strike-length of 10.5 km around the periphery of the domes (Fig. 3, 4). The sections clearly distinguish the Chuos and Ghaub diamictites and demonstrate unequivocally that the wedge of diamictite in the south dome belongs to the Chuos Formation. We use the stratigraphies of the underlying and overlying units to show that the Chuos wedge, which has an aspect ratio of 0.15, or 15% grade (0.22/1.5 km), was a moraine-like body with positive topographic relief and did not fill a palaeovalley. This exercise illustrates the importance of measuring multiple, closely-spaced, stratigraphic sections for the interpretation of Cryogenian glacial stratigraphy.

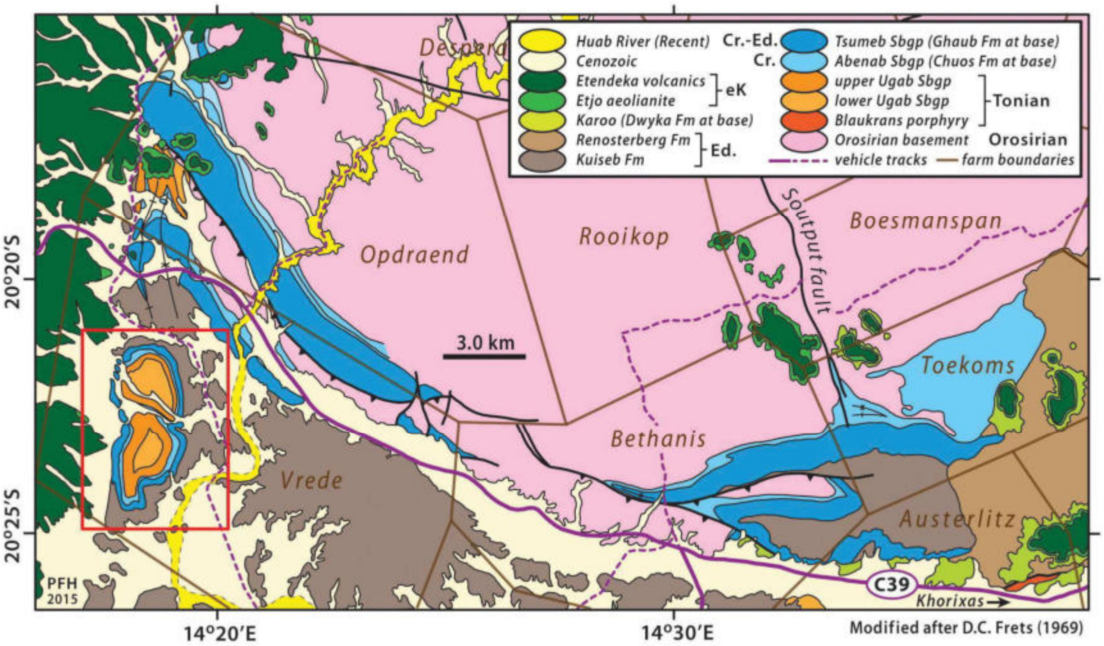

Figure 2: Geology of the southwestern border of the Kamanjab inlier at the junction of the Damara and Kaoko belts (modified after Frets, 1969). The southwest-dipping thrust system (barbed black lines) that parallels road C39 (purple line) separates the allochthonous Northern Zone to the southwest from the autochthonous-parautochthonous Northern Margin Zone to the northeast (Miller, 2008). Vrede domes occur within the red rectangle, which shows the area of Fig. 3. The Huab River drainage is indicated by the yellow band. The Ugab Subgroup (Tonian) is limited to the Northern Margin Zone. Abbreviations in legend: Cr. Cryogenian; Ed. Ediacaran; eK, Early Cretaceous.

Methods

Formation contacts were mapped on enlargements of national 1:50,000 monochrome air photographs (frames 746-5-298, 746-5-299, 746-6-378 and 746-6-379) and polychrome satellite imagery from Google Earth (Fig. 4). Key units like the Rasthof Formation were walked out. Stratigraphic sections were measured (in the palaeovertical) with a folding 2 metre scale, usually unfolded to 1.5 m for convenience. This was facilitated by generally steeply dipping strata, rugged topography, and minimal vegetation due to average annual precipitation of 15-20 cm. The geographical coordinates of the base and top of each section are given in Table 1.

Table 1. Geographical coordinates of measured sections

Section	Coordinates at base of section	Coordinates at top of section
I	20° 23' 37.8" S; 14° 09' 19.2" E	20° 23' 30.20" S; 14° 08' 55.1" E
II	20° 23' 33.3" S; 14° 09' 32.1" E	20° 23' 33.5" S; 14° 08' 53.6" E
III	20° 22' 13.7" S; 14° 09' 38.5" E	20° 22' 10.6" S; 14° 09' 54.4" E
IV	20° 21' 45.1" S; 14° 09' 15.9" E	20° 21' 38.1" S; 14° 09' 10.0" E
1	20° 22' 59.1" S; 14° 09' 02.0" E	20° 23' 05.0" S; 14° 08' 59.2" E
2	20° 13' 18.4" S; 14° 09' 02.5" E	20° 23' 15.9" S; 14° 08' 55.6" E
3	20° 23' 44.2" S; 14° 08' 52.4" E	20° 23' 43.3" S; 14° 08' 43.1" E
4	20° 23' 59.3" S; 14° 08' 52.4" E	20° 23' 58.0" S; 14° 08' 46.3" E
5	20° 24' 13.7" S; 14° 08' 54.4" E	20° 24' 15.0" S; 14° 08' 42.6" E
6	20° 24' 20.0" S; 14° 08' 58.5" E	20° 24' 31.4" S; 14° 08' 49.9" E
7	20° 24' 20.1" S; 14° 08' 58.7" E	20° 24' 31.8" S; 14° 09' 00.2" E
8	20° 24' 16.7" S; 14° 09' 06.9" E	20° 24' 18.6" S; 14° 09' 12.2" E
9	20° 24' 09.8" S; 14° 09' 10.3" E	20° 24' 10.3" S; 14° 09' 13.0" E
10	20° 24' 03.0" S; 14° 09' 13.1" E	20° 24' 06.8" S; 14° 09' 16.1" E
11	20° 24' 00.5" S; 14° 09' 19.2" E	20° 24' 02.7" S; 14° 09' 16.8" E
12	20° 23' 59.9" S; 14° 09' 32.7" E	20° 24' 03.1" S; 14° 09' 26.9" E
13	20° 23' 54.2" S; 14° 09' 40.0" E	20° 23' 55.1" S; 14° 09' 45.9" E
14	20° 23' 27.5" S; 14° 09' 50.3" E	20° 23' 29.1" S; 14° 10' 01.3" E
15	20° 23' 08.9" S; 14° 09' 44.4" E	20° 23' 06.9" S; 14° 09' 47.7" E
16	20° 22' 27.0" S; 14° 09' 58.1" E	20° 22' 35.5" S; 14° 10' 04.4" E
17	20° 22' 10.9" S; 14° 09' 54.4" E	20° 22' 12.9" S; 14° 10' 02.1" E
18	20° 21' 51.4" S; 14° 09' 46.2" E	20° 21' 50.4" S; 14° 09' 55.1" E
19	20° 21' 35.3" S; 14° 09' 34.4" E	20° 21' 30.2" S; 14° 09' 35.5" E
20	20° 21' 38.1" S; 14° 09' 10.0" E	20° 21' 25.4" S; 14° 09' 01.1" E

The lithological divisions used to measure, describe and graphically present the measured sections (Fig. 5, 6) are described in Table 2. The measured sections have not been corrected for tectonic strain, which is most likely to be significant for the rheologically weak Narachaams Member (Fig. 6). Stratigraphic nomenclature follows SACS (1980), modified by Hoffmann & Prave (1996), Schreiber (2006) and Miller (2008). The Cryogenian period has yet to be formally defined. In this paper, we place the Tonian–Cryogenian boundary at the base of the Chuos Formation, rather than at the provisional chronometric boundary of 850 Ma. We correlate the Cryogenian–Ediacaran boundary with the base of the Keilberg Member (Karibib Formation), following Narbonne *et al.* (2012).

Table 2. Carbonate lithofacies

Lithofacies	Description	Palaeoenvironment
Microbialaminite	Lamination crinkly to undulatory with small-scale channels and unconformities, intraclast breccias, polygonal tepees and tepee breccias	Upper littoral and supratidal zones
Grainstone	Massive to bedded arenite in beds >0.2 m thick, commonly crossbedded, oolitic and/or intraclastic grains, selectively replaced by authigenic chert	Shallow sub-littoral and lower littoral zones of continuously breaking waves
Stromatolite	Laminated microbial growth structures with mounded or columnar forms, commonly associated with grainstone	Shallow sub-littoral and lower littoral zones of intermittently breaking waves
Ribbonite	Thin bedded (<0.2 cm) lutite or fine-grained arenite with low-angle cross-stratification and wavy or current rippled surfaces	Weakly agitated bottom water above storm wave base but below the zone of breaking waves
Rhythmite	Parallel flat-laminated lutite, lacking structures related to wave action or traction currents. Parallel-sided graded beds (turbidites) may be present	Quiet bottom water below storm wave base

Tonian

Ugab Subgroup

Both domes are cored by Tonian strata that predate the Chuos glaciation (Fig. 2). Maloof (2000) assigned the pre-Chuos succession, comprising 0.35-0.45 km of mixed clastics and carbonates, to the Ombombo Subgroup (Otavi Group) of the Northern Platform. He subdivided it into four units, Ombombo-1 through 4. Schreiber (2006) retained Maloof's subdivisions but reassigned them to the Ugab Subgroup (Swakop Group), consistent with stratigraphic usage in the Northern Zone of the Damara Orogen. Hoffman & Halverson (2008) retained the carbonate-dominated units 3 and 4 in the Ugab Subgroup, but correlated the coarse-clastic unit 2 with the Naauwpoort Formation, which crops out in the Austerlitz, Welwitschia and Summas Mountains inliers to the east of Vrede domes. However, the bimodal terrestrial volcanic assemblage that generally overlies coarse-clastic rocks in the Naauwport Formation elsewhere is absent in the domes. As no major disconformity, which could have truncated the Naauwpoort volcanics, is evident between units 2 and 3 (Fig. 5), we follow Schreiber (2006) in placing all four pre-glacial units within the Ugab Subgroup, designated U1-U4. In the Summas Mountains, the Ugab Subgroup overlies the Naauwpoort volcanics, dated at 746 ± 2 Ma at the top (Hoffman *et al.* 1996; Hoffman & Halverson, 2008), but the base of the Ugab Subgroup could be regionally diachronous. The litho- and chemostratigraphy of the Ugab Subgroup in the Vrede domes is currently under investigation by one of us (KGL) as part of a M.Sc. thesis project at McGill University.

Unit U1

Maloof (2000) recognized unit U1 only in the core of the south dome (Fig. 3-5). Structurally it overlies white limestone-marble tectonite, within which there is a coherent, mappable, carbonate-clast diamictite of unknown origin. On the western and northern flanks of the dome, unit 1 consists of black and maroon limestone interbedded with quartz-arenite and conglomerate. It is characterized by refolded, metre- to decametre-scale, flexural-flow folds, reflecting a rheological contrast between weak limestone and quartz-arenite under greenschist-grade metamorphic conditions. On the eastern plunge of the south dome, the carbonate is a more competent dolomite, which includes interstratified ribbonite, stromatolite and grainstone lithofacies

(Table 2, Fig. 5). The top of unit 1 is a significant flooding surface, where coarse-grained conglomerate is overlain by thin-bedded argillaceous siltstone of unit 2.

Unit U2

Unit U2 is a generally coarsening-upward sequence of mixed terrigenous and carbonate lithologies (Fig. 5). Conglomerates with granitoid and quartzite clasts overlie sharp erosive contacts and grade upward into thin-bedded micaceous and locally feldspathic sandstones and quartz-wackes, with variable amounts of brown-weathering authigenic dolomite, commonly in beds exhibiting medium-scale cross-bedding. These form multiple, decametre-scale, fining-upward cycles. These coarse-grained clastic sediments grade distally into cycles of dolomite ribbonite, stromatolite and grainstone. Stromatolite units are typically pinkish in colour and massive in appearance, with a subtle lamination that defines bush-like columnar stromatolites, with a strongly diverging style of branching characteristic the stromatolite form-genus *Tungussia* (Hofmann, 1969). The top of unit 2 is a significant flooding surface where deeper-water lithofacies abruptly overlie conglomerate or dolomite grainstone (Fig. 5).

Units U3 and U4

The conformable base of unit 3 marks an upward shift to carbonate-dominated strata from clastic-dominated in all but section II (Fig. 5). The carbonate is exclusively dolomite and can be divided into five basic depth-dependent lithofacies: rhythmite, ribbonite, stromatolite, grainstone and microbialaminite (Table 2), in order of decreasing water depth. The lithofacies are organized in generally shoaling-upward cycles. A major flooding surface overlain by ribbonite defines the base of unit 4. This serves as a stratigraphic marker below the base of the Chuos Formation diamictite (Fig. 5).

Cryogenian

Chuos Formation

The Chuos Formation ranges from 0 to 219 m in thickness within Vrede domes (Fig. 6). The lenticular shape of the main mass of the Chuos Formation in Figure 6 is an artifact of the curvature of the line of sections (Fig. 3). The actual geometry is a southwestward-thickening wedge, with a zero isopach that intersects the line of sections between sections 1-2 and 12-13 (Fig. 3). Smaller masses of carbonate diamictite occur in the North Dome in sections 16 and 18. The dominant lithology is polymictic matrix-supported diamictite in which subrounded pebbles and boulders of basement rocks, quartzite and dolomite, in variable proportions, are dispersed in a green argillaceous matrix. Less abundant carbonate diamictite has a detrital carbonate wackestone matrix, with subrounded clasts of dolomite, chert and subordinate basement debris. Variations in clast size, composition and concentration, as well as matrix composition, define distinct bodies of diamictite (Fig. 6). Stratified diamictites are distinctly-bedded intervals of fine-grained clastics with rafted debris (dropstones). Intervals of laminated or massive siltstone and mudstone lacking rafted debris also occur. Clast-supported roundstone conglomerate (orthoconglomerate) is a minor component of the Chuos Formation (Fig. 6). The base of the formation is a sharp erosion surface with local shattering (brecciation) of underlying dolomite (Ugab Subgroup). The top of the formation is a flooding surface sharply overlain by black-and-tan laminated dolomite of the Rasthof Formation.

The Chuos Formation is inferred to have been deposited in the grounding-zone of a dynamic and unstable ice-mass. Massive diamictite likely includes both melt-out and subaqueous rain-out deposits - tectonic strain makes them difficult to distinguish. Stratified diamictite accumulated in subaqueous periglacial environments at greater distance from the grounding line. Lenses of size-sorted orthoconglomerate, intimately associated with massive diamictite, imply channelized subglacial meltwater flow. Clast-free siltstone and argillite could represent ice-free interglacials (Le Heron *et al.* 2013) or glacial maxima, when thick shelf ice suppressed outlet glaciers (Dowdeswell *et al.* 2000). Alternations between basement-dominated and carbonate-dominated diamictite, can be accounted for by ice-stream switching, a well-established phenomenon on Quaternary glaciated continental shelves (e.g. Dowdeswell *et al.* 2006). No primary carbonate or wave-generated sedimentary structures were observed within the Chuos Formation in Vrede domes.

We have no idea what part of the Sturtian glaciation the Chuos Formation in Vrede domes represents. The volume of sediment could have been deposited in a few centuries by a temperate tidewater glacier in a tectonically active area (Koppes & Hallet, 2006). The estimated duration of ~58 Myr for the Sturtian low-latitude glaciation globally (Rooney *et al.* 2014, 2015) implies that the thickest section of the Chuos Formation in Vrede domes accumulated either extremely slowly (<0.004 mm/yr on average), or represents only a miniscule time fraction of the total glacial epoch.

The high aspect ratio (0.15) of the diamictite wedge in the South Dome suggests either confinement in a palaeovalley or a moraine-like buildup with positive relief. These alternatives are distinguishable through reciprocal thickness variation in the older and younger strata, respectively. We return to this issue after the younger strata have been described.

Rasthof Formation

The Rasthof Formation is the postglacial cap carbonate of the Chuos glaciation. Its average thickness in Vrede domes is only 2.4 m, with extremes of 0.6 and 4.3 m. Its base and top are sharply defined. A thin basal interval (0.2-0.3 m) of dolomite ribbonite, olive-tan in colour and not everywhere present, grades into the characteristic coal-black weathering, finely-laminated dolomite, easily recognizeable in float. Evidence of subaerial exposure is lacking, but small-scale irregularities and crinkling suggest a subaqueous microbial origin for the lamination. This is confirmed by excellent examples of rollup structures (Pruss *et al.* 2010) in section 20 (also present in section 12), implying that the laminae were pliable but cohesive at the sediment-water interface, presumably due to microbial binding of sediment grains. Black microbial dolomite is sharply overlain by green argillite of the basal Narachaams Member.

The Rasthof Formation was deposited during the highstand of Cryogenian postglacial flooding in a permanently subaqueous environment. Water depth relative to wave-base is difficult to determine because of bottom stabilization by microbial mats. The thickness of the Rasthof Formation in Vrede domes does not appear to have been limited by accommodation, as there is no evidence of shoaling, subaerial exposure or erosion at the top of the formation.

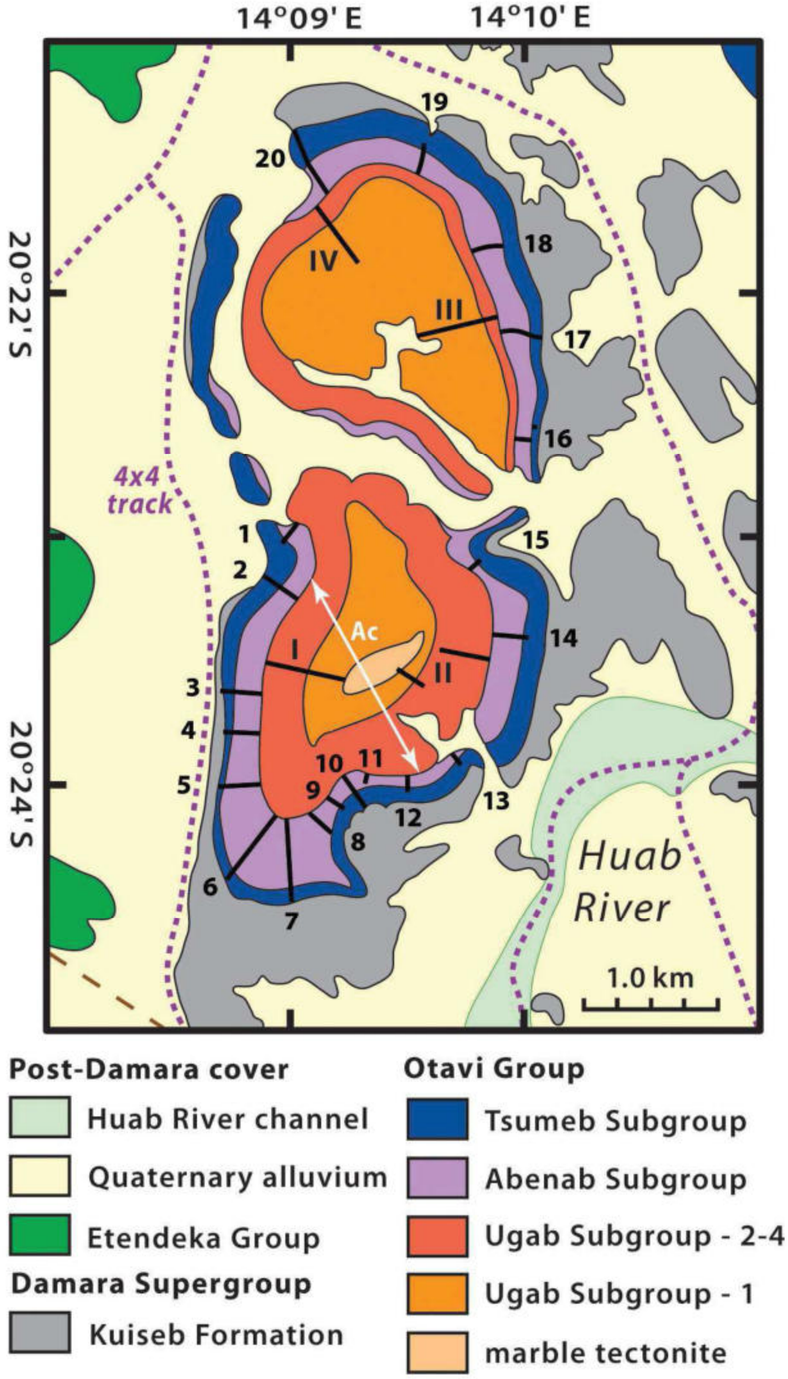

Figure 3: Geology of the Vrede domes (modified after Maloof, 2000) showing locations of measured sections of the Ugab Subgroup (sections I-IV, Fig. 5), and the Abenab Subgroup and lower Karibib Formation (sections 1-20, Fig. 6). The white line labelled Ac is the interpolated zero isopach of the southwestward-thickening wedge of Chuos Formation diamictite.

Narachaams Member

The Narachaams Member (Hoffman & Halverson, 2008) conformably overlies the Rasthof Formation and disconformably underlies the Ghaub Formation, or the Karibib Formation where the Ghaub is absent (Fig. 6). Composed of fine-grained siliciclastic sediments and deeper-water carbonate, in part authigenic, the Narachaams Member represents a basinal-facies equivalent of the upper Rasthof, Gruis and Ombaatjie formations (Abenab Subgroup) of the Northern Platform (Hoffman & Halverson, 2008). In the Northern Margin Zone, the Narachaams Member is overlain by carbonate rhythmite, turbidites and oolitic debrite of the Franniaus Member, which is interpreted as a glacioeustatic falling-stand wedge preceding the Ghaub (Marinoan) glaciation (Hoffman & Halverson, 2008). Within the Vrede domes, the Narachaams Member ranges from 0 to 237 m in thickness (Fig. 6). Three factors potentially account for the large variability: depositional onlap against the Chuos diamictite, differential truncation beneath the sub-Ghaub disconformity, and tectonic strain of the rheologically weak Narachaams Member during the formation of the structural domes.

The Narachaams Member is composed of the following lithologies: (1) parallel-laminated green argillite, locally pyritic; (2) argillite with silty laminae and occasional low-angle cross-stratification; (3) argillite with brown-weathering concretions (authigenic) and graded beds (turbidites) of marly dolomite or limestone, and (4) marly dolomite ribbonite. Carbonate is concentrated in the lower and upper parts of the unit (Fig. 6). The unit was deposited mainly below fairweather wave base and contains no evidence of subaerial exposure.

Ghaub Formation

The glacigenic Ghaub Formation is poorly represented in Vrede domes, ranging from 0 to 5.5 m in thickness. Where present, it has a sharp erosive contact with the underlying Narachaams Member and an abrupt conformable one with the overlying Keilberg Member. The Ghaub Formation is well developed in section 17 (Fig. 6), where 0.5 m of massive carbonate diamictite, in which clasts of dolomite and quartzite are dispersed in a dolomite wackestone matrix, is overlain by 2.6 m of parallel-laminated quartz siltstone with rafted dropstones of quartzite and dolomite, the latter as much as 24 cm in diameter. Thinner intervals of diamictite and/or siltstone with lonestones occur in sections 3, 10, 12-13 and 18-20 (Fig. 6). In section 6, 2.0 m of stratified carbonate-clast diamictite with possible Rasthof-derived clasts lies sharply on polymictic basement- and Ugab-derived diamictite of the Chuos Formation (Fig. 6). In three sections, 7 and 15-16, the Ghaub Formation is demonstrably absent and the Keilberg Member disconformably overlies the Narachaams Member.

The Ghaub Formation is identified with the late Cryogenian Marinoan glaciation through its association with a lithologically distinct cap dolostone, the basal Ediacaran Keilberg Member (Hoffmann & Prave, 1996; Narbonne *et al.* 2012). The glacial deposits are much thicker on Bethanis Farm in the autochthonous Northern Margin Zone, 20 km to the east (Fig. 2), where the Ghaub Formation includes 30-240 m of mainly massive limestone-clast diamictite (Hoffman & Halverson, 2008). The more distal character of glacigenic facies in Vrede domes - laminated siltstone with lonestones - suggests a location seaward of the grounding-zone wedge exposed at Bethanis. Similar proximal-distal relations occur 120 km to the east between Fransfontein Ridge (Domack & Hoffman, 2011) and the Summas Mountains dome (Hoffman & Halverson, 2008).

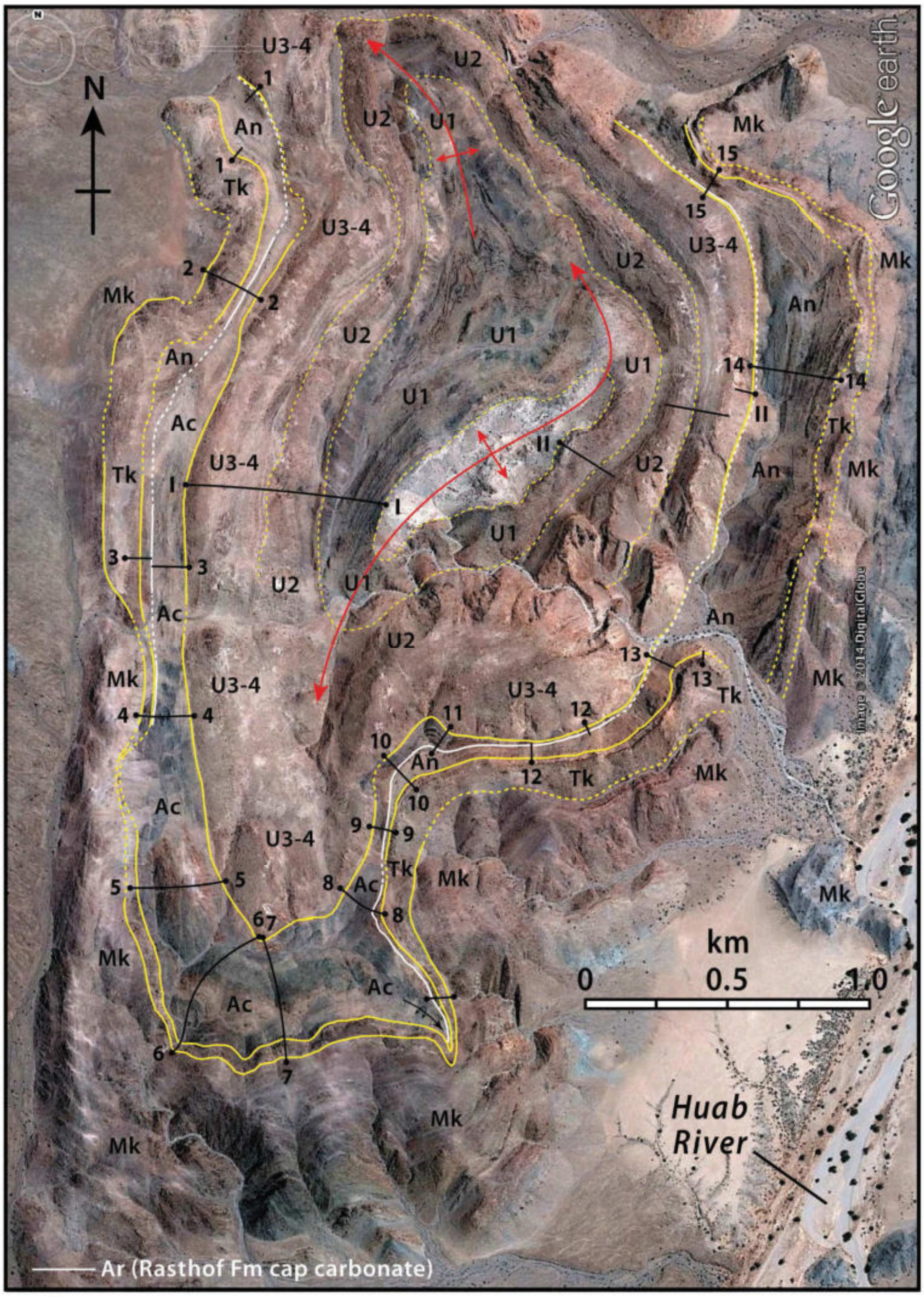

Figure 4: Satellite image (Google earth) of the south dome on Vrede Farm, showing contacts (yellow lines) between units U1, U2 and U3-4 (combined) of the Ugab Subgroup, Chuos Formation (Ac), Rasthof Formation (white line), Narachaams Member (An), Karibib Formation (Tk) and Kuiseb Formation (Mk). Black lines with dotted end-points indicate measured sections, numbered as in Figures 5 and 6.

Ediacaran

Keilberg Member (basal Karibib Formation)

The Keilberg Member is the basal transgressive unit of the Karibib Formation, ranging in thickness from 6.0 m in section 2 to 19.3 m in section 7 (Fig. 6). It consists of pale grey to pale pinkish-grey, tan-weathering, micropeloidal dolomite. Its base is sharply conformable on the Ghaub Formation, or disconformable on older units where the Ghaub is absent. The top grades into deeper water, marly limestone and/or dolomite rhythmite, representing the maximum post-glacial flooding. In Vrede domes, the Keilberg Member is similar in facies to the 'distal foreslope' on Fransfontein Ridge (Hoffman *et al.* 2007): a sheet-crack cement zone occurs near the base and tubestone stromatolite is absent. Section 13 is representative of the vertical sequence of structures (Fig. 6). A thin diamictite (0.3 m) with dolomite, quartzite and porphyritic granite clasts (Ghaub Formation) is sharply overlain by 0.2 m of pale tan dolomite ribbonite with scattered lonestones (<0.02 m) of dolomite. The ribbonite is gradationally overlain by 2.3 m of pale pinkish micropeloidal dolomite with buckled bedding-parallel cracks filled by fibrous-isopachous dolomite cement (Hoffman & Macdonald, 2010). Sheet-crack cement forms a continuous zone in the lower, but not basal, part of the Keilberg Member. In section 13, the sheet-cracked zone is overlain by 10.5 m of pale tan-coloured micropeloidal dolomite with mechanical lamination including low-angle cross-lamination. The uppermost 3.5 m of dolomite is a ribbonite that becomes finer-grained and darker coloured upward, grading into thin-bedded marly rhythmite of the middle Karibib Formation.

Karibib Formation

On the Northern Platform, the Ediacaran (post-Ghaub glaciation) part of the Tsumeb Subgroup comprises the Maieberg, Elandshoek and Hüttenberg formations (Hedberg, 1979; Hoffman & Halverson, 2008). In the Northern and Northern Margin zones, these formations cannot be distinguished lithologically because sequence boundaries are lacking in the foreslope facies. The name Karibib Formation conveniently encompasses the entire Ediacaran carbonate sequence in those zones (Schreiber, 2006), which is greatly attenuated relative to the Northern Platform. In the Northern Margin Zone, the Karibib Formation ranges in thickness from 468 m at Fransfontein to 327 m at Bethanis (Hoffman & Halverson, 2008). It is thinner in the Vrede domes, ranging from 127 m (section 20) to 5 m (section 4). Thinning is due to downslope condensation (section 20) and erosional truncation beneath the Kuiseb Formation (section 4). The maximum flooding zone of the lower Karibib Formation, directly above the Keilberg Member, is well exposed in the small drainage at section 16. The Keilberg Member (10.1 m) is conformably overlain by 6.4 m of flaggy, tan-coloured, marly-dolomite rhythmite, followed by 66.5 m of tan- to grey-coloured, thin- to medium-bedded (0.3 m), non-marly dolomite rhythmite. No seafloor cement (crystal fans) was observed. In more complete sections to the north and south, increasingly numerous dolomite debrites (rhythmite breccia) occur stratigraphically upward. The Karibib Formation is heavily silicified below the erosional disconformity at the base of the overlying Kuiseb Formation, which cuts all the way down to the Keilberg Member in sections 4-7 (Fig. 6).

Kuiseb Formation

A major regional disconformity separates Otavi Group carbonates from overlying clastics of the Kuiseb Formation in the Northern Zone and the stratigraphically equivalent Braklaagte Formation of the Northern Margin Zone (Frets, 1969). Around Vrede domes, the Kuiseb

Formation is comprised of feldspathic and non-feldspathic quartz-chert arenites (with ankerite or siderite concretions), polymictic conglomerate, green argillite and siltstone, and argillite-hosted carbonate- and chert-clast debrite and megabreccia.

Destruction of the carbonate platform and burial under clastic sediments is related to diachronous (southward-younging) abortive subduction of the Northern Platform westward beneath the Dom Feliciano - Ribeira magmatic arc of southeastern Brazil ~590 Ma (Stanistreet *et al.* 1991; Goscombe *et al*. 2005; Oyhantçabal *et al.* 2009; Faleiros *et al.* 2011; Chemale *et al.* 2012; Tupinambá *et al*. 2012; Alves *et al.* 2013; Heilbron *et al.* 2013; Jung *et al.* 2014). In this view, the Kuiseb Formation is a progradational marine facies of the stratigraphically overlying fluvial sandstones ('molasse') of the Renosterkop Formation, in which large-scale cross-bedding indicates southeastward-directed sediment transport (Hoffman & Halverson, 2008).

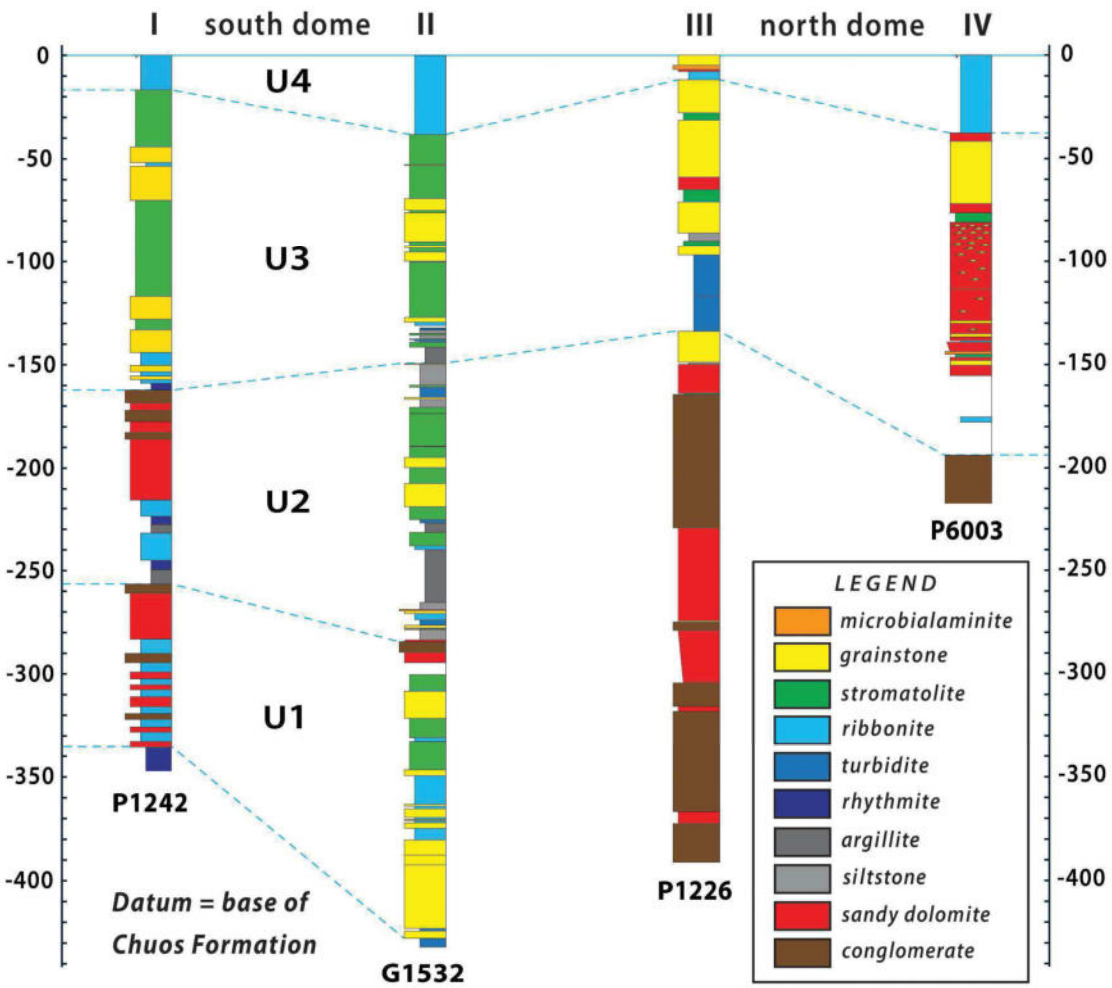

Figure 5: Graphical logs of measured sections and tentative subdivision of the Ugab Subgroup in the Vrede domes (see Fig. 3 for section locations). Datum is base of the Chuos Formation. See Table 2 for carbonate lithofacies description and interpretation. The continuity of unit U4 between sections I and II, above which the Chuos diamictite is ~160 m and 5.5 m thick respectively, demonstrates that the wedge of diamictite (Fig. 6) is not accommodated by an incised palaeovalley.

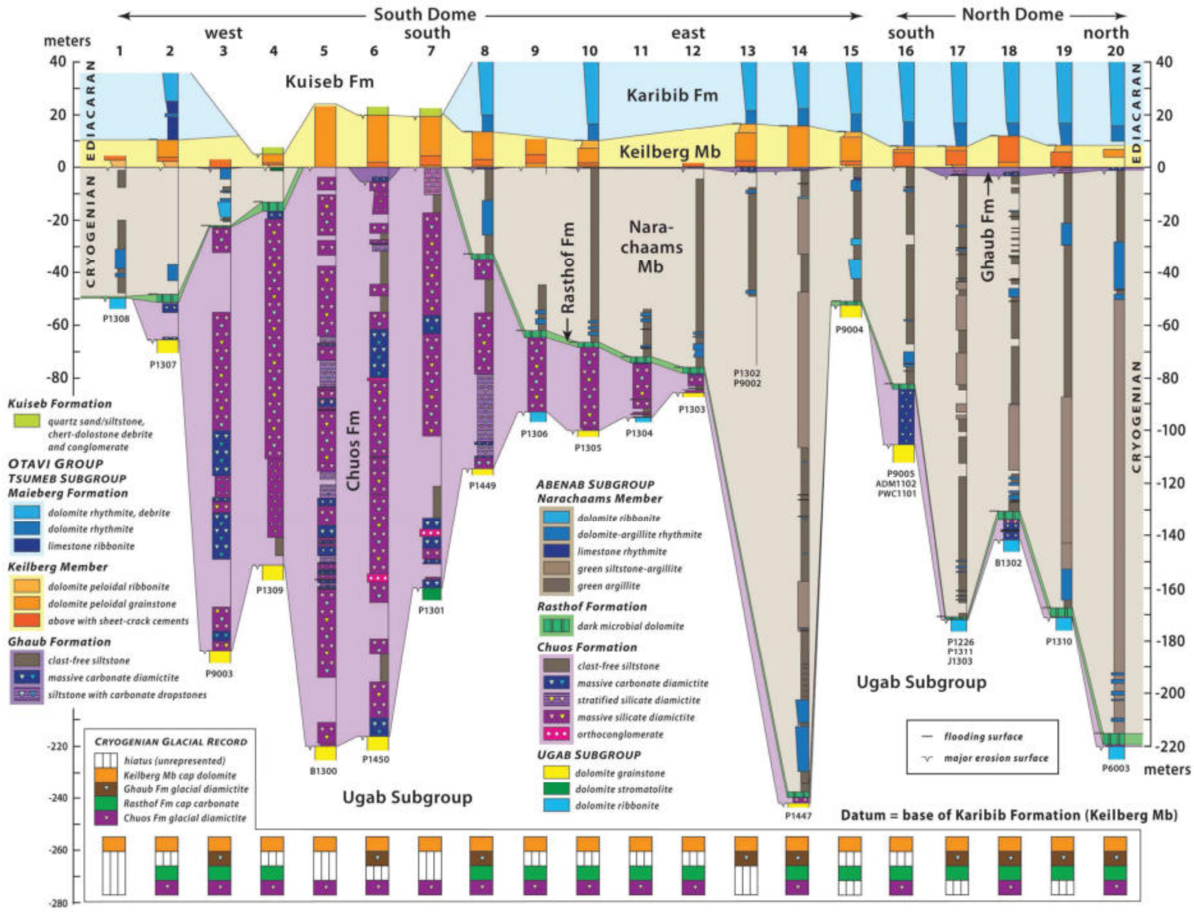

Figure 6: Graphical logs of measured sections of Cryogenian and earliest Ediacaran strata in the Vrede domes (see Fig. 3 for section locations). Datum is base of the Keilberg Member, corresponding to the base of the Ediacaran Period (Narbonne *et al.* 2012). See Table 1 for the geographical coordinates of each section and Table 2 for carbonate lithofacies description and interpretation. The lensoidal form of the Chuos diamictite between sections 2 and 12 is an artifact of the ovoid line of sections (Fig. 3). The projected shape of the diamictite body is a northeastward tapering wedge with an apex between sections 5 and 6. Inset at base symbolizes the presence or absence of each Cryogenian diamictite and its respective 'cap carbonate.' Only 5 of the 20 sections are 'complete.' The Narachaams Member has not been decompacted and may have undergone differential tectonic strain between sections (*e.g.* between sections 14 and 15).

Chuos diamictite wedge: palaeovalley or moraine?

The wedge-shaped mass of diamictite in the South Dome (sections 2-12) undoubtedly belongs to the Chuos Formation as it stratigraphically underlies the Rasthof Formation cap carbonate (Fig. 6). The thickness (<220 m) and high aspect ratio (0.15) of the wedge demand an explanation. Was it confined within a palaeovalley or was it a positive topographic feature like a moraine or drumlin? A palaeovalley would be indicated by incision of underlying strata. This is not observed (Fig. 5). Section I of the Ugab Subgroup, which underlies ~150 m of Chuos diamictite (Fig. 4), is truncated little more than sections II-IV, where the Chuos Formation is thin or absent.

If the wedge of diamictite was a buildup with positive topographic relief, it should have a reciprocal relationship with the thickness of overlying strata. The Rasthof cap carbonate Formation forms a drape of near-constant thickness, <4.3 m, except where it was erosionally removed at the apex of the wedge (Fig. 6). The Narachaams Member, in contrast, reciprocates in thickness with the Chuos Formation. The reciprocal relationship (Fig. 6) would be more quantitative if the argillaceous Narachaams Member was decompacted. It may have undergone 50% or more differential compaction, relative to the diamictite and carbonate lithofacies. It is not clear if the reciprocal relationship is due to depositional onlap or differential erosion beneath the Ghaub glacial surface (Fig. 6). Stratigraphic subdivision of the Narachaams Member is required to answer this question definitively. The complete disappearance of the Narachaams Member in sections 5-7 implies a significant role for sub-Ghaub erosion. This is itself significant given the paucity of Ghaub diamictite in the Vrede domes. The magnitude of diamictite locally is no measure of the local depth of glacial erosion.

Conclusions

The wedge of glacigenic diamictite composed largely of basement debris in the southern structural dome on Vrede Farm belongs to the early Cryogenian (Sturtian) Chuos Formation. It stratigraphically underlies the cap carbonate (Rasthof Formation), which although thin (0.6-4.3 m) is easily recognizable in outcrop and float. The apex of the wedge is truncated at the younger Cryogenian (Marinoan) Ghaub Formation glacial surface. The Ghaub Formation itself is poorly developed in the Vrede domes (0-5.5 m), but the lithologically distinctive basal Ediacaran cap dolostone, the Keilberg Member, is present in every section and ranges from 6.0 to 19.3 m in thickness. The Keilberg cap dolostone rests disconformably on the Chuos diamictite at the apex of the wedge, locally with carbonate-clast diamictite of the Ghaub Formation between them. The wedge of Chuos diamictite does not fill a palaeovalley incised into the underlying Ugab Subgroup. It appears to represent a moraine-like buildup that was draped by the Rasthof carbonate, fully buried by the argillaceous Narachaams Member, and erosionally decapitated during the Ghaub glaciation.

Acknowledgements

Field work was carried out under a research agreement with the Geological Survey of Namibia. Travel and operating costs were partly funded by the Earth Systems Evolution Program of the Canadian Institute for Advanced Research (CIFAR). ADM was supported by a grant from Hamilton College. GPH and KGL were supported by a Canadian National Science and Engineering Research Council (NSERC) Discovery grant to GPH.

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