A giant glacial erratic of Cryogenian (end-Sturtian) age

Paul F. Hoffman[1,2*] and Adrian Tasistro-Hart[3]

1. School of Earth & Ocean Sciences, University of Victoria, Victoria, BC V8P 5C2, Canada
**Corresponding author <paulfhoffman@gmail.com>*
2. Department of Earth & Planetary Sciences, Harvard University, Cambridge, MA 02138, USA
3. Department of Earth Science, University of California, Santa Barbara, CA 93106, USA

Abstract :- Near the village of Duurwater Pos at the foot of the Fransfontein Ridge, north-western Namibia, an erratic megalith of basement monzogranite (Huab gneiss), 130 m long by 52 m wide, is perched on a pedestal of early Cryogenian (Sturtian) tillite. The pedestal had at least 134 m of palaeotopographic relief, plus the additional 41 m (tilt-corrected) height of the erratic itself. The tillite pedestal is inferred to be a hoodoo structure formed by differential erosion with shielding of the pedestal by the hard basement erratic. The erratic and its pedestal were preserved because of rapid marine inundation during Snowball Earth deglaciation, followed by onlap and burial by postglacial carbonate sediments of the middle Cryogenian Berg Aukas and Okonguarri Formations. As a glacial erratic, it is possibly the largest and oldest example known.

Keywords :- Glacial erratic, Cryogenian, Chuos glaciation, Snowball Earth, Fransfontein Ridge

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Introduction

Erratic boulders, lithologically incompatible with local bedrock, are among the most visible memorials to the power of vanished Quaternary ice sheets in Patagonia, New Zealand, Eurasia and North America (Sugden and John, 1976; Denton and Hughes, 1981; McCabe, 2008; Krüger, 2013; Evans *et al.*, 2021). They are susceptible to erosion, however, and few if any such erratics have been described from pre-Quaternary ice ages. The largest Quaternary example is said to be Okotoks ('big rock' in the indigenous Blackfoot language), an erratic of Cambrian quartzite, derived from the Rocky Mountains and measuring 41 x 18 m where it lies (in two pieces) on the plains of southern Alberta in western Canada.

The purpose of this paper is to describe a larger and older erratic from the Sturtian (local Chuos) glaciation, the older of two Cryogenian (720 and 635 Ma) 'Snowball Earth' epochs. It measures 130 by 52 m in exposed diameter and is composed of weakly-foliated, porphyritic monzogranite derived from the Orosirian crystalline basement (1.86−1.83 Ga) of the Kamanjab Inlier (Burger *et al.*, 1976; Kleinhanns *et al.*, 2015). It is located near the village of Duurwater Pos (−20.203° S, 15.152° E) at the foot of the Fransfontein Ridge (Kunene Region, northern Namibia). Restoration of the enclosing Cryogenian strata, which are inclined ~52° towards the southwest, shows that the erratic is mounted atop a 134 m-high pedestal of glacial tillite (Chuos Formation). Corrected for tilt, the erratic itself was ≥41 m high from base to top, and was onlapped and buried by postglacial marine carbonate sediments of mid-Cryogenian age, following inundation by syndeglacial sea-level rise. Its position atop a pedestal of tillite is most easily explained by differential subaerial erosion, the pedestal having been protected from erosion by the erratic itself. Rapid burial saved it from further erosion until its Recent exhumation. Hidden by *Acacia mellifera* trees, the erratic is no longer a wonder to the eye, but its restoration is wondrous for the imagination.

Location, palaeogeography and stratigraphic succession

The erratic is centered at longitude 15.14638° on the Fransfontein Ridge, a southwards-dipping monocline of carbonate-dominated Cryogenian and early Ediacaran strata (Otavi/Swakop Group) at the southern limit of the anticlinal Kamanjab basement inlier (Fig. 1). The sedimentary succession in the area of the erratic consists of four sequences, the youngest of which (Karibib Formation, Tkb) is Ediacaran in age. The early and late Cryogenian sequences, i. e. the Chuos (Ac) and Ghaub (Tg) Formations, respectively (Figs 2 and 3), represent the global Sturtian (717−662 Ma) and Marinoan (645±6−635 Ma) 'Snowball Earth' glaciations. The 11 to 23 Ma long middle Cryogenian ('inter-Snowball') sequence consists of the Berg Aukas (Aa), Okonguarri (Ao), Narachaams (An) and Frannis-aus (Af) Formations in ascending order.

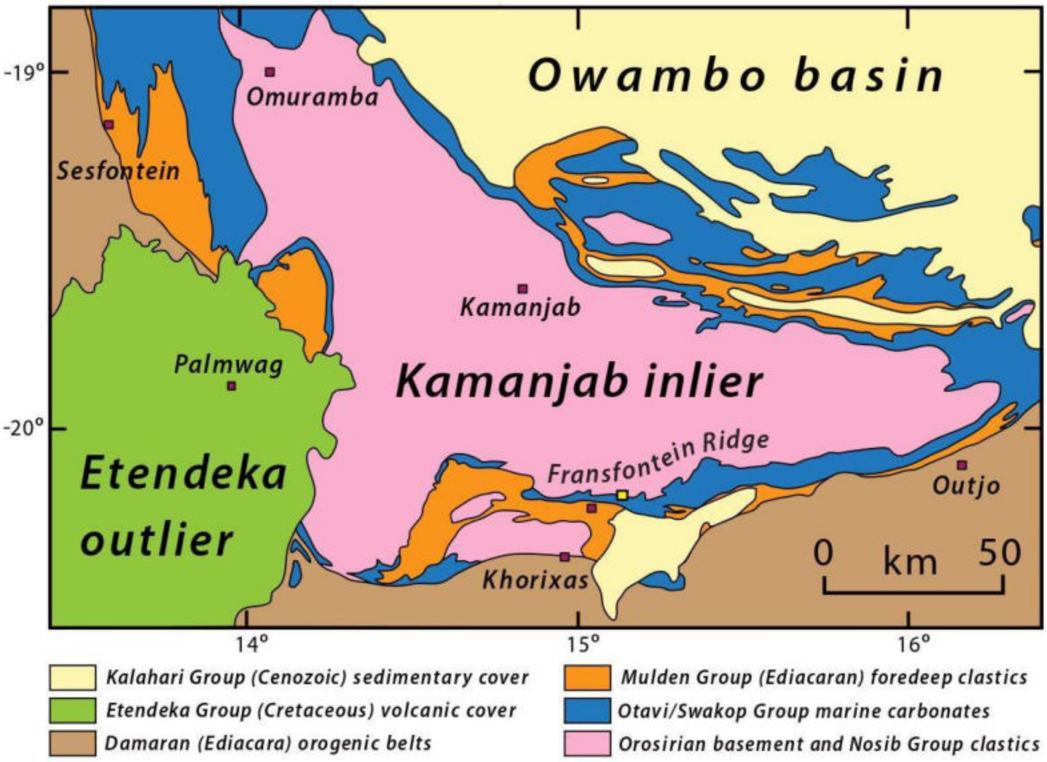

Figure 1. Bedrock geology around the Kamanjab Inlier exposing Orosirian basement rocks of the Congo Craton at the junction of the Ediacaran Central Kaoko Zone (upper left) and the Northern Damara Zone (lower right). The area shown in Fig. 2A is indicated by the tiny yellow box beneath the 'fo' in Fransfontein Ridge.

The erratic rests on Chuos Formation diamictite deposited in a small terrestrial rift-basin within a broad rift-shoulder uplift of exposed crystalline basement during the Sturtian glaciation. Middle Cryogenian crustal flexure, near the tip-line of a regional-scale south-dipping normal fault, transformed the area into the middle foreslope of a rapidly-subsiding Otavi Group carbonate shelf (Hoffman and Halverson, 2008; Hoffman, 2021a; Hoffman *et al*., 2021). The WNW−ESE trend of the Fransfontein Ridge in the area of the erratic (Fig. 2) was roughly parallel to the inferred slope contours. To the east, the strike of the Fransfontein Ridge changes to SW−NE and the outcrop section climbs obliquely across the upper foreslope and onto the outer shelf (Hoffman *et al*., 2021). Carbonate production ended when the area became part of a collisional foredeep during closure of the Northern Damara (Outjo) Sea at ca 600−590 Ma (Lehmann *et al*., 2015; Hoffman, 2021b).

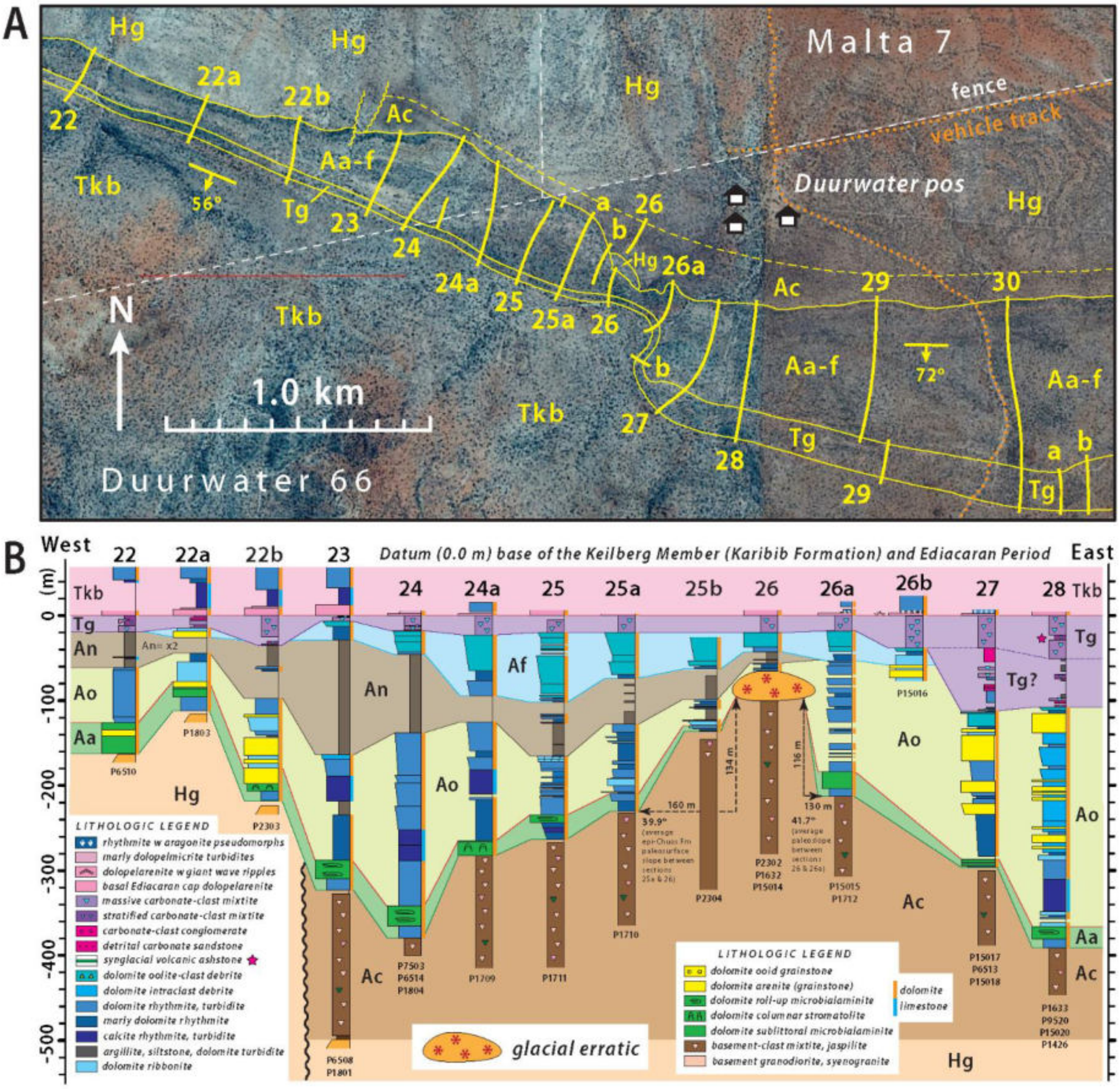

Figure 2. Bedrock geology of the Fransfontein Ridge in the area of Duurwater Pos: (**A**) Annotated satellite image showing farm boundary (white dashed line), vehicle tracks (orange dotted lines) and stratigraphic contacts (thin yellow lines) with units symbolised as in B and described in the text; strata dip 56−72° towards SSE. Heavy yellow lines are measured sections numbered 22 to 28 from west to east. Google Earth: Image © 2020 CNES/Airbus. (**B**) Fence diagram of columnar sections measured normal to stratification. Units: Hg, Huab Gneiss, Orosirian granitoids; Ac, Chuos Formation (Sturtian glaciation); Aa, Berg Aukas Formation; Ao, Okonguarri Formation; An, Narachaams Formation; Af, Frannis-aus Formation; Tg, Ghaub Formation (Marinoan glaciation); Tkb, Karibib Formation with basal Ediacaran 'cap' dolomite. Datum is the base of the Karibib Formation (base of the Ediacaran Period). Stratigraphic assignment of the interval labelled Tg? is tentative. It could alternatively be interpreted as Narachaams (±Frannis-aus) Formation. Average palaeosurface slopes (in magenta) are calculated from the horizontal distance (h) and difference in stratigraphic height (v), relative to the datum, of the top of the Chuos Formation between sections 25a and 26, and between 26 and 26a (tan α = v/h).

In the area of the erratic, the Chuos Formation (Ac, Fig. 2) exceeds 130 m in thickness and is composed of mainly massive, polymictic diamictite (tillite) in which rounded boulders of basement granodiorite are dispersed in a schistose siltwacke matrix. The diamictite is interspersed with thin layers of jaspilite and detrital dololutite. West of section 23 (Fig. 2), the Chuos Formation abuts against a high-angle rift-fault that is overstepped by the Berg Aukas Formation, the post-Sturtian 'cap' dolomite. The basement in the footwall of the rift fault is a granodiorite gneiss (Hg, Fig. 2), in which subordinate mafic minerals (biotite and hornblende?) are replaced by retrograde chlorite.

The Berg Aukas Formation (Aa, Fig. 2B) sharply overlies the Chuos Formation and is generally a laterally continuous dark- to pale-grey dolomite, 20−40 m thick. It begins with flat-laminated rhythmite and shoals upwards into sublittoral microbialaminite, locally with columnar stromatolites, pillored thrombolites or microbial roll-up structures (Pruss *et al*., 2010). Its top is a subaqueous flooding surface (i. e. an abrupt increase in inferred water depth), but it lacks both the upper grainstone member that characterises the post-Sturtian Rasthof Formation on the western shelf area and the subaerial exposure surface at its top (Hoffman *et al*., 2021).

The Okonguarri Formation (Ao, Fig. 2B) is a polycyclic assemblage of limestone and dolomite rhythmites and ribbonites (flat and wavy-bedded, respectively). It passes eastwards (upslope) into dolomite grainstone, in part oolitic and stromatolitic, resembling the Gauss Formation of the Otavi Mountainland but lacking the plethora of tepeed subaerial exposure surfaces that characterise the Gruis Formation on the western Otavi Group shelf area (Hoffman *et al*., 2021). Westwards, the Okonguarri Formation is dominated by carbonate turbidites and rhythmite (e. g. in the Soutput subbasin on farm Toekoms 508 west of Khorixas (Hoffman *et al*., 2021).

The recessive Narachaams Formation (An, Fig. 2B), much favoured by thorn bushes, is composed of argillite with thin beds of buff-coloured dolomite turbidite. It is sharply overlain by the Frannis-aus Formation (Af, Fig. 2B), an upward-coarsening sequence of dolomite rhythmite, turbidite and intraclast debrite, interpreted as a glacio-eustatic falling-stand wedge related to extratropical ice-sheet growth in advance of the Ghaub glaciation on the Otavi Group palaeo-platform.

The Ghaub Formation (Tg, Fig. 2) represents the Marinoan Snowball Earth. In the area of the erratic, it disconformably overlies the Frannis-aus, Narachaams or Okonguarri (?) Formation, depending on the depth of sub-Ghaub erosion (Fig. 2). Its dominant lithology is massive, polymictic, carbonate diamictite, with subordinate stratified diamictite, carbonate-clast rudite (conglomerate) and arenite, all of glaciomarine origin (Domack and Hoffman, 2011; Hoffman *et al*., 2021). The Ghaub Formation in section 28 (Fig. 2) contains a volcanic tuff yielding zircon grains with a published U−Pb CA-ID-TIMS age of 639.29 ± 0.26 Ma (Prave *et al*., 2016). The stratigraphic assignment of the lower Ghaub Formation (Tg?, Fig. 2) in sections 27−28 is tentative. This interval could alternatively be Narachaams ± Frannis-aus Formation. Thin diamictites within this interval could be debrites, which occur low in the Narachaams Formation in other areas.

The Ghaub Formation is conformably overlain by the Karibib Formation (Tkb, Fig. 2), at the base of which is a post-Marinoan 'cap' dolomite correlative with the Keilberg Member (basal Maieberg Formation) of the Otavi Group (Tk, Fig. 3). Its base marks the start of the Ediacaran Period (Knoll *et al.* 2006; Narbonne *et al.* 2012). The cap dolomite consists of laminated, pale buff to pinkish, peloidal dolarenite, that thins eastwards from an average of 11.0 m in sections 22a to 23, to 5.9 m in section 26 (above the erratic) and 3.0 m in sections 26a to 27 (Fig. 2). It passes upwards gradationally into marly limestone or dolomite of the maximum post-glacial flooding stage, with pseudomorphosed crystal fans of benthic aragonite cement in the transition zone of sections 26a to 27 (Fig. 2). The remainder of the Karibib Formation consists of dolomite rhythmite, turbidite, debrite and cherty dolarenite, hundreds of metres thick in aggregate. The Karibib Formation is correlative with the entire Tsumeb Subgroup on the Otavi Group palaeo-platfom (Halverson *et al*., 2005) and is disconformably overlain by synorogenic foredeep siliciclastic deposits of the Kuiseb Formation and Mulden Group (Hoffman, 2021b; Hoffman *et al*., 2021).

Palaeorestoration of the Duurwater Pos erratic and its source

The datum for the stratigraphic 'fence' diagram (Fig. 2B) is the base of the Karibib Formation. The top of the Chuos Formation beneath the erratic in section 26 is closer to the datum than in any other section. This suggests that the erratic was perched on a palaeotopographic high on the final surface of Chuos diamictite. This is supported by evident onlap of middle Cryogenian strata. The Berg Aukas Formation is absent over the erratic and must pinch-out against the inferred 39.9° (tan α=134/160 m) and 41.7° (tan α=116/130 m) average palaeosurface slopes (relative to the datum) to the west (sections 25a to 26) and east (26 to 26a) of the erratic, respectively (Fig. 2B). The calculated average palaeoslope west of the erratic would steepen if the Narachaams Formation argillite were decompacted. The Okonguarri Formation thins dramatically from 147.4 m (section 25a) and 131.4 m (section 26a) to only 9.9 m above the erratic (section 26). Thinning of the Narachaams and Frannis-aus Formations is much less (Fig. 2), consistent with burial of the erratic by the end of Okonguarri deposition and partial compaction of Narachaams argillite before the end of Frannis-aus accumulation. Taken together, these stratigraphic relations imply that the erratic, before burial, was mounted on a pedestal of unlithified glacial till (Chuos Formation) with at least 116−134 m of palaeotopographic relief. Corrected for tilt, the erratic itself would have added ~41 m (52 m times sin 52°; Fig. 3) to the height of the hoodoo.

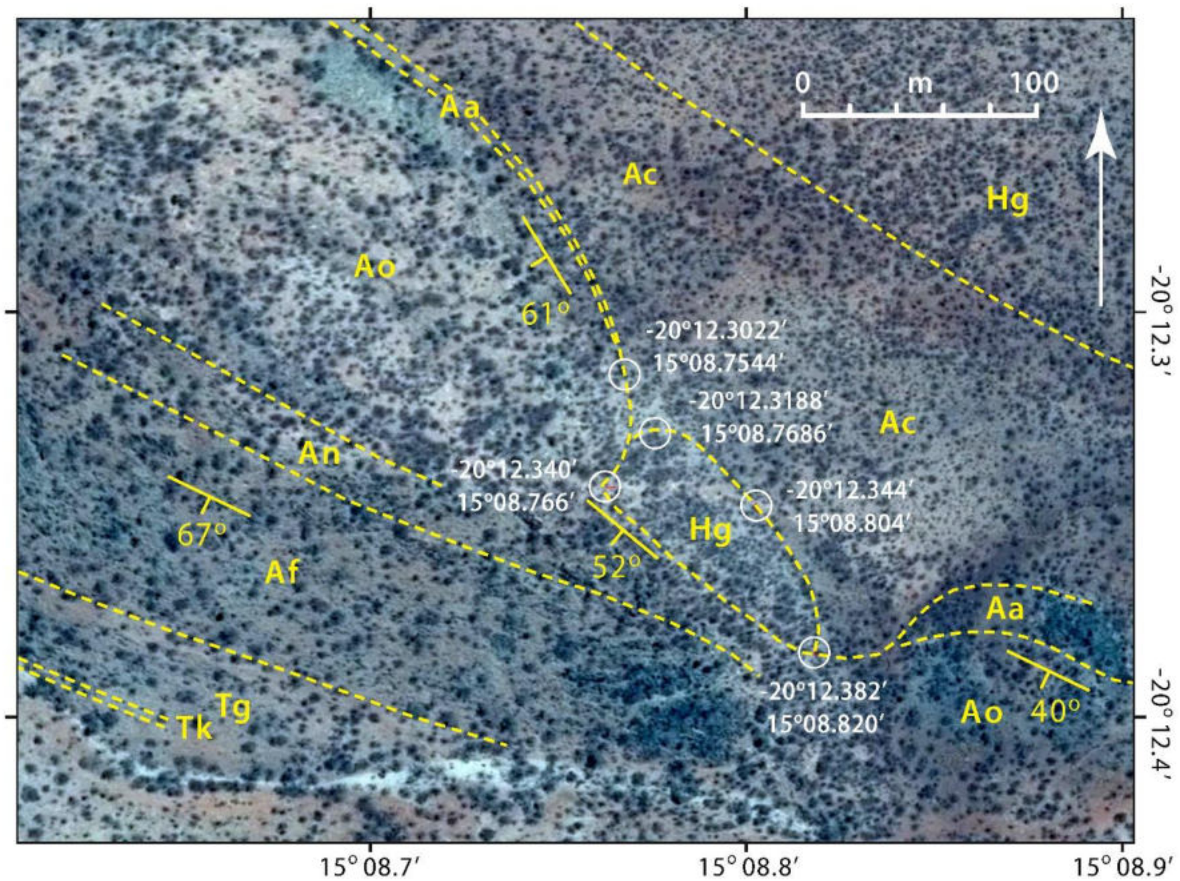

Figure 3. Annotated satellite image of the glacial erratic (Hg, centre right), located 650 southwest of Duurwater Pos. Coordinates are for circled locations that define its dimensions. The west to east drainage between circled locations provides the best-exposed section of the erratic and its relations with the enclosing strata (Fig. 2B), which dip 60−67° towards the southwest (Google Earth: Image © 2024 Airbus)

Assuming that the erratic was carried by a glacier, did the till pedestal exist when the erratic was placed there by glacial meltdown? This cannot be ruled out, but a more consanguineous explanation is that the till pedestal is a product of differential erosion, during which the general till surface was lowered but the pedestal was protected by the presence of the relatively hard monzogranite erratic. American geomorphologists describe such landforms as 'hoodoos,' a term apparently co-opted from African mythology (Jackson, 1997). Subaerial erosion predicts that boulder lags would have formed in axial channels on the till surface, but none were encountered.

From where was the erratic derived? One possible source is the synglacial rift fault between sections 22b and 23 (Fig. 2), which is only 1.03 km distant in the line of the sections. The erratic (porphyritic monzogranite) is not a perfect lithologic match for the basement granodiorite exposed on both sides of the fault. Tilt correcting the ESE-dipping strata (Fig. 2A) would have little effect on the strike of the fault plane, which projects north of the erratic. But there is no independent constraint on the flow direction of Chuos glacial ice.

Conclusions

Near the village of Duurwater Pos at the foot of the Fransfontein Ridge, an outcrop of basement monzogranite, 130 m long and ≤52 m wide, is sandwiched between early Cryogenian tillite (Chuos Formation) and post-Sturtian middle Cryogenian marine carbonate (Fig. 3). Stratigraphic restoration reveals that the monzogranite erratic was mounted on a pedestal of tillite with ≥134 m of palaeotopographic relief, to which was added the ≥41 m height of the erratic itself (Fig. 2B). The pedestal is interpreted as a palaeo-hoodoo, formed by differential erosion and shielding of the pedestal by the erratic itself. If correctly interpreted, this palaeo-erratic is perhaps the largest and oldest glacial erratic on record. What is extraordinary about the Duurwater Pos erratic is less about its formation than about its preservation. Preservation may be related to the magnitude and speed of sea-level rise that accompanied the meltdown of a Snowball Earth, as well as the high rate of carbonate production in its torrid aftermath.

Acknowledgments

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