Duration and nature of the end-Cryogenian (Marinoan) glaciation

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ABSTRACT

The end-Cryogenian glaciation (Marinoan) was Earth's last global glaciation yet its duration and character remain uncertain. Here we report U-Pb zircon ages for two discrete ash beds within glacimarine deposits from widely separated localities of the Marinoan-equivalent Ghaub Formation in Namibia: 639.29 ± 0.26/0.31/0.75 Ma and 635.21 ± 0.59/0.61/0.92 Ma. These findings, for the first time, verify the key prediction of the Snowball Earth hypothesis for the Marinoan glaciation: longevity, with a duration of ≥4.08 ± 0.64 Myr. They also show that glacigenic sedimentation, erosion, and at least intermittent open-water conditions occurred 4 million years prior to termination of the Marinoan glaciation and that the interval of non-glacial conditions between the two Cryogenian glaciations was 20 Myr or less.

INTRODUCTION

The Cryogenian Period (*c*. 720 – 635 Ma) was marked by the two most severe glaciations in Earth history (Hoffman et al., 1998; Fairchild and Kennedy, 2007), the older Sturtian and younger Marinoan, and their association with unique lithofacies of cap carbonates (Kennedy et al., 2001; Hoffman and Schrag, 2002; Hoffman et al., 2011), stable isotope fluctuations (carbon, oxygen, boron, calcium; Halverson et al., 2005; Kasemann et al., 2005; Bao et al., 2008) and banded iron formation are evidence for global-scale environmental changes with postulated links to oceanatmosphere oxygenation and biosphere evolution (Butterfield, 2009; Och and Sjields-Zhou, 2012; Sperling et al., 2013). Creation of a unified theory explaining those phenomena, however, has been hampered by one key obstacle: a lack of temporal constraints. Recently, the Sturtian was shown to have spanned an astonishing 56 Myr, from about 716 Ma to 660 Ma (Bowring et al., 2007; Macdonald et al., 2010; Rooney et al., 2014; Rooney et al., 2015). In contrast, the duration of the Marinoan is unresolved: it terminated at *c*. 635 Ma (Hoffmann et al. 2004; Calver et al., 2004; Condon et al., 2005; Zhang et al., 2008) but its initiation can only be stated as being younger than interglacial strata, which in Mongolia have been dated as *c*. 659 Ma (Rooney et al., 2014) and in China as *c*. 655 Ma (Zhang et al., 2008). Here we report new dates for the Marinoan-equivalent Ghaub Formation in Namibia that provide a basis for assessing the timing and nature of Earth's last global glaciation.

GEOLOGY: SAMPLES DW-1 AND NAV-00-2B

The Nosib, Otavi and Mulden Groups comprise the Neoproterozoic sedimentary record of the Congo craton in northern Namibia (Fig. 1). The Otavi Group (and correlative rocks in the Swakop Group of the Outjo and Swakop Zones) is a 2-5 km thick carbonate platform-slope-basin succession formed in the tropics along the margin of the Congo Craton. It is punctuated by two Cryogenian glacial units (Hoffmann and Prave, 1996; Hofman and Halverson, 2008), the older Chuos and the younger Ghaub formations and their respective cap carbonates, the Rasthof and Keilberg formations. U-Pb zircon ages on igneous and volcanic units provide geochronological constraints (see Fig. 1) that bracket deposition of the glacigenic-bearing strata in the Otavi Group to between *c*. 756 Ma and 635 Ma.

One of the most informative exposures of the Ghaub Formation in northern Namibia is along Fransfontein Ridge (Fig. 1). There, the Ghaub rocks vary in thickness from 1 to 600 m and can be traced continuously for *c*. 70 km; they consist mostly of stratified and massive carbonate-clast-rich diamictite, minor intervals of rippled and cross-stratified dolomitic grainstone, marl and shale, and an upper unit, the 1 to 15 m thick Bethanis member (Hoffman and Halverson, 2008) typified by cm- to dcm-thick stratified diamictite and grainstone-mudstone, all with abundant variably sized dropstones. Detailed studies (Hoffman and Halverson, 2008; Domack and Hoffmann, 2011) of those lithofacies have interpreted them as a succession of moraine and glacimarine sediments deposited along the margin of a repeatedly advancing and back-stepping ice-grounding line (Domack and Hoffmann, 2011).

Along Fransfontein Ridge, the diamictite-dominated Ghaub Formation contains lenses, generally a few metres thick, consisting of graded grainstone and laminated to massive calcareous-dolomitic marl-shale with stringers of dropstones. At Duurwater (Fig. 2) one of these lenses about 15 m below the base of the Keilberg cap dolostone contains a prominent ash bed, sampled as DW-1 (Fig. 3). The DW-1 ash bed is 0.3 m thick, pale tan to pale yellow in colour, characterised by sharp upper and lower contacts, displays a slight fining-upward grading, contains rare disseminated quartz spar crystals and is overlain and underlain by IRD beds (Fig. 4A). These features indicate that this bed is an air-fall tuff contemporaneous with deposition of the glacimarine sediments, hence its age would also be the age of sedimentation for this part of the Ghaub Formation. Below the DW-1 ash bed is 10-15m of massive diamictite and then a more than 100-m-thick succession of carbonate rhythmite, breccia, laminated marl and shale with dispersed dropstones and isolated metre-scale and larger blocks derived from pre-Ghaub formation units. These lithofacies fill a steep-sided incision cut into the pre-Ghaub stratigraphy (Figs. 2, 3); in places along the Fransfontein outcrop belt as much as 300 m of strata have been cut out along this surface.

Sample NAV-00-2B comes from an ash bed in the basinal equivalent of the Ghaub Formation *c*. 30 m below the contact with the Keilberg cap dolostone at Navachab in central Namibia (Fig. 3). This occurrence was reported by Hoffman et al. (2004) and readers are referred to that paper for details.

METHODS AND RESULTS

All zircon dates in this study were obtained using established chemical abrasion (CA) isotope dilution thermal ionisation mass spectrometry (ID-TIMS) methods at the NERC Isotope

Geoscience Laboratory of the British Geological Survey (Noble et al., 2015; see Data Repository for details). U-Pb dates have been determined relative to the gravimetrically calibrated EARTHTIME mixed U/Pb tracers (Condon et al., 2015; McLean et al., 2015) and ^{238}U and ^{235}U decay constants (Jaffey et al., 1971; Mattinson, 2010).

Sample DW-1 yielded a population of zircons with a consistent morphology (aspect ratio ~2 and long axis typically 200 to 300 μm) and colour. Ten zircons were dated by CA-ID-TIMS; U-Pb data for each analysis are concordant when the uncertainty in the ^{238}U and ^{235}U decay constants (Mattinson, 2010) are considered (Fig. 4B; Data Repository Table 1). All analyses yield a weighted-mean ^{207}Pb/^{206}Pb date of 639.1 ± 1.7/1.8/5.0 (n=10, MSWD=1.08). Of those, one analysis has dispersion beyond that expected due to analytical scatter (see Data Repository) and is an obvious outlier with a U-Pb date younger than the main population. Excepting this grain, the other nine analyses yield a weighted mean ^{206}Pb/^{238}U date of 639.29 ± 0.26/0.31/0.75 Ma (95% confidence interval, n=9, MSWD=2.6), which we interpret as the age of deposition.

Sample NAV-00-2B is an aliquot of the sample dated previously as 635.5 ±1.2 Ma (Hoffmann et al., 2004) at the Massachusetts Institute of Technology. Re-analysis of this sample was done to capitalise on the use of CA for the effective elimination of Pb-loss (Mattinson, 2005) and the EARTHTIME tracer and its comprehensive gravimetric calibration and uncertainty model (Condon et al., 2015; McLean et al., 2015). The ^{206}Pb/^{238}U date for NAV-00-2B derived in this study is 635.21 ± 0.59/0.61/0.92 Ma (95% confidence interval, n=5, MSWD=3.4; Fig. 4B, Data Repository Table 2). This date is based upon a subset of the analyses (as explained in the Data Repository) and, even given improved analytical precision and accuracy, is indistinguishable from the date published in Hoffmann et al. (2004).

DISCUSSION

The 639.29 ± 0.26/0.31/0.75 Ma age for the DW-1 ash bed at Duurwater and the revised age of 635.21 ± 0.59/0.61/0.92 Ma for the NAV-00-2B ash bed at Navachab now, for the first time, confirm that the Marinoan glaciation was long-lived, lasting at least 4.08 ± 0.64 Myr. This verifies the key prediction of the Snowball Earth hypothesis for a long duration glaciation. The revised age for NAV-00-2B also refines and reconfirms that the timing of termination of the Marinoan glaciation was synchronous worldwide (*i.e*. within error of the age data), occurring between 635.21 ± 0.59/0.61/0.92 Ma and 635.2 ± 0.5 Ma, the age of an ash bed in the lower part of the cap carbonate sequence in China (Condon et al., 2005); a conclusion reinforced by the U-Pb zircon age of 636.41 ± 0.45 Ma for a volcaniclastic unit in the glacial-cap carbonate transition in Tasmania (Calver et al., 2004).

Since the debut of the Snowball Earth hypothesis, debate has ensued regarding the extent of land and sea ice during Cryogenian glaciations, the causes of repetitive patterns of inferred proximal-distal and advance-retreat deposits, and the overall timing and duration of glacial sedimentation (*e.g*. see discussion by Spence et al., 2016, and references therein). Further, the lack of well-defined age models has led to an array of climate state and sedimentation scenarios, ranging from surmising that the Marinoan rock record formed by glacial-interglacial-scale epochs (*e.g*. Allen and Etienne, 2008; LeHeron et al., 2011) to interpretations of the bulk of that record as having been deposited during a brief interval of time near to the end of the glacial state (*e.g*. Benn et al., 2015). Although these interpretations are not necessarily mutually exclusive, assessing them remains speculative because of the lack of constraints for the absolute timing of sedimentation. Our new geochronological data provide a better temporal framework for understanding the Marinoan glaciation. For example, the *c*. 639 Ma DW-1 ash bed occurring above a *c*. 100-m-thick glacimarine succession shows that glacial erosion and sediment accumulation concurrent with at least intermittent open-water conditions in the tropics existed more than 4 million years before the ultimate meltback phase of the Marinoan ice sheets. This impacts on a range of issues regarding the Marinoan climate state: it provides constraints and corroboration of models that yield results consistent with such conditions, including predictions of plausible CO_2 levels permissive of enabling ice-line migration and associated sedimentation in the tropics, as documented for the Ghaub Formation (e.g. Domack and Hoffman, 2011), to considerations of low-latitude *refugia* and the survival of eukaryotic organisms within the main phase of the Marinoan glaciation. Further, given our new age that provides a minimum duration for the Marinoan glaciation and the *c*. 660 Ma age for the end of the older Cryogenian glaciation (Sturtian), the intervening interglacial interval and associated biogeochemical and isotopic events represent a timespan of 20 Myr or less (Fig. 4C). Determining how and why this period of non-glacial conditions punctuated an otherwise apparently consistently and largely ice-covered Earth poses an intriguing research question.

CONCLUSION

The 639.1 ± 1.7/1.8/5.0 Ma age obtained on an ash bed in glacimarine sediments of the Marinoan-equivalent Ghaub Formation in northern Namibia combined with a refined age of 635.21 ± 0.59/0.61/0.92 Ma for an ash bed in the basinal equivalent of the Ghaub Formation in central Namibia confirm that the Marinoan glaciation was long-lived, at least 4 Myr in duration, and that the preceding interval of non-glacial conditions was less than 20 Myr in duration. Our data also confirm that the sedimentary archive of the Marinoan glaciation records glacial erosion-sedimentation and at least intermittent open-water conditions as much as 4 million years prior to terminal meltback at *c*. 635 Ma.

ACKNOWLEDGMENTS

This work was supported by NIGFSC grant IP XXXXX.

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Figure 1. Generalised geologic framework of northern Namibia. Ages for the Naauwpoort Formation (NF) and Oas Syenite (OS) are from Hoffman et al. (1996), for the Ombombo Subgroup from Halverson et al. (2005), and for the Ghaub Formation from Hoffmann et al. (2004) and this paper. See Miller (2008, and references therein) for the ages of the granites that post-date the Swakop Group rocks.

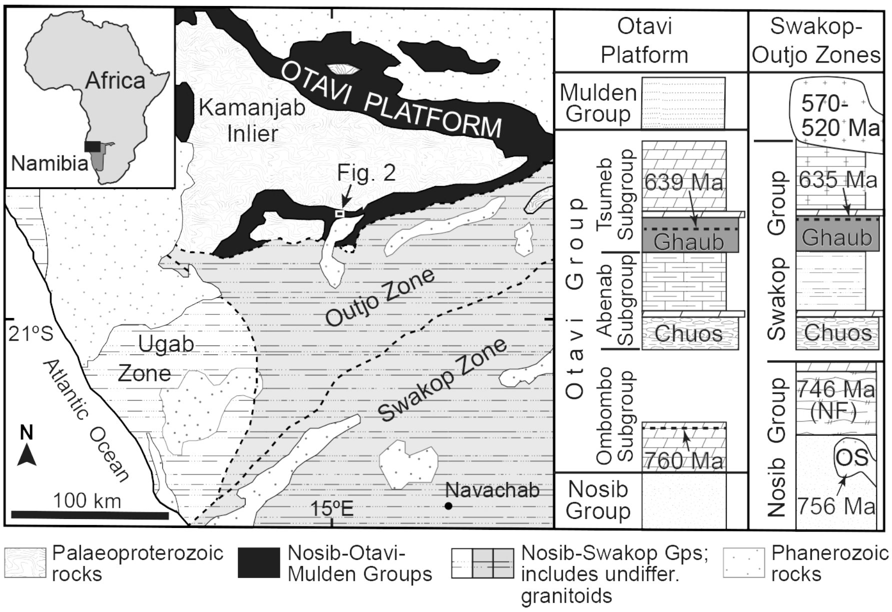

Figure 2. A. Fransfontein Ridge geology in the vicinity of sample DW-1. See Figure 1 for location.

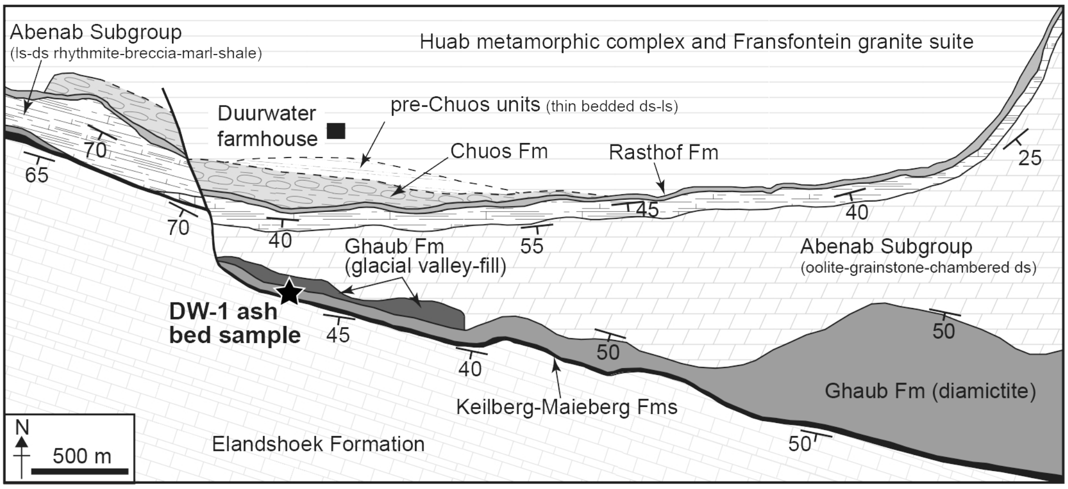

Figure 3. Simplified stratigraphy of the Duurwater and Navachab sections (for details of the Navachab section see Hoffmann et al., 2004); left column is a detailed section showing the stratigraphic position of the DW-1 ash bed within the diamictic interval of the Ghaub Formation.

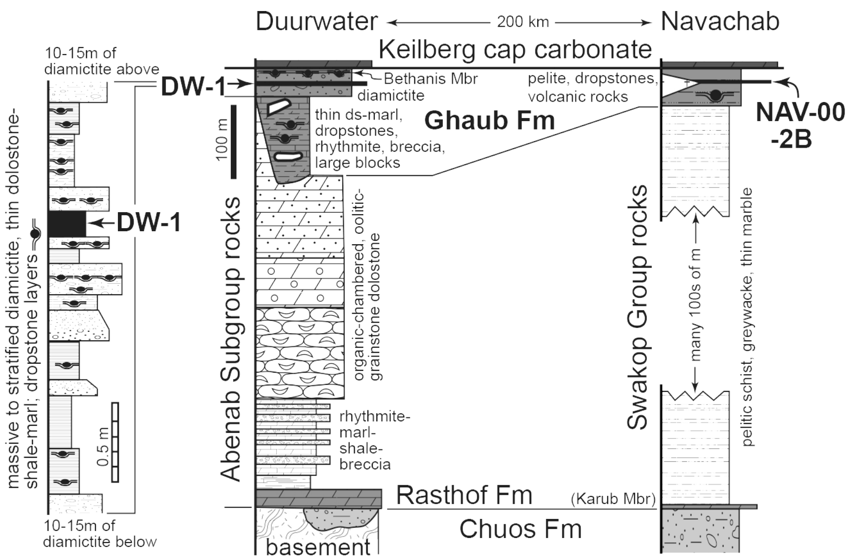

Figure 4. A. DW-1 ash bed between ice-rafted-debris beds, Duurwater section. **B.** U-Pb Concordia plot of data for samples DW-1 and NAV-00-2B; solid ellipses represent analyses included in age calculation, dashed ellipses are not included (see Data Repository for explanation). **C.** Neoproterozoic timeline trends for key isotope proxy datasets: S isotopes after (from Och and Shields-Zhou, 2012, and references therein); Sr and C isotopes after (Halverson et al., 2005) and our own data. U-Pb age data from: 1–Cox et al. (2015), 2–Macdonald et al. (2010), 3–Zhou et al. (2004), 4–Zhang et al. (2008), 5–Condon et al. (2005). Bold ages are reported herein.