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The arc of the Snowball: U-Pb dates constrain the Islay anomaly and the initiation of the Sturtian glaciation

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ABSTRACT

In order to understand the onset of Snowball Earth events, precise geochronology and chemostratigraphy are needed on complete sections leading into the glaciations. While deposits associated with the Neoproterozoic Sturtian glaciation have been found on nearly every continent, time-calibrated stratigraphic sections that record paleoenvironmental conditions leading into the glaciation are exceedingly rare. Instead, the transition to glaciation is normally expressed as erosive contacts with overlying diamictites, and the best existing geochronological constraints come from volcanic successions with little paleoenvironmental information. We report new stratigraphic and geochronological data from the upper Tambien Group in northern Ethiopia, which indicates that the glacigenic diamictite at the top of the succession is Sturtian in age. U-Pb zircon dates obtained from two tuffaceous siltstones that are 74 and 84 m below the diamictite are 719.68 ± 0.46 Ma and 719.68 ± 0.56 Ma (2σ), respectively. We also report a U-Pb date of 735.25 ± 0.25 Ma from a crystal-rich tuff located 2 m above the nadir of a high-amplitude, basin-wide, negative $\delta^{13}C$ excursion previously correlated with the Islay anomaly. This age for the anomaly agrees with Re-Os age constraints from Laurentia, suggesting that the $\delta^{13}C$ signal is globally synchronous and preceded the Sturtian glaciation by ~18 m.y. The interval between the Islay anomaly and Sturtian glaciation is recorded in the Tambien Group as an ~600 m succession of predominantly shallow-water carbonates and siliciclastics with $\delta^{13}C$ values recording a prolonged period at +5‰, followed by an interval of lower, but still positive, values leading up to the glaciation. Our data are consistent with synchronous global onset of the Sturtian glaciation at ca. 717 Ma. Shallow-water carbonates in strata directly below the first diamictite suggest that glacial onset was rapid in terranes of the Arabian-Nubian Shield.

INTRODUCTION

The two glacial episodes that define the Cryogenian, the Sturtian and Marinoan, are both preceded by large negative $\delta^{13}C$ isotope excursions that have been identified in numerous sections globally (Halverson et al., 2005; Prave et al., 2009). It has been proposed that these excursions have a causal relationship to the onset of glacial conditions, as the $\delta^{13}C$ signals were interpreted to reflect large perturbations to the global carbon cycle (Hoffman et al., 1998; Schrag et al., 2002). It now has been shown that, preceding both the Sturtian and Marinoan Snowball events, carbon isotopes recover from deeply negative values prior to glacial conditions (Halverson et al., 2005; Prave et al., 2009; Rose et al., 2012). Re-Os age constraints place the negative isotope excursion preceding the Sturtian glaciation (Islay anomaly) between 739 ± 6 Ma and 732 ± 4 Ma, that is, >15 m.y. before the first diamictites (Rooney et al., 2014; Strauss et al., 2014).

Models for the mechanisms driving Sturtian Snowball initiation include enhanced organic production and remineralization under anaerobic conditions (Tziperman et al., 2011), increased CO_2 sequestration through weathering of large volumes of mafic extrusions at equatorial latitudes (Goddéris et al., 2003; Macdonald et al., 2010), and sulfate injection into the stratosphere caused by equatorial basaltic eruptions (Macdonald and Wordsworth, 2017). Regardless of the initiation mechanism, once ice sheet extent reaches ~30° of latitude, numerical models predict that ice expansion to the equator should occur over thousands of years due to the ice albedo feedback (Baum and Crowley, 2001).

Temporally constrained chemo- and lithostratigraphic records that are continuous into glacial events are critical for testing the Snowball Earth hypothesis and its proposed initiation mechanisms. In this contribution, we present new geochronology and carbonate $\delta^{13}C$ chemostratigraphy from the upper Tambien Group in northern Ethiopia deposited during the lead-up to Sturtian glaciation.

GEOLOGICAL SETTING

The Tambien Group (Tigray Region, northern Ethiopia) is a thick Tonian-Cryogenian carbonate-siliciclastic succession that culminates in diamictite interpreted to have been deposited during the Sturtian 'Snowball Earth' glaciation (Fig. 1; Beyth et al., 2003; Miller et al., 2003, 2009; Swanson-Hysell et al., 2015). The Tambien Group overlies a thick succession of extrusive volcanics and volcaniclastic rocks associated with arc magmatism within the present-day Arabian-Nubian Shield (see the GSA Data Repository[1] for a geological map). The succession was folded during the East African Orogeny (Stern, 1994; Johnson, 2014), and now is exposed within NNE-trending structures (see the Data Repository).

This study focuses on the upper ~1 km of the Tambien Group (Fig. 1). It begins with the Didikama Formation—extensively dolomitized and recrystallized pale-brown carbonates interbedded with siltstones. This transitions into well-preserved limestone ribbonite (micrite with ribbon-like laminations) with molar tooth structures of the Matheos Formation. Carbonates near the contact between these two formations record a large negative $\delta^{13}C$ excursion to values below −6‰ that was tentatively correlated with the Islay anomaly (Swanson-Hysell et al., 2015), and that we now reproduce in additional sections across the basin (Fig. 1). The ribbonites that record the recovery from the negative anomaly transition into the upper Matheos Formation, which is dominated by oolitic grainstones with abundant molar tooth structures. Dolomitized stromatolites and minor fine-grained siliciclastics serve as a distinctive and consistent

[1]GSA Data Repository item 2018176, description and photographs/micrographs of carbonate lithofacies and geochronological samples, as well as geochronological and chemostratigraphic methodologies and datasets, is available online at http://www.geosociety.org/datarepository/2018/ or on request from editing@geosociety.org.

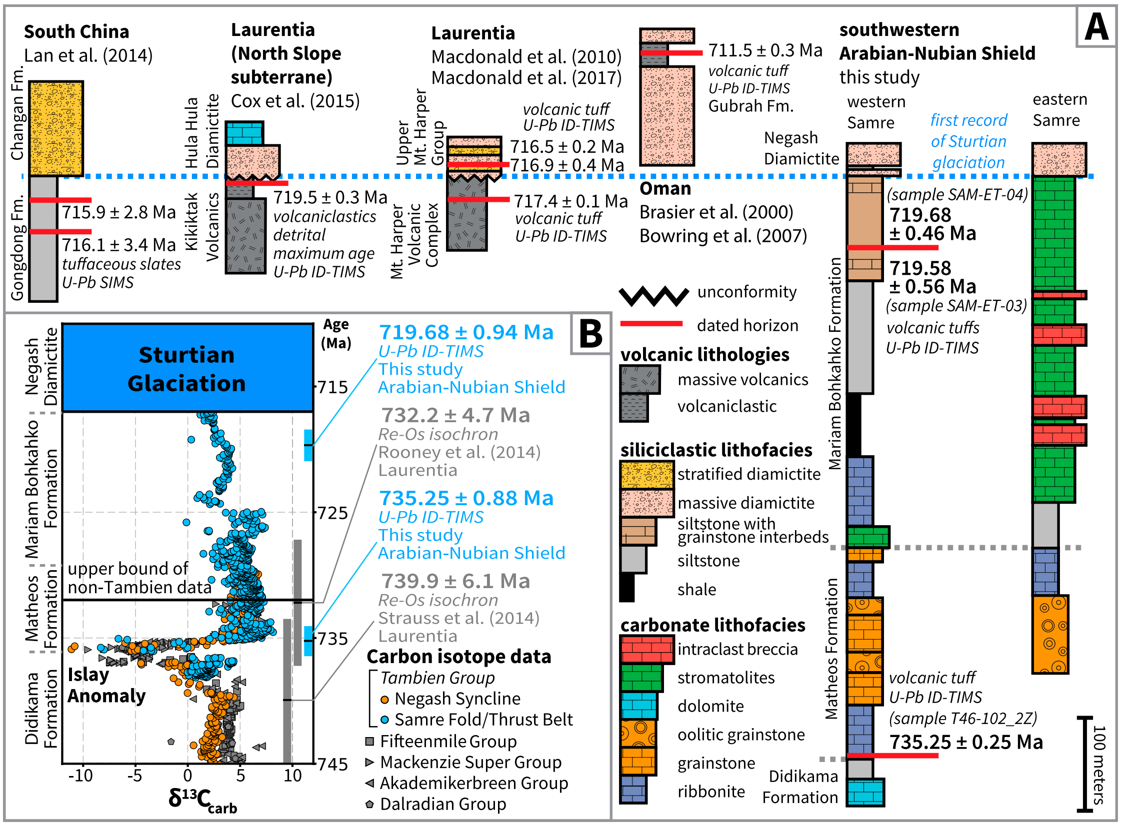

Figure 1. A: Simplified lithostratigraphic columns summarizing the stratigraphic and geochronological constraints on successions deposited before and during the Sturtian glaciation from the South China craton, Laurentia, Oman, and the Arabian-Nubian Shield (Samre, northern Ethiopia) (including 2σ internal uncertainties). B: δ¹³C values from carbonates and geochronological constraints (including all external uncertainties) from pre-Sturtian successions. Fm.—Formation, SIMS—secondary ion mass spectrometry, ID-TIMS—isotope dilution–thermal ionization mass spectrometry.

marker for the base of the overlying Mariam Bohkahko Formation. The Mariam Bohkahko Formation exhibits two lithofacies that are geographically separated: (1) a dominantly carbonate, or (2) a fine-grained siliciclastic and lesser carbonate lithofacies (Fig. 1). They are interpreted to be temporally synchronous, but reflect different depositional conditions. Where the formation is dominated by carbonate, the lithofacies typically are stromatolitic with intercalated intraclast breccias suggestive of a warm, shallow-water carbonate platform. In the siliciclastic facies–dominated area, the formation is composed of shales and siltstone with allodapic ribbonite and minor grainstone interbeds. Rippled fine sandstone, oncolite, and carbonate intraclast breccia beds occur at the top of the formation.

Diamictites of the Negash Formation atop the Mariam Bohkahko Formation previously were reported only within the core of the Negash Syncline (see the Data Repository), but new mapping has led to the discovery of exposures of the diamictite and underlying strata near the town of Samre (see the Data Repository for a regional geological map). These exposures significantly expand known exposure of the formation, which is dominated by matrix-supported diamictite with intervals of conglomerate and sandstone. The contact with the underlying Mariam Bohkahko formation is distinct but seemingly conformable. However, in isolated areas within the carbonate-dominated facies, a carbonate conglomerate occurs along the contact, indicating some erosion of the carbonate lithologies did occur and some time may be missing.

Clasts within the diamictite include carbonate lithologies likely sourced from the Tambien Group, volcanic lithologies probably sourced from the basement arc volcanics, and other lithologies such as granite and felsic gneiss that are likely extra-basinal. Striated clasts can be found within the diamictite, which along with stratigraphic arguments, have led to a glacigenic interpretation for the unit (e.g., Miller et al., 2003). The additional exposure near Samre has presented an opportunity to develop further chemostratigraphic and geochronologic constraints on the interval immediately preceding the Sturtian Glaciation.

Existing Geochronological Constraints on Pre-Sturtian Stratigraphy

Glacial sedimentary rocks correlated with the Sturtian glaciation have been reported from most Proterozoic continents (Hoffman and Li, 2009), but few successions have radiometric age constraints (Figs. 1 and 2). Most sedimentary successions have been assigned a Sturtian age based on chemo- and lithostratigraphic correlations (e.g., Halverson et al., 2005).

A chemical abrasion–isotope dilution–thermal ionization mass spectrometry (CA-ID-TIMS) U-Pb zircon date of 711.5 ± 0.3 Ma (all dates presented with 2σ errors that include analytical uncertainty only) from a volcaniclastic interval within the Ghubrah diamictite of Oman provides a minimum age constraint on the initiation of Sturtian glaciation (Bowring et al., 2007). Two CA-ID-TIMS U-Pb zircon dates of 716.9 ± 0.4 and 717.43 ± 0.14 Ma from volcanic rocks within and below glacial diamictites of the upper Mount Harper Group, northern Laurentia, bracket the onset of low-latitude glaciation (Macdonald et al., 2010, 2017). There is the possibility, however, that these dates represent a minimum age for the onset of the Sturtian, as mafic volcanics underlie the glacial diamictite in this area, and are not the ideal lithology to record glacial influence (Macdonald et al., 2010, 2017). It is therefore important to test these temporal constraints in other successions.

A volcaniclastic sandstone that directly underlies, but is unconformable with, Sturtian diamictite in northern Alaska (USA) yielded a CA-ID-TIMS U-Pb zircon date of 719.47 ± 0.29 Ma (Fig. 2; Cox et al., 2015) that is interpreted as a maximum depositional age. Lower-precision U-Pb secondary ion mass spectrometry analyses (SIMS) on zircons from tuffaceous siltstones from strata preceding Sturtian diamictites in South China have yielded dates of 715.9 ± 2.9 Ma and 716.1 ± 3.4 Ma (Fig. 2; Lan et al., 2014). These dates are within the uncertainty of the ID-TIMS dates from Laurentia (Fig. 2; Macdonald et al., 2010).

The Islay anomaly is a sharp negative $\delta^{13}C$ excursion with a nadir below –6‰ recognized to precede the Sturtian glaciation (Hoffman et al., 2012). The anomaly currently is bracketed stratigraphically by two

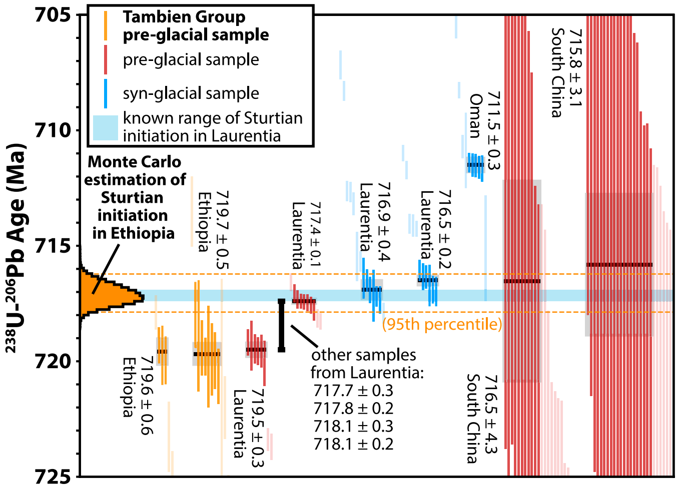

Figure 2. U-Pb date distribution plots of dates constraining the age of the initiation of Sturtian glaciation (2σ internal uncertainties). Histogram shows the distribution of estimated ages for the initiation of glacial sedimentation in the Tambien Group estimated with the Monte Carlo method, with the dashed orange lines showing the bounds for 95% of the estimates. Data sources are Bowring et al. (2007), Macdonald et al. (2010), Lan et al. (2014), and Macdonald et al., 2017).

Re-Os isochron ages of 732.2 ± 4.7 Ma and 739.9 ± 6.1 Ma (2σ errors with all external uncertainties) from Laurentia (Rooney et al., 2014; Strauss et al., 2014). These constraints suggest that the Islay anomaly precedes the Sturtian glaciation by >15 m.y., which negates direct causative links between the $\delta^{13}C$ excursion and the initiation of Snowball Earth events (Hoffman et al., 1998; Schrag et al., 2002; Pavlov et al., 2003; Rothman et al., 2003; Tziperman et al., 2011). Confirming this age difference with another radiometric method from other basins will bolster this conclusion, and test whether the excursion is globally synchronous.

RESULTS AND INTERPRETATION

We identified a number of horizons interpreted to have volcanic input in the Samre area, and sampled them for U-Pb zircon dating. Carbonate samples were also collected for $\delta^{13}C$ analysis (Fig. 1). Two samples (SAM-ET-03 and SAM-ET-04) of light-colored ~25-cm-thick tuffaceous siltstones in the upper Mariam Bohkahko Formation were collected. Details regarding sample location, preparation, and U-Pb analysis are available in the Data Repository. The zircon grains typically were small (c axis <80 µm) and showed signs of metamictization. The analyzed zircons yield ^{238}U-^{206}Pb dates from 840 to 698 Ma. The age spectra are interpreted to indicate the presence of detrital grains. However, both samples show distinct age clusters at ca. 719 Ma that overlap with uncertainties of ~1 m.y. (see the Data Repository). Weighted mean ages of 719.68 ± 0.46 Ma (n = 8) and 719.58 ± 0.56 Ma (n = 3) were calculated for samples SAM-ET-04 and SAM-ET-03, respectively, using these age clusters (Fig. 2). Within the two samples, there are three younger grains that do not overlap with the cluster at ca. 719 Ma (see the Data Repository). While these young zircon dates could indicate that all the grains older than 698 Ma are detrital, we favor the interpretation that the young dates arose from zones of residual Pb loss that escaped chemical abrasion. This interpretation is favored given that these closely stratigraphically spaced samples both have statistically indistinguishable clusters at ca. 719 Ma, while the younger zircons have very different ages, and were not reproduced in 40 single zircon grain analyses. Therefore, we interpret the 719.68 ± 0.46 Ma and 719.58 ± 0.56 Ma dates as eruptive ages that constrain the depositional age of the strata (see the Data Repository for the implications of alternative interpretations noted above).

A couplet of crystal-rich tuffs, 4 and 8 cm thick, and separated by 7 cm, were collected as a single sample (T46–102_2Z) just above the contact between the Didikama and Matheos Formations. The tuffs are within the recovery from the Islay anomaly, as they are 2 m above $\delta^{13}C$ values of –4‰, and within carbonates with $\delta^{13}C$ values of ~0‰. Zircons separated from the sample were translucent and euhedral. Dates from these zircons were confined to between 738 and 735 Ma, indicating a lack of detrital zircon input. The weighted mean date for the sample, 735.25 ± 0.25/0.88 Ma (2σ; without/with external uncertainties), is within uncertainty of the Re-Os isochron dates of 732.2 ± 4.7 Ma and 739.9 ± 6.1 Ma (2σ; including external uncertainties) that are interpreted to bracket the Islay anomaly (Rooney et al., 2014; Strauss et al., 2014). Independent Re-Os and U-Pb age constraints now indicate that the deeply negative Islay isotope anomaly is globally synchronous and precedes the Sturtian glaciation by ~18 m.y. The integrated chemostratigraphy and geochronology now confirm that the Tambien basin uniquely records a prolonged $\delta^{13}C$ +5‰ plateau preserved in the Matheos and lower most Mariam Bohkahko Formations, followed by less positive values (~+2‰), prior to deposition of the first diamictites (Fig. 1).

DISCUSSION

The two dates near the contact with the Negash Formation diamictite confirm the interpretation that the Negash diamictite is Sturtian in age as originally proposed by Beyth et al., (2003). These dates provide new constraints on the timing of initiation of the Sturtian glaciation in the Arabian-Nubian Shield to be after ca. 719 Ma. By making the assumption that sediment accumulation rate over long timescales was controlled by regional subsidence, and therefore remained relatively constant, the timing of glacial onset can be better approximated. Monte Carlo simulations taking into account age and stratigraphic thickness uncertainty were used to calculate sediment accumulation rates between samples T46–102_2Z and SAM-ET-03/SAM-ET-04. Using these rates, we estimated the time represented by the stratal thickness of 74 m between the SAM-ET-04 tuff and the first diamictite. While short-term sedimentation rates will vary considerably with lithofacies, these variations are muted over the million-year timescales in this study. The simulations yield a median age for the base of the diamictite of 717.1 +0.7/–0.9 Ma (95% confidence interval; Fig. 2). This estimated age falls between existing maximum and minimum age constraints on the onset of Sturtian glaciation in Laurentia (Fig. 2; Macdonald et al., 2010, 2017), and is therefore consistent with global synchronicity of glacial initiation, as predicted at low latitudes by the Snowball Earth hypothesis.

The calculated sediment accumulation rates can also be used to estimate the duration of the Islay anomaly. The duration from the initiation of the downturn in $\delta^{13}C$ values through the nadir, to values below –6‰, to the recovery to ~5‰ is implied to be between 0.7 and 1 m.y. In other successions, the recovery of $\delta^{13}C$ values from the nadir of the Islay anomaly is variably truncated by overlying glacial deposits such that they reach –3‰ in the Akademikerbreen Group of Svalbard (Hoffman et al., 2012), 1‰ in the Appin Group of Scotland (Prave et al., 2009), and >5‰ in the Coates Lake Group of northwest Canada (Rooney et al., 2014). The Tambien Group data reproduce the recovery to >5‰ values following the Islay anomaly and show that the plateau of values at ~5‰ was sustained for millions of years prior to Sturtian glaciation (Fig. 1). As evidenced by these data and previous age constraints (Rooney et al., 2014), the mechanism driving $\delta^{13}C$ in carbonate down to ~–6‰ is therefore temporally unrelated to the Sturtian Snowball Earth. In contrast, the upper Mariam Bohkahko Formation records a longer-term trend toward slightly positive $\delta^{13}C$ values directly below the diamictite, making it the most continuous chemostratigraphic record prior to the Sturtian glaciation yet discovered.

Our age model for the Mariam Bohkahko Formation, coupled with the presence of substantial stromatolitic carbonate and beds of oncoids in sediments directly below the diamictite, suggests that conditions remained warm enough to sustain shallow-water carbonate production until just prior to the deposition of glacial diamictite. This interpretation implies that the transition to low-latitude glaciation was rapid—consistent with the Snowball Earth hypothesis.

CONCLUSIONS

A U-Pb zircon age within the sharp recovery from a deeply negative $\delta^{13}C$ excursion in the upper Tambien Group overlaps with existing Re-Os isochron ages for the Islay anomaly in Laurentia, implying that it is globally synchronous. These dates demonstrate that the Islay anomaly precedes the Sturtian Snowball Earth by >18 m.y., and that there is no direct causative link between the carbon cycle perturbation that caused the excursion and the initiation of low-latitude glaciation. U-Pb zircon dates from strata just below the upper Tambien Group diamictite confirm that it is Sturtian in age. The ages are consistent with global synchronicity of Sturtian glacial sediments and rapid onset of Snowball Earth conditions at ca. 717 Ma.

ACKNOWLEDGMENTS

This research was partially funded by National Science Foundation grants EAR-1325230 (Maloof) and EAR-1323158 (Swanson-Hysell). Robert Bussert alerted the authors to the possible presence of Neoproterozoic diamictite in the Samre area. Carol Dehler and anonymous reviewers are thanked for valuable feedback.

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Manuscript received 3 October 2017
Revised manuscript received 2 April 2018
Manuscript accepted 4 April 2018

Printed in USA