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Dodging snowballs: Geochronology of the Gaskiers glaciation and the first appearance of the Ediacaran biota

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ABSTRACT

The snowball Earth hypothesis predicts that low-latitude glaciation lasted millions of years while CO_2 built up to critical levels to culminate in catastrophic deglaciation in a supergreenhouse climate. The Gaskiers Formation of eastern Newfoundland (Canada) has been attributed to a snowball glaciation event, but the lack of robust paleomagnetic data and precise geochronological constraints has precluded tests of the hypothesis. Here we present high-precision U-Pb zircon geochronology (chemical abrasion–isotope dilution–thermal ionization mass spectrometry) from eight tuffs from multiple distant stratigraphic sections that bracket glacial diamictites and the first appearance of large Ediacaran fossils. Including internal error, deposition of the Gaskiers diamictite on the Avalon Peninsula is constrained to have been between 580.90 ± 0.40 and 579.88 ± 0.44 Ma, and the Trinity diamictite on Bonavista Peninsula was deposited between 579.63 ± 0.15 and 579.24 ± 0.17 Ma. Assuming approximately synchronous deglaciation, these results imply a maximum duration for deposition of the Trinity diamictite of ≤340 k.y.; this is inconsistent with the multimillion year duration predicted by the snowball Earth hypothesis. Our geochronologic data also constrain the first appearance datum of Ediacaran fossils to <9.5 m.y. after the Gaskiers glaciation. Thus, despite existing paleomagnetic constraints that indicate that marine ice sheets extended to low to middle latitudes, it appears that Earth narrowly escaped a third Neoproterozoic snowball glaciation just prior to the late Ediacaran expansion of metazoan ecosystems.

INTRODUCTION

Energy balance models indicate that if sea ice extends to a critical threshold below lat ~30°, the ice-albedo feedback effect will result in global glaciation (Budyko, 1969), known as snowball Earth. If precipitation, erosion, and runoff were curtailed during global glaciation, CO_2 released from volcanoes would build to critical levels over millions to tens of millions of years and culminate in catastrophic deglaciation and supergreenhouse conditions (Hoffman et al., 1998; Kirschvink, 1992; Pierrehumbert et al., 2011; Walker et al., 1981). Thus, the snowball Earth hypothesis can be tested by using the geological record, specifically with paleomagnetism to determine the extent of ice and geochronology to define the duration of glaciation.

Previous paleomagnetic studies demonstrate robust low-latitude sites for multiple glacial deposits associated with Cryogenian glaciations (Evans and Raub, 2011). Geochronological studies indicate a long duration and globally synchronous deglaciations for the ca. 717–660 Ma Sturtian glaciation (Rooney et al., 2015) and the 639 Ma, or older, to 635 Ma Marinoan glaciation (Prave et al., 2016). Critically, diamictites of both Cryogenian glaciations are succeeded by transgressive sequences and post-glacial cap carbonate units, which provide evidence for a strong CO_2 hysteresis and extreme weathering (Bao et al., 2008; Hoffman et al., 1998). These features are consistent with the fundamental predictions of the snowball Earth hypothesis.

A third group of younger Neoproterozoic glacial deposits exists on at least eight different paleocontinents (Hoffman and Li, 2009; McGee et al., 2013), and in four Australian sections these deposits are associated with moderately robust low-latitude paleomagnetic results (e.g., Gostin et al., 2010). Assuming synchroneity, this event has been referred to as the Gaskiers glaciation, after deposits in the Gaskiers Formation of eastern Newfoundland that are succeeded by the oldest known assemblages of large complex Ediacaran fossils (Narbonne and Gehling, 2003). Evidence that the Gaskiers glacial deposits represent snowball Earth conditions includes mid-Ediacaran paleomagnetic data from the Avalon terrane that suggest paleolatitudes as low as 19.1° ± 11.1° (Pisarevsky et al., 2011) and the presence of a thin discontinuous cap carbonate with a negative carbon isotopic signature (Myrow and Kaufman, 1999). Although early geochronologic work by Bowring et al. (2003) based on U-Pb zircon dating of intercalated ash beds associated with the Gaskiers Formation is widely cited, these results were published in a conference abstract without supporting analytical data, and predated modern zircon pretreatment (chemical abrasion) techniques and improved U-Pb analytical calibrations and procedures. As a consequence, it has remained difficult to assess the precise age, duration, and nature of the Gaskiers glaciation.

Here we present new high-precision U-Pb zircon geochronology determined by chemical abrasion–isotope dilution–thermal ionization mass spectrometry (CA-ID-TIMS) on ash beds intercalated in the upper Neoproterozoic, diamictite-bearing successions of eastern Newfoundland (Canada). The results place tight constraints on the timing and duration of the Gaskiers glaciation, test the snowball Earth hypothesis for the Gaskiers episode, and delineate its temporal relationship to the rise of complex multicellular life at the end of the Neoproterozoic Era.

GEOLOGICAL BACKGROUND

Neoproterozoic strata on the Avalon Peninsula in eastern Newfoundland include as much as 7.5 km of submarine fan and slope deposits of the Conception and St. John's Groups that pass upward into a thick wedge of deltaic and fluvial coarse-grained facies of the Signal Hill Group (Myrow, 1995; Williams and King, 1979). The Conception Group consists of the Mall Bay, Gaskiers, and Drook Formations, which together are >2.3 km thick (Fig. 1), dominated by turbiditic facies, and contain minor volcanic tuffs (Myrow, 1995). The regionally extensive diamictite of the

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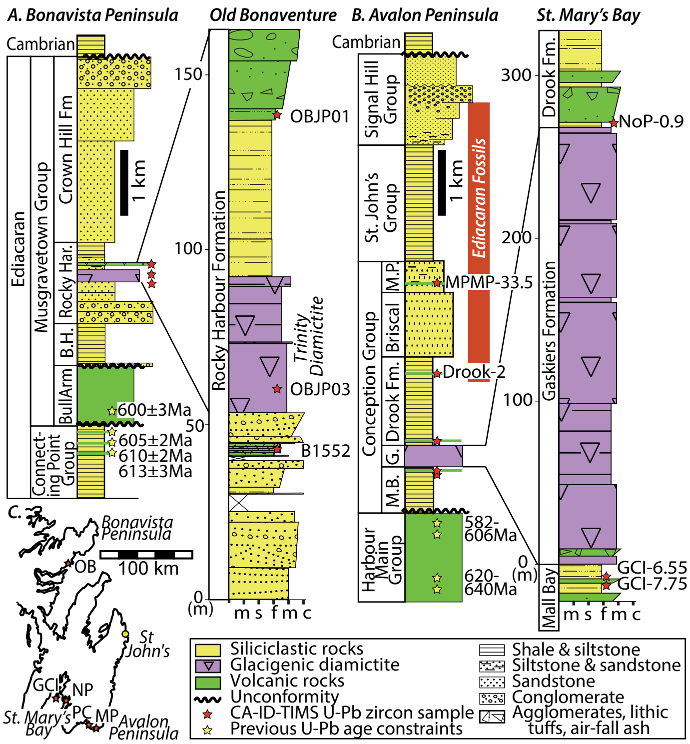

Figure 1. Ediacaran stratigraphy of eastern Newfoundland showing stratigraphic position of tuffs sampled for geochronology. A: Stratigraphy of the Connecting Point and Musgravetown Groups of Bonavista Peninsula, modified after Normore (2011) with expansion of section B1552 of the Rocky Harbour Formation measured at Old Bonaventure (Fig. DR2; see footnote 1). B: Stratigraphy of the Avalon Peninsula, modified after Myrow (1995), with expansion of the Gaskiers Formation in St. Mary's Bay modified after Williams and King (1979). OB—Old Bonaventure; GCI—Great Colinet Island; NP—North Point Bay; PC—Portugal Cove (Trepassey Bay); MP—Mistaken Point. Age constraints are from Krogh et al. (1988), Mills et al. (2016), and Sparkes et al. (2005). Previous dates from the Conception Group reported in or recalculated from abstracts are not shown because these preliminary ages are made obsolete by the data presented herein.

Gaskiers Formation is as much as 300 m thick and contains glacially derived dropstones, striated clasts, and chatter-marked garnets (Eyles and Eyles, 1989). At Conception Bay, a <50-cm-thick discontinuous carbonate bed locally overlies the Gaskiers Formation (Fig. DR1D in the GSA Data Repository[1]) and has depleted $\delta^{13}C$ values as low as −7.8‰ (Myrow and Kaufman, 1999). The overlying Drook and Mistaken Point Formations are slope deposits that host a well-known assemblage of Ediacaran fossils (Narbonne and Gehling, 2003).

Correlative Ediacaran strata and volcanic rocks of the Musgravetown Group are present on the Bonavista Peninsula (Fig. 1). The Musgravetown Group is divided into the Bull Arm, Big Head, Rocky Harbour, and Crown Hill Formations (Normore, 2011), and was previously thought to postdate the Gaskiers Formation based on a reported 570 +5/–3 Ma U-Pb ID-TIMS age from volcanic rocks that were originally assigned to the Bull Arm Formation (O'Brien et al., 1989). However, the dated volcanic rocks have an unclear stratigraphic relationship to the rest of the succession and likely represent a higher stratigraphic level in the Rocky Harbour Formation (O'Brien and King, 2004). The Bull Arm Formation is overlain by fine-grained siliciclastic rocks with graded beds of the Big Head Formation, which were deposited below wave base. These units are succeeded by shallow-marine coarse-grained strata of the Rocky Harbour Formation (Fig. DR2), which includes a recently recognized glacigenic diamictite with dropstones (Fig. DR1F) and striated clasts referred to as the Trinity facies (Normore, 2011).

U-Pb GEOCHRONOLOGY

We provide geochronologic constraints on the age and duration of upper Neoproterozoic glaciation in eastern Newfoundland based on U-Pb CA-ID-TIMS zircon analyses from ash beds intercalated with marine sedimentary successions of the Conception Group on the Avalon Peninsula and the Rocky Harbour Formation on the Bonavista Peninsula (Fig. 1). For details of analyzed samples, U-Pb analytical procedures, tabulated U-Pb isotopic data, and date calculation strategy, see the Data Repository.

Calculated weighted mean $^{206}Pb/^{238}U$ dates and their detailed uncertainties are presented in Table 1. For calculating durations from U-Pb dates produced using the same isotopic tracer, only the analytical (internal) uncertainties need to be considered, as followed herein. Systematic errors must be taken into account for comparison with dates produced by different techniques or by laboratories using different U-Pb tracers.

RESULTS

Two tuff beds sampled from the upper Mall Bay Formation (Fig. 1) on Great Colinet Island (7.75 m and 6.55 m below the base of the Gaskiers Formation) and one tuff from the basal Drook Formation at North Point (0.9 m above the Gaskiers Formation) constrain the age of the Gaskiers Formation on the Avalon Peninsula to between 580.90 ± 0.40 and 579.88 ± 0.44 Ma (Table 1; Fig. 2). At Pigeon Cove in eastern Trepassey Bay, a tuff bed from the upper Drook Formation (Fig. DR1E) that marks the first appearance datum of Ediacaran fossils in Newfoundland (Liu et al., 2012; Narbonne and Gehling, 2003) is dated as 570.94 ± 0.38 Ma. Farther east at Mistaken Point, another tuff bed marking a fossil horizon 33.56 m above the base of the Mistaken Point Formation (Landing et al., 1988) produced a 566.25 ± 0.35 Ma date. The latter two dates provide constraints on the first known occurrences of Ediacaran fossil assemblages in the upper Conception Group (Fig. 3).

On Bonavista Peninsula, near the town of Old Bonaventure, the age of the Trinity diamictite of the Rocky Harbour Formation is constrained to between 579.63 ± 0.15 and 579.24 ± 0.17 Ma (Table 1; Figs. 1 and 2) by tuffs from 11.1 m below and 47.8 m above the diamictite (Fig. DR2). Two zircon analyses from the latter tuff produced outlier dates as young as 571.02 ± 0.48 Ma (Fig. DR3), a result we attribute to persistent lead loss. A tuffaceous sample from within the Trinity diamictite (6.7 m above

TABLE 1. SUMMARY OF CALCULATED U-Pb AGES AND THEIR UNCERTAINTIES

Sample	Formation	$^{206}Pb/^{238}U$ age	Uncertainty (2σ) X	Y	Z	MSWD	*n*
Trepassey Bay, Newfoundland							
MPMP33.56	Mistaken Point	566.25	0.35	0.48	0.77	1.3	5
Drook-2	Drook	570.94	0.38	0.46	0.77	0.33	5
St. Mary's Bay, Newfoundland							
NoP-0.9	Drook	579.88	0.44	0.52	0.81	0.82	5
GCI-neg6.55	Mall Bay	580.90	0.40	0.53	0.82	1.1	9
GCI-neg7.75	Mall Bay	580.34	0.52	0.62	0.88	0.36	5
Bonavista Peninsula, Newfoundland							
OBJP-01	Rocky Harbour	579.24	0.17	0.30	0.69	1.3	9
OBJP-03	Rocky Harbour	579.35	0.33	0.42	0.75	0.73	4
B1552–42.2	Rocky Harbour	579.63	0.15	0.29	0.68	0.018	6

Note: *X*—internal (analytical) uncertainty in the absence of all external or systematic errors; *Y*—incorporates the U-Pb tracer calibration error; *Z*—includes X and Y, as well as the uranium decay constant errors; MSWD—mean square of weighted deviates; *n*—number of analyses included in the calculated weighted mean date.

[1]GSA Data Repository item 2016326, U-Pb analytical procedures, sample descriptions, and data tables, is available online at http://www.geosociety.org/pubs/ft2016.htm or on request from editing@geosociety.org.

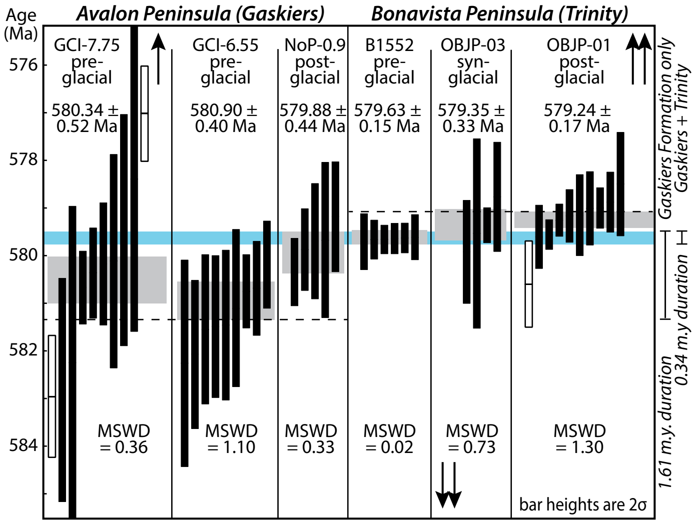

Figure 2. Date distribution plots of the analyzed tuff samples constraining the timing of the Gaskiers glaciation from the Avalon and Bonavista Peninsulas of Newfoundland. Vertical bars represent 2σ analytical uncertainty of individual zircon analyses; filled bars are data used in age calculation. Gray bands signify weighted mean $^{206}Pb/^{238}U$ dates with their 2σ uncertainties. The lower dashed line shows the maximum age constraint on the Gaskiers Formation on the Avalon Peninsula; the upper dashed line shows the minimum age constraint on the Trinity diamictite on the Bonavista Peninsula; the blue bar shows the maximum duration of the Gaskiers glaciation if constraints from both regions are used. Arrows point to analyses that fall outside of the plot area. See Table DR1 (see footnote 1) for complete U-Pb data, and Table 1 for details of geochronology.

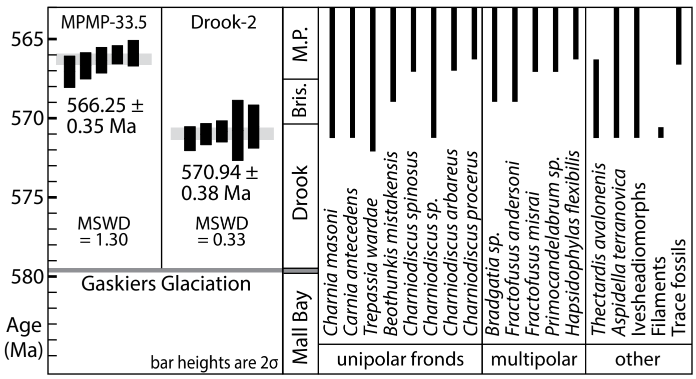

Figure 3. Date distribution plots of analyzed tuff samples from the upper Drook and Mistaken Point Formations of Avalon Peninsula showing the relationship to the stratigraphic ranges of Ediacaran fossils (Liu et al., 2012). Symbols and data sources as in Figure 2.

its base) contained demonstrably detrital grains older than 600 Ma, but also contained a coherent population of zircon that yielded a date of 579.35 ± 0.33 Ma. These age results confirm the first-order synchroneity of Ediacaran glacigenic deposits in Newfoundland.

DISCUSSION

Our new U–Pb geochronologic data provide a robust chronostratigraphic framework for the Ediacaran diamictite- and fossil-bearing successions of eastern Newfoundland. Our results expand upon and supersede the widely cited preliminary dates reported by Bowring et al. (2003) and indicate that the Trinity facies on the Bonavista Peninsula is correlative with the Gaskiers Formation on Avalon Peninsula.

Recent paleomagnetic data from the Bull Arm Formation sampled at two locations yielded Ediacaran paleopoles that place the Bonavista Peninsula at 23.6° +9.4°/–7.5° (Pisarevsky et al., 2011). Pisarevsky et al. (2011) gave these poles an age of ca. 570 Ma based on previous correlations with volcanic rocks that have an unclear stratigraphic relationship to the rest of the succession (O'Brien et al., 1989). Our results suggest that the dated volcanic rocks are not correlative with the Bull Arm Formation (cf. O'Brien and King, 2004) and that the paleopoles of Pisarevsky et al. (2011) acquired their magnetization between 605.0 and 579.5 Ma, and thus do not provide a robust low-latitude constraint on the overlying Trinity diamictite.

Although the paleomagnetic test for a low-latitude extent of the Gaskiers glaciation in Newfoundland remains ambiguous, our new geochronological data provide an additional test of the snowball Earth hypothesis. In St. Mary's Bay, diamictite of the Gaskiers Formation was deposited after 580.90 ± 0.40 Ma and before 579.88 ± 0.44 Ma, suggesting a maximum duration of deposition of 1.61 m.y. On the Bonavista Peninsula, the Trinity diamictite was deposited between 579.63 ± 0.15 and 579.24 ± 0.17 Ma, with a maximum duration of 0.62 m.y. (Fig. 2). Durations were calculated by taking the difference between two ages based on their stratigraphic order and adding their 2σ errors in quadrature. Assuming that the postglacial transgressive sequence is correlative and that deglaciation was synchronous, these data imply that the Trinity diamictite was deposited after 579.63 ± 0.15 Ma and before 579.88 ± 0.44 Ma, with stratigraphic constraints giving a maximum duration of 340 k.y. when the 2σ error bounds are considered for both ages (Fig. 2).

At other localities on Avalon Peninsula, rare dropstones have been observed in the upper Mall Bay Formation (Fig. DR1B). Due to lateral facies change, these dropstone-bearing horizons may be correlative with the base of the Gaskiers Formation at Great Colinet Island. In addition, on Bonavista Peninsula, shoaling from deep-water turbidites of the Big Head Formation to the shallow-water cross-bedded sandstone in the lower Rocky Harbour Formation may be related to glacioeustasy and correlative with the lower-most glacial deposits on Avalon Peninsula. In this scenario, the 579.63 ± 0.15 Ma age from the lower Rocky Harbour Formation would strictly represent a synglacial onset constraint, but without full ice cover, and the maximum constraint would be provided by the 580.90 ± 0.40 Ma age from the Mall Bay Formation. Thus, although it is possible that there was an earlier ice advance on the Avalon Peninsula, no glacial deposits have been identified below the Trinity Formation (Fig. DR2) or below the dated horizons of the Mall Bay Formation at Great Colinet Island, and the geochronological data are consistent with glaciation beginning throughout eastern Newfoundland after 579.63 ± 0.15 Ma and ending within 340 k.y. This short duration contrasts with the ~57-m.y.-long Sturtian glaciation (Rooney et al., 2015) and >4-m.y.-long Marinoan glaciation (Prave et al., 2016), and indicates a fundamentally different character of the Gaskiers glaciation.

Although the paucity of geochronological constraints on other Ediacaran glacial deposits opens up the possibility that they are diachronous and represent multiple Cenozoic-style ice advances and retreats, in Newfoundland we have not found evidence for multiple ice advances and retreats, and only one glacial horizon has been identified in any single Ediacaran succession globally. If low-latitude paleomagnetic data for the Gaskiers glaciation prove robust, the short duration of the glaciation may be consistent with the metastable Jormungand (Abbot et al., 2011) or Waterbelt (Rose, 2015) scenarios, which have large equatorial ice-free zones and do not require multimillion year durations to build up atmospheric CO_2 to a critical threshold for deglaciation. Alternatively, an Ediacaran snowball Earth may have deglaciated via a mechanism other than CO_2 buildup, such as a rapid increase in planetary albedo (cf. Abbot and Halevy, 2010).

Our geochronologic data also constrain the first appearance datum of Ediacaran fossils to 570.94 ± 0.38 Ma. This is significantly younger than the commonly reported preliminary age of 575 Ma on the same horizon from Bowring et al. (2003) and other subsequent reinterpretations, and only 4.69 (±0.52) m.y. older than the 566.25 ± 0.35 Ma age from the Mistaken Point assemblage. These dates constrict the temporal range of Ediacaran fossil appearances in Newfoundland. The age of the first *in situ* appearance of Ediacaran fossils also postdates the Gaskiers glaciation by 8.94 ± 0.58 m.y. While it is tempting to infer a relationship between the end of glaciation, apparent changes in local redox conditions, and the first appearance of large complex animals (Canfield et al., 2007), a statistical study of iron-speciation data does not support an Ediacaran oxygenation event (Sperling et al., 2015). Furthermore, the fortuitous preservation of the fossils below volcanic tuff layers suggests a taphonomic control, and morphologically complex animals may have been present prior to the Gaskiers glaciation without necessarily being limited by oxygen availability (Sperling et al., 2015). Instead, the progressive decrease in duration of successive Neoproterozoic glaciations may have permitted a more habitable late Ediacaran Earth for large animals.

CONCLUSIONS

High-precision geochronological data from eastern Newfoundland bracket the age of the Ediacaran Gaskiers glaciation to between 579.63 ± 0.15 and 579.88 ± 0.44 Ma, indicating a duration of ≤340 k.y. If the low-latitude paleomagnetic data associated with Ediacaran glacial deposits are robust, then this short duration could suggest that the Gaskiers glaciation represents a metastable state with significant open water, or that a snowball Earth event was ended by a mechanism other than CO_2 buildup. Alternatively, latitudinal inferences from Ediacaran paleomagnetic data are imprecise, and the Gaskiers glaciation could represent a Phanerozoic-style regional glaciation. In either case, the short duration suggests that the Gaskiers glaciation may not have been a critical barrier for macroscopic animal evolution; this is consistent with the first appearance of morphologically complex Ediacaran fossils <9.5 m.y. later.

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