GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G49593.1

Manuscript received 12 August 2021
Revised manuscript received 25 October 2021
Manuscript accepted 14 November 2021

Published online 25 February 2022

Calibrating the Russøya excursion in Svalbard, Norway, and implications for Neoproterozoic chronology

Alexie E.G. Millikin[1], Justin V. Strauss[2], Galen P. Halverson[3], Kristin D. Bergmann[4], Nicholas J. Tosca[5] and Alan D. Rooney[1]
[1]Department of Earth and Planetary Sciences, Yale University, New Haven, Connecticut 06511, USA
[2]Department of Earth Sciences, Dartmouth College, Hanover, New Hampshire 03755, USA
[3]Department of Earth and Planetary Sciences, McGill University, Montreal, Quebec H3A 0E8, Canada
[4]Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
[5]Department of Earth Sciences, University of Cambridge, Cambridge CB2 3EQ, UK

ABSTRACT

The Tonian–Ediacaran Hecla Hoek succession of Svalbard, Norway, represents one of the most complete and well-preserved Neoproterozoic sedimentary successions worldwide. With diverse fossil assemblages, an extensive carbonate $\delta^{13}C$ record, and sedimentary evidence for two distinct Cryogenian glaciations, this succession will continue to yield insights into the Neoproterozoic Earth system; however, at present there are no direct radiometric age constraints for these strata. We present two new Re-Os ages and initial Os isotope data that constrain the timing of Neoproterozoic glaciation in Svalbard, providing further support for two globally synchronous Cryogenian glaciations and insight into pre- and post-snowball global weathering conditions. An age from the Russøya Member (Elbobreen Formation) facilitates correlation of the negative carbon isotope excursion recorded therein with the pre-glacial "Islay" excursion of the Callison Lake Formation of northwestern Canada and the Didikama and Matheos Formations of Ethiopia. We propose that this globally synchronous ca. 735 Ma carbon isotope excursion be referred to as the Russøya excursion with northeastern Svalbard as the type locality. This new age provides an opportunity to construct a time-calibrated geological framework in Svalbard to assess connections between biogeochemical cycling, evolutionary innovations within the eukaryotes, and the most extreme climatic changes in Earth history.

INTRODUCTION

The early to middle Neoproterozoic Era (1000–541 Ma), consisting of the Tonian (1000–720 Ma) and Cryogenian (720–635 Ma) periods, represents one of the most eventful chapters of Earth's history. The formation and breakup of the supercontinent Rodinia reorganized global paleogeography in the middle to late Tonian (Li et al., 2008), which in turn may have paved the way for dynamic marine redox conditions, changes to biogeochemical cycling, and repeated biological innovations (e.g., Sperling et al., 2013; Strauss et al., 2014; Cox et al., 2016; Cohen and Riedman, 2018). Beginning with the ca. 810–800 Ma Bitter Springs excursion, many large-magnitude (>8‰) negative carbon isotope excursions (CIEs) punctuate the long-term enriched $\delta^{13}C$ values of the Neoproterozoic (Halverson et al., 2005; Shields-Zhou et al., 2016). To interrogate potential links between these various events more fully, a temporal framework derived from globally distributed geologic archives calibrated by robust radiometric age constraints is required (e.g., Macdonald et al., 2010; Rooney et al., 2015; Prave et al., 2016).

The lower and middle Hecla Hoek succession (Veteranen, Akademikerbreen, and Polarisbreen Groups) in Svalbard records long-term shallow-marine deposition through the Tonian and Cryogenian periods (Fig. 1A; see the Supplemental Material[1]). Diverse fossil assemblages (e.g., Knoll and Calder, 1983; Butterfield et al., 1994; Riedman et al., 2021) and an extensive carbonate $\delta^{13}C$ record (Halverson et al., 2005) in these strata have played an important role in our understanding of Neoproterozoic biological evolution and biogeochemical cycles. Furthermore, these strata record both the Sturtian and Marinoan snowball Earth events with glacial diamictites and have provided key insights into extreme Neoproterozoic climate events (e.g., Halverson et al., 2005, 2018a; Bao et al., 2009; Hoffman et al., 2012, and references therein; Fairchild et al., 2016). However, despite its importance, the Hecla Hoek succession lacks direct radiometric age constraints. We provide two new Re-Os dates bracketing glacial strata in Svalbard that confirm their Cryogenian age and bolster correlation of pre-Cryogenian chemo- and biostratigraphic records.

GEOLOGIC BACKGROUND

Svalbard consists of three pre-Devonian basement domains juxtaposed by significant north-south–trending Paleozoic strike-slip faults (Fig. 1B; e.g., Harland, 1997). Well-preserved Neoproterozoic strata of the Hecla Hoek succession are exposed in Svalbard's Eastern basement domain in the northeastern part of Spitsbergen and on Nordaustlandet. The Hecla Hoek succession consists of the siliciclastic-dominated Veteranen Group (early to middle Tonian), carbonate-dominated Akademikerbreen Group (middle to late Tonian), mixed carbonate-siliciclastic Polarisbreen Group (late Tonian to late Ediacaran), and carbonate-dominated Oslobreen Group (Cambrian to Ordovician) (Fig. 1A). These strata are interpreted to have been deposited on the northeastern margin of Laurentia in a thermally subsiding basin adjacent to East Greenland and without a proximal source of volcanic ash (Harland, 1997; Halverson et al., 2018a, 2018b).

[1]Supplemental Material. Detailed analytical methods and sample information, data tables containing all geochemical data, and compiled geochronological and chemostratigraphic data. Please visit https://doi.org/10.1130/GEOL.S.18172280 to access the supplemental material, and contact editing@geosociety.org with any questions.

CITATION: Millikin, A.E.G., et al., 2022, Calibrating the Russøya excursion in Svalbard, Norway, and implications for Neoproterozoic chronology: Geology, v. 50, p. 506–510, https://doi.org/10.1130/G49593.1

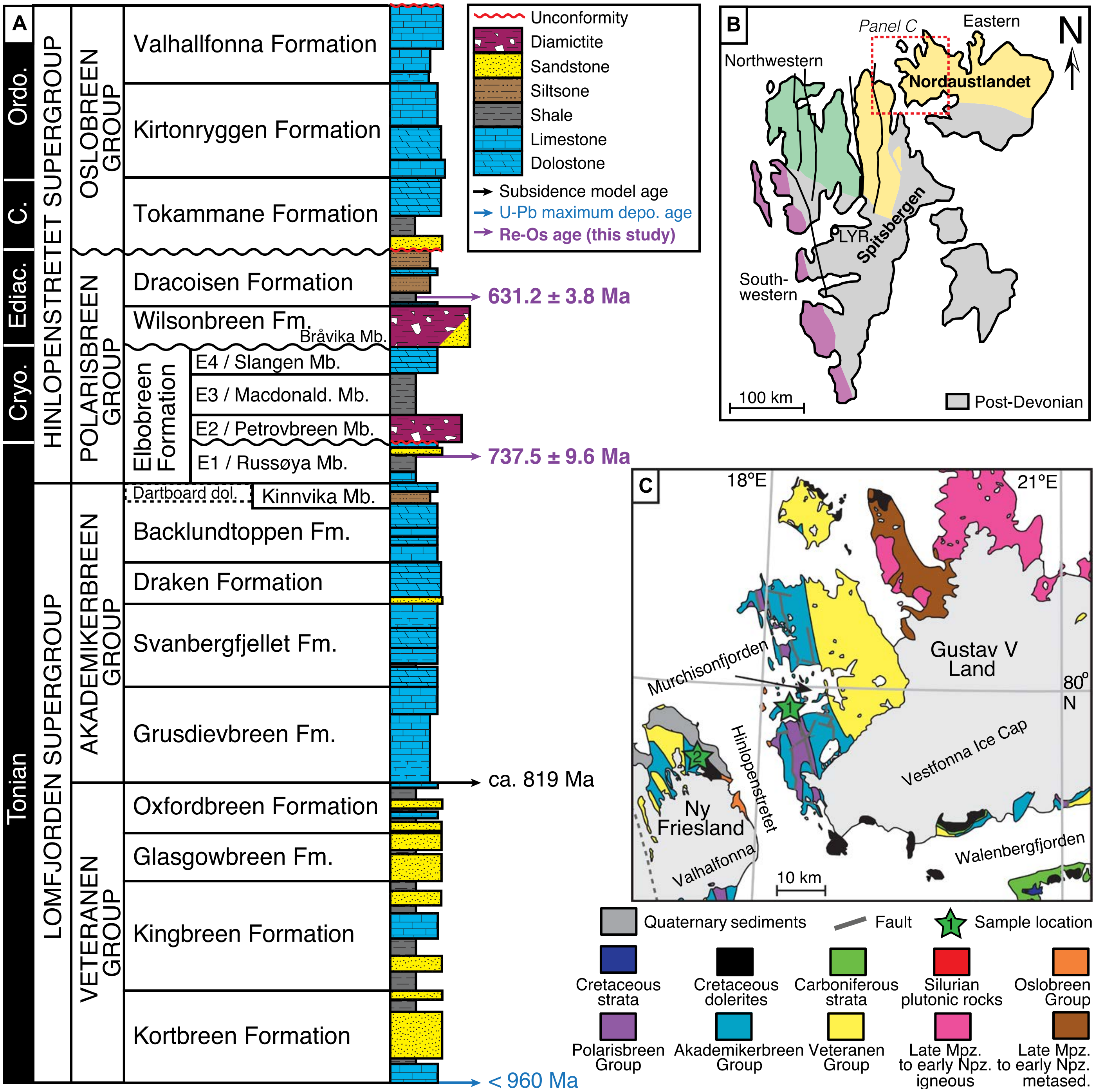

Figure 1. Simplified map and stratigraphy of the Neoproterozoic–Ordovician Hecla Hoek succession, Svalbard, Norway. (A) Schematic stratigraphy of the Hecla Hoek succession with existing and new age constraints (see the Supplemental Material [see footnote 1] for references). Stratigraphic thicknesses are not to scale. Cryo.—Cryogenian; Ediac.—Ediacaran; C.—Cambrian; Ordo.—Ordovician; Dol.—Dolomite; Macdonald.—Macdonaldryggen; Fm.—Formation; Mb.—Member; depo.—depositional. (B) Simplified geological map of Svalbard showing basement domains and significant faults. Island names are in bold, and red box indicates location of panel C. LYR—Longyearbyen. (C) Simplified geologic map of northeastern Svalbard, after Dallmann (2015). Sample locations: 1—Søre Russøya (sample SR-161.5, Russøya Member); 2—Gråvela River (sample J1630, Dracoisen Formation). Mpz.—Mesoproterozoic; Npz.—Neoproterozoic; metased.—metasediments.

Global correlations for the Hecla Hoek succession are based primarily on lithostratigraphy and carbon and strontium isotope chemostratigraphy (Kaufman et al., 1997; Halverson et al., 2005). The ~2-km-thick Akademikerbreen Group hosts the ca. 810 Ma Bitter Springs CIE in the upper Grusdievbreen and lower Svanbergfjellet Formations (Halverson et al., 2018a, 2018b), and the upper Russøya Member of the Elbobreen Formation records a negative CIE that has been correlated with the pre-Sturtian ca. 735 Ma "Islay" excursion (see the Supplemental Material; Hoffman et al., 2012; Rooney et al., 2014; Strauss et al., 2014; Halverson et al., 2018a, 2018b; MacLennan et al., 2018). Given age uncertainties in the pre-Sturtian negative CIE of the Islay Limestone of Scotland, it has been suggested that the name "Islay" should be abandoned for this ca. 735 Ma event (Fairchild et al., 2018). The overlying Petrovbreen Member (Elbobreen Formation) is interpreted to record the ca. 717–661 Ma Sturtian glaciation, while the Wilsonbreen Formation is considered to record the ca. 651(?)–635 Ma Marinoan glaciation (Hoffman et al., 2012;

Halverson et al., 2018b); the Dracoisen Formation begins with the ca. 635 Ma Marinoan cap dolostone and its associated negative $\delta^{13}C$ excursion (Halverson et al., 2005).

RESULTS

Re-Os Geochronology

Two new Re-Os ages were obtained from black shale horizons in the Russøya Member (Elbobreen Formation) and the Dracoisen Formation in Nordaustlandet and northern Ny Friesland, respectively (Fig. 1C). Details regarding sample location, preparation, and Re-Os isotopic analysis are available in the Supplemental Material. Sample SR-161.5 from the Russøya Member yielded a model 1 age of 737.5 ± 9.6 Ma (n = 6, mean square of weighted deviates [MSWD] = 1.8) with an initial $^{187}Os/^{188}Os$ (Os_i) composition of 0.26 ± 0.03 (Fig. 2A; Table S1 in the Supplemental Material); and sample J1630 from the Dracoisen Formation yielded a model 1 age of 631.2 ± 3.8 Ma (n = 7, MSWD = 0.71) with an Os_i of 0.89 ± 0.03 (Fig. 2B; Table S1). Total uncertainties are reported at 2σ and include the uncertainty of the ^{187}Re decay constant.

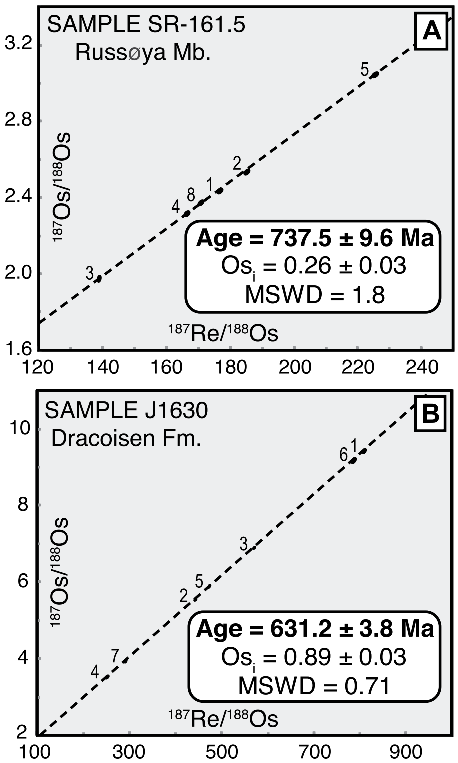

Figure 2. Re-Os isochron diagrams of sample SR-161.5 from the Russøya Member (Mb.), Akademikerbreen Group (Svalbard, Norway) (A); and sample J1630 from Dracoisen Formation (Fm.), Polarisbreen Group (Svalbard) (B). Data-point labels correspond with those in Table S1 (see footnote 1). Data-point ellipses represent 2σ uncertainty and include the uncertainty of the ^{187}Re decay constant. Os_i—initial $^{187}Os/^{188}Os$; MSWD—mean square of weighted deviates.

DISCUSSION

Early to Middle Neoproterozoic Chronology

The new Re-Os ages from the lower and middle Hecla Hoek succession add to a growing body of radiometric ages that bracket Cryogenian glacial deposits globally. The age of 737.5 ± 9.6 Ma from 44 m below the negative CIE in the Russøya Member (Fig. S1) supports a Sturtian assignment for the overlying Petrovbreen Member diamictite and suggests a >10 m.y. unconformity between the Russøya and Petrovbreen Members (Fig. 1A). This inference is consistent with truncation of the negative CIE and a distinctive columnar *Kussiella* biostrome bed at the top of the Russøya Member across northeastern Svalbard (Halverson et al., 2018a). The Petrovbreen diamictite is overlain by shale and siltstone of the Macdonaldryggen Member and carbonate of the Slangen Member, which are interpreted to represent the post-Sturtian glacioeustatic transgressive sequence (Fig. 1A; e.g., Hoffman et al., 2012). The Re-Os age of 631.2 ± 3.8 Ma from the Dracoisen Formation, 104 m above the base of the cap dolostone and ~60 m above the maximum flooding surface, confirms a Marinoan age for the Wilsonbreen Formation. This age also confirms correlation to terminal Marinoan successions in South China, Canada, Namibia, and Australia, supporting a globally synchronous deglaciation at ca. 635 Ma, as predicted by the snowball Earth hypothesis (Fig. 3; Condon et al., 2005; Calver et al., 2013; Rooney et al., 2015; Prave et al., 2016; Zhou et al., 2019).

Tonian Chemo- and Biostratigraphy

Robust stratigraphic correlations are crucial for understanding the drivers behind and feedbacks between the numerous evolutionary, biogeochemical, climatic, and tectonic events that occurred during the Neoproterozoic Era. Our new Re-Os ages are consistent with existing correlations of the lower and middle Hecla Hoek succession with carbon isotope profiles from other successions leading into the Sturtian glaciation. Data from Svalbard, northwestern Canada, and Ethiopia demonstrate a large-magnitude pre-Sturtian negative CIE (down to ~−5‰ $\delta^{13}C_{carb}$ [carb—carbonate]) followed by a recovery up to +5‰ referred to as either the Islay (Macdonald et al., 2010; Strauss et al., 2014; MacLennan et al., 2018) or Russøya excursion (Fig. 4A; see the Supplemental Material; Hoffman et al., 2012; Halverson et al., 2018a). This CIE is bracketed by ages of 739.9 ± 6.5 Ma and 732.2 ± 4.7 Ma from northwestern Canada (Strauss et al., 2014; Rooney et al., 2014), which are consistent with an age of 735.25 ± 0.88 Ma during the recovery from the excursion in Ethiopia (MacLennan et al., 2018). Our new 737.5 ± 9.6 Ma age from the Russøya Member, 44 m below the onset of the CIE, supports a globally synchronous ca. 735 Ma pre-Sturtian CIE that is decoupled from the onset of glaciation by ~15 m.y. (Fig. 4A). Here, we propose that the ca. 735 Ma CIE preserved in Svalbard, Canada, and Ethiopia be referred to as the Russøya excursion, with northeastern Svalbard as the type locality (following Halverson et al., 2018a). By doing so, we abandon the name "Islay" due to a lack of radiometric age constraints on the Dalradian Supergroup in Scotland from which the name was derived (see the Supplemental Material). A distinct and younger latest Tonian negative $\delta^{13}C$ excursion (reaching ~−4‰ $\delta^{13}C_{carb}$) that is closely associated with the onset of the Sturtian glaciation, documented in the Garvellach Islands of Scotland (Fairchild et al., 2018), the Tambien Group of Ethiopia (MacLennan et al., 2018), and the Ugab Subgroup of northern Namibia (Lamothe et al., 2019), leaves open the possibility for a mechanistic link between carbon-cycle fluctuations and the onset of glaciation.

More broadly, the Russøya Member age adds to a growing body of radiometric age constraints that are consistent with global synchroneity of Neoproterozoic CIEs within the existing geological and analytical uncertainties, such as the ca. 810 Ma Bitter Springs (Swanson-Hysell et al., 2015) and ca. 570 Ma Shuram (Rooney et al., 2020) excursions. Therefore, current geochronological data support the careful use of carbon isotope chemostratigraphic correlations where independent age constraints are not available and suggests that these isotopic characteristics were imparted early in the depositional and/or diagenetic history of the sediment. Generating this improved Neoproterozoic time scale is imperative for investigating the source of these anomalous carbon isotope signatures, whether CIEs are related to global carbon-cycle perturbations (e.g., Kump and Arthur, 1999) or instead reflect local platformal processes that are broadly coincident globally due to tectonic or environmental drivers (e.g., Ahm et al., 2021).

The Russøya Member Re-Os age also provides an important constraint on the occurrence of vase-shaped microfossils (VSMs) from the Draken, Backlundtoppen, and Elbobreen Formations (Fig. 1A; Knoll and Calder, 1983; Riedman et al., 2021). VSMs of the same age and with similar morphological characteristics from the Chuar, Uinta Mountain, and Pahrump Groups of the western United States; Coates Lake and Mount Harper Groups of northwestern Canada; Eleonore Bay Group of East Greenland; and Togari Group of Tasmania demonstrate the potential for species-level VSM biostratigraphy in the early to middle Neoproterozoic (see the Supplemental Material and Fig. S2; Strauss et al., 2014; Riedman et al., 2018). Recent work indicates that VSMs from the Russøya Member, as well as from Tonian strata in Tasmania and the western United States, are associated with apatite-kerogen scales, pointing to higher seawater phosphorous concentration than in the modern ocean (Riedman et al., 2021); thus,

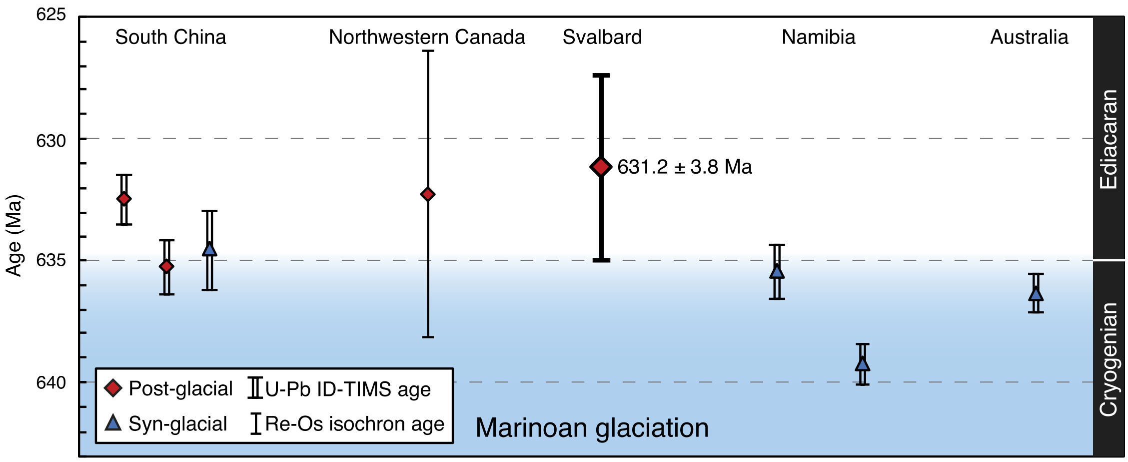

Figure 3. Existing age constraints for termination of Marinoan glaciation at ca. 635 Ma. Data from this study are shown in bold. Ages used for this figure can be found in Table S2 (see footnote 1). Age constraints include all systematic uncertainties. ID-TIMS—isotope dilution thermal ionization mass spectrometry.

improving age constraints on additional VSM-bearing units may prove useful in determining the existence, timing, and causes of a unique biogeochemical and/or evolutionary window that occurred prior to 737.5 ± 9.6 Ma in Svalbard and between 729.0 ± 0.9 and 751.0 ± 7.6 Ma in the western United States (Rooney et al., 2018).

The initial osmium isotopic (Os_i) composition of seawater obtained from the units in Svalbard can also provide insight into the relative contribution of juvenile mantle-derived (i.e., hydrothermal input) and evolved crustal (i.e., continental weathering) sources to the ocean (Peucker-Ehrenbrink and Ravizza, 2002). Combined with the limited existing Tonian Os_i chemostratigraphic data, the Russøya Member Os_i value of 0.26 ± 0.03 supports a trend toward increasingly juvenile sources preceding the Sturtian glaciation (Fig. 4B; Rooney et al., 2014, 2015; Strauss et al., 2014). These data confirm that the late Tonian ocean was unradiogenic globally, which is consistent with the hypothesis that weathering of juvenile material may have contributed to CO_2 drawdown and global cooling leading into the Sturtian glaciation (Goddéris et al., 2003; Rooney et al., 2014; Cox et al., 2016; Park et al., 2020). In contrast, the more radiogenic Os_i value of 0.89 ± 0.03 from the postglacial Dracoisen Formation is consistent with an increased continental weathering flux resulting from deglaciation, which is also recorded in the Os_i value of 1.21 ± 0.04 at ca. 632 Ma from the post-Marinoan Sheepbed Formation in northwestern Canada (Rooney et al., 2015).

CONCLUSIONS

Two new Re-Os ages of 737.5 ± 9.6 Ma (Russøya Member, Elbobreen Formation) and 631.2 ± 3.8 Ma (Dracoisen Formation) provide the first direct radiometric age constraints on Neoproterozoic strata in Svalbard. These dates (1) confirm previous litho- and chemostratigraphic correlations between Svalbard and other key Neoproterozoic successions; (2) provide further support for two globally synchronous

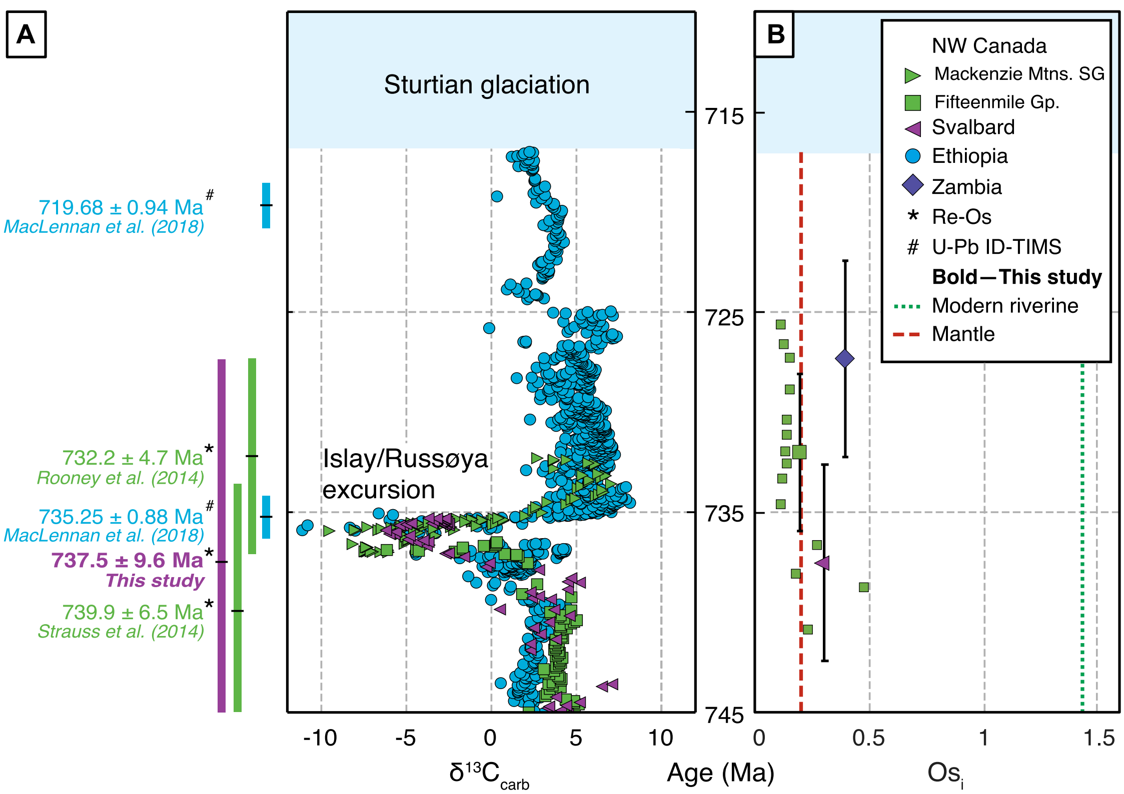

Figure 4. Pre–Sturtian glaciation chemostratigraphy. (A) $\delta^{13}C_{carb}$ (carb—carbonate) data from pre-Sturtian carbonate successions globally, after MacLennan et al. (2018). Age constraints include all systematic uncertainties. Age-model values for $\delta^{13}C_{carb}$ data (based on correlation to Ethiopia) are within the uncertainty of radiometric age constraints. (B) Initial osmium (Os_i) data plotted with reference lines for osmium isotopic composition of modern average riverine and mantle fluxes (Peucker-Ehrenbrink and Ravizza, 2002). Large points with age uncertainty are initial values from isochrons, while smaller points are chemostratigraphic data. Uncertainty in Os_i is smaller than data points in all cases. Data from Rooney et al. (2014, 2015) and this study can be found in Table S3 (see footnote 1). Mtns.—Mountains; SG—Supergroup; Gp.—Group; ID-TIMS—isotope dilution thermal ionization mass spectrometry.

glaciations during the Cryogenian; (3) are consistent with the synchroneity of the ca. 735 Ma Russøya CIE; and (4) strengthen the role of the lower and middle Hecla Hoek succession as a key Neoproterozoic reference section. Integrating paleontological and chemostratigraphic records from Svalbard with other globally distributed sections may prove useful in elucidating the cause of major biogeochemical, evolutionary, and climatic change during the Neoproterozoic.

ACKNOWLEDGMENTS

This research was supported by a National Geographic Society grant (CP-129R-17) awarded to J.V. Strauss; U.S. National Science Foundation (NSF) grants EAR-1929593 and EAR-1929597 awarded to J.V. Strauss and A.D. Rooney, respectively; and grants from the Lewis and Clark Fund for Exploration and Field Research, the Yale Institute of Biospheric Studies, and the Geological Society of America awarded to A.E.G. Millikin. We thank S. Anseeuw for laboratory assistance and the Sysselmesteren of Svalbard for a sampling permit (RIS-ID 6867). T. Mackey, T. Gibson, and R. Anderson are thanked for help in the field. Reviews from N. Swanson-Hysell and two anonymous reviewers improved this manuscript.

REFERENCES CITED

Ahm, A.S.C., Bjerrum, C.J., Hoffman, P.F., Macdonald, F.A., Maloof, A.C., Rose, C.V., Strauss, J.V., and Higgins, J.A., 2021, The Ca and Mg isotope record of the Cryogenian Trezona carbon isotope excursion: Earth and Planetary Science Letters, v. 568, p. 117002, https://doi.org/10.1016/j.epsl.2021.117002.

Bao, H., Fairchild, I.J., Wynn, P.M., and Spötl, C., 2009, Stretching the envelope of past surface environments: Neoproterozoic glacial lakes from Svalbard: Science, v. 323, p. 119–122, https://doi.org/10.1126/science.1165373.

Butterfield, N.J., Knoll, A.H., and Swett, K., 1994, Paleobiology of the Neoproterozoic Svanbergfjellet Formation, Spitsbergen: Lethaia, v. 27, p. 1–88, https://doi.org/10.1111/j.1502-3931.1994.tb01558.x.

Calver, C.R., Crowley, J.L., Wingate, M.T.D., Evans, D.A.D., Raub, T.D., and Schmitz, M.D., 2013, Globally synchronous Marinoan deglaciation indicated by U-Pb geochronology of the Cottons Breccia, Tasmania, Australia: Geology, v. 41, p. 1127–1130, https://doi.org/10.1130/G34568.1.

Cohen, P.A., and Riedman, L.A., 2018, It's a protist-eat-protist world: Recalcitrance, predation, and evolution in the Tonian–Cryogenian ocean: Emerging Topics in Life Sciences, v. 2, p. 173–180, https://doi.org/10.1042/ETLS20170145.

Condon, D., Zhu, M., Bowring, S., Wang, W., Yang, A., and Jin, Y., 2005, U-Pb ages from the Neoproterozoic Doushantuo Formation, China: Science, v. 308, p. 95–98, https://doi.org/10.1126/science.1107765.

Cox, G.M., Halverson, G.P., Stevenson, R.K., Vokaty, M., Poirier, A., Kunzmann, M., Li, Z.X., Denyszyn, S.W., Strauss, J.V., and Macdonald, F.A., 2016, Continental flood basalt weathering as a trigger for Neoproterozoic Snowball Earth: Earth and Planetary Science Letters, v. 446, p. 89–99, https://doi.org/10.1016/j.epsl.2016.04.016.

Dallmann, W.K., 2015, Geoscience Atlas of Svalbard: Tromsø, Norsk Polarinstitutt Tromsø, 292 p.

Fairchild, I.J., et al., 2016, The Late Cryogenian warm interval, NE Svalbard: Chemostratigraphy and genesis: Precambrian Research, v. 281, p. 128–154, https://doi.org/10.1016/j.precamres.2016.05.013.

Fairchild, I.J., et al., 2018, Tonian-Cryogenian boundary sections of Argyll, Scotland: Precambrian Research, v. 319, p. 37–64, https://doi.org/10.1016/j.precamres.2017.09.020.

Goddéris, Y., Donnadieu, Y., Nédélec, A., Dupré, B., Dessert, C., Grard, A., Ramstein, G., and François, L.M., 2003, The Sturtian 'snowball' glaciation: Fire and ice: Earth and Planetary Science Letters, v. 211, p. 1–12, https://doi.org/10.1016/S0012-821X(03)00197-3.

Halverson, G.P., Hoffman, P.F., Schrag, D.P., Maloof, A.C., and Rice, A.H.N., 2005, Toward a Neoproterozoic composite carbon-isotope record: Geological Society of America Bulletin, v. 117, p. 1181–1207, https://doi.org/10.1130/B25630.1.

Halverson, G.P., Kunzmann, M., Strauss, J.V., and Maloof, A.C., 2018a, The Tonian-Cryogenian transition in Northeastern Svalbard: Precambrian Research, v. 319, p. 79–95, https://doi.org/10.1016/j.precamres.2017.12.010.

Halverson, G.P., Porter, S.M., and Gibson, T.M., 2018b, Dating the late Proterozoic stratigraphic record: Emerging Topics in Life Sciences, v. 2, p. 137–147, https://doi.org/10.1042/ETLS20170167.

Harland, W.B., 1997, Proto-basement in Svalbard: Polar Research, v. 16, p. 123–147, https://doi.org/10.1111/j.1751-8369.1997.tb00254.x.

Hoffman, P.F., Halverson, G.P., Domack, E.W., Maloof, A.C., Swanson-Hysell, N.L., and Cox, G.M., 2012, Cryogenian glaciations on the southern tropical paleomargin of Laurentia (NE Svalbard and East Greenland), and a primary origin for the upper Russøya (Islay) carbon isotope excursion: Precambrian Research, v. 206, p. 137–158, https://doi.org/10.1016/j.precamres.2012.02.018.

Kaufman, A.J., Knoll, A.H., and Narbonne, G.M., 1997, Isotopes, ice ages, and terminal Proterozoic Earth history: Proceedings of the National Academy of Sciences of the United States of America, v. 94, p. 6600–6605, https://doi.org/10.1073/pnas.94.13.6600.

Knoll, A.H., and Calder, S., 1983, Microbiotas of the Late Precambrian Ryssö Formation, Nordaustlandet, Svalbard: Paleontology, v. 26, p. 467–496.

Kump, L.R., and Arthur, M.A., 1999, Interpreting carbon-isotope excursions: Carbonates and organic matter: Chemical Geology, v. 161, p. 181–198, https://doi.org/10.1016/S0009-2541(99)00086-8.

Lamothe, K.G., Hoffman, P.F., Greenman, J.W., and Halverson, G.P., 2019, Stratigraphy and isotope geochemistry of the pre-Sturtian Ugab Subgroup, Otavi/Swakop Group, northwestern Namibia: Precambrian Research, v. 332, 105387, https://doi.org/10.1016/j.precamres.2019.105387.

Li, Z.X., et al., 2008, Assembly, configuration, and break-up history of Rodinia: A synthesis: Precambrian Research, v. 160, p. 179–210, https://doi.org/10.1016/j.precamres.2007.04.021.

Macdonald, F.A., Schmitz, M.D., Crowley, J.L., Roots, C.F., Jones, D.S., Maloof, A.C., Strauss, J.V., Cohen, P.A., Johnston, D.T., and Schrag, D.P., 2010, Calibrating the Cryogenian: Science, v. 327, p. 1241–1243, https://doi.org/10.1126/science.1183325.

MacLennan, S., Park, Y., Swanson-Hysell, N., Maloof, A., Schoene, B., Gebreslassie, M., Antilla, E., Tesema, T., Alene, M., and Haileab, B., 2018, The arc of the Snowball: U-Pb dates constrain the Islay anomaly and the initiation of the Sturtian glaciation: Geology, v. 46, p. 539–542, https://doi.org/10.1130/G40171.1.

Park, Y., et al., 2020, The lead-up to the Sturtian Snowball Earth: Neoproterozoic chemostratigraphy time-calibrated by the Tambien Group of Ethiopia: Geological Society of America Bulletin, v. 132, p. 1119–1149, https://doi.org/10.1130/B35178.1.

Peucker-Ehrenbrink, B., and Ravizza, G., 2002, The marine osmium isotope record: Terra Nova, v. 12, p. 205–219, https://doi.org/10.1046/j.1365-3121.2000.00295.x.

Prave, A.R., Condon, D.J., Hoffmann, K.H., Tapster, S., and Fallick, A.E., 2016, Duration and nature of the end-Cryogenian (Marinoan) glaciation: Geology, v. 44, p. 631–634, https://doi.org/10.1130/G38089.1.

Riedman, L.A., Porter, S.M., and Calver, C.R., 2018, Vase-shaped microfossil biostratigraphy with new data from Tasmania, Svalbard, Greenland, Sweden and the Yukon: Precambrian Research, v. 319, p. 19–36, https://doi.org/10.1016/j.precamres.2017.09.019.

Riedman, L.A., Porter, S.M., and Czaja, A.D., 2021, Phosphatic scales in vase-shaped microfossil assemblages from Death Valley, Grand Canyon, Tasmania, and Svalbard: Geobiology, v. 19, p. 364–375, https://doi.org/10.1111/gbi.12439.

Rooney, A.D., Macdonald, F.A., Strauss, J.V., Dudás, F.Ö., Hallmann, C., and Selby, D., 2014, Re-Os geochronology and coupled Os-Sr isotope constraints on the Sturtian snowball Earth: Proceedings of the National Academy of Sciences of the United States of America, v. 111, p. 51–56, https://doi.org/10.1073/pnas.1317266110.

Rooney, A.D., Strauss, J.V., Brandon, A.D., and Macdonald, F.A., 2015, A Cryogenian chronology: Two long-lasting synchronous Neoproterozoic glaciations: Geology, v. 43, p. 459–462, https://doi.org/10.1130/G36511.1.

Rooney, A.D., Austermann, J., Smith, E.F., Li, Y., Selby, D., Dehler, C.M., Schmitz, M.D., Karlstrom, K.E., and Macdonald, F.A., 2018, Coupled Re-Os and U-Pb geochronology of the Tonian Chuar Group, Grand Canyon: Geological Society of America Bulletin, v. 130, p. 1085–1098, https://doi.org/10.1130/B31768.1.

Rooney, A.D., Cantine, M.D., Bergmann, K.D., Gómez-Pérez, I., Al Baloushi, B., Boag, T.H., Busch, J.F., Sperling, E.A., and Strauss, J.V., 2020, Calibrating the coevolution of Ediacaran life and environment: Proceedings of the National Academy of Sciences of the United States of America, v. 117, p. 16,824–16,830, https://doi.org/10.1073/pnas.2002918117.

Shields-Zhou, G.A., Porter, S., and Halverson, G.P., 2016, A new rock-based definition for the Cryogenian Period (circa 720–635 Ma): Episodes, v. 39, p. 3–8, https://doi.org/10.18814/epiiugs/2016/v39i1/89231.

Sperling, E.A., Frieder, C.A., Raman, A.V., Girguis, P.R., Levin, L.A., and Knoll, A.H., 2013, Oxygen, ecology, and the Cambrian radiation of animals: Proceedings of the National Academy of Sciences of the United States of America, v. 110, p. 13,446–13,451, https://doi.org/10.1073/pnas.1312778110.

Strauss, J.V., Rooney, A.D., Macdonald, F.A., Brandon, A.D., and Knoll, A.H., 2014, 740 Ma vase-shaped microfossils from Yukon, Canada: Implications for Neoproterozoic chronology and biostratigraphy: Geology, v. 42, p. 659–662, https://doi.org/10.1130/G35736.1.

Swanson-Hysell, N.L., Maloof, A.C., Condon, D.J., Jenkin, G.R.T., Alene, M., Tremblay, M.M., Tesema, T., Rooney, A.D., and Haileab, B., 2015, Stratigraphy and geochronology of the Tambien Group, Ethiopia: Evidence for globally synchronous carbon isotope change in the Neoproterozoic: Geology, v. 43, p. 323–326, https://doi.org/10.1130/G36347.1.

Zhou, C., Huyskens, M.H., Lang, X., Xiao, S., and Yin, Q.Z., 2019, Calibrating the terminations of Cryogenian global glaciations: Geology, v. 47, p. 251–254, https://doi.org/10.1130/G45719.1.

Printed in USA