A Cryogenian chronology: Two long-lasting synchronous Neoproterozoic glaciations

Alan D. Rooney[1], Justin V. Strauss[1], Alan D. Brandon[2], and Francis A. Macdonald[1]
[1]Department of Earth and Planetary Sciences, Harvard University, Cambridge, Massachusetts 02138, USA
[2]Department of Earth and Atmospheric Sciences, University of Houston, Houston, Texas 77204, USA

ABSTRACT

The snowball Earth hypothesis predicts globally synchronous glaciations that persisted on a multimillion year time scale. Geochronological tests of this hypothesis have been limited by a dearth of reliable age constraints bracketing these events on multiple cratons. Here we present four new Re-Os geochronology age constraints on Sturtian (717–660 Ma) and Marinoan (635 Ma termination) glacial deposits from three different paleocontinents. A 752.7 ± 5.5 Ma age from the base of the Callison Lake Formation in Yukon, Canada, confirms nonglacial sedimentation on the western margin of Laurentia between ca. 753 and 717 Ma. Coupled with a new 727.3 ± 4.9 Ma age directly below the glacigenic deposits of the Grand Conglomerate on the Congo craton (Africa), these data refute the notion of a global ca. 740 Ma Kaigas glaciation. A 659.0 ± 4.5 Ma age directly above the Maikhan-Uul diamictite in Mongolia confirms previous constraints on a long duration for the 717–660 Ma Sturtian glacial epoch and a relatively short nonglacial interlude. In addition, we provide the first direct radiometric age constraint for the termination of the Marinoan glaciation in Laurentia with an age of 632.3 ± 5.9 Ma from the basal Sheepbed Formation of northwest Canada, which is identical, within uncertainty, to U-Pb zircon ages from China, Australia, and Namibia. Together, these data unite Re-Os and U-Pb geochronological constraints and provide a refined temporal framework for Cryogenian Earth history.

INTRODUCTION

After more than one billion years without robust evidence of glaciation, Cryogenian (ca. 850–635 Ma) strata record arguably the most extreme episodes of climate change in Earth's history. The widespread occurrence of low-latitude glacial deposits on every paleocontinent, coupled with the unique geochemistry and sedimentology of cap carbonates (Hoffman et al., 1998; Bao et al., 2008), inspired the snowball Earth hypothesis (Kirschvink, 1992). However, the general paucity of radiometric age constraints from multiple paleocontinents for the onset and demise of Cryogenian glaciations (Sturtian ca. 717–660 Ma, and Marinoan ending ca. 635 Ma), as well as reports of putative pre-Sturtian glaciations (Frimmel et al., 1996), has fostered doubts about the synchronicity and global extent of these events (e.g., Allen and Etienne, 2008; Kendall et al., 2006). In particular, an apparent disagreement between various geochronological constraints has fueled the idea Cryogenian glaciations were not particularly unique or extreme events; however, it remains unclear if these age differences represent true geological mismatches or the combination of analytical error and/or poor cross-calibration between different geochronometers. Here we present four new Re-Os ages from strata that bound Cryogenian glacial deposits in northwest Canada, Zambia, and Mongolia. We then integrate these data with preexisting age constraints from multiple paleocontinents to produce an updated global Cryogenian chronology.

GEOLOGICAL SETTING

Black carbonaceous shales were sampled at four separate localities on three different Neoproterozoic paleocontinents (Fig. 1; Table DR1 in the GSA Data Repository[1]). The Callison Lake Formation of the Mount Harper Group is exposed in the Ogilvie Mountains of Yukon, Canada, and is composed of an ~400-m-thick succession of mixed carbonate and siliciclastic strata deposited in an episodically restricted marine basin (Strauss et al., 2014; Fig. 1). Current age constraints on the Mount Harper Group include an Re-Os age of 739.9 ± 6.1 Ma from the uppermost Callison Lake Formation and a U-Pb chemical abrasion–isotope dilution–thermal ionization mass spectrometry age on zircon of 717.4 ± 0.1 Ma from the overlying Mount Harper Volcanics (Macdonald et al., 2010a; Strauss et al., 2014). To further refine the geological history of this succession, a black shale horizon was sampled from the lower Callison Lake Formation for Re-Os geochronology (Fig. 1; Fig. DR1 in the Data Repository).

The Katanga Supergroup of the Congo craton has been subdivided into the Roan, Nguba, and Kundelungu Groups and comprises a mixed carbonate and siliciclastic succession with two diamictite horizons (Fig. 1; Wendorff, 2003; Master et al., 2005). In the Chambishi area of Zambia, the Mwashya subgroup of the Nguba Group records subtidal deposition in a restricted marginal marine setting and comprises an ~120-m-thick succession of black carbonaceous shale with a gradational to locally disconformable contact with the overlying glaciogenic deposits of the Grand Conglomerate (Fig. 1; Selley et al., 2005). Age constraints on the Katanga Supergroup are limited to a maximum age for the onset of Roan Group sedimentation from a U-Pb sensitive high-resolution ion microprobe (SHRIMP) age of 883 ± 10 Ma (Armstrong et al., 2005) and ages of ca. 760 Ma from various volcanics within the Nguba Group (Key et al., 2001). Samples of carbonaceous black shale were collected from the Mwashya subgroup over a vertical interval of 6.49 m up to ~0.5 m below the Grand Conglomerate for Re-Os geochronology (MJCZ9 drill core; Bodiselitsch et al., 2005).

The Tsagaan-Olom Group of the Zavkhan terrane in southwest Mongolia consists of as much as 2 km of carbonate-dominated strata that host two glacial deposits, the Maikhan-Uul and Khongor diamictites, which are considered to be the Sturtian and Marinoan equivalents, respectively (Fig. 1; Macdonald et al., 2009). Samples for Re-Os geochronology were sampled at the Taishir locality (Macdonald et al., 2009), 1.2 m above the contact with the Maikhan-Uul diamictite (Fig. 1) and within the Sturtian cap carbonate.

The Cryogenian–Ediacaran-age Hay Creek and upper groups of the Windermere Supergroup are exposed in the Mackenzie Mountains, northwest Canada, and host Marinoan-age glacial deposits of the Stelfox Member of the Ice Brook Formation (Fig. 1; Aitken, 1991; James et al., 2001). A Marinoan age (ca. 635 Ma) for the Stelfox Member is supported by carbon isotope profiles and sedimentological characteristics of the Ravensthroat and Hayhook cap carbonate. Samples for Re-Os geochronology were collected from the Sheepbed Formation near Shale Lake (Aitken, 1991), 0.9 m above the contact with the underlying Hayhook limestone. The Sheepbed Formation consists of >700 m of siliciclastics deposited in a proximal to distal slope environment during a pronounced glacioeustatic transgression (Fig. 1; Dalrymple and Narbonne, 1996).

GEOCHRONOLOGY

Black shale from the lower part of the Callison Lake Formation of Yukon yields a Re-Os

---

[1] GSA Data Repository item 2015157, summary of sampling techniques, detailed analytical methods, and data tables containing all isotopic and/or geochronological data, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

GEOLOGY, May 2015; v. 43; no. 5; p. 459–462; Data Repository item 2015157 | doi:10.1130/G36511.1 | Published online 27 March 2015

depositional age of 752.7 ± 5.5 Ma (all age uncertainties also include the uncertainty in the ^{187}Re decay constant, λ, 2σ, *n* = 5, mean square of weighted deviates, MSWD, of 0.30) with an initial ^{187}Os/^{188}Os (Os$_i$) composition of 0.33 ± 0.03 (Fig. 2A). Regression of the Re-Os isotopic composition data from the Mwashya subgroup of Zambia yields a depositional age of 727.3 ± 4.9 Ma (2σ, *n* = 7, MSWD = 0.50) with an unradiogenic Os$_i$ value of 0.35 ± 0.03 (Fig. 2B). The basal Taishir Formation of Mongolia yields a depositional Re-Os age of 659.0 ± 4.5 Ma (2σ, *n* = 6, MSWD = 0.67), with a moderately radiogenic Os$_i$ value of 0.60 ± 0.01 (Fig. 2C). Regression of the isotopic composition data from samples of the Sheepbed Formation of northwest Canada yields a Re-Os age of 632.3 ± 5.9 Ma (2σ, *n* = 5, MSWD = 0.58), with a highly radiogenic Os$_i$ value of 1.21 ± 0.04 (Fig. 2D). These new Re-Os ages coupled with existing Re-Os and magmatic U-Pb age constraints are combined to produce a refined geochronological framework for the Cryogenian as summarized in Figure 3 (Table DR2).

DISCUSSION

The existence of a pre-Sturtian, global Kaigas glaciation has been suggested from the apparent relationship between inferred glacial deposits and the following age constraints: a 741 ± 6 Ma Pb-Pb zircon evaporation age in the Gariep belt of the Kalahari craton (Frimmel et al., 1996); a 740 ± 7 Ma U-Pb SHRIMP age from near the base of the Bayisi diamictite on the Tarim craton (Xu et al., 2009); and a 735 ± 5 Ma U-Pb SHRIMP age from the Kundelungu Basin of the Congo craton (Key et al., 2001). However, previously published U-Pb and Re-Os ages from time-equivalent strata in Laurentia (Karlstrom et al., 2000; Macdonald et al., 2010a; Strauss et al., 2014) and the Re-Os age presented here from the Callison Lake Formation (Fig. 2A) document nonglacial sedimentation from ca. 753 to 717 Ma on the western margin of Laurentia, arguing against low-latitude glaciation during this interval. Macdonald et al. (2010b) observed that the 741 ± 6 Ma Pb-Pb evaporation age from the Gariep belt (Frimmel et al., 1996) was sampled from volcanic rocks that are not in direct contact with glacial deposits and that conglomerate of the Kaigas Formation was previously miscorrelated with glacigenic strata of the Numees

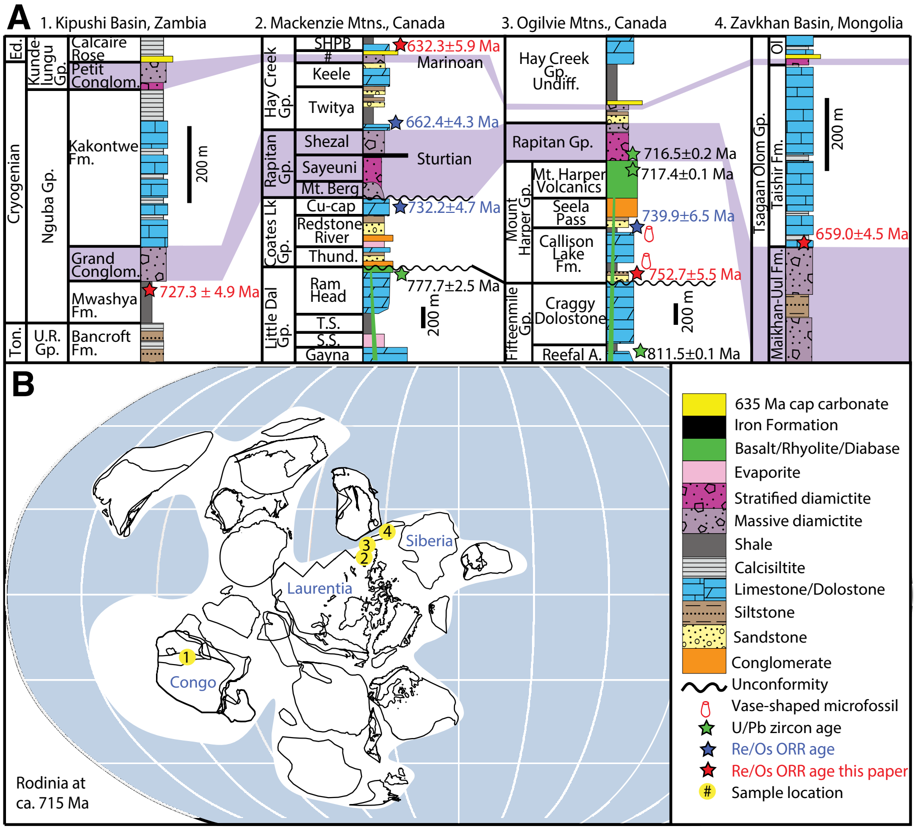

Figure 1. A: Schematic stratigraphy of sample locations 1–4, adapted from Bodiselitsch et al. (2005), Macdonald et al. (2009, 2010a), and Strauss et al. (2014). Geochronological constraints are from Jefferson and Parrish (1989), Macdonald et al. (2010a), Rooney et al. (2014), and Strauss et al. (2014). Ton.—Tonian; Ed.—Ediacaran; Gp.—Group; Fm.—Formation; Conglom.—Conglomerate; U.R.—Upper Roan; SHPB—Sheepbed Formation; Lk—lake; Cu-cap.—Coppercap Formation; Thund.—Thundercloud Formation; T.S.—Ten Stone Formation; S.S.—Snail Spring Formation; A.—assemblage; Mt.—Mount; Mtns.—mountains; #—includes the Ravensthroat and Hayhook formations. B: Paleogeographic reconstruction of Rodinia at ca. 715 Ma, modified from Li et al. (2013). ORR—organic-rich rock.

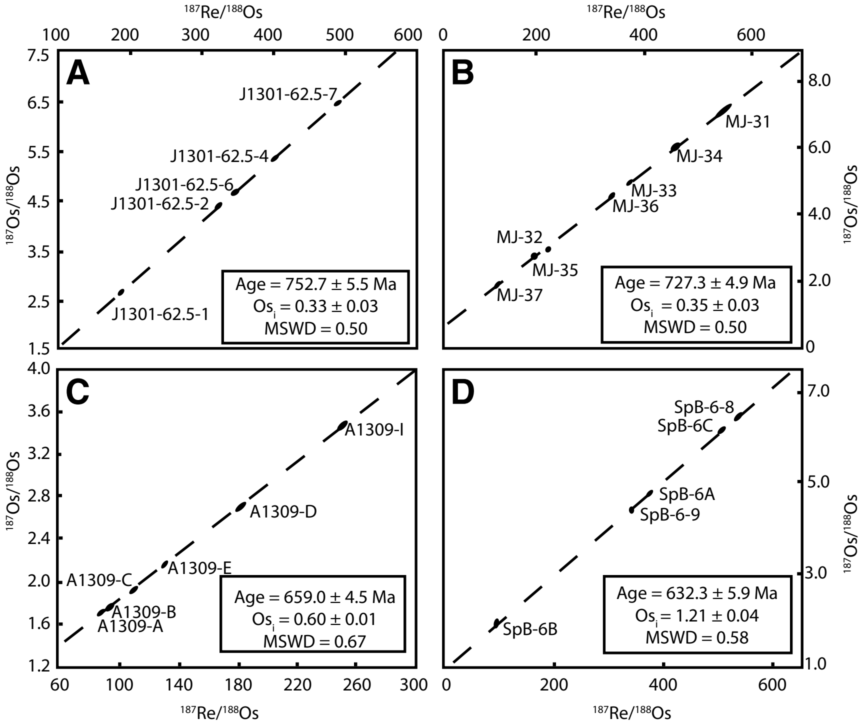

Figure 2. Re-Os isochron diagrams. A: Lower Callison Lake Formation. B: Mwashya subgroup (MJ-31–MJ-37, 172.61–179.10 m). C: Taishir Formation. D: Sheepbed Formation. All data point error ellipses are 2σ and their diameters are larger than calculated error ellipses. All isotopic composition and elemental abundance data are presented in Table DR1 (see footnote 1). MSWD—mean square of weight deviates.

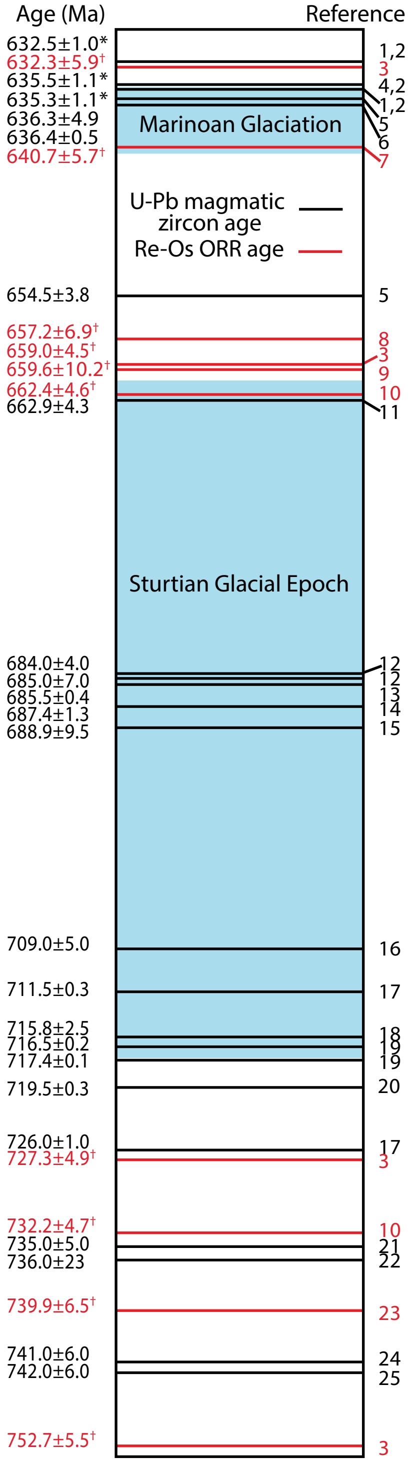

Figure 3. Compilation of geochronological constraints for Neoproterozoic strata for the interval 753–630 Ma. No detrital U-Pb zircon data are included, because they cannot constrain the onset or cessation of glaciation. ORR—organic-rich rock. Asterisks—U-Pb magmatic zircon ages including uncertainties recalculated by Schmitz (2012); daggers—Re-Os ages including uncertainty in ^{187}Re decay constant (λ). Details of geochronological data and accompanying references (numbered) are provided in the Data Repository (see footnote 1).

Formation. Therefore, this age only provides a maximum age constraint on the Sturtian-age Numees Formation. Similarly, no definitive evidence for glacial sedimentation has been demonstrated in the Bayisi diamictite of the Tarim block, and the 740 ± 7 Ma U-Pb age of Xu et al. (2009) is potentially undermined by the fact that the analysis includes many zircon grains that are possibly inherited from underlying ca. 750 Ma volcanic rocks. Consequently, the 735 ± 5 Ma U-Pb SHRIMP age on the Luatama breccia of the Congo craton (Key et al., 2001) has remained a final holdout for the putative ca. 740 Ma Kaigas glaciation. However, this U-Pb age is compromised not only by the inclusion of grains that were possibly inherited from the underlying ca. 765 Ma mafic volcanic rocks of the lowermost Mwashya subgroup (Key et al., 2001), but also by the poorly constrained nature of the contact between the Luatama breccia and the glacial deposits (Selley et al., 2005). Our new 727.3 ± 4.9 Ma Re-Os age from directly below the Grand Conglomerate is consistent with a Sturtian age for the oldest Cryogenian glacial deposits on the Congo craton (Figs. 2B and 3).

The Re-Os age of 752.7 ± 5.5 Ma for the basal Callison Lake Formation provides a new depositional age constraint for the lower portion of this unit and expands the range of vase-shaped microfossil occurrences in northwest Canada (Strauss et al., 2014). It is interesting that the Os_i value from this basin at the time of deposition was markedly unradiogenic (Os_i = 0.33), in contrast to the Os_i value presented for the upper Callison Lake Formation at 739.9 ± 6.1 Ma (Os_i = 0.60; Strauss et al., 2014) and modern-day seawater (Os_i = 1.06; Peucker-Ehrenbrink and Ravizza, 2012). This Os_i value suggests that the dominant source of Os entering this basin was either derived from the localized weathering of juvenile crustal material (e.g., basalt) or sourced from hydrothermal inputs. Similarly, the unradiogenic Os_i value of 0.35 for the Mwashya subgroup is suggestive of a significant influx of unradiogenic Os into this basin. These pre-Sturtian Os_i values, together with earlier work from northwest Canada (Rooney et al., 2014), lend further support to the so-called fire and ice mechanism of snowball Earth initiation, whereby the weathering of voluminous unradiogenic basalts at low latitudes would have enhanced CO_2 drawdown, resulting in a climate sensitive enough to enter a global glaciation (Goddéris et al., 2003).

The Re-Os age of 659.0 ± 4.5 Ma for the Taishir Formation constrains the termination of the Sturtian-age Maikhan-Uul glaciation in Mongolia. This age is identical, within uncertainty, to Re-Os and U-Pb zircon age constraints for post-Sturtian horizons from northwest Canada, China, and Australia, and confirms a long duration (>55 m.y.) for the Sturtian glacial epoch (Fig. 3; Zhou et al., 2004; Kendall et al., 2006; Macdonald et al., 2010a; Lan et al., 2014; Rooney et al., 2014). The Os_i value of 0.60 is moderately unradiogenic, in contrast to modern-day seawater, and is similar to values reported near the base of the post-glacial Twitya Formation in northwest Canada (0.54 versus 0.60).

An existing Re-Os date of 607.8 ± 4.7 Ma from shale of the Windermere Supergroup, Canada, was suggested to represent a termination age for the Marinoan glaciation (Kendall et al., 2004). However, this Re-Os age is from an isolated outcrop that is not in direct contact with the underlying Marinoan-age glacial deposits or cap carbonate (Kendall et al., 2004). Our new Re-Os age of 632.3 ± 5.9 Ma from 0.9 m above the distinctive Ravensthroat-Hayhook cap carbonate is within uncertainty of multiple ca. 635 Ma U-Pb zircon ages on the deglaciation of the Marinoan snowball Earth event worldwide (Figs. 2D and 3; Hoffmann et al., 2004; Condon et al., 2005; Calver et al., 2013.

CONCLUSION

The four Re-Os ages presented herein help refine our current Neoproterozoic chronology. These data refute the evidence for an earlier global Kaigas glaciation and suggest instead that the initiation of the Sturtian glacial epoch ca. 717 Ma marked the first unambiguous glacial event in more than a billion years. Together with existing geochronological data, the new Re-Os ages constrain the onset and demise of the long-lasting (717–660 Ma) Sturtian glacial epoch and further bolster correlations for the end-Cryogenian Marinoan glaciation ca. 635 Ma (Fig. 3). The long duration (>55 m.y.) of the Sturtian glacial epoch implies a relatively short Cryogenian nonglacial interlude (<25 m.y.), consistent with a repeated trigger for glaciation related to the tectonic background conditions that drive weathering and the consumption of CO_2 on 1–10 m.y. time scales (Mills et al., 2011). This updated Neoproterozoic chronology provides new constraints to test and refine climate models of a long-duration glacial epoch and the nature of a relatively short nonglacial interlude. The Os_i data presented here confirm enhanced weathering of juvenile crustal material prior to the onset of the Sturtian glacial epoch, consistent with a basalt weathering trigger for initiation of the Sturtian glacial epoch (e.g., Goddéris et al., 2003; Rooney et al., 2014). These ages confirm the central prediction of the snowball Earth hypothesis of long-lived (~10 m.y.) glaciation with globally synchronous deglaciation.

ACKNOWLEDGMENTS

We thank Sharad Master for access to the Zambian drill core. Supported by the Massachusetts Institute of Technology NASA Astrobiology Institute node, the National Science Foundation (NSF) Sedimentary Geology and Paleobiology Program (grant EAR-1148058), an NSF Graduate Research Fellowship (to Strauss), the Yukon Geological Survey, and Fireweed Helicopters and Canadian Helicopters (support and transportation). We also thank Lyle Nelson, Uyanga Bold, and Sarah Moon for assistance in the field; Charlie Roots, Erik Sperling, Galen Halverson, Dave Selby, and Paul Hoffman for fruitful conversations; and four reviewers for constructive comments.

REFERENCES CITED

Aitken, J.D., 1991, Two Late Proterozoic glaciations, Mackenzie Mountains, northwestern Canada: Geology, v. 19, p. 445–448, doi:10.1130/00917613(1991)019<0445:TLPGMM>2.3.CO;2.

Allen, P.A., and Etienne, J.L., 2008, Sedimentary challenges to Snowball Earth: Nature Geoscience, v. 1, p. 817–825, doi:10.1038/ngeo355.

Armstrong, R.A., Master, S., and Robb, L.J., 2005, Geochronology of the Nchanga Granite, and constraints on the maximum age of the Katanga supergroup, Zambian copperbelt: Journal of African Earth Sciences, v. 42, p. 32–40, doi:10.1016/j.jafrearsci.2005.08.012.

Bao, H., Lyons, T.W., and Zhou, C., 2008, Triple oxygen isotope evidence for elevated CO$_2$ levels after a Neoproterozoic glaciation: Nature, v. 453, p. 504–506, doi:10.1038/nature06959.

Bodiselitsch, B., Koeberl, C., Master, S., and Reimold, W.U., 2005, Estimating duration and intensity of Neoproterozoic snowball glaciations from Ir anomalies: Science, v. 308, p. 239–242, doi:10.1126/science.1104657.

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, doi:10.1130/G34568.1.

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, doi:10.1126/science.1107765.

Dalrymple, R.W., and Narbonne, G.M., 1996, Continental slope sedimentation in the Sheepbed Formation (Neoproterozoic, Windermere Supergroup), Mackenzie Mountains, N.W.T: Canadian Journal of Earth Sciences, v. 33, p. 848–862, doi:10.1139/e96-064.

Frimmel, H.E., Klötzli, U., and Seigfried, P., 1996, New Pb-Pb single zircon age constraints on the timing of Neoproterozoic glaciation and continental break-up in Namibia: Journal of Geology, v. 104, p. 459–469, doi:10.1086/629839.

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, doi:10.1016/S0012-821X(03)00197-3.

Hoffman, P.F., Kaufman, A.J., Halverson, G.P., and Schrag, D.P., 1998, A Neoproterozoic Snowball Earth: Science, v. 281, p. 1342–1346, doi:10.1126/science.281.5381.1342.

Hoffmann, K.H., Condon, D.J., Bowring, S.A., and Crowley, J.L., 2004, U-Pb zircon date from the Neoproterozoic Ghaub Formation, Namibia: Constraints on Marinoan glaciation: Geology, v. 32, p. 817–820, doi:10.1130/G20519.1.

James, N.P., Narbonne, G.M., and Kyser, T.K., 2001, Late Neoproterozoic cap carbonates: Mackenzie Mountains, northwestern Canada: Precipitation and global glacial meltdown: Canadian Journal of Earth Sciences, v. 38, p. 1229–1262, doi:10.1139/e01-046.

Jefferson, C.W., and Parrish, R., 1989, Late Proterozoic stratigraphy, U/Pb zircon ages and rift tectonics, Mackenzie Mountains, northwestern Canada: Canadian Journal of Earth Sciences, v. 26, p. 1784–1801, doi:10.1139/e89-151.

Karlstrom, K.E., et al., 2000, Chuar Group of the Grand Canyon: Record of breakup of Rodinia, associated change in the global carbon cycle, and ecosystem expansion by 740 Ma: Geology, v. 28, p. 619–622, doi:10.1130/0091-7613(2000)28<619:CGOTGC>2.0.CO;2.

Kendall, B.S., Creaser, R.A., Ross, G.M., and Selby, D., 2004, Constraints on the timing of Marinoan ''snowball Earth'' glaciation by ^{187}Re- ^{187}Os dating of a Neoproterozoic, post-glacial black shale in western Canada: Earth and Planetary Science Letters, v. 222, p. 729–740, doi:10.1016/j.epsl.2004.04.004.

Kendall, B., Creaser, R.A., and Selby, D., 2006, Re-Os geochronology of postglacial black shales in Australia: Constraints on the timing of "Sturtian" glaciation: Geology, v. 34, p. 729–732, doi:10.1130/G22775.1.

Key, R.M., Liyungu, A.K., Njamu, F.M., Somwe, V., Banda, J., Mosley, P.N., and Armstrong, R.A., 2001, The western arm of the Lufilian Arc in NW Zambia and its potential for copper mineralization: Journal of African Earth Sciences, v. 33, p. 503–528, doi:10.1016/S0899-5362(01)00098-7.

Kirschvink, J.L., 1992, Late Proterozoic low-latitude glaciation: The snowball Earth, *in* Schopf, J.W., and Klein, C., eds., The Proterozoic biosphere: A multidisciplinary study: Cambridge, UK, Cambridge University Press, p. 51–52.

Lan, Z., Li, X., Zhu, M., Chen, Z., Zhang, Q., Li, Q., Lu, D., Liu, Y., and Tang, G.A., 2014, Rapid and synchronous initiation of the wide spread Cryogenian glaciations: Precambrian Research, v. 255, p. 401–411, doi:10.1016/j.precamres.2014.10.015.

Li, Z.X., Evans, D.A.D., and Halverson, G.P., 2013, Neoproterozoic glaciations in a revised global paleogeography from the breakup of Rodinia to the assembly of Gondwanaland: Sedimentary Geology, v. 294, p. 219–232, doi:10.1016/j.sedgeo.2013.05.016.

Macdonald, F.A., Jones, D.S., and Schrag, D.P., 2009, Stratigraphic and tectonic implications of a newly discovered glacial diamictite–cap carbonate couplet in southwestern Mongolia: Geology, v. 37, p. 123–126, doi:10.1130/G24797A.1.

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., 2010a, Calibrating the Cryogenian: Science, v. 327, no. 5970, p. 1241–1243, doi:10.1126/science.1183325.

Macdonald, F.A., Strauss, J.V., Rose, C.V., Dudás, F.Ö., and Schrag, D.P., 2010b, Stratigraphy of the Port Nolloth Group of Namibia and South Africa and implications for the age of Neoproterozoic iron formations: American Journal of Science, v. 310, p. 862–888, doi:10.2475/09.2010.05.

Master, S., Rainaud, C., Armstrong, R.A., Phillips, D., and Robb, L.J., 2005, Provenance ages of the Neoproterozoic Katanga Supergroup (Central African Copperbelt) with implications for basin evolution: Journal of African Earth Sciences, v. 42, p. 41–60, doi:10.1016/j.jafrearsci.2005.08.005.

Mills, B., Watson, A.J., Goldblatt, C., Boyle, R., and Lenton, T.M., 2011, Timing of Neoproterozoic glaciations linked to transport-limited global weathering: Nature Geoscience, v. 4, p. 861–864, doi:10.1038/ngeo1305.

Peucker-Ehrenbrink, B., and Ravizza, G., 2012, Osmium isotope stratigraphy, *in* Gradstein, F.M., et al., The geological time scale 2012: Elsevier, Amsterdam, p. 145–166, doi:10.1016/B978-0-444-59425-9.00008-1.

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: National Academy of Sciences Proceedings, v. 111, p. 51–56, doi:10.1073/pnas.1317266110.

Schmitz, M.D., 2012, Appendix 2: Radiometric ages used in GTS 2012, *in* Gradstein, F.M., et al., The geological time scale 2012: Elsevier, Amsterdam, p. 1045–1083.

Selley, D., Broughton, D., Scott, R.J., Hitzman, M., Bull, S.W., Large, R.R., McGoldrick, P.J., Croaker, M., and Pollington, N., 2005, A new look at the geology of the Zambian Copperbelt, *in* Hedenquist, J.W., et al., eds., One hundredth anniversary volume 1905–2005: Littleton, Colorado, Society of Economic Geologists, p. 965–1000.

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, doi:10.1130/G35736.1.

Wendorff, M., 2003, Stratigraphy of the Fungurume Group—Evolving foreland basin succession in the Lufilian fold-thrust belt, Neoproterozoic–lower Paleozoic, Democratic Republic of Congo: South African Journal of Geology, v. 106, p. 17–34, doi:10.2113/1060017.

Xu, B., Xiao, S., Zou, H., Chen, Y., Li, Z.X., Song, B., and Yuan, X., 2009, SHRIMP zircon U-Pb age constraints on Neoproterozoic Quruqtagh diamictites in NW China: Precambrian Research, v. 168, p. 247–258, doi:10.1016/j.precamres.2008.10.008.

Zhou, C., Tucker, R., Xiao, S., Peng, Z., Yuan, X., and Chen, Z., 2004, New constraints on the ages of Neoproterozoic glaciations in south China: Geology, v. 32, p. 437–440, doi:10.1130/G20286.1.

Manuscript received 9 December 2014
Revised manuscript received 5 March 2015
Manuscript accepted 5 March 2015

Printed in USA