Supplemental Materials for “Calibrating the Russøya excursion in Svalbard, Norway, and implications for Neoproterozoic chronology”

GEOLOGIC CONTEXT FOR THE HECLA HOEK SUCCESSION AND SAMPLES

The Hecla Hoek succession is an informal name for the ~6 km thick Neoproterozoic-Ordovician sedimentary succession exposed in the Eastern basement domain of the Svalbard archipelago, Norway (Fig. 1). Historically, this designation has variably included underlying metasedimentary and igneous units, but here we follow the definition of Halverson et al. (2018a) that only includes the Neoproterozoic-Ordovician sedimentary units under this title. In Ny Friesland, Spitsbergen, the Hecla Hoek succession consists of the Lomfjorden Supergroup, comprising the Veteranen and Akademikerbreen groups, and Hinlopenstretet Supergroup, which includes the Polarisbreen and Oslobreen groups. We follow Halverson et al. (2018a) by extending these designations to correlative strata in Nordaustlandet, which has historically been called the Murchisonfjorden Supergroup, comprising the Galtedalen, Franklinsundet, Celsiusberget, and Roaldtoppen groups (e.g., Sandelin et al., 2001).

The Veteranen Group unconformably overlies both the late Mesoproterozoic Brennevinsfjorden Group and the Tonian Kapp Hansteen Group in Nordaustlandet (Gee et al., 1995; Johansson et al., 2005). Igneous U-Pb dates from the Kapp Hansteen Group of ca. 960 Ma provide a maximum age constraint for the Hecla Hoek succession (Fig. 1A; Johansson et al., 2000). The lowermost units of the Veteranen Group are only exposed in discontinuous outcrops in Nordaustlandet (Sandelin et al., 2001), but the remaining 4+ km of strata can be found in continuous outcrop in both Ny Friesland, Spitsbergen, and Gustav V Land, Nordaustlandet (Fig. 1C). The Veteranen Group consists of shale, siltstone, and quartzite units with minor carbonate. Basin subsidence modelling provides an estimated age of ~819 Ma for the Veteranen-Akademikerbreen contact (Fig. 1A; Halverson et al., 2018b). The Veteranen-Akademikerbreen contact is transitional and marked by a gradual increase in carbonate content and the eventual establishment of a carbonate platform (Fig. 1A; Halverson et al., 2018a). The Akademikerbreen Group is overlain by mixed siliciclastic-carbonate of the Polarisbreen Group. A 0-3 m thick silicified solution breccia at the Akademikerbreen-Polarisbreen contact in Spitsbergen implies some subaerial exposure at this contact, although this same surface is usually transitional in Nordaustlandet (Halverson et al., 2018a).

The basal unit of the Polarisbreen Group, the Russøya Member of the Elbobreen Formation, consists of black shale, siltstone, sandstone, dolomite, and limestone deposited mainly in a shallow subtidal marine setting (Fig. S1; Fairchild et al., 2016; Halverson et al., 2018a). The thickness of the Russøya Formation varies across Svalbard from ~80 to >150 m and consists of two transgressive-regressive sequences (T-R7 and T-R8 of Halverson et al., 2018a). In northern outcrops (Fig. 1B and C; note that the extent of panel C only shows northern outcrop exposures), where the Russøya member is carbonate-dominated, sequence T-R7 has a well-defined shoaling-upward sequence beginning with black shale and limestone rhythmite grading

upwards into limestone with abundant molar tooth structures, oolitic grainstone, and microbial laminite. In southern outcrop exposures, the Russøya Member is more siliciclastic-rich and the T-R7 sequence can be divided into two parasequences. The lower consists of limestone rhythmite capped by a siltstone unit, and the upper parasequence is dominantly shale and is capped by a red trough cross-bedded quartz arenite. These facies relationships suggest a north-to-south deepening during deposition of the Russøya Member. $\delta^{13}\text{C}_{\text{carb}}$ values from T-R7 show a trend of increasing values from ~ 0.5 to $> 7\text{‰}$ which is followed by a decrease to 0‰ and return to slightly positive ($\sim 2\text{‰}$) values. Sequence T-R8 can be subdivided into three parasequences (a-c) that consist of shale overlain by carbonate, with stromatolitic units capping the upper two parasequences. T-R8 records a transition to highly negative values ($\sim -7\text{‰}$) with the minima and recovery to moderately high values (-2.5 to -4‰) recorded in a distinctive columnar *Kussiella* biostrome bed that tops T-R8c and reaches up to 8.4 m in thickness (Halverson et al., 2018a). The presence and thickness of this bed is used in conjunction with the carbon isotope chemostratigraphy to determine the extent of erosion on the upper contact of the Russøya Member with the Petrovreen diamictite. Variable truncation of the negative carbon isotope excursion (CIE) preserved in the upper Russøya Member across Spitsbergen and Nordaustlandet suggests sub-glacial erosion of this unit, where the degree of erosion correlates with the thickness of the overlying diamictite (Halverson et al., 2004, 2018a).

Re-Os sample SR-161.5 from this study was taken from 76.5 m above the base of the Russøya Formation from Sore Russøya in a horizon 44 m below the onset of the CIE with $\delta^{13}\text{C}_{\text{carb}}$ values $\sim 3\text{--}4\text{‰}$ (Fig. S1; Table S1; Halverson et al., 2004, 2018a). In this location, the CIE, as defined from the initial downturn from $\sim 5\text{‰}$, is up to 50 m thick. The age of 737.5 ± 9.6 Ma from the Russøya Member suggests a >10 Myr unconformity between the Russøya and overlying Petrovreen Member. This pre-Sturtian unconformity is of similar magnitude to that between the Coppercap Formation and overlying Sturtian glacial deposits of the Rapitan Group in northwest Canada (Rooney et al., 2014).

The Petrovreen Member consists of massive to stratified glaciomarine diamictite with clasts derived from the underlying Russøya Member and occasional interbedded shale (Fig. 1). The thickness of this unit ranges from 0 to 52 m across Spitsbergen and Nordaustlandet and has been correlated globally with the ca. 717-660 Ma Sturtian glaciation (Halverson et al., 2018a). The diamictite is overlain by the ~ 200 m thick Macdonaldryggen Member (Elbobreen Formation), which consists of dolomitic shale and siltstone deposited below storm wave base (Fairchild et al., 2016). The upper Macdonaldryggen Member shoals upward into limestones transitional with the overlying 15-25 m thick Slangen Member (Elbobreen Formation), which comprises mixed carbonate-siliciclastic strata. The contact of the Slangen Member with the Wilsonbreen Formation is occasionally marked by a silicified and brecciated surface, while in other locations it is gradational with mud-cracked siltstone and quartz arenite of the Bråvika Member (Elbobreen Formation). This is overlain by terrestrial glacial deposits of the ~ 150 m thick Wilsonbreen Formation (Fairchild et al., 2016), which consists of diamictite, sandstone,

and rare carbonate that have been correlated globally with the ca. 650-635 Ma Marinoan glaciation (Halverson et al., 2004).

The Wilsonbreen Formation is sharply overlain by the Dracoisen Formation. The lowermost undifferentiated member is a typical basal Ediacaran cap dolostone unit with distinctive sedimentary features such as megaripples, peloids, and a negative carbon isotope signature of -2 to -4‰ $\delta^{13}\text{C}_{\text{carb}}$ (Halverson et al., 2004). This cap dolostone is succeeded by an interval of interbedded shale and limestone which transitions into shale up-section. Sample J1630 was taken from the shale-dominated interval of the Dracoisen Formation 88 m above the top of the cap dolostone and 60 m above the maximum flooding surface in the lower Dracoisen Formation at Gravela River in Ny Friesland, Spitsbergen (Table S1). The contact between the Ediacaran Dracoisen Formation and the lower Cambrian Tokammane Formation of the Oslobreen Group likely represents a major disconformity judging from the absence of the middle Ediacaran glacial deposits, the Shuram negative $\delta^{13}\text{C}$ excursion, and Ediacaran fossils.

CORRELATION OF THE RUSSØYA/ISLAY CARBON ISOTOPE EXCURSION

A CIE underlying Sturtian glacial deposits was first identified from a composite carbon isotope record of the Dalradian Supergroup in Scotland by Prave et al. (2009). The Dalradian Supergroup consists of the Tonian siliciclastic-dominated Grampian Group, the conformably overlying mixed carbonates and siliciclastic units of the Appin Group, and the dominantly siliciclastic Argyll Group. The basal member of the later is the Port Askaig Tillite member of the Islay Formation, which is thought to correlate with the Sturtian glaciation globally (Fairchild et al., 2018). Prave et al. (2009) identified a -4 to -6‰ CIE that recovers up to 0 to 1‰ in carbonates immediately below the Port Askaig Tillite, and Hoffman et al. (2012) subsequently informally named this the “Islay” excursion. This excursion was linked to other sub-Sturtian anomalies of similar magnitude preserved in Svalbard and northwest Canada. However, the lack of a recovery to values ~ 6‰, which is present in northwest Canada, made correlations tentative. Although there are still no reliable high-precision age constraints for the sub-Sturtian interval in Scotland, recent work by Fairchild et al. (2018) argues that the CIE recorded in carbonates of the Garvellach Islands in Scotland, that was originally called the Islay excursion, records a return to values of only ~ 1‰ yet is transitional into the overlying tillite, making it a younger CIE than the excursion recorded in northwest Canada now dated at ca. 735 Ma. Fairchild et al. (2018) therefore rename this CIE the Garvellach excursion. If primary this younger excursion should be present in latest Tonian stratigraphy ca. 717 Ma. However, due to the lack of robust age constraints it could still be a correlated with the ca. 735 Ma excursion (Halverson et al., 2018a).

In northwest Canada, the pre-Sturtian interval records a negative CIE in both the Ogilvie Mountains of Yukon Territories and the Mackenzie Mountains of Northwest Territories (Fig. 4). In the Ogilvie Mountains, the carbonate-dominated middle Tonian Fifteenmile Group is overlain by the carbonate-dominated Callison Lake Formation (Mount Harper Group; Strauss et al., 2015), which is in turn overlain by the Seela Pass Formation (Mount Harper Group) diamictite of the ca. 719 Ma Eagle Creek Formation (Rapitan Group; Macdonald et al., 2018). The uppermost

30 m of the Callison Lake Formation records a decrease in $\delta^{13}\text{C}_{\text{carb}}$ values from $\sim 4\text{‰}$ down to -8‰ before recovering up section to $\sim -2\text{‰}$ (Strauss et al., 2014). A Re-Os age of 739.9 ± 6.5 Ma from a shale within the Callison Lake Formation constrains the onset of the CIE (Strauss et al., 2014). In the Mackenzie Mountains, the base of the Windermere Supergroup comprises mixed siliciclastic, carbonate, and evaporite strata of the Coates Lake Group, which includes the Thundercloud, Redstone River, and Coppercap formations, all of which are overlain by the glacialigenic ca. 720 Ma Rapitan Group (Turner, 2011). The ~ 400 m thick Coppercap Formation is divided into 6 units, CP1-6. $\delta^{13}\text{C}_{\text{carb}}$ values from the Coppercap Formation decrease from -2‰ to -8‰ at the CP1-2 boundary, rise slightly through CP2 and CP3 reaching 0‰ at the CP3-4 boundary, and stabilize $\sim 7\text{‰}$ above the CP4-5 boundary (Rooney et al., 2014). A Re-Os age of 732.2 ± 4.7 Ma from unit CP4 puts an upper age constraint on the negative CIE recorded in CP1-3 (Rooney et al., 2014). Together, the Re-Os ages from northwest Canada confirm the presence of an ~ 735 Ma negative CIE that was referred to regionally as the Islay excursion (Rooney et al., 2014; Strauss et al., 2014).

A negative CIE of similar magnitude from the Russøya Member in northeastern Svalbard has been correlated with the ~ 735 Ma CIE of northwest Canada, but has been referred to as the Russøya excursion due to a lack of radiometric age constraints for the Hecla Hoek succession (Halverson et al., 2018a). Our new age of 737.5 Ma from 44 m below the excursion in the upper Russøya Member from Sore Russøya confirms the correlation of the ~ 735 Ma CIEs in Svalbard and northwest Canada. Additionally, variable truncation of the CIE due to subglacial erosion is evidence for the syn-depositional acquisition of this carbon isotope signature.

The ~ 735 Ma CIE is also recorded in carbonate-siliciclastic strata of the Didikama and Matheos formations of the upper Tambien Group in the Tigray region of northern Ethiopia. The Didikama Formation consists of dolomitized brown carbonate interbedded with siltstone that transitions into the overlying Matheos Formation, which is characterized by well-preserved limestone ribbonite with molar tooth structures (Swanson-Hysell et al., 2015). An excursion to $\delta^{13}\text{C}_{\text{carb}}$ values $\sim -6\text{‰}$ is recorded in carbonate at the contact between these two formations (Swanson-Hysell et al., 2015; MacLennan et al., 2018). The recovery from the CIE is recorded in the lower Matheos Formation ribbonite. Unlike the records in Svalbard and northwest Canada, conformable younger sedimentary units overlie the ~ 735 Ma CIE in Ethiopia and are transitional into Sturtian glacial deposits (Park et al., 2020). Interestingly, there is no clear record of a negative ($\sim -7\text{‰}$) ca. 717 Ma Garvellach CIE as suggested by Fairchild et al. (2018) in Scotland, however $\delta^{13}\text{C}$ values decrease to $\sim 1\text{‰}$ in the uppermost Mariam-Bohkahko Formation (MacLennan et al., 2018). The upper Matheos Formation consists of oolitic grainstone with abundant molar tooth structures. The Mariam-Bohkahko Formation consists of geographically distinct carbonate-dominated and siliciclastic-dominated facies that are interpreted to be coeval but representative of different shallow water depositional settings (MacLennan et al., 2018). The Mariam Bohkahko Formation is overlain by diamictite of the Negash Formation which contain occasional striated clasts of local origin, including the Tambien Group carbonates and volcanics from basement arcs, as well as extra-basinal sediment.

The mixed siliciclastic and carbonate Damara Supergroup of northwestern Namibia has played an important role in current understanding of Neoproterozoic Earth history and generating a composite carbon isotope curve for this interval (Halverson et al., 2005). Deposited on the southern extent of the Congo Craton, the Damara Supergroup consists of Tonian siliciclastic and volcanic units of the Nosib Group, the platform Otavi Group and deepwater equivalents in the Swakop Group, and the overlying clastic Mulden Group (Hoffman and Halverson, 2008). The Otavi Group comprises the carbonate-dominated Ombombo (Otavi Group) or Ugab (Swakop Group), Abenab, and Tsumeb subgroups punctuated by glacial deposits, including the Sturtian Chuos Formation and the Marinoan Ghaub Formation. Recent work by Lamothe et al. (2019) documented two distinct CIEs in the sub-Sturtian Ugab Subgroup including an older excursion with a nadir of $\sim -5\%$ and younger of $\sim -4\%$. Geochronologic constraints, including a maximum depositional ash-flow tuff age of 746 ± 2 Ma from the underlying Nauwpoort Formation (Hoffman et al., 1996) and a minimum age constraint from the overlying ca. 717 Ma sub-Chuos Formation erosional unconformity (Macdonald et al., 2010), indicate that both of these excursions occurred during the ca. 30 Myr preceding the Sturtian glaciation. Chemostratigraphic correlation of the composite Ugab Subgroup carbon isotope curve with radiometrically-calibrated Tonian stratigraphy of Ethiopia indicate the presence of both a ca. 735 Ma and < 719 Ma CIE (MacLennan et al., 2018; Lamothe et al., 2019). The younger excursion is tentatively correlated with the Garvellach excursion of Scotland (Fairchild et al., 2018), implying that sub-Sturtian erosion cuts out the recovery from the ca. 717 CIE in both Ethiopia and Namibia (Lamothe et al., 2019).

Figure 4 was originally produced by MacLennan et al. (2018) with carbon isotope data from: Halverson et al. (2005; 2007), Miller et al. (2009), Macdonald et al. (2010), Rooney et al. (2014), Swanson-Hysell et al. (2015), Cox et al. (2016), and MacLennan et al. (2018). Carbon isotope correlations are based on the composite record from Ethiopia where the most-continuous carbon isotope record of the pre-Sturtian interval is directly dated with a high-precision U-Pb ID-TIMS age of 735.25 ± 0.88 Ma from the lowermost Matheos Formation during the nadir of the CIE (MacLennan et al., 2018). Age-model values for $\delta^{13}\text{C}_{\text{carb}}$ data are within uncertainty of existing radiometric age constraints from northwest Canada of 732.2 ± 4.7 Ma during the CIE recovery (Rooney et al., 2014) and 739.9 ± 6.5 Ma during the onset of the CIE (Strauss et al., 2014), and the new Re-Os age of 737.5 ± 9.6 Ma immediately preceding the CIE from Svalbard.

RHENIUM-OSMIUM GEOCHRONOLOGY

Individual Re-Os samples weighing 50-200 g were collected for Re-Os geochronology. Samples for J1630 ($n=7$) were collected over a ~ 30 cm vertical interval from ~ 2 m along strike, as it is best practice to use a large horizontal sampling strategy to maximize the spread of $^{187}\text{Re}/^{188}\text{Os}$. SR-161.5 samples ($n=6$) were collected from a ~ 20 cm vertical interval from ~ 2 m along strike.

Weathered surfaces were removed from samples using a diamond-coated rock saw and samples were then hand-polished with a diamond-plated polishing pad to remove potential

contamination from the saw blade. Samples were dried overnight at room temperature and then crushed to a fine ($\sim 30\ \mu\text{m}$) powder in a SPEX 8500 Shatterbox using a zirconium grinding container and puck in order to homogenize any Re and Os heterogeneity present in the samples.

Re and Os isotopic abundances and compositions were determined at the Yale Geochemistry and Geochronology Center. $\sim 0.8\ \text{g}$ of sample was digested and equilibrated in 8 ml of $\text{Cr}^{\text{VI}}\text{O}_3\text{-H}_2\text{SO}_4$ together with a mixed tracer (spike) solution of ^{190}Os and ^{185}Re in carius tubes at 220°C for 48 hours. The $\text{Cr}^{\text{VI}}\text{O}_3\text{-H}_2\text{SO}_4$ digestion was employed as it has been shown to preferentially liberate hydrogenous Re and Os yielding more accurate and precise age determinations than other dissolution techniques (Kendall et al., 2004). Rhenium and osmium were extracted and purified using solvent extraction (NaOH , $(\text{CH}_3)_2\text{CO}$, and CHCl_3), micro-distillation, anion column chromatography methods, and negative mass spectrometry as outlined by Selby and Creaser (2003).

Total procedural blanks for sample SR-161.5 were $41 \pm 2\ \text{pg}$ and $0.13 \pm 0.1\ \text{pg}$ for Re and Os respectively, with an average $^{187}\text{Os}/^{188}\text{Os}$ value of $0.15 \pm 0.05\ (1\sigma)$, and $35 \pm 3\ \text{pg}$ and $0.21 \pm 0.05\ \text{pg}$ for Re and Os respectively, with an average $^{187}\text{Os}/^{188}\text{Os}$ value of $0.13 \pm 0.15\ (1\sigma)$ for sample J1630. Isotopic measurements were performed using a ThermoElectron TRITON PLUS mass spectrometer via static Faraday collection for Re and ion-counting using a secondary electron multiplier in peak-hopping mode for Os (Creaser et al., 1991; Volkening et al., 1991). In-house Re and Os solutions were continuously analyzed during the course of this study to ensure and monitor long-term mass spectrometer reproducibility. The Yale Geochemistry and Geochronology Center Re standard solution measured on the Faraday cups yields an average $^{185}\text{Re}/^{187}\text{Re}$ value of $0.59820 \pm 0.0042\ (2\sigma, n = 1)$ for sample SR-161.5 and $0.60010 \pm 0.0080\ (2\sigma, n = 1)$ for sample J1630, which agree with the accepted value within error (Gramlich et al., 1973). The measured difference in $^{185}\text{Re}/^{187}\text{Re}$ values for the Re solution and the accepted $^{185}\text{Re}/^{187}\text{Re}$ value (0.5974; Gramlich et al., 1973) is used to correct the Re sample data. The Os isotope standard solution used at Yale Metal Isotope Center is the Durham Romil Osmium Standard (DROsS; Luguet et al., 2008). Over the past three years on this Triton, the runs yield a $^{187}\text{Os}/^{188}\text{Os}$ ratio of $0.16087 \pm 0.00037\ (2\sigma, n = 292)$ that is identical, within uncertainty, to the value reported by other laboratories (e.g., Luguet et al., 2008; Liu and Pearson, 2014). The Os samples were loaded onto 99.995% Pt wire (H-Cross, NJ) in 9 N HBr and covered with a saturated solution of $\text{Ba}(\text{OH})_2$ in 0.1 N NaOH as activator and analyzed as oxides of Os. Interference of $^{187}\text{ReO}_3$ on $^{187}\text{OsO}_3$ was corrected by the measured intensity of $^{185}\text{ReO}_3$. Mass fractionation was corrected with $^{192}\text{Os}/^{188}\text{Os} = 3.0826$, using the exponential fractional law.

Uncertainties for $^{187}\text{Re}/^{188}\text{Os}$ and $^{187}\text{Os}/^{188}\text{Os}$ are determined by error propagation of uncertainties in Re and Os mass spectrometry measurements, blank abundances and isotopic compositions, spike calibrations, and reproducibility of standard Re and Os isotopic values. The Re-Os isotopic data, 2σ calculated uncertainties for $^{187}\text{Re}/^{188}\text{Os}$ and $^{187}\text{Os}/^{188}\text{Os}$, and the associated error correlation function (ρ) are regressed to yield a Re-Os date using Isoplot v. 4.15 with the $\lambda\ ^{187}\text{Re}$ constant of $1.666 \times 10^{-11}\text{yr}^{-1}$ (Ludwig, 1980, 2008; Smoliar et al., 1996).

Elemental Re and Os abundances for sample SR-161.5 range from 5 to 10 ppb, and 180 to 300 ppt, respectively, with $^{187}\text{Re}/^{188}\text{Os}$ and $^{187}\text{Os}/^{188}\text{Os}$ ratios between 135 and 185, and 2 and 3 respectively (Table S1). Regression of the isotopic composition data for these samples yields a Model 1 age of 737.5 ± 9.6 Ma (^{187}Re decay constant uncertainty is included, $n = 6$, Mean Square of Weighted Deviates [MSWD] = 1.8, initial $^{187}\text{Os}/^{188}\text{Os} = 0.26 \pm 0.03$; Fig. 2A). The Re and Os abundances of sample J1630 range from 1.5 to 20 ppb, and 42 to 260 ppt, respectively, with $^{187}\text{Re}/^{188}\text{Os}$ and $^{187}\text{Os}/^{188}\text{Os}$ ratios between 250 and 810, and 3.5 and 10 respectively (Table S1). Regression of the isotopic composition data for these samples yields a Model 1 age of 631.2 ± 3.8 Ma (^{187}Re decay constant uncertainty is included, $n = 7$, Mean Square of Weighted Deviates [MSWD] = 0.71, initial $^{187}\text{Os}/^{188}\text{Os} = 0.89 \pm 0.03$; Fig. 2B).

VASE-SHAPED MICROFOSSILS

Herein we provide additional age constraints for vase-shaped microfossil (VSM)-bearing stratigraphy that may prove useful in global stratigraphic correlations where radiometric are constraints are still lacking (Strauss et al., 2014). VSMs are characterized by as having tear-shaped morphology that appears circular in transverse section, radial or bilateral symmetry, and circular, triangular, or crenulate apertures (Porter et al., 2003; Strauss et al., 2014; Riedman et al., 2018). These microfossils range in length from 20 to 300 μm and in width 15 to 120 μm with apertures ranging from 10 to 40 μm wide and test walls between 1 to 3 μm thick. VSMs are preserved in a variety of lithologies including carbonates, shales, cherts, and phosphatic nodules. Beyond their use in stratigraphic correlation VSMs, placed phylogenetically under the protistan clades Amoebozoa and Rhizaria, represent an important evolutionary milestone as they record the first evidence for eukaryovory and are associated with phosphatic scales (Riedman et al., 2018, 2021).

Based on morphological and taphonomic similarities Strauss et al. (2014) suggest that VSMs from the temporally-equivalent Chuar Group of Arizona, USA and Callison Lake Formation of Northwest, Canada represent a species-level assemblage zone similar to those used in the Phanerozoic to delimit time. The first appearance VSM datum is constrained by a maximum age constraint of 756.0 ± 6.8 in the Chuar Group and depositional age of 752.7 ± 5.5 Ma from the Windermere Supergroup (Rooney et al., 2015, 2018). An age of 729 ± 0.9 Ma from VSM-bearing strata in the Chuar Group extends the known occurrence of VSMs for 20 Myr (Fig. S2; Rooney et al., 2018). Detailed morphological and taphonomic work by Riedman et al. (2018) extend these biostratigraphic correlations by proposing the “*Cycliocyrrillium simplex* assemblage”, consisting of *Cycliocyrrillium simplex*, *C. Torquata*, *Bonniea dacruchares*, *B. pyatinaia*, and *Melanocyrrillium hexodiadema*, occurring between the termination of the Bitter Springs CIE ca. 789 Ma (Swanson-Hysell et al., 2015) and ca. 735 “Islay”/Russøya CIE. Beyond the Chuar Group and Callison Lake Formation this assemblage is identified in the Togari Group of Tasmania, Akademikerbreen Group of Svalbard, Eleonore Bay Group of Greenland, Visingsö Group of Sweden, and the Pahrump and Uintah Mountain Groups of western USA. VSM biostratigraphy has the potential to subdivide the 280 Myr Tonian Period, however these

correlations remain to be tested with direct radiometric age constraints beyond Northwest Canada and the western USA. Our new Re-Os age of 737.5 ± 9.6 from the Russøya Member allows for correlation of VSMs described from Svalbard (Fig. S2; Knoll and Calder, 1983).

DATA REPOSITORY TABLE AND FIGURE CAPTIONS

Table S1. Re and Os abundance and isotope composition data for the Hecla Hoek succession.

Table S2. High-precision age constraints for the terminal Cryogenian Marinoan deglaciation.

Table S3. Compilation of pre-Sturtian global initial osmium isotopic composition data.

Figure S1. Stratigraphic section G332 with accompanying $\delta^{13}\text{C}_{\text{carb}}$ data from Halverson et al. (2004) showing height of Re-Os sample SR-161.5. See supplementary text for details on transgressive-regressive (T-R) sequences and parasequences (labelled a-c). Abbreviations: B.—Backlundtoppen, Kinn.—Kinnvika, Mb.—Member, P.—Petrovbrean Member (from Halverson et al. [2018a]). Figure modified from Halverson et al. (2018a).

Figure S2. Schematic lithostratigraphic columns with carbon isotope chemostratigraphy and radiometric age constraints for vase shaped microfossil (VSM)-bearing stratigraphy across North America and Svalbard. Note that $\delta^{13}\text{C}_{\text{carb}}$ data are shown in black and $\delta^{13}\text{C}_{\text{org}}$ are shown in blue. Numbers correlate to location shown on the inset map. Abbreviations: AK—Alaska; Mex.—Mexico; carb—carbonate; org—organic; VSM—vase-shaped microfossil; Mtns—Mountains; conglom.—conglomerate; Akadem.—Akademikerbreen Group; B—Backlundtoppen Formation; Kin.—Kinnvika Member; Mb.—Member; 15 Mi.—Fifteenmile Group; LDB—Little Dal basalt; RAP.—Rapitan Group; KP—Kingston Peak Formation; VS—Virgin Spring limestone; LCS—Lower Crystal Spring Formation; RCQ—Red Creek Quartzite; Camb.—Cambrian; CB—Carbon Butte Member; NK. Fm.—Nankoweap Formation; Unk. Gp.—Unkar Group; LA-ICP-MS—laser ablation–inductively coupled plasma–mass spectrometry; CA-TIMS—chemical abrasion–thermal ionization mass spectrometry. Letters correlate to geochronologic constraints from a) this study, b) Macdonald et al. (2010), c) Strauss et al. (2014) d) Rooney et al. (2015), e) Rooney et al. (2014), f) Milton et al. (2017), g) Mahon et al. (2014), h) Heaman and Grotzinger (1992), i) Dehler et al. (2010), j) Nelson et al. (2011), k) Rooney et al. (2018), l) Dehler et al. (2017), and m) Elston and McKee (1982). Updated from Strauss et al. (2014) with data from Rooney et al. (2015; 2018), Halverson et al. (2018a), and Riedman et al. (2021).

REFERENCES CITED

- 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>.
- 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, <http://dx.doi.org/10.1016/j.epsl.2016.04.016>.
- Creaser, R.A., Papanastassiou, D.A., and Wasserburg, G. J., 1991, Negative thermal ion mass spectrometry of osmium, rhenium and iridium: *Geochimica et Cosmochimica Acta*, v. 55, p. 397–401, [https://doi.org/10.1016/0016-7037\(91\)90427-7](https://doi.org/10.1016/0016-7037(91)90427-7).
- Dehler, C.M., Fanning, C.M., Link, P.K., Kingsbury, E.M., and Rybczynsk, D., 2010, Maximum depositional age and provenance of the Uinta Mountain Group and Big Cottonwood Formation, northern Utah: *Paleogeography of rifting western Laurentia: Geological Society of America Bulletin*, v. 122, p. 1686-1699, <https://doi.org/10.1130/B30094.1>.
- Dehler, C.M., Gehrels, G., Porter, S., Heizler, M., Karlstrom, K., Cox, G., Crossey, L. and Timmons, M., 2017, Synthesis of the 780–740 Ma Chuar, Uinta Mountain, and Pahrump (ChUMP) groups, western USA: Implications for Laurentia-wide cratonic marine basins: *GSA Bulletin*, v. 129, p. 607-624, <https://doi.org/10.1130/B31532.1>.
- Elston, D.P., and McKee, E.H., 1982, Age and correlation of the late Proterozoic Grand Canyon disturbance, northern Arizona: *Geological Society of America Bulletin*, v. 93, p. 681-699, [https://doi.org/10.1130/0016-7606\(1982\)93<681:AACOTL>2.0.CO;2](https://doi.org/10.1130/0016-7606(1982)93<681:AACOTL>2.0.CO;2).
- Fairchild, I.J., Bonnand, P., Davies, T., Fleming, E.J., Grassineau, N., Halverson, G.P., Hambrey, M.J., McMillan, E.M., McKay, E., Parkinson, I.J. and Stevenson, C.T., 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., Spencer, A.M., Ali, D.O., Anderson, R.P., Anderton, R., Boomer, I., Dove, D., Evans, J.D., Hambrey, M.J., Howe, J., Sawaki, Y., Shields, G.A., Skelton, A., Tucker, M.E., Wang, Z., and Zhou, Y., 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>.

- 350 Fedo, C.M., Nesbitt, H.W., and Young, G.M., 1995, Unraveling the effects of potassium
351 metasomatism in sedimentary rocks and paleosols, with implications for paleoweathering
352 conditions and provenance: *Geology*, v. 23, p. 921-924, [https://doi.org/10.1130/0091-7613\(1995\)023<0921:UTEOPM>2.3.CO;2](https://doi.org/10.1130/0091-7613(1995)023<0921:UTEOPM>2.3.CO;2).
353
- 354 Gee, D.G., and Tebenkov, A.M., 2004, Svalbard: a fragment of the Laurentian margin:
355 Geological Society, London, Memoirs, v. 30, p. 191–206,
356 <https://doi.org/10.1144/GSL.MEM.2004.030.01.16>.
- 357 Gramlich, J.W., Murphy, T.J., Garner, E.L., and Shields, W.R., 1973, Absolute Isotopic
358 Abundance Ratio and Atomic Weight of a Reference Sample of Rhenium: *Journal of*
359 *Research of the National Bureau of Standards, Section A, Physics and chemistry*, v. 77, p.
360 691–698, <https://doi.org/10.6028/jres.077A.040>.
- 361 Halverson, G.P., Maloof, A.C., and Hoffman, P.F., 2004, The Marinoan glaciation
362 (Neoproterozoic) in northeast Svalbard: *Basin Research*, v. 16, p. 297–324,
363 <https://doi.org/10.1111/j.1365-2117.2004.00234.x>.
- 364 Halverson, G.P., Hoffman, P.F., Schrag, D.P., Maloof, A.C., and Rice, A.H.N., 2005, Toward a
365 Neoproterozoic composite carbon-isotope record: *Geological Society of America Bulletin*,
366 v. 117, p. 1181-1207, <https://doi.org/10.1130/b25630.1>.
- 367 Halverson, G.P., Maloof, A.C., Schrag, D.P., Dudás, F.Ö., and Hurtgen, M., 2007, Stratigraphy
368 and geochemistry of a ca. 800 Ma negative carbon isotope interval in northeastern
369 Svalbard: *Chemical Geology*, v. 237, p. 5–27,
370 <https://doi.org/10.1016/j.chemgeo.2006.06.013>.
- 371 Halverson, G.P., Kunzmann, M., Strauss, J.V., and Maloof, A.C., 2018a, The Tonian-
372 Cryogenian transition in Northeastern Svalbard: *Precambrian Research*, v. 319, p. 79–95,
373 <https://doi.org/10.1016/j.precamres.2017.12.010>.
- 374 Halverson, G.P., Porter, S.M., and Gibson, T.M., 2018b, Dating the late Proterozoic stratigraphic
375 record: *Emerging Topics in Life Sciences*, v. 2, p. 137–147,
376 <https://doi.org/10.1042/etls20170167>.
- 377 Heaman, L.M., and Grotzinger, J.P., 1992, 1.08 Ga diabase sills in the Pahrump Group,
378 California: Implications for development of the Cordilleran miogeocline: *Geology*, v. 20, p.
379 637-640, [https://doi.org/10.1130/0091-7613\(1992\)020<0637:GDSITP>2.3.CO;2](https://doi.org/10.1130/0091-7613(1992)020<0637:GDSITP>2.3.CO;2).
- 380 Hoffman, P., and Halverson, G., 2008, Otavi Group of the Western Northern Platform, the
381 Eastern Kaoko Zone and the Western Northern Margin Zone, in *The Geology of Namibia*,
382 Windhoek, Namibia, Geological Survey of Namibia, Handbook of the Geological Survey
383 of Namibia, p. 87.
- 384 Hoffman, P.P., Hawkins, D.P., Isachsen, C.E., and Bowring, S.A., 1996, Precise U-Pb zircon
385 ages for early Damaran magmatism in the Summas Mountains and Welwitschia Inlier,

- 386 northern Damara belt, Namibia: Communications of the geological survey of Namibia, v.
387 11, p. 7.
- 388 Hoffman, P.F., Halverson, G.P., Domack, E.W., Maloof, A.C., Swanson-Hysell, N.L., and Cox,
389 G.M., 2012, Cryogenian glaciations on the southern tropical paleomargin of Laurentia (NE
390 Svalbard and East Greenland), and a primary origin for the upper Russøya (Islay) carbon
391 isotope excursion: Precambrian Research, v. 206, p. 137-158,
392 <https://doi.org/10.1016/j.precamres.2012.02.018>.
- 393 Hoffmann, K.-H., Condon, D.J., Bowring, S.A., and Crowley, J.L., 2004, U-Pb zircon date from
394 the Neoproterozoic Ghaub Formation, Namibia: Constraints on Marinoan glaciation:
395 Geology, v. 32, p. 817–820, <https://doi.org/10.1130/G20519.1>.
- 396 Johansson, Å., Larionov, A.N., Tebenkov, A.M., Gee, D.G., Whitehouse, M.J., and Vestin, J.,
397 2000, Grenvillian magmatism of western central Nordaustlandet, northeastern Svalbard:
398 Earth and Environmental Science Transactions of The Royal Society of Edinburgh, v. 90,
399 p. 221–254, <https://doi.org/10.1017/s0263593300002583>.
- 400 Johansson, Å., Gee, D.G., Larionov, A.N., Ohta, Y., and Tebenkov, A.M., 2005, Grenvillian and
401 Caledonian evolution of eastern Svalbard - a tale of two orogenies: Terra Nova, v. 17, p.
402 317–325, <https://doi.org/10.1111/j.1365-3121.2005.00616>.
- 403 Kendall, B. S., Creaser, R. A., Ross, G. M., and Selby, D., 2004, Constraints on the timing of
404 Marinoan “Snowball Earth” glaciation by ^{187}Re – ^{187}Os dating of a Neoproterozoic, post-
405 glacial black shale in Western Canada: Earth and Planetary Science Letters, v. 222, p. 729–
406 740, <https://doi.org/10.1016/j.epsl.2004.04.004>.
- 407 Knoll, A.H., and Calder, S., 1983, Microbiotas of the Late Precambrian Ryssö Formation,
408 Nordaustlandet, Svalbard: Paleontology, v. 26, p. 467-496.
- 409 Lamothe, K.G., Hoffman, P. F., Greenman, J.W., and Halverson, G.P., 2019, Stratigraphy and
410 isotope geochemistry of the pre-Sturtian Ugab Subgroup, Otavi/Swakop Group,
411 northwestern Namibia: Precambrian Research, v. 332, p. 105387,
412 <https://doi.org/10.1016/j.precamres.2019.105387>.
- 413 Liu, J., and Pearson, D.G., 2014, Rapid, precise and accurate Os isotope ratio measurements of
414 nanogram to sub-nanogram amounts using multiple Faraday collectors and amplifiers
415 equipped with $10^{-12}\Omega$ resistors by N-TIMS: Chemical Geology, v. 363, p. 301–311,
416 <https://doi.org/10.1016/j.chemgeo.2013.11.008>.
- 417 Ludwig, K.R., 1980, Calculation of uncertainties of U-Pb isotope data: Earth and Planetary
418 Science Letters, v. 46, p. 212–220, [https://doi.org/10.1016/0012-821X\(80\)90007-2](https://doi.org/10.1016/0012-821X(80)90007-2).
- 419 Ludwig, K.R., 2008, Isoplot version 4.15: a geochronological toolkit for Microsoft Excel.

- 420 Luguet, A., Nowell, G.M., and Pearson, D.G., 2008, $^{184}\text{Os}/^{188}\text{Os}$ and $^{186}\text{Os}/^{188}\text{Os}$ measurements
421 by Negative Thermal Ionisation Mass Spectrometry (N-TIMS): Effects of interfering
422 element and mass fractionation corrections on data accuracy and precision: *Chemical*
423 *Geology*, v. 248, p. 342–362, <https://doi.org/10.1016/j.chemgeo.2007.10.013>.
- 424 Macdonald, F.A., Schmitz, M.D., Crowley, J.L., Roots, C.F., Jones, D.S., Maloof, A.C., Strauss,
425 J.V., Cohen, P.A., Johnston, D.T., and Schrag, D.P., 2010, Calibrating the Cryogenian:
426 *Science*, v. 327, p. 1241–1243, <https://doi.org/10.1126/science.1183325>.
- 427 Macdonald, F.A., Schmitz, M.D., Strauss, J.V., Halverson, G.P., Gibson, T.M., Eyster, A., Cox,
428 G., Mamrol, P. and Crowley, J.L., 2018, Cryogenian of Yukon: Precambrian Research, v.
429 319, p. 114-143, <https://doi.org/10.1016/j.precamres.2017.08.015>.
- 430 MacLennan, S., Park, Y., Swanson-Hysell, N., Maloof, A., Schoene, B., Gebreslassie, M.,
431 Antilla, E., Tesema, T., Alene, M., and Haileab, B., 2018, The arc of the Snowball: U-Pb
432 dates constrain the Islay anomaly and the initiation of the Sturtian glaciation: *Geology*, v.
433 46, p. 539–542, <https://doi.org/10.1130/G40171.1>.
- 434 Mahon, R.C., Dehler, C.M., Link, P.K., Karlstrom, K.E., and Gehrels, G.E., 2014,
435 Geochronologic and stratigraphic constraints on the Mesoproterozoic and Neoproterozoic
436 Pahrump Group, Death Valley, California: A record of the assembly, stability, and breakup
437 of Rodinia: *GSA Bulletin*, v. 126, p. 652-664, <https://doi.org/10.1130/B30956.1>.
- 438 McLennan, S.M., 1993, Weathering and global denudation: *The Journal of Geology*, v. 101, p.
439 295-303, <https://doi.org/10.1086/648222>.
- 440 Miller, N.R., Stern, R.J., Avigad, D., Beyth, M. and Schilman, B., 2009, Cryogenian slate-
441 carbonate sequences of the Tambien Group, Northern Ethiopia (I): Pre-“Sturtian”
442 chemostratigraphy and regional correlations: *Precambrian Research*, v. 170, p. 129-156,
443 <https://doi.org/10.1016/j.precamres.2008.12.004>.
- 444 Milton, J.E., Hickey, K.A., Gleeson, S.A., and Friedman, R.M., 2017, New U-Pb constraints on
445 the age of the Little Dal Basalts and Gunbarrel-related volcanism in Rodinia: *Precambrian*
446 *Research*, v. 296, p. 168-180, <https://doi.org/10.1016/j.precamres.2017.04.030>.
- 447 Nelson, S.T., Hart, G.L. and, Frost, C.D., 2011, A reassessment of Mojavia and a new Cheyenne
448 Belt alignment in the eastern Great Basin: *Geosphere*, v. 7, p. 513-527,
449 <https://doi.org/10.1130/GES00595.1>.
- 450 Nesbitt, H.W., and Young, G.M., 1982, Early Proterozoic climates and plate motions inferred
451 from major element chemistry of lutites: *Nature*, v. 299, p. 715-717,
452 <https://dx.doi.org/10.1038/299715a0>.
- 453 Nesbitt, H.W. and Young, G.M., 1984, Prediction of some weathering trends of plutonic and
454 volcanic rocks based on thermodynamic and kinetic considerations: *Geochimica et*
455 *cosmochimica acta*, v. 48, p. 1523-1534, [https://doi.org/10.1016/0016-7037\(84\)90408-3](https://doi.org/10.1016/0016-7037(84)90408-3).

- 456 Park, Y., Swanson-Hysell, N.L., MacLennan, S.A., Maloof, A.C., Gebreslassie, M., Tremblay,
457 M.M., Schoene, B., Alene, M., Anttila, E.S., Tesema, T. and Haileab, B., 2020, The lead-up
458 to the Sturtian Snowball Earth: Neoproterozoic chemostratigraphy time-calibrated by the
459 Tambien Group of Ethiopia: *GSA Bulletin*, v. 132, p.1119-1149,
460 <https://doi.org/10.1130/B35178.1>.
- 461 Parker, A., 1970, An index of weathering for silicate rocks: *Geological Magazine*, v. 107, p. 501-
462 504, <https://doi.org/10.1017/S0016756800058581>.
- 463 Porter, S.M., Meisterfeld, R., and Knoll, A.H., 2003, Vase-shaped microfossils from the
464 Neoproterozoic Chuar Group, Grand Canyon: a classification guided by modern testate
465 amoebae: *Journal of Paleontology*, v. 77, p. 409-429,
466 <https://doi.org/10.1017/S0022336000044140>.
- 467 Prave, A.R., Fallick, A.E., Thomas, C.W., and Graham, C.M., 2009, A composite C-isotope
468 profile for the Neoproterozoic Dalradian Supergroup of Scotland and Ireland: *Journal of*
469 *the Geological Society of London*, v. 166, p. 845-857, [https://doi.org/10.1144/0016-](https://doi.org/10.1144/0016-76492008-131)
470 [76492008-131](https://doi.org/10.1144/0016-76492008-131).
- 471 Prave, A.R., Condon, D.J., Hoffmann, K.H., Tapster, S., and Fallick, A.E., 2016, Duration and
472 nature of the end-Cryogenian (Marinoan) glaciation: *Geology*, v. 44, p. 631–634,
473 <https://doi.org/10.1130/G38089.1>.
- 474 Riedman, L.A., Porter, S.M., and Calver, C.R., 2018, Vase-shaped microfossil biostratigraphy
475 with new data from Tasmania, Svalbard, Greenland, Sweden and the Yukon: *Precambrian*
476 *Research*, v. 319, p. 19–36, <http://dx.doi.org/10.1016/j.precamres.2017.09.019>.
- 477 Riedman, L.A., Porter, S.M., and Czaja, A.D., 2021, Phosphatic scales in vase-shaped
478 microfossil assemblages from Death Valley, Grand Canyon, Tasmania, and Svalbard:
479 *Geobiology*, p. 1–12, <https://doi.org/10.1111/gbi.12439>.
- 480 Rooney, A.D., Macdonald, F.A., Strauss, J.V., Dudas, F.O., Hallmann, C., and Selby, D., 2014,
481 Re-Os geochronology and coupled Os-Sr isotope constraints on the Sturtian snowball
482 Earth: *Proceedings of the National Academy of Sciences*, v. 111, p. 51–56,
483 <https://doi.org/10.1073/pnas.1317266110>.
- 484 Rooney, A.D., Strauss, J.V., Brandon, A., and Macdonald, F.A., 2015, A Cryogenian
485 chronology: Two long-lasting synchronous Neoproterozoic glaciations: *Geology*, v. 43, p.
486 459–462, <https://doi.org/10.1130/g36511.1>.
- 487 Rooney, A.D., Atermann, J., Smith, E.F., Li, Y., Selby, D., Dehler, C.M., Schmitz, M.D.,
488 Karlstrom, K.E. and Macdonald, F.A., 2018, Coupled Re-Os and U-Pb geochronology of
489 the Tonian Chuar Group, Grand Canyon: *GSA Bulletin*, v. 130, p. 1085-1098,
490 <https://doi.org/10.1130/B31768.1>.

- 491 Rudnick, R.L., and Gao, S., 2014, Composition of the Continental Crust, *in*
492 R.L. Rudnick, H.D. Holland, K.K. Turekian, eds., *Treatise on geochemistry 3: The*
493 *crust*, Amsterdam, Elsevier, p. 1-64, <https://doi.org/10.1016/B978-0-08-095975-7.00301-6>.
- 494 Sandelin, S., Tebenkov, A.M., and Gee, D.G., 2001, The stratigraphy of the lower part of the
495 Neoproterozoic Murchisonfjorden Supergroup in Nordaustlandet, Svalbard: *GFF*, v. 123, p.
496 113–127, <https://doi.org/10.1080/11035890101232113>.
- 497 Schmitz, M.D., Gradstein, F., Ogg, J., and Ogg, G., 2012, Appendix 2—Radiometric ages used
498 in GTS2012, *The Geologic Time Scale*, v. 2, p. 1045-1082, [https://doi.org/10.1016/B978-](https://doi.org/10.1016/B978-0-444-59425-9.15002-4)
499 [0-444-59425-9.15002-4](https://doi.org/10.1016/B978-0-444-59425-9.15002-4).
- 500 Selby, D., and Creaser, R.A., 2003, Re–Os geochronology of organic rich sediments: an
501 evaluation of organic matter analysis methods: *Chemical Geology*, v. 200, p. 225–240,
502 [https://doi.org/10.1016/S0009-2541\(03\)00199-2](https://doi.org/10.1016/S0009-2541(03)00199-2).
- 503 Smoliar, M.I., Walker, R.J., and Morgan, J.W., 1996, Re–Os Ages of Group IIA, IIIA, IVA, and
504 IVB Iron Meteorites: *Science*, v. 271, p. 1099–1102,
505 <https://doi.org/10.1126/science.271.5252.1099>.
- 506 Strauss, J.V., Rooney, A.D., Macdonald, F.A., Brandon, A., and Knoll, A.H., 2014, 740 Ma
507 vase-shaped microfossils from Yukon, Canada: Implications for Neoproterozoic
508 chronology and biostratigraphy: *Geology*, v. 42, p. 659-662,
509 <https://doi.org/10.1130/g35736.1>.
- 510 Swanson-Hysell, N.L., Maloof, A.C., Condon, D.J., Jenkin, G.R.T., Alene, M., Tremblay, M.M.,
511 Tesema, T., Rooney, A.D., and Haileab, B., 2015, Stratigraphy and geochronology of the
512 Tambien Group, Ethiopia: Evidence for globally synchronous carbon isotope change in the
513 Neoproterozoic: *Geology*, v. 43, p. 323–326, <https://doi.org/10.1130/g36347.1>.
- 514 Taylor, S.R., and McLennan, S.M., 1985. *The Continental Crust: Its Composition and Evolution*:
515 Oxford, U.K., Blackwell, 312 p.
- 516 Turner, E.C., 2011. Stratigraphy of the Mackenzie Mountains supergroup in the Wernecke
517 Mountains, Yukon, *in* K.E. MacFarlane, L.H. Weston and C. Relf, eds., *Yukon Exploration*
518 *and Geology 2010*, Yukon Geological Survey, p. 207-231.
- 519 Volkening, J., Walczyk, T., and Heumann, K.G., 1991, Osmium isotope ratio determinations by
520 negative thermal ionization mass spectrometry: *International Journal of Mass Spectrometry*
521 *and Ion Processes*, v. 105, p. 147–159, [https://doi.org/10.1016/0168-1176\(91\)80077-Z](https://doi.org/10.1016/0168-1176(91)80077-Z).
- 522 Zhou, C., Huyskens, M.H., Lang, X., Xiao, S., and Yin, Q.-Z., 2019, Calibrating the terminations
523 of Cryogenian global glaciations: *Geology*, v. 47, p. 251–254,
524 <https://doi.org/10.1130/G45719.1>.

Millikin, Figure S1

Millikin, Figure S2

TABLE S1. Re AND Os ABUNDANCE AND ISOTOPE COMPOSITION DATA FOR THE HECLA HOEK SUCCESSION

Location	Sample	Re (ng/g)	±	Os (pg/g)	±	¹⁹² Os (pg/g)	±	¹⁸⁷ Re/ ¹⁸⁸ Os	±	¹⁸⁷ Os/ ¹⁸⁸ Os	±	rho *	Os _i ^{†§}	±
<u>Gravela River</u>	J1630													
N 79.877067, E 17.532567	-1	19.70	0.04	259.68	1.62	48.40	0.14	809.85	2.87	9.44	0.04	0.624	0.884	0.067
Decimal Degrees WGS 84	-2	8.91	0.02	165.51	0.87	39.96	0.11	443.80	1.65	5.57	0.02	0.606	0.880	0.037
	-3	12.08	0.03	192.45	1.09	42.14	0.12	570.28	2.06	6.92	0.03	0.631	0.889	0.047
	-4	1.52	0.01	42.191	0.34	12.05	0.09	251.33	2.40	3.54	0.03	0.565	0.884	0.059
	-5	7.18	0.02	128.19	0.78	30.17	0.11	473.57	2.16	5.91	0.03	0.668	0.903	0.050
	-6	14.84	0.03	198.21	1.52	37.48	0.16	787.50	3.79	9.20	0.05	0.666	0.878	0.093
	-7	4.98	0.02	123.52	0.85	34.00	0.15	291.30	1.61	3.96	0.03	0.525	0.881	0.044
<u>Søre Russøya</u>	SR-161.5													
N 79.958650, E 18.292533	-1	6.56	0.02	232.70	1.07	73.81	0.21	176.76	0.69	2.44	0.01	0.500	0.255	0.013
Decimal Degrees WGS 84	-2	6.86	0.01	234.85	1.15	73.77	0.23	185.01	0.70	2.54	0.01	0.549	0.251	0.015
	-3	6.88	0.01	296.18	1.57	98.51	0.28	138.94	0.48	1.98	0.01	0.352	0.260	0.014
	-4	6.93	0.01	257.85	1.24	82.79	0.23	166.49	0.58	2.32	0.01	0.473	0.261	0.013
	-5	9.65	0.02	284.90	1.31	85.17	0.22	225.41	0.74	3.05	0.01	0.564	0.263	0.015
	-8	4.99	0.01	181.87	0.81	58.06	0.17	170.91	0.63	2.38	0.01	0.587	0.264	0.012

Note: Uncertainties are given as 2σ for ¹⁸⁷Re/¹⁸⁸Os, ¹⁸⁷Os/¹⁸⁸Os, and ¹⁹²Os. For the latter uncertainty includes the 2 SE uncertainty for mass spectrometer analysis plus uncertainties for Os blank abundance and isotopic composition. Ages are calculated using the $\lambda^{187}\text{Re} = 1.666 \times 10^{-11}\text{y}^{-1}$ (Smoliar et al., 1996).

* Rho is the associated error correlation (Ludwig, 1980).

[†] Os initial (Os_i) = ¹⁸⁷Os/¹⁸⁸Os isotope composition calculated at 631 Ma for Dracöisen Formation sample J1630.

[§] Os initial (Os_i) = ¹⁸⁷Os/¹⁸⁸Os isotope composition calculated at 737 Ma for Russøya Member sample SR-161.5.

TABLE S2. HIGH-PRECISION AGE CONSTRAINTS FOR THE TERMINAL CRYOGENIAN MARINOAN DEGLACIATION

Location	Age (Ma)	±	Technique	Grains	Relationship to Glacial Deposit	Reference
Svalbard	631.2	3.8	Re-Os	isochron	above Wilsonbreen	This paper
Northwest Canada	632.3	5.9	Re-Os	isochron	above Ice Brook	Rooney et al., 2015, <i>Geology</i> , v. 43, p. 459-462
<i>South China</i>	<i>632.5</i>	<i>2.0</i>	<i>U-Pb ID-TIMS</i>	<i>magmatic</i>	<i>above Nantuo</i>	<i>Condon et al., 2005, Science, v.308, p. 95-98</i>
South China	632.5	1.0	U-Pb ID-TIMS	magmatic	above Nantuo	Schmitz, M.D., Geological Time Scale 2012, v. 2, p. 1045-1082 - recalculation of above date
<i>South China</i>	<i>635.2</i>	<i>2.1</i>	<i>U-Pb ID-TIMS</i>	<i>magmatic</i>	<i>above Nantuo</i>	<i>Condon et al., 2005, Science, v.308, p. 95-98</i>
South China	635.3	1.1	U-Pb ID-TIMS	magmatic	above Nantuo	Schmitz, M.D., Geological Time Scale 2012, v. 2, p. 1045-1082 - recalculation of above date
South China	634.6	1.6	U-Pb ID-TIMS	magmatic	top most Nantuo	Zhou et al., 2019, <i>Geology</i> , v. 47, p. 251-254
<i>Namibia</i>	<i>635.2</i>	<i>0.9</i>	<i>U-Pb ID-TIMS</i>	<i>magmatic</i>	<i>within Ghuab</i>	<i>Hoffmann et al., 2004, Geology, v.32, p. 817-820; Prave et al., 2016, Geology, v. 44, p. 631-634</i>
Namibia	635.5	1.1	U-Pb ID-TIMS	magmatic	within Ghuab	Schmitz, M.D., Geological Time Scale 2012, v. 2, p. 1045-1082 - recalculation of above date
Namibia	639.3	0.8	U-Pb ID-TIMS	magmatic	within Ghuab	Prave et al., 2016, <i>Geology</i> , v. 44, p. 631-634
Australia	636.4	0.8	U-Pb ID-TIMS	magmatic	within/above Cottons Breccia	Calver et al., 2013, <i>Geology</i> , v. 41, p. 1127-1130

Note: Ages in italics are not plotted. Uncertainties are given as 2σ and include all systematic uncertainties including those associated with tracer calibration and decay constants.

TABLE S3. COMPILATION OF PRE-STURTIAN GLOBAL INITIAL OSMIUM ISOTOPIC COMPOSITION

Location	Unit	Type	Age (Ma)*	Age uncertainty	Osi ^{†§}	Osi uncertainty	Reference
Northeast terrane Svalbard, Norway	Russoya Member, Elbowbreen Formation	isochron	737.5	9.6	0.260	0.03	This paper
Kipushi Basin, Zambia	Mwashya Formation	isochron	727.3	4.9	0.350	0.03	Rooney et al. (2015)
Mackenzie Mountains, NW Canada	Coppercap Formation	isochron	732.2	4.7	0.150	0.002	Rooney et al. (2014)
Mackenzie Mountains, NW Canada	Coppercap Formation	chemostrat	725.7		0.117		Rooney et al. (2014)
Mackenzie Mountains, NW Canada	Coppercap Formation	chemostrat	726.7		0.135		Rooney et al. (2014)
Mackenzie Mountains, NW Canada	Coppercap Formation	chemostrat	727.3		0.157		Rooney et al. (2014)
Mackenzie Mountains, NW Canada	Coppercap Formation	chemostrat	728.9		0.161		Rooney et al. (2014)
Mackenzie Mountains, NW Canada	Coppercap Formation	chemostrat	730.4		0.145		Rooney et al. (2014)
Mackenzie Mountains, NW Canada	Coppercap Formation	chemostrat	731.1		0.144		Rooney et al. (2014)
Mackenzie Mountains, NW Canada	Coppercap Formation	chemostrat	732.0		0.142		Rooney et al. (2014)
Mackenzie Mountains, NW Canada	Coppercap Formation	chemostrat	732.6		0.149		Rooney et al. (2014)
Mackenzie Mountains, NW Canada	Coppercap Formation	chemostrat	733.4		0.125		Rooney et al. (2014)
Mackenzie Mountains, NW Canada	Coppercap Formation	chemostrat	734.6		0.122		Rooney et al. (2014)
Mackenzie Mountains, NW Canada	Coppercap Formation	chemostrat	736.7		0.277		Rooney et al. (2014)
Mackenzie Mountains, NW Canada	Coppercap Formation	chemostrat	738.1		0.183		Rooney et al. (2014)
Mackenzie Mountains, NW Canada	Coppercap Formation	chemostrat	738.8		0.483		Rooney et al. (2014)
Mackenzie Mountains, NW Canada	Coppercap Formation	chemostrat	740.9		0.235		Rooney et al. (2014)

Note: Uncertainties are given as 2 σ for age and Osi. Ages are calculated using the $\lambda^{187}\text{Re} = 1.666 \times 10^{-11} \text{y}^{-1}$ (Smoliar et al., 1996).

*Rough ages for the Osi chemostratigraphic samples of Rooney et al. (2014) were obtained using the calculated sedimentation rate of ~9.9m/Myr for the Coppercap formation given the Re-Os age from the same paper and the U-Pb age of 717.4 Ma for the basal Rapitan Group from Macdonald et al. (2010).

[†]All Osi values associated with isochron samples were calculated using the isochron age.

[§]Osi chemostratigraphic samples from Rooney et al. (2014) were calculated at 732 Ma.