# DATA REPOSITORY ITEM 2014244

## CARBONATE CARBON AND OXYGEN ISOTOPES

We report $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ measurements of 48 samples from sections J1204 and F930 of the Callison Lake Dolostone (Table DR1). These are parallel measured sections (~1-2 m apart) *of the exact same strata* from a small drainage south of Mount Gibben at N64°40'53.6" W139°13'55.6" in the Coal Creek inlier, Yukon Territory, Canada. In Fig. 1 of the manuscript, we present $\delta^{13}C_{carb}$ data solely from J1204 because F930 is a lower resolution repetition of the same section. We use the $\delta^{13}C_{org}$ data from F930 based on very straightforward bed-by-bed correlations combined with matching the same $\delta^{13}C_{carb}$ values (Table DR1).

Carbon ($\delta^{13}C_{carb}$) and oxygen ($\delta^{18}O_{carb}$) isotopic results are reported in per mil notation of $^{13}C/^{12}C$ and $^{18}O/^{16}O$, respectively, relative to the standard VPDB (Value of the Pee-Dee Belemnite). Dolostone samples were cut perpendicular to bedding, polished, and carefully microdilled (~2-10 mg of powder) to avoid secondary veins, cements, and siliciclastic components. Carbonate $\delta^{13}C$ and $\delta^{18}O$ isotopic data were acquired simultaneously on a VG Optima dual inlet isotope ratio mass spectrometer coupled with a VG Isocarb preparation device (Micromass, Milford, MA) in the Laboratory for Geochemical Oceanography at Harvard University. Approximately 1 mg of sample powder was reacted in a common, purified phosphoric acid ($H_3PO_4$) bath at 90°C. The evolved $CO_2$ was collected cryogenically and analyzed using an in-house reference gas. Measured data were calibrated to VPDB using the Cararra marble standard. Total analytical errors (1σ) are better than ± 0.1‰ for both $\delta^{13}C$ and $\delta^{18}O$ based on repeat analysis of standards and samples. Increasing the reaction time to eleven minutes for dolomite samples minimized potential "memory effects" resulting from the common acid-bath system, with the total memory effect estimated at <0.1‰ based on reproducibility of standards run directly after samples.

## ORGANIC CARBON ISOTOPES

We report $\delta^{13}C_{org}$ measurements from 13 samples of section F930 of the Callison Lake Dolostone (Table DR1). $\delta^{13}C_{org}$ values were obtained from the total organic carbon (TOC) of insoluble residues. Whole rock samples were initially trimmed to remove weathered material and secondary veins and then crushed into a powder in a SPEX 8500 Shatterbox using a hardened steel grinding container and puck. Analyses were performed on large (~10-20g) samples to accommodate low TOC values. Samples were decalcified with concentrated HCl (6N) for 48 hours, buffered back to a neutral pH (>pH5), filtered, and dried. Care was taken to ensure that acid was added and acidification continued until there was absolutely no visible carbonate dissolution so that the analyses would not be affected by contamination from residual inorganic carbon. Homogenized residues were analyzed in the Harvard University Laboratory for Geochemical Oceanography on a Carlo Erba Elemental Analyzer attached to a ThermoFinnigan Delta V configured in continuous flow mode. Samples and standards were bracketed such that our 13 organic carbon analyses (each run in duplicate) were associated with 6 internal standards. These standards, each with known organic carbon contents and isotope values, were used to calibrate TOC contents and isotopic compositions. The mass of insoluble residue was taken as siliciclastic content, and TOC values for the bulk samples were calculated by

combining the carbonate concentration data obtained from the Delta with measurements of the ratio of insoluble residue to original pre-decarbonated powder.

## RHENIUM-OSMIUM GEOCHRONOLOGY

Organic-rich (TOC = 1.15–2.5%), vase-shaped microfossil-bearing black shale was sampled from section J1204. Ten samples large enough for Re-Os geochronology (~50-200 g) were collected over an interval of 2.2 m (J1204-16.8–18.2 m) after an ~25 cm deep trench was dug to remove weathered material from the outcrop. Seven of these ten samples (Table DR2: B–H) were collected horizontally from a very thin (<10 cm) vertical interval (17.7 m), as a large horizontal sampling technique is generally used to maximize the spread of $^{187}Re/^{188}Os$ (Kendall et al., 2009). Given the lack of variability from this small horizon, we incorporated three other vertical samples (Table DR2: A, I, and J) to develop our final isochron age (Fig. 3 of manuscript). This 2.2 m interval is sedimentologically identical and the Os*i* values (Table DR2) of every sample is practically indistinguishable from one another.

All of the sample weathered surfaces were removed with a diamond-coated rock saw and samples were then hand-polished using a diamond-plated polishing pad to remove cutting marks and eliminate any potential for contamination from the saw blade. The samples were dried overnight at ~60 °C and then crushed to a fine (~30 μm) 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 Department of Earth and Atmospheric Sciences, University of Houston (UH) following methodology developed by van Acken et al. (2012) and Wittig et al. (2013).

0.6 g of sample was digested and equilibrated in 8 ml of $Cr^{VI}O_3$-$H_2SO_4$ together with a mixed tracer (spike) solution of $^{190}Os$ and $^{185}Re$ in carius tubes at 220 °C for 48 hours. Rhenium and osmium was extracted and purified using solvent extraction (NaOH, $(CH_3)_2CO$, and $CHCl_3$,), micro-distillation, anion column chromatography methods, and negative mass spectrometry as outlined by Selby and Creaser (2003) and Cumming et al. (2013). The $Cr^{VI}O_3$-$H_2SO_4$ digestion method was employed as it has been shown to preferentially liberate hydrogenous Re and Os yielding more accurate and precise age determinations (Selby and Creaser, 2003; Kendall et al., 2004; Rooney et al., 2011). Total procedural blanks during this study were 12.3 ± 0.1 pg and 0.05 ± 0.15 pg for Re and Os respectively, with an average $^{187}Os/^{188}Os$ value of 0.172 ± 0.208 (1σ, $n$ = 3).

Isotopic measurements were performed using the UH 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. 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 University of Houston Re standard solution measured on the faraday cups yields an average $^{185}Re/^{187}Re$ value of 0.59827 ± 0.00158 (2σ, $n$ = 10), which is identical to that of (Rooney et al., 2010). The measured difference in $^{185}Re/^{187}Re$ values for the Re solution and the accepted $^{185}Re/^{187}Re$ value (0.5974) (Gramlich et al., 1973) is used to correct the Re sample data. The Os isotope standard solution used at UH is the in-house standard from the University of Maryland. Over the past two years on this Triton, the runs yield a $^{187}Os/^{188}Os$ ratio of

0.11388 ± 0.00116 (2σ, *n* = 41) that is identical, within uncertainty, to the accepted value reported in Brandon et al., (1999).

Uncertainties for $^{187}Re/^{188}Os$ and $^{187}Os/^{188}Os$ 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 $^{187}Re/^{188}Os$ and $^{187}Os/^{188}Os$, and the associated error correlation function (rho) are regressed to yield a Re-Os date using *Isoplot V. 4.15* with the $\lambda$ $^{187}Re$ constant of $1.666 \times 10^{-11} a^{-1}$ (Ludwig, 1980; Smoliar et al., 1996; Ludwig, 2011). Elemental Re and Os abundances for the J1204 samples range from 0.7 to 9.5 ppb, and 61.8 to 357.6 ppt, respectively, with $^{187}Re/^{188}Os$ and $^{187}Os/^{188}Os$ ratios between 63 and 196, and 1.421 and 3.050 respectively (Table DR2). Regression of the isotopic composition data for these samples yields a Model 1 age of 739.9 ± 6.1 Ma (6.5 if the $^{187}Re$ decay constant uncertainty is included, *n* = 10, Mean Square of Weighted Deviates [MSWD] = 0.62, initial $^{187}Os/^{188}Os$ = 0.609 ± 0.01; Fig. 3).

**REFERENCES CITED**

Brandon, A.D., Norman, M.D., Walker, R.J., Morgan, J.W., l999, $^{186}Os$-$^{187}Os$ systematics of Hawaiian picrites: Earth and Planetary Science Letters, v. 174, p. 25-42.

Cumming, V.M., Poulton, S.W., Rooney, A.D., Selby, D., 2013, Anoxia in the terrestrial environment during the late Mesoproterozoic: Geology, v. 41, p. 583-586.

Gramlich, J.W., Murphy, T.J., Garner, E.L., Shields, W.R., 1973, Absolute isotopic abundance ratio and atomic weight of a reference sample of rhenium: Journal of Research of the National Bureau of Standards. Section A: Physics and Chemistry, v. 77A, p. 691-698.

Kendall, B.S., Creaser, R.A., Ross, G.M., Selby, D., 2004, Constraints on the timing of Marinoan "Snowball Earth" glaciation by $^{187}Re$-$^{188}Os$ dating of a Neoproterozoic post-glacial black shale in Western Canada: Earth and Planetary Science Letters, v. 222, p. 729-740.

Kendall, B.S., Creaser, R.A., and Selby, D., 2009, $^{187}Re$-$^{188}Os$ geochronology of Precambrian organic-rich sedimentary rocks: Geological Society of London Special Publications, v. 326, p. 85-107.

Ludwig, K.R., 1980, Calculation of uncertainties of U-Pb isotope data: Earth and Planetary Science Letters, v. 46, p. 212-220.

Ludwig, K.R., 2011, Isoplot/Ex, Version 4.15: A geochronological toolkit for Microsoft Excel: Geochronology Center Berkeley, v. 4, p. 1-70. http://www.bgc.org/isoplot_etc/isoplot.html.

Rooney, A.D., Selby, D., Houzay, J.-P., Renne, P.R., 2010, Re-Os geochronology of a Mesoproterozoic sedimentary succession, Taoudeni basin, Mauritania: Implications for basin-wide correlations and Re-Os organic-rich sediments systematics: Earth and Planetary Science Letters, v. 289, p. 486-496.

Rooney, A.D., Chew, D.M., Selby, D., 2011, Re-Os geochronology of the Neoproterozoic-Cambrian Dalradian Supergroup of Scotland and Ireland: Implications for Neoproterozoic stratigraphy, glaciation and Re-Os systematics: Precambrian Research, v. 185, p. 202-214.

Selby, D., and Creaser, R.A., 2003, Re-Os geochronology of organic-rich sediments: an evaluation of organic matter analysis methods: Chemical Geology, v. 200, p. 225-240.

Smoliar, M.I., Walker, R.J., Morgan, J.W., 1996, Re-Os ages of Group IIA, IIIA, IVA and IVB iron meteorites: Science, v. 271, p. 1099-1102.

van Acken, D., Brandon, A.D., Lapen, T.J., 2012. Highly siderophile element and osmium isotope evidence for postcore formation magmatic and impact processes on the aubrite parent body: Meteoritics and Planetary Science, v. 47, p. 1606-1623.

Wittig, N., Humayun, M., Brandon, A.D., Huang, S., Leya, I., 2013. Coupled W-Os-Pt systematics of IVB iron meteorites: In situ neutron dosimetry for W isotope chronology: Earth and Planetary Science Letters, v. 361, p. 152-161.

**Table DR1: Carbonate Carbon, Organic Carbon and Oxygen isotopes of the upper Callison Lake Dolostone**

| Section | Stratigraphic Height (m) | $\delta^{13}C_{carb}$ (‰) | $\delta^{18}O_{carb}$ (‰) | $\delta^{13}C_{org}$ (‰) | Epsilon (‰) | Siliclastic Content (%) | Carbonate Content (%) | TOC (%) |
|---|---|---|---|---|---|---|---|---|
| J1204 | 0.3 | 4.00 | -2.84 | – | – | – | – | – |
| J1204 | 1 | 3.91 | -3.11 | – | – | – | – | – |
| J1204 | 1.3 | 3.61 | -5.12 | – | – | – | – | – |
| J1204 | 2 | 3.77 | -4.16 | – | – | – | – | – |
| J1204 | 2.5 | 3.61 | -4.36 | – | – | – | – | – |
| J1204 | 3 | 3.78 | -2.45 | – | – | – | – | – |
| J1204 | 3.4 | 3.15 | -2.96 | – | – | – | – | – |
| J1204 | 4.1 | 2.58 | 0.35 | – | – | – | – | – |
| J1204 | 4.4 | 2.26 | -0.19 | – | – | – | – | – |
| J1204 | 5 | 2.01 | -0.93 | – | – | – | – | – |
| J1204 | 5.5 | 1.67 | 0.42 | – | – | – | – | – |
| J1204 | 6.1 | 1.63 | 0.11 | – | – | – | – | – |
| J1204 | 6.5 | 1.29 | -0.19 | – | – | – | – | – |
| J1204 | 7 | 0.73 | 0.31 | – | – | – | – | – |
| J1204 | 7.4 | 0.01 | 0.92 | – | – | – | – | – |
| J1204 | 8 | 1.05 | 1.33 | – | – | – | – | – |
| J1204 | 8.3 | 0.58 | 1.00 | – | – | – | – | – |
| J1204 | 19.3 | -2.78 | -1.19 | – | – | – | – | – |
| J1204 | 20 | -2.67 | -1.22 | – | – | – | – | – |
| J1204 | 20.4 | -4.02 | -1.56 | – | – | – | – | – |
| J1204 | 20.9 | -3.77 | -0.94 | – | – | – | – | – |
| J1204 | 21.1 | -3.60 | -0.62 | – | – | – | – | – |
| J1204 | 21.9 | -7.00 | -1.30 | – | – | – | – | – |
| J1204 | 22.3 | -2.76 | -4.21 | – | – | – | – | – |
| J1204 | 22.9 | -4.21 | -1.87 | – | – | – | – | – |
| J1204 | 23.3 | -3.96 | -2.01 | – | – | – | – | – |
| J1204 | 23.9 | -3.94 | -2.07 | – | – | – | – | – |
| J1204 | 24.4 | -4.07 | -2.22 | – | – | – | – | – |
| J1204 | 25.4 | -2.88 | -5.85 | – | – | – | – | – |
| J1204 | 25.9 | -6.53 | -2.16 | – | – | – | – | – |
| J1204 | 27.2 | -5.64 | -2.07 | – | – | – | – | – |
| J1204 | 27.5 | -5.50 | -1.89 | – | – | – | – | – |
| J1204 | 29.6 | -3.26 | -0.82 | – | – | – | – | – |
| J1204 | 30.9 | -2.97 | -2.95 | – | – | – | – | – |
| J1204 | 32.2 | -2.37 | -0.28 | – | – | – | – | – |
| F930 | 2 | 3.73 | -3.65 | -25.14 | 28.87 | 9.62 | 90.25 | 0.13 |
| F930 | 3 | 3.38 | -1.71 | -29.19 | 32.58 | 13.82 | 86.07 | 0.11 |
| F930 | 5 | 2.30 | -0.08 | -26.93 | 29.23 | 13.42 | 86.44 | 0.14 |
| F930 | 6 | 1.61 | 0.33 | -30.50 | 32.11 | 10.20 | 89.72 | 0.09 |
| F930 | 8 | 1.15 | -0.40 | -30.08 | 31.22 | 13.16 | 86.74 | 0.09 |
| F930 | 9 | -0.98 | 0.98 | -31.18 | 30.20 | 23.08 | 76.73 | 0.19 |
| F930 | 16 | -3.31 | -0.16 | -31.22 | 27.91 | 6.37 | 93.58 | 0.04 |
| F930 | 18 | -6.77 | -1.91 | -31.53 | 24.76 | 10.03 | 89.86 | 0.11 |
| F930 | 20 | -4.55 | -2.72 | -27.68 | 23.13 | 27.58 | 72.33 | 0.09 |
| F930 | 21 | -5.88 | -1.88 | -30.11 | 24.23 | 4.41 | 95.50 | 0.08 |
| F930 | 22 | -3.89 | 0.03 | -28.16 | 24.27 | 3.64 | 96.29 | 0.07 |
| F930 | 23 | -4.83 | -0.62 | -28.88 | 24.05 | 2.01 | 97.95 | 0.04 |
| F930 | 25 | -1.39 | -0.14 | -32.87 | 31.48 | 41.57 | 58.41 | 0.01 |
| F930 | 26 | -1.62 | -0.39 | -34.99 | 33.36 | 45.42 | 54.55 | 0.03 |

***F930-2–9 m = J1204-0.3–8.3 m and F930-16–26m = J1204-19.3–32.2 m***

**Table DR2: Re and Os abundance and isotope composition data for the Callison Lake Dolostone**

| Sample | Isochron point | Re (ppb) | ± | Os (ppt) | ± | $^{192}$Os (ppt) | ± | $^{187}$Re / $^{187}$Os | ± | $^{187}$Os/$^{188}$Os | ± | rho[a] | Os initial[b] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 16.8 | A | 0.71 | 0.01 | 61.8 | 0.2 | 21.8 | 0.1 | 64.6 | 1.1 | 1.421 | 0.016 | 0.489 | 0.620 |
| 17.7#1 | B | 3.29 | 0.02 | 138.8 | 0.4 | 44.0 | 0.1 | 148.8 | 1.0 | 2.453 | 0.013 | 0.659 | 0.608 |
| 17.7#2 | C | 1.93 | 0.01 | 80.3 | 0.3 | 25.4 | 0.1 | 151.5 | 1.5 | 2.479 | 0.022 | 0.732 | 0.600 |
| 17.7#3 | D | 3.55 | 0.02 | 174.1 | 0.8 | 56.9 | 0.1 | 124.1 | 1.0 | 2.152 | 0.032 | 0.395 | 0.613 |
| 17.7#4 | E | 5.67 | 0.02 | 203.3 | 2.1 | 63.9 | 0.4 | 182.8 | 0.5 | 2.880 | 0.018 | 0.668 | 0.613 |
| 17.7#5 | F | 9.51 | 0.04 | 357.6 | 4.9 | 77.9 | 0.3 | 171.8 | 0.5 | 2.738 | 0.029 | 0.384 | 0.608 |
| 17.7#6 | G | 4.71 | 0.03 | 159.7 | 1.8 | 53.6 | 0.3 | 196.2 | 0.7 | 3.050 | 0.022 | 0.617 | 0.617 |
| 17.7#7 | H | 4.87 | 0.02 | 178.3 | 1.8 | 42.2 | 0.1 | 177.5 | 0.5 | 2.814 | 0.017 | 0.680 | 0.612 |
| 18.1 | I | 1.87 | 0.01 | 92.6 | 0.3 | 30.3 | 0.2 | 123.1 | 1.1 | 2.131 | 0.015 | 0.704 | 0.605 |
| 18.2 | J | 1.68 | 0.01 | 148.3 | 0.5 | 52.6 | 0.1 | 63.4 | 0.7 | 1.393 | 0.015 | 0.462 | 0.606 |

Uncertainties are given as 2σ for $^{187}$Re/$^{188}$Os, $^{187}$Os/$^{188}$Os and $^{192}$Os

For the latter the uncertainty includes the 2 SE uncertainty for mass spectrometer analysis plus uncertainties for Os blank abundance and isotopic composition.

Ages are calculated using the $\lambda^{187}$Re = 1.666 x $10^{-11}y^{-1}$ (Smoliar et al., 1996).

a Rho is the associated error correlation (Ludwig, 1980)

b Os initial = $^{187}$Os/$^{188}$Os isotope composition calculated at 739 Ma

**Table DR3: Locations where VSMs have been described in the literature (after Porter and Knoll, 2000). Age constraints are rough and noted from italisized references when neccessary.**

| Formation/Rock Unit | Location | Paleocontinent | Relationship to Islay anomaly? | Approximate Age | Reference |
|---|---|---|---|---|---|
| *A. Assemblages with multiple VSM species in common:* | | | | | |
| Backlundtoppen Formation | Spitsbergen, Svalbard | Laurentia | Older | 780–716 Ma | Knoll et al. (1989); *Halverson et al. (2004)* |
| Callison Lake Dolostone | Yukon, Canada | Laurentia | Yes | ca. 740 Ma | This paper |
| Draken Formation | Spitsbergen, Svalbard | Laurentia | Older | 780–716 Ma | Knoll et al. (1991); *Halverson et al. (2004)* |
| Chuar Group | Grand Canyon, Arizona | Laurentia | Older? | 785–742 Ma | Bloeser (1985); Porter et al. (2003); *Karlstrom et al. (2000); Dehler et al. (2012)* |
| Beck Springs Dolomite | Death Valley, California | Laurentia | Yes | 770–716 Ma | Licari (1978); Horodyski (1993); *Macdonald et al. (2013); Mahon et al. (2014)* |
| Russøya Member, Elbobreen Formation | Nordhaustlandet, Svalbard | Laurentia | Yes | 780–716 Ma | Knoll and Calder (1983); *Halverson et al. (2004)* |
| Uinta Mountain Group | Uinta Mountains, Utah | Laurentia | Older? | 785–716 Ma | Link et al. (1993); *Dehler et al. (2010)* |
| *B. Assemblages with broad morphological similarity to the Callison Lake Dolostone, but with distinct taxa or insufficient systematic research* | | | | | |
| Bed 18, Eleonore Bay Group | East Greenland | Laurentia | Unknown | 780–716 Ma | Vidal (1979); Green et al. (1988); *Hoffman et al. (2012)* |
| Chatkaragai Suite | Tien Shan, Russia/Kyrgyzstan | Kazakstan | Unknown | 800–766 Ma | Kraskov (1985); Yankaouskas (1989); *Sergeev and Schopf (2010); Meert et al. (2011)* |
| Chichkan Formation | Kazakstan | Kazakstan | Unknown | 800–766 Ma | Sergeev and Schopf (2010); *Meert et al. (2011)* |
| Jabal Rockham | Saudi Arabia | Arabia | Unknown | >650 Ma | Binda and Bokhari (1980); *Johnson (2003)* |
| Togari Group | Tasmania | Australia | Yes | 780–716 Ma | Saito et al. (1988); *Turner et al. (1998)* |
| Visingsö Beds | Sweden | Baltica | Unknown | 805–663 Ma | Ewetz (1933); Knoll and Vidal (1980); *Vidal and Siedlecka (1983); Martí Mus and Moczydlowska (2000)* |
| *C. Reported vasiform microfossils that are distinct from the Callison Lake Dolostone, insufficiently illustrated, or poorly preserved* | | | | | |
| Bonahaven Formation, Dalradian Supergroup | Scotland | Laurentia? | Younger | 665–635 Ma | Anderson et al. (2013) |
| Dengying Formation | China | South China | Younger | 551–542 Ma | Zhang and Li (1991); Ding et al. (1992); Duan et al. (1993); Zhang (1994); *Condon et al. (2005)* |
| Doushantuo Formation | China | South China | Younger | 635–551 Ma | Duan (1986); Duan et al. (1993); Li et al. (2008); *Condon et al. (2005)* |
| Jacadigo Group | Brazil | Amazonia | Younger | 716–635 Ma | Fairchild et al. (1978); *Freitas et al. (2011)* |
| Rasthof Formation | Namibia | Congo | Younger | 665–635 Ma | Bosak et al. (2011) |
| Simla Slates | India | India | Unknown | 823–716 Ma | Nautiyal (1978); *Jiang et al. (2003)* |
| Tanafjorden Group | Norway | Baltica | Unknown | 807–716 Ma | Vidal and Siedlecka (1983); *Vidal and Moczydlowska (1995)* |
| Tindir Group | Alaska | Laurentia | Unknown | 811–716 Ma | Allison and Awramik (1994); *Macdonald et al. (2010)* |
| Tsagaan Oloom Formation | Mongolia | Mongolia | Younger | 665–635 Ma | Bosak et al. (2011) |
| Upper Min'yar Formation | Urals, Russia | Baltica | Unknown | 820–687 Ma | Maslov et al. (1994); *Maslov (2004)* |
| Vaishnodevi Limestone | Himalaya, India | India | Unknown | <950 Ma | Venkatachala and Kumar (1998); *McKenzie et al. (2011)* |
| Vindhyan Supergroup | India | India | Unknown | >650 Ma? | Maithy and Babu (1988); *Ray et al. (2002)* |
| Virgin Springs Limestone | Death Valley, California | Laurentia | Younger | 740–716 Ma | Macdonald et al. (2013); *This paper* |

**References**


Allison, C.W., and Awramik, S.M., 1989, Organic-walled microfossils from the earliest Cambrian or latest Proterozoic Tindir Group rocks, Northwest Canada: Precambrian Research, v. 43, p. 253–294.
Anderson, R.P., Fairchild, I.J., Tosca, N.J., and Knoll, A.H., 2013, Microstructures in metasedimentary rocks from the Neoproterozoic Bonahaven Formaton, Scotland: Microconcretions, impact spherules, or microfossils?: Precambrian Research, v. 233, p. 59–72.
Binda, P.L., and Bokhari, M.M., 1980, Chitinozoanlike microfossils in a late Precambrian dolostone from Saudi Arabia: Geology, v. 8, p. 70-71.
Bloeser, B., 1985, *Melanocyrillium*, a new genus of structurally complex Late Proterozoic microfossils from the Kwagunt Formation (Chuar Group), Grand Canyon, Arizona: Journal of Paleontology, v. 59, p. 741–765.
Bosak, T., Lahr, D.J.G., Pruss, S.B., Macdonald, F.A., Dalton, L., and Matys, E., 2011, Agglutinated tests in post-Sturtian cap carbonates of Namibia and Mongolia: Earth and Planetary Science Letters, v. 308, p. 29–40.
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.
Dehler, C.M., Fanning, C.M., Link, P.K., Kingsbury, E.M., and Rybczynski, 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, no. 9-10, p. 1686–1699.
Dehler, C.W., Karlstrom, K.E., Gehrels, G.E., Timmons, M.J., and Crossey, L.J., 2012, Stratigraphic revision, provenance, and new age constraints on the Nankoweap Formation and Chuar Group, Grand Canyon Supergroup, Grand Canyon, Arizona: Geological Society of America Abstracts with Programs, v. 44, no. 6, p. 82.
Ding, L.F., Zhang, L.Y., Li, Y., Dong, J.S., 1992, The study of the late Sinian–Early Cambrian biota from the northern margin of Yangtze Platform: Scientific and Technical Documents Publishing House, Beijing, p. 1–156.
Duan, C., 1985, The earliest Cambrian vase-shaped microfossils of Fangxian County, Hubei Province: Bulletin of the Tianjin Institute of Geology and Mineral Resources, v. 13, p. 87–107.
Duan, C., Cao, F., and Zhang, L., 1993, Vase-shaped microfossils from the top of the Tongying Formation in Xixiang, Shaanxi: Acta Micropaleontologica, v. 10, p. 397–408.
Ewetz, C.E., 1933, Einige neue Fossilfunde in der Visingsöformation: Geologiska Föreningens I Stockholm Förhandlingar, v. 55, p. 506–518.
Fairchild, T.R., Barbour, A.P., and Haralyi, N.L.E., 1978, Microfossils in the 'Eopaleozoic' Jacadigo Group at Urucum, Mato Grosso, southwest Brazil: Boletim IG, v. 9, p. 74–79.
Freitas, B.T., Warren, L.V., Boggiani, P.C., Paes De Almeida, R., and Piacentini, T., 2011, Tectono-sedimentary evolution of the Neoproterozic BIF-bearing Jacadigo Group, SW Brazil: Sedimentary Geology, v. 238, p. 48–70.
Green, J.W., Knoll, A.H., and Swett, K., 1988, Microfossils from oolites and pisolites of the upper Proterozoic Eleonore Bay Group, Central East Greenland: Journal of Paleontology, v. 62, p. 835–852.
Halverson, G.P., Maloof, A.C., and Hoffman, P.F., 2004, The Marinoan glaciation (Neoproterozoic) in northeast Svalbard: Basin Research, v. 16, p. 297–324.
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. 206-207, p. 137-158.
Horodyski, R.J., 1993, Paleontology of Proterozoic shales and mudstones: examples from the Belt Supergroup, Chuar Group, and Pahrump Group, western USA: *in* B. Nagy, J.S. Leventhal, and R.F. Grant, eds., Metalliferous black shales and related ore deposits: Precambrian Research, v. 61, p. 241–278.
Jiang, G., Sohl, L.E., and Christie-Blick, N., 2003, Neoproterozoic stratigraphic comparison of the Lesser Himalaya: Geology, v. 31, no. 10, p. 917–920.
Johnson, P.R., 2003, Post-amalgamation basins of the NE Arabian shield and implications for Neoproterozoic III tectonism in the northern East African orogen: Precambrian Research, v. 123, p. 321–337.
Karlstrom, K.E., Bowring, S.A., Dehler, C.M., Knoll, A.H., Porter, S.M., Marais, Des, D.J., Weil, A.B., Sharp, Z.D., Geissman, J.W., Elrick, M.B., Timmons, J.M., Crossey, L.J., and Davidek, K.L., 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, no. 7, p. 619–622.
Knoll, A.H., and Calder, S., 1983, Microbiota of the Late Precambrian Ryssö Formation, Nordaustlandet, Svalbard: Palaeontology, v. 26, p. 467-496.
Knoll, A.H., and Vidal, G., 1980, Late Proterozoic vase-shaped microfossils from the Visingsö Beds, Sweden: Geologiska Föreningens i Stockholm Förhandlingar, v. 102, p. 207–211.
Knoll, A.H., Swett, K., and Burkhart, E., 1989, Paleoenvironmental distribution of microfossils and stromatolites in the Upper Proterozoic Backlundtoppen Formation, Spitsbergen: Journal of Paleontology, v. 63, p. 129–145.
Knoll, A.H., Swett, K., and Mark, J., 1991, Paleobiology of a Neoproterozoic tidal flat/lagoonal complex: the Draken Conglomerate Formation, Spitsbergen: Journal of Paleontology, v. 65, p. 531–570.
Kraskov, L.N., 1985, Nakhodka problematichnikh organizmov votlozheniykh chatkaragaikoii sviti (Talasskii khrebet): *in*, A.M. Obut and N.J. Tchernysheva, eds., Problematika pozdnego dokembriya I paleozoya, p. 149–152.
Li, Y., Guo, J., Zhang, X., Zhang, W., Liu, Y., Yang, W., Li, Y., Liu, L., and Shu, D., 2008, Vase-shaped microfossils from the Ediacaran Weng'an biota, Guizhou, South China: Gondwana Research, v. 14, no. 1-2, p. 263-268.
Licari, G.R., 1978, Biogeology of the late pre-Phanerozoic Beck Springs Dolomite of eastern California: Journal of Paleontology, v. 52, p. 767–792.
Link, P.K., Christie-Blick, N., Devlin, W.J., Elston, D.P., Horodyski, R.J., Levy, M., Miller, J.M.G., Pearson, R.C., Prave, A., Stewart, J.H., Winston, D., Wright, L.A., Wrucke, C.T., 1993, Middle and Late Proterozoic stratified rocks of the western U.S. Cordillera, Colorado Plateau, and Basin and Range province: in, J.C. Reed Jr., M.E. Bickford, R.S. Houston, P.K. Link, D.W. Rankin, P.K. Sims, and W.R. Van Schmus, eds., The geology of North America: Geological Society of America, Boulder, CO, p. 463–595.
Macdonald, F.A., Halverson, G.P., Strauss, J.V., Smith, E.F., Cox, G.M., Sperling, E.A., and Roots, C.F., 2010, Early Neoproterozoic basin formation in Yukon, Canada: Implications for the make-up and break-up of Rodinia: Geoscience Canada, v. 39, p. 77-99.
Macdonald, F.A., Prave, A., Petterson, R., Smith, E.F., Pruss, S., Oates, K., Waechter, F., Trotzuk, D., and Fallick, A., 2013, The Laurentian record of Neoproterozoic glaciation, tectonism, and eukaryotic evolution in Death Valley, California: Geological Society of America Bulletin, v. 125, no. 7-8, p. 1203–1223.
Mahon, R.C., Dehler, C.M., Link, P.K., Karlstrom, K.E., and Gehrels, G.E., 2014, Geochronologic and stratigraphic constraints on the Mesoproterozoic and Neoproterozoic Pahrump Group, Death Valley, California: A record of the assembly, stability, and break of Rodinia: Geological Society of America Bulletin, v. XXX, p. XXX.
Maithy, P.K., and Babu, R., 1988, Chitinozoa-like remains from Vindhyan Supergroup of Son Valley: Palaeobotanist, v. 37, p. 77–80.
Martí Mus, M., and Moczydlowska, M., 2000, Internal morphology and taphonomic history of the Neoproterozoic vase-shaped microfossils from the Visingsö Group, Sweden: Norsk Geologisk Tidsskrift, v. 80, p. 213–228.
Maslov, A.V., Abduazimova, Z.M., Karsten, L.A., and Puchkov, V.N., 1994, Pervye nakhodki *Mellanoserillium* v etalonnykh rifeya na Yuzhnon Urale: Sostoyanie, problemy I zadachi geologicheskogo kartirovaniya oblastei rasvitiya dokembrya na territorii Rossi, p. 90–91.
Maslov, A.V., Riphean and Vendian sedimentary sequences of the Timanides and Uralides, the eastern periphery of the East European Craton: Geological Society of London Memoirs, v. 30, p. 19–35.
McKenzie, N.R., Hughes, N.C., Myrow, P.M., Xiao, S., and Sharma, M., 2011, Correlation of Precambrian–Cambrian sedimentary successions across northern India and utility of isotopic signatures of Himalayan lithotectonic zones: Earth and Planetary Science Letters, v. 312, p. 471–483.
Meert, J.G., Gibsher, A.S., Levashova, N.M., Grice, W.C., Kamenov, G.D., and Ryabinin, A.B., 2011, Glaciation and ~770 Ma Ediacara (?) fossils from the Lesser Karatau Microcontinent, Kazakhstan: Gondwana Research, v. 19, p. 867–880.
Nautiyal, A.C., 1978, Discovery of cyanophycean remains and chitinozoans from the late Precambrian argillaceous sequence of Satpuli, Garhwal Himalaya, India: Current Science, v. 47, p. 222–226.
Porter, S.M., Meisterfield, R., and Knoll, A.H., 2003, Vase-shaped microfossils from the Neoproterozoic Chuar Group, Grand Canyon: A classification guided by modern testate amoebae: Journal of Paleontology, v. 77, no. 3, p. 409–429.
Ray, J.S., Martin, M.W., Veizer, J., and Bowring, S.A., 2002, U-Pb zircon dating and Sr isotope systematics of the Vindhyan Supergroup, India: Geology, v. 30, no. 2, p. 131–134.
Saito, Y., Tiba, T., and Matsubara, S., 1988, Precambrian and Cambrian cherts in Northwestern Tasmania: Bulletin of the National Science Museum, Tokyo, v. 14, p. 59–70.
Sergeev, V.N., and Schopf, J.W., 2010, Taxonomy, paleoecology, and biostratigraphy of the Late Neoproterozoic Chichkan microbiota of south Kazakhstan: The marine biosphere on the even of metazoan radiation: Journal of Paleontology, v. 84, no. 3, p. 363–401.
Turner, N.J., Black, L.P., and Kamperman, M., 1998, Dating of Neoproterozoic and Cambrian orogenies in Tasmania: Australian Journal of Earth Science, v. 45, no. 5, p. 789–806.
Venkatachala, B.S., and Kumar, A., 1998, Fossil microbiota from the Vaishnodevi Limestone, Himalayan Foothills, Jammu: age and paleoenvironmental implications: Journal of the Geological Society of India, v. 52, p. 529–536.
Vidal, G., 1979, Acritarchs from the Upper Proterozoic and Lower Cambrian of East Greenland: Grønlands Geologiske Undersøgelse Bulletin, v. 131, p. 1–55.
Vidal, G., and Moczydlowska, M., 1995, The Neoproterozoic of Baltica–stratigraphy, palaeobiology, and general geological evolution: Precambrian Research, v. 28, p. 197–216.
Vidal, G., and Siedlecka, A., 1983, Planktonic, acid-resistant microfossils from the Upper Proterozoic strata of the Barents Sea Region of Varanger Peninsula, East Finmark, Northern Norway: Norges Geologiske Undersokelse, v. 382, p. 45–79.
Yankaouskas, T.V., ed., 1989, Mikrofossilii dokembriia SSSR, Nauka, Leningrad.
Zhang, L.Y., 1994, A new progress in research on vase-shaped microfossils from the Dengying Formation of Sinian in southern Shaanxi Province: Acta Geologica Gansu, v. 13, p. 1–8.
Zhang, L., and Li, Y., 1991, The Late Sinian vasiform microfossils of Ningqiang, Shaanxi Province: Bulletin of the Xi'an Institute of Geological and Mineralogical Research: Chinese Academy of Geological Sciences, v. 31, p. 77–86.