GSA Data Repository 2017060

Equable end Mesoproterozoic climate in the absence of high CO_2

Fiorella and Sheldon

Detailed Model Setup and Branched Runs

1) Additional details on albedo calculation for the land surface and sea-ice

In the absence of land plants, land surface albedos in CESM1.2/CLM4 are determined by the prescribed soil color and the volumetric water content in the first soil layer (Oleson et al., 2010). Albedo decreases in visible and near-IR bands with soil water content between dry and saturated limits. All simulations use soil class 20, except for those with "sc" in their names. Simulations containing "sc1" use soil class 1, which has dry-limit albedos of 0.36/0.61 visible/near-IR and saturated-limit albedos of 0.25/0.50 visible/near-IR. Simulations containing "sc11" use soil class 11, which has dry-limit albedos of 0.24/0.37 visible/near-IR and saturated limit albedos of 0.13/0.26 visible/near-IR.

The albedo of sea ice in CESM1.2 depends on the ice thickness, ice and snow physical properties (i.e., grain size), and the presence or absence of snow and melt ponds (Holland et al., 2012). "Inherent" optical properties are calculated based on the physical properties of the ice and snow. The albedo is highest in thick ice, which lacks melt ponds and is covered with small-grained snow. In contrast, melt ponds decrease the effective albedo of the ice. These inherent optical properties are combined with a delta-Eddington parameterization of shortwave radiation to calculate the "apparent"/macroscopic optical properties (Holland et al., 2012). The model also accounts for aerosol deposition on to sea-ice; the abundance of aerosols in the ice is included in the shortwave radiation calculations. Additional details on the delta-Eddington approach in CESM1.2/CICE4 are provided in Briegleb and Light (2007) and Holland et al. (Holland et al., 2012).

2) Initiation of branched simulations

In order to examine a wider range of parameter values, two series of sensitivity tests were initiated from the end of the fully coupled runs. These sensitivity tests were carried out using a different configuration of CESM1.2, where they dynamic ocean was replaced with a mixed-layer ocean that parameterizes ocean heat transport (OHT) instead of explicitly calculating it. The mixed-layer ocean configuration has a large computational advantage over the dynamic ocean configuration, as the model no longer calculates advective transport in the ocean. As the exchange between the surface ocean and the deep ocean is assumed to be negligible in this setup, model simulations in this configuration reach equilibrium in 100–200 simulation years, instead of 2000+ when vertical exchange between the surface and deep oceans is included. In our sensitivity simulations, we created six OHT boundary conditions from the coupled runs G1–G4, R1, and R2. For each simulation, a monthly-varying OHT climatology is calculated from the final 50 years of the coupled simulation (after Bitz et al., 2012). These OHT boundary conditions are then applied to the appropriate sensitivity simulations. After generating these OHT files, simulations G1–G4, R1, and R2 were continued using the new OHT file as a control run to ensure that the new OHT file did not alter the simulated climate (simulations G1c–G4c, R1c, and R2c).

The first set of sensitivity tests examined how our choices of aerosol prescription (noaero), soil color (sc), and ocean heat transport (noht) influenced our simulation results. Aerosols were removed in the “noaero” series of simulations by setting the mixing ratios of all aerosol species to zero everywhere. In the “sc” series of simulations, the soil color was changed from 20 to 11 (medium albedo) and 1 (high albedo) (Oleson et al., 2010). In the “noht” series of simulations, the calculated OHT boundary conditions were replaced with zero OHT at all latitudes and months. In the second set of simulations, CO_2 levels of 10x, 5x, and 1x PAL were paired with CH_4:CO_2 ratios of 1:20, 1:100, 1:400, and 0, and simulations that included or excluded OHT (Table DR3). In order to isolate the effect of greenhouse forcing only, the OHT boundary conditions corresponding to G1 were applied to all simulations including OHT. The simulations excluding OHT had zero OHT at all latitudes and months.

Table DR1. Summary of late Mesoproterozoic-early Neoproterozoic sedimentary sequences

Sedimentary Sequences Indicating Non-Glacial Conditions from 1.2-0.8 Ga					
Unit	**Age (Ga)**	**Modern Location**	**Estimated Paleolatitude***	**Evidence counter to glaciation**	**References**
Belt and Purcell Supergroups	~1.5–1.1	Montana, USA; Alberta, Canada	30–45	Lacustrine or peritidal marine, stromatolites and microbially-induced sedimentary structures	(Horodyski, 1993; Frank et al., 1997; Schieber, 1998)
Sibley Group	1.339	Thunder Bay, Ontario, Canada	45–60	Lacustrine deposition with desiccation cracks, dunes, and stromatolites	(Franklin et al., 1980; Cheadle, 1986; Rogala et al., 2007)
Society Cliffs Formation	1.2	Baffin Island, Nunavut, Canada	45–60	Peritidal marine with calcified cyanobacteria	(Kah et al., 2001; Kah and Riding, 2007)
Stoer Group	1.2	Scotland	60–75	Red beds, alluvial and fluvial deposits, microbialites	(Upfold, 1984; Stewart, 1990; Prave, 2002)
Keweenawan Supergroup	1.1	Michigan, Minnesota, Wisconsin, USA; Ontario, Canada	45–60	Floodplain and lacustrine deposition with desiccation cracks, stromatolites, paleosols, acritarchs, microbially-induced sedimentary structures	(Elmore, 1983; Elmore, 1984; Mitchell and Sheldon, 2009; Mitchell and Sheldon, 2010; Mitchell and Sheldon, 2016)
Torridonian Group	~0.98	Scotland	60–75	Fluvial and alluvial sediments, lacustrine sediments, stromatolites, acritarchs, microbially-induced sedimentary structures	(Prave, 2002; Kinnaird et al., 2007)
Jacobsvile Sandstone	~0.96	Michigan, Wisconsin, USA; Ontario, Canada	45–60	Non-marine highly weathered floodplain	(Malone et al., 2016; Mitchell and Sheldon, 2016)
Uinta Mountain Supergroup, Chuar and Pahrump Groups	~0.76–0.74	Utah, Arizona and California, USA	20–40	Micro- and macro-fossil bearing sandstones, limestones, and shales; marine, alluvial, fluvial deposition	(Vidal and Ford, 1985; Horodyski, 1993; Dehler et al., 2010)
Thule Group	1.3–0.7	NW Greenland	45–60	Microfossils and acritarchs, fine grained siliciclastic units	(Samuelsson et al., 1999)
Atar Group	1.0–0.76	Mauritania, Africa	50–75	Shallow marine deposition of alternating siliciclastic and carbonate layers, abundant stromatolites	(Bertrand-Sarfati and Moussine-Pouchkine, 1985; Kah et al., 2012)
Bitter Springs Formation	1.0–0.76	Australia	0–20	Saline lacustrine deposition with microfossils	(Southgate, 1986)

Dismal Lakes Group	1.2	Northwest Territories, Canada	30–45	Microfossils in black cherts	(Horodyski and Donaldson, 1980)
Shorikha and Burovaya Group, Sukhaya Tuguska Formation, Turukhansk Uplift	1.2–0.8, poorly constrained	Siberia, Russia	0–30	Microfossils and acritarchs in peritidal carbonates	(Sergeev et al., 1997; Sergeev, 2001)
Sedimentary Sequences with evidence of glaciation at 1.0 Ga					
Unit	**Age (Ga)**	**Modern Location**	**Estimated Paleolatitude***	**Evidence supporting glaciation**	**References**
Stoer Group	1.2	Scotland	60–75	Inferred ice-rafted origin of clasts in basal conglomerate and breccia	(Davison and Hambrey, 1996), but depositional interpretation challenged in (Stewart, 1997; Young, 1999)
Vazante Group	1.2–1.0	Brazil	30–60	Diamictites containing dropstones	(D'Agrella-Filho et al., 1990; Azmy et al., 2008)

* Estimated paleolatitude in the Li et al. (2008) 1.0 Ga reconstruction; does not necessarily correspond to the paleolatitude where units were deposited.

Table DR2. Sensitivity tests for fully-coupled simulations and parameter sensitivity tests

Case name	CO_2, ppm	CH_4, ppm	Global avg T	Global land T	Global ocean T	Tropics avg T	Tropics land T	Tropics ocean T	Planetary Albedo	Surface Albedo	Cloud coverage (%)	Mean sea-ice lat*	Land, Tavg < 0°C (%)	Snow cover† (%)
G1c	1400	3.5	4.4	-5.3	7.6	19.5	18.2	19.8	0.369	0.233	59	51.2	48	54
G2c	1400	70	12.8	5.8	15.1	23.7	23.5	23.7	0.341	0.149	61.4	68	36	37
G3c	2800	28	16.5	11.1	18.2	25.6	25.9	25.6	0.330	0.115	62.1	76.7	29	23
G4c	2800	140	20.7	17.2	21.8	28.4	29.0	28.2	0.321	0.090	62.2	89.8	18	0
R1c	1400	3.5	1.5	-2.8	2.9	16.4	14.8	16.9	0.382	0.253	60	47.1	41	48
R2c	2800	140	21.5	21.0	21.7	29.2	30.7	28.7	0.318	0.080	62.8	89.9	1	0
G1noht	1400	3.5	-43.7	-49.9	-41.6	-30.7	-31.1	-30.7	0.582	0.628	44.7	0.1	100	100
G2noht	1400	70	-23.2	-33.4	-19.9	-4.5	-4.6	-4.5	0.509	0.492	52.7	17.0	82	97
G3noht	2800	28	0.3	-8.9	3.2	18.7	18.6	18.8	0.401	0.285	58.9	43.1	54	62
G4noht	2800	140	7.2	-0.5	9.8	23.1	23.7	22.9	0.375	0.228	60	51.4	45	47
R1noht	1400	3.5	-47.5	-50.8	-46.4	-35.0	-35.0	-35.0	0.606	0.655	39.5	0.1	100	100
R2noht	2800	140	4.6	2.2	5.4	21.0	22.3	20.6	0.387	0.253	59.9	46.6	40	44
G1sc1	1400	3.5	-7.3	-22.4	-2.4	11.3	5.6	12.6	0.43	0.364	57.7	38.1	74	81
G2sc1	1400	70	-6.3	-19.7	-1.9	12.2	7.4	13.4	0.434	0.370	57.8	37.2	72	80
G3sc1	2800	28	-5.0	-16.5	-1.3	12.9	9.2	13.8	0.433	0.368	57.9	37.1	69	77
G4sc1	2800	140	7.7	-0.5	10.4	21.4	18.5	22.1	0.382	0.251	60	54.4	49	50
R1sc1	1400	3.5	-2.3	-8.5	-0.1	13.8	9.6	15.3	0.404	0.315	58.4	43.3	46	55
R2sc1	2800	140	18.6	16.0	19.4	26.0	24.6	26.5	0.335	0.125	63.2	89.9	7	1
G1sc11	1400	3.5	1.0	-11.7	5.1	17.5	14.5	18.2	0.388	0.276	58.4	48.1	58	66
G2sc11	1400	70	9.6	-0.6	12.9	21.9	20.0	22.3	0.357	0.192	60.6	63.6	46	51
G3sc11	2800	28	7.5	0.6	9.8	21.3	20.1	21.6	0.373	0.234	59.8	53.8	46	49
G4sc11	2800	140	17.7	10.7	20.0	26.7	25.9	26.9	0.336	0.128	61.9	89.4	31	22
R1sc11	1400	3.5	1.8	-3.0	3.4	17.1	14.9	17.8	0.383	0.269	58.7	47.5	41	49
R2sc11	2800	140	20.4	19.1	20.8	28.0	28.7	27.8	0.324	0.101	62.7	90	4	0
G1noaero	1400	3.5	5.5	-4.4	8.7	20.2	18.9	20.5	0.362	0.226	59.1	52.6	47	53
G2noaero	1400	70	14.0	7.2	16.3	24.4	24.3	24.4	0.334	0.141	61.6	70.2	35	34
G3noaero	2800	28	18.2	13.0	19.9	26.5	26.7	26.5	0.321	0.103	62.1	85.1	27	17
G4noaero	2800	140	21.5	18.3	22.6	29.0	29.8	28.8	0.382	0.089	62.2	89.9	14	0
R1noaero	1400	3.5	4.5	0.4	5.9	19.0	17.6	19.5	0.367	0.235	59.4	49.9	39	44
R2noaero	2800	140	22.3	21.9	22.4	29.8	31.5	29.3	0.314	0.079	62.9	90	0	0

Table DR3. Greenhouse gas sensitivity tests

Case name	CO_2, ppm	CH_4, ppm	Estimated ΔRF[1] from CO_2	Estimated ΔRF[1] from CH_4	Total Estimated ΔRF*	Global avg T	Global land T	Global ocean T	Planetary Albedo	Surface Albedo	Cloud coverage, (%)	Mean sea-ice lat†	Land, Tavg <0°C (%)	Snow cover§ (%)
$10xCO_2$, 1:20 CH_4:CO_2, w/OHT	2800	140	14.37	7.28	21.65	18.8	13.0	20.7	0.325	0.120	61.0	74.9	26	23
$10xCO_2$, 1:100 CH_4:CO_2, w/OHT	2800	28	14.37	3.92	18.29	14.9	7.5	17.3	0.335	0.145	60.7	68.7	32	32
$10xCO_2$, 1:400 CH_4:CO_2, w/OHT	2800	7	14.37	1.86	16.23	9.5	1.2	12.3	0.352	0.194	59.9	57.5	39	42
$10xCO_2$, no CH_4, w/OHT	2800	$1x10^{-10}$	14.37	-1.04	13.33	6.4	-2.8	9.4	0.362	0.218	59.4	53.5	45	51
$5xCO_2$, 1:20 CH_4:CO_2, w/OHT	1400	70	9.62	4.77	14.39	10.4	2.2	13.0	0.350	0.188	59.8	58.4	38	41
$5xCO_2$, 1:100 CH_4:CO_2, w/OHT	1400	14	9.62	2.80	12.42	6.4	-2.8	9.5	0.363	0.219	59.2	53.4	45	49
$5xCO_2$, 1:400 CH_4:CO_2, w/OHT	1400	3.5	9.62	1.12	10.74	4.4	-5.3	7.6	0.369	0.233	59	51.2	48	54
$5xCO_2$, no CH_4, w/OHT	1400	$1x10^{-10}$	9.62	-1.04	8.58	0.4	-10.1	3.7	0.384	0.267	58.7	46.2	54	61
$1xCO_2$, 1:20 CH_4:CO_2, w/OHT	280	14	0.04	2.80	2.83	-44.7	-48.9	-43.3	0.584	0.630	43.6	0.4	100	100
$1xCO_2$, 1:100 CH_4:CO_2, w/OHT	280	2.8	0.04	0.92	0.96	-45.3	-49.3	-44.0	0.585	0.631	43	0.4	100	100
$1xCO_2$, 1:400 CH_4:CO_2, w/OHT	280	0.7	0.04	-0.01	0.03	-45.7	-49.4	-44.4	0.586	0.631	42.7	0.4	100	100
$1xCO_2$, no CH_4, w/OHT	280	$1x10^{-10}$	0.04	-1.04	-1.00	-45.9	-49.5	-44.7	0.586	0.631	42.6	0.4	100	100
$10xCO_2$, 1:20 CH_4:CO_2, w/o OHT	2800	140	14.37	7.28	21.65	7.2	-0.5	9.8	0.375	0.228	60	51.4	45	47
$10xCO_2$, 1:100 CH_4:CO_2, w/o OHT	2800	28	14.37	3.92	18.29	0.3	-8.9	3.2	0.401	0.285	58.9	43.1	54	62
$10xCO_2$, 1:400 CH_4:CO_2, w/o OHT	2800	7	14.37	1.86	16.23	-22.3	-32.4	-19.0	0.504	0.487	53.4	17.8	81	95
$10xCO_2$, no CH_4, w/o OHT	2800	$1x10^{-10}$	14.37	-1.04	13.33	-42.8	-48.5	-41.0	0.591	0.640	45.5	0.4	100	100
$5xCO_2$, 1:20 CH_4:CO_2, w/o OHT	1400	70	9.62	4.77	14.39	-23.2	-33.4	-19.9	0.509	0.492	52.7	17.0	82	97
$5xCO_2$, 1:100 CH_4:CO_2, w/o OHT	1400	14	9.62	2.80	12.42	-44.0	-50.9	-41.7	0.589	0.636	43.1	0.1	100	100
$5xCO_2$, 1:400 CH_4:CO_2, w/o OHT	1400	3.5	9.62	1.12	10.74	-43.7	-49.9	-41.6	0.582	0.628	44.7	0.1	100	100
$5xCO_2$, no CH_4, w/o OHT	1400	$1x10^{-10}$	9.62	-1.04	8.58	-44.5	-50.6	-42.5	0.584	0.629	43.7	0.1	100	100
$1xCO_2$, 1:20 CH_4:CO_2, w/o OHT	280	14	0.04	2.80	2.83	-45.9	-51.6	-44.0	0.583	0.628	42	0.1	100	100
$1xCO_2$, 1:100 CH_4:CO_2, w/o OHT	280	2.8	0.04	0.92	0.96	-46.3	-51.8	-44.6	0.584	0.628	41.6	0.1	100	100
$1xCO_2$, 1:400 CH_4:CO_2, w/o OHT	280	0.7	0.04	-0.01	0.03	-46.7	-52.1	-45.0	0.585	0.629	41.2	0.1	100	100
$1xCO_2$, no CH_4, w/o OHT	280	$1x10^{-10}$	0.04	-1.04	-1.00	-47.0	-52.3	-45.3	0.585	0.629	41.1	0.1	100	100

*: estimated radiative forcing calculated using equations in table 2 of Byrne and Goldblatt (2014). The 2.5–100 ppmv CH_4 equation was used to estimate radiative forcing at 140 ppmv CH_4. ΔRF here is estimated with respect to 278 ppmv CO_2, 715 ppbv CH_4.
†: mean sea-ice latitude was calculated as the inverse sine of the global, annual mean open ocean fraction (after Abbot et al., 2011).
§: percentage of land area possessing permanent snow cover.

References

Abbot, D.S., Voigt, A., and Koll, D., 2011, The Jormungand global climate state and implications for Neoproterozoic glaciations: Journal of Geophysical Research, v. 116, no. D18, p. D18103–14, doi: 10.1029/2011JD015927.

Azmy, K., Kendall, B., Creaser, R.A., Heaman, L., and de Oliveira, T.F., 2008, Global correlation of the Vazante Group, São Francisco Basin, Brazil: Re–Os and U–Pb radiometric age constraints: Precambrian Research, v. 164, no. 3-4, p. 160–172, doi: 10.1016/j.precamres.2008.05.001.

Bertrand-Sarfati, J., and Moussine-Pouchkine, A., 1985, Evolution and environmental conditions of Conophyton—jacutophyton associations in the atar dolomite (upper proterozoic, Mauritania): Precambrian Research, v. 29, no. 1-3, p. 207–234, doi: 10.1016/0301-9268(85)90069-5.

Bitz, C.M., Shell, K.M., Gent, P.R., Bailey, D.A., Danabasoglu, G., Armour, K.C., Holland, M.M., and Kiehl, J.T., 2012, Climate Sensitivity of the Community Climate System Model, Version 4: Journal of Climate, v. 25, no. 9, p. 3053–3070, doi: 10.1175/JCLI-D-11-00290.1.

Briegleb, B.P., and Light, B., 2007, A Delta-Eddington Multiple Scattering Parameterization for Solar Radiation in the Sea Ice Component of the Community Climate System Model.: NCAR/TN-472+STR, 1–108 p.

Byrne, B., and Goldblatt, C., 2014, Radiative forcing at high concentrations of well-mixed greenhouse gases: Geophysical Research Letters, v. 41, no. 1, p. 152–160, doi: 10.1002/2013GL058456.

Cheadle, B.A., 1986, Alluvial-playa sedimentation in the lower Keweenawan Sibley Group, Thunder Bay District, Ontario: Canadian Journal of Earth Sciences, v. 23, no. 4, p. 527–542, doi: 10.1139/e86-053.

D'Agrella-Filho, M.S., Pacca, I.G., and Teixeira, W., 1990, Paleomagnetic evidence for the evolution of Meso-to Neo-Proterozoic glaciogenic rocks in central-eastern Brazil: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 80, no. 3-4, p. 255–265, doi: 10.1016/0031-0182(90)90136-u.

Davison, S., and Hambrey, M.J., 1996, Indications of glaciation at the base of the Proterozoic Stoer Group (Torridonian), NW Scotland: Journal of the Geological Society, v. 153, no. 1, p. 139–149, doi: 10.1144/gsjgs.153.1.0139.

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, doi: 10.1130/B30094.1.

Elmore, R.D., 1983, Precambrian non-marine stromatolites in alluvial fan deposits, the Copper Harbor Conglomerate, upper Michigan: Sedimentology, v. 30, no. 6, p. 829–842, doi: 10.1111/j.1365-3091.1983.tb00713.x.

Elmore, R.D., 1984, The Copper Harbor Conglomerate: A late Precambrian fining-upward alluvial fan sequence in northern Michigan: Geological Society of America Bulletin, v. 95, no. 5, p. 610–617, doi: 10.1130/0016-7606(1984)95<610:TCHCAL>2.0.CO;2.

Frank, T.D., Lyons, T.W., and Lohmann, K.C., 1997, Isotopic evidence for the paleoenvironmental evolution of the Mesoproterozoic Helena Formation, Belt Supergroup, Montana, USA: Geochimica et Cosmochimica Acta, v. 61, no. 23, p. 5023–5041, doi: 10.1016/s0016-7037(97)80341-9.

Franklin, J.M., McIlwaine, W.H., Poulsen, K.H., and Wanless, R.K., 1980, Stratigraphy and depositional setting of the Sibley Group, Thunder Bay district, Ontario, Canada: Can. J. Earth Sci, v. 17, no. 5, p. 633–651, doi: 10.1139/e80-060.

Holland, M.M., Bailey, D.A., Briegleb, B.P., and Light, B., 2012, Improved sea ice shortwave radiation physics in CCSM4: the impact of melt ponds and aerosols on Arctic sea ice*: Journal of Climate, v. 25, no. 5, p. 1413–1430, doi: 10.1175/jcli-d-11-00078.1.

Horodyski, R.J., 1993, Paleontology of Proterozoic shales and mudstones: examples from the Belt Supergroup, Chuar Group and Pahrump Group, western USA: Precambrian Research, v. 61, no. 3-4, p. 241–278, doi: 10.1016/0301-9268(93)90116-j.

Horodyski, R.J., and Donaldson, J.A., 1980, Microfossils from the Middle Proterozoic Dismal Lakes Groups, Arctic Canada: Precambrian Research, v. 11, no. 2, p. 125–159, doi: 10.1016/0301-9268(80)90043-1.

Kah, L.C., and Riding, R., 2007, Mesoproterozoic carbon dioxide levels inferred from calcified cyanobacteria: Geology, v. 35, no. 9, p. 799–4, doi: 10.1130/G23680A.1.

Kah, L.C., Bartley, J.K., and Teal, D.A., 2012, Chemostratigraphy of the Late Mesoproterozoic Atar Group, Taoudeni Basin, Mauritania: Muted isotopic variability, facies correlation, and global isotopic trends: Precambrian Research, v. 200-203, p. 82–103, doi: 10.1016/j.precamres.2012.01.011.

Kah, L.C., Lyons, T.W., and Chesley, J.T., 2001, Geochemistry of a 1.2 Ga carbonate-evaporite succession, northern Baffin and Bylot Islands: implications for Mesoproterozoic marine evolution: Precambrian Research, v. 111, no. 1-4, p. 203–234, doi: 10.1016/s0301-9268(01)00161-9.

Kinnaird, T.C., Prave, A.R., and Kirkland, C.L., 2007, The late Mesoproterozoic–early Neoproterozoic tectonostratigraphic evolution of NW Scotland: the Torridonian revisited: Journal of the Geological Society, v. 164, no. 3, p. 541–551, doi: 10.1144/0016-76492005-096.

Li, Z.X. et al., 2008, Assembly, configuration, and break-up history of Rodinia: A synthesis: Precambrian Research, v. 160, no. 1-2, p. 179–210, doi: 10.1016/j.precamres.2007.04.021.

Malone, D.H., Stein, C.A., Craddock, J.P., Kley, J., Stein, S., and Malone, J.E., 2016, Maximum depositional age of the Neoproterozoic Jacobsville Sandstone, Michigan: Implications for the evolution of the Midcontinent Rift: Geosphere, v. 12, no. 4, p. 1271–1282, doi: 10.1130/GES01302.1.

Mitchell, R.L., and Sheldon, N.D., 2016, Sedimentary provenance and weathering processes in the 1.1Ga Midcontinental Rift of the Keweenaw Peninsula, Michigan, USA: Precambrian Research, v. 275, p. 225–240, doi: 10.1016/j.precamres.2016.01.017.

Mitchell, R.L., and Sheldon, N.D., 2010, The ~1100Ma Sturgeon Falls paleosol revisited: Implications for Mesoproterozoic weathering environments and atmospheric CO_2 levels: Precambrian Research, v. 183, no. 4, p. 738–748, doi: 10.1016/j.precamres.2010.09.003.

Mitchell, R.L., and Sheldon, N.D., 2009, Weathering and paleosol formation in the 1.1Ga Keweenawan Rift: Precambrian Research, v. 168, no. 3-4, p. 271–283, doi: 10.1016/j.precamres.2008.09.013.

Oleson, K.W. et al., 2010, Technical Description of version 4.0 of the Community Land Model (CLM): NCAR/TN-478+STR, 1–266 p.

Prave, A.R., 2002, Life on land in the Proterozoic: Evidence from the Torridonian rocks of northwest Scotland: Geology, v. 30, no. 9, p. 811, doi: 10.1130/0091-7613(2002)030<0811:lolitp>2.0.co;2.

Rogala, B., Fralick, P.W., Heaman, L.M., and Metsaranta, R., 2007, Lithostratigraphy and chemostratigraphy of the Mesoproterozoic Sibley Group, northwestern Ontario, Canada: Can. J. Earth Sci, v. 44, no. 8, p. 1131–1149, doi: 10.1139/E07-027.

Samuelsson, J., Dawes, P.R., and Vidal, G., 1999, Organic-walled microfossils from the Proterozoic Thule Supergroup, Northwest Greenland: Precambrian Research, v. 96, no. 1–2, p. 1–23.

Schieber, J., 1998, Possible indicators of microbial mat deposits in shales and sandstones: examples from the Mid-Proterozoic Belt Supergroup, Montana, USA: Sedimentary Geology, v. 120, no. 1-4, p. 105–124, doi: 10.1016/s0037-0738(98)00029-3.

Sergeev, V.N., 2001, Paleobiology of the Neoproterozoic (Upper Riphean) Shorikha and Burovaya silicified microbiotas, Turukhansk Uplift, Siberia: Journal of Paleontology, v. 75, no. 02, p. 427–448, doi: 10.1017/s0022336000018229.

Sergeev, V.N., Knoll, A.H., and Petrov, P.Y., 1997, Paleobiology of the Mesoproterozoic-Neoproterozoic transition: the Sukhaya Tunguska Formation, Turukhansk Uplift, Siberia: Precambrian Research, v. 85, no. 3, p. 201–239.

Southgate, P.N., 1986, Depositional environment and mechanism of preservation of microfossils, upper Proterozoic Bitter Springs Formation, Australia: Geology, v. 14, no. 8, p. 683, doi: 10.1130/0091-7613(1986)14<683:deamop>2.0.co;2.

Stewart, A.D., 1997, Discussion on indications of glaciation at the base of the Proterozoic Stoer Group (Torridonian), NW Scotland: Journal of the Geological Society, v. 154, no. 6, p. 1087–1088, doi: 10.1144/gsjgs.154.6.1087.

Stewart, A.D., 1990, Geochemistry, provenance and climate of the Upper Proterozoic Stoer Group in Scotland: Scottish Journal of Geology, v. 26, no. 2, p. 89–97, doi: 10.1144/sjg26020089.

Upfold, R.L., 1984, Tufted microbial (cyanobacterial) mats from the Proterozoic Stoer Group, Scotland: Geological Magazine, v. 121, no. 4, p. 351–355, doi: 10.1017/S0016756800029253.

Vidal, G., and Ford, T.D., 1985, Microbiotas from the late Proterozoic Chuar Group (northern Arizona) and Uinta Mountain Group (Utah) and their chronostratigraphic implications: Precambrian Research, v. 28, no. 3-4, p. 349–389, doi: 10.1016/0301-9268(85)90038-5.

Young, G.M., 1999, Some aspects of the geochemistry, provenance and palaeoclimatology of the Torridonian of NW Scotland: Journal of the Geological Society, v. 156, no. 6, p. 1097–1111, doi: 10.1144/gsjgs.156.6.1097.