ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER
10.1029/2022GL101903

Elizabeth J. Trower and James R. Gutoski contributed equally to this work.

Key Points:

- Guttulatic microfabric is a characteristic fingerprint of ikaite, a mineral that forms only in cold-water depositional environments
- We report guttulatic microfabrics in grains and cements associated with giant ooids in the Tonian Beck Spring Dolomite
- Our findings demonstrate that global climate was cold millions of years before the onset of the Sturtian glaciation

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

E. J. Trower,
lizzy.trower@colorado.edu

Citation:

Trower, E. J., Gutoski, J. R., Wala, V. T., Mackey, T. J., & Simpson, C. (2023). Tonian low-latitude marine ecosystems were cold before Snowball Earth. *Geophysical Research Letters*, *50*, e2022GL101903. https://doi.org/10.1029/2022GL101903

Received 27 OCT 2022
Accepted 11 FEB 2023

Author Contributions:

Conceptualization: Elizabeth J. Trower, Carl Simpson
Data curation: James R. Gutoski
Investigation: Elizabeth J. Trower, James R. Gutoski, Virginia T. Wala, Tyler J. Mackey, Carl Simpson
Methodology: Elizabeth J. Trower, James R. Gutoski, Virginia T. Wala
Project Administration: Elizabeth J. Trower

Tonian Low-Latitude Marine Ecosystems Were Cold Before Snowball Earth

Elizabeth J. Trower[1], James R. Gutoski[1], Virginia T. Wala[2], Tyler J. Mackey[3], and Carl Simpson[1,4]

[1]Department of Geological Sciences, University of Colorado Boulder, Boulder, CO, USA, [2]Utah Department of Natural Resources, Salt Lake City, UT, USA, [3]Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM, USA, [4]Museum of Natural History, University of Colorado Boulder, Boulder, CO, USA

Abstract Precambrian marine carbonate strata are commonly assumed to have formed in warm-water carbonate factories due to the temperature dependence of non-skeletal carbonate precipitation rates. However, some climate models and geological observations suggest that global climate was cool for tens of millions of years prior to the onset of Snowball Earth glaciation at ∼717 Ma, in conflict with common interpretations of pre-glacial carbonates as warm-water carbonate factories. We report the occurrence of guttulatic microfabric—a petrographic fingerprint of ikaite, a carbonate mineral that only forms in cold sedimentary environments—in the Beck Spring Dolomite, a carbonate succession deposited in a low-latitude shallow marine environment between ∼780 and 730 Ma. This interpretation of pre-glacial carbonate factories aligns cold conditions with vase-shaped microfossils, possible algal fossils, and molecular clock dates for crown-group metazoans. Our observations indicate that these marine ecosystems were able to thrive in cold low-latitude environments millions of years before the Snowball glaciations.

Plain Language Summary Between 717 and 635 million years ago, Earth experienced two dramatic global glacial events, known as "Snowball Earth" glaciations, during which ice covered the oceans all the way to the equator. Geoscientists are still seeking to fully understand what caused these extreme climate events and how life on Earth survived them. Although geochemists have a variety of tools to reconstruct the temperature of ancient oceans, these methods are difficult to apply in rocks this old because primary signals have been too altered. Instead, we looked for a key microscopic fingerprint ("guttulatic microfabric") of a type of calcium carbonate mineral ("ikaite") that only forms in cold-water environments. Previous work had proposed that we might expect to find evidence of this cold-water carbonate mineral associated with a specific type of sediment called "giant ooids." We found abundant evidence of guttulatic microfabric in sedimentary rocks containing giant ooids that formed in a low-latitude shallow marine environment millions of years before the onset of global glaciation. Our observations suggest that Earth's climate was cold before the onset of global glaciation, which could mean that marine organisms were accustomed to cold conditions well before the Snowball glaciations.

1. Introduction

Models (Donnadieu et al., 2004; Goddéris et al., 2003; Schrag et al., 2002), geochemical data (Cox et al., 2016; Rooney et al., 2014), and geological evidence (MacLennan et al., 2020) support the hypothesis that global climate was already cool due to enhanced weathering of Laurentian continental flood basalts at low paleo-latitudes prior to the final trigger of the first Neoproterozoic Snowball Earth event (the Sturtian glaciation, lasting from 717 to 660 Ma, Rooney et al., 2015). If correct, this "Fire and Ice" (Goddéris et al., 2003) hypothesis implies that the origin of crown-group metazoans (Erwin et al., 2011) coincided with cold conditions, and that marine ecosystems had millions of years to adapt to cold environments prior to the onset of the Sturtian glaciation. However, many late Tonian successions also include carbonate strata that are commonly interpreted to have formed in warm-water (≥20°C) carbonate factories analogous to the modern Bahamas (Gutstadt, 1968; MacLennan et al., 2020; Tucker, 1992), that do not exist in "Fire and Ice" climate model simulations (Goddéris et al., 2007). Late Tonian climate is difficult to directly constrain due to the challenges of applying stable or clumped isotope paleothermometry to carbonate rocks of this age (Mackey et al., 2020). Evidence of a low-latitude glaciolacustrine succession predating the start of the Sturtian glaciation by ∼33 Myr (MacLennan et al., 2020) only indirectly constrains seawater temperatures because the altitude of the depositional environment is unknown.

Supervision: Elizabeth J. Trower, Carl Simpson
Visualization: Elizabeth J. Trower
Writing – original draft: Elizabeth J. Trower
Writing – review & editing: Elizabeth J. Trower, James R. Gutoski, Tyler J. Mackey, Carl Simpson

An unusual abundance of giant ooids (concentrically coated carbonate grains with diameters >2 mm) in carbonate strata underlying both Sturtian and Marinoan glacial diamictites (Sumner & Grotzinger, 1993; Thorie et al., 2018; Trower, 2020) may provide a new avenue for constraining pre-Snowball climate. Ooids are typically sand-sized grains, but many late Tonian and Cryogenian carbonate strata contain gravel-sized ooids (grain diameters commonly ≥5 mm) (Sumner & Grotzinger, 1993; Thorie et al., 2018; Trower, 2020) that are difficult to explain dynamically. For sand-sized ooids, grain diameter reflects an equilibrium between growth via chemical precipitation and diminution via physical abrasion (Trower et al., 2017, 2018, 2020). Tonian and Cryogenian giant ooids cannot be explained in this framework assuming modern Bahamas-like conditions because aragonite and calcite precipitation rates are far outpaced by abrasion rates for grains this large (Trower, 2020). One hypothesis for occurrence of these gravel-sized giant ooids is that they formed as ikaite (Trower, 2020), a hydrated $CaCO_3$ mineral ($CaCO_3{\bullet}6H_2O$) that only precipitates in cold-water sedimentary environments in fluids with elevated alkalinity (J. L. Bischoff et al., 1993; Boch et al., 2015; Buchardt et al., 1997, 2001; Dieckmann et al., 2008; Field et al., 2017; Ito, 1996; Jansen et al., 1987; Pauly, 1963; Schubert et al., 1997; Suess et al., 1982; Whiticar & Suess, 1998). Theoretically, ikaite giant ooids are plausible due to the low density of ikaite relative to calcite and aragonite and a reduced abrasion rate due to the high viscosity of cold seawater (Trower, 2020). The ikaite giant ooid hypothesis is consistent with the cool pre-Sturtian climate hypothesis, but conflicts with the common assumption that low-latitude carbonate strata imply deposition in warm-water carbonate factories analogous to modern carbonate platforms (Gutstadt, 1968; MacLennan et al., 2020; Tucker, 1992) and that ooids can only form as aragonite or calcite.

Although the precipitation of ikaite has been documented in a variety of modern Earth surface environments (J. L. Bischoff et al., 1993; Boch et al., 2015; Buchardt et al., 1997, 2001; Dieckmann et al., 2008; Field et al., 2017; Ito, 1996; Jansen et al., 1987; Pauly, 1963; Schubert et al., 1997; Suess et al., 1982; Whiticar & Suess, 1998), ikaite is geologically unstable at Earth surface pressure (Marland, 1975; Suess et al., 1982). Where ikaite forms in modern sedimentary environments, it can be observed dehydrating rapidly to more stable phases, particularly when warmed (Huggett et al., 2005; Jansen et al., 1987; Suess et al., 1982). The loss of structural waters associated with ikaite dehydration results in a 68.6% volume reduction (Huggett et al., 2005; Larsen, 1994; Shearman et al., 1989). The diagenetic dehydration and stabilization of ikaite commonly produces a characteristic microfabric termed "guttulatic" defined by ∼10–100 μm pseudo-hexagonal or spherical crystals with zoned hexagonal to elliptical overgrowths, with compositionally and petrographically contrasting cement filling the former pore spaces between crystals (Scheller et al., 2022). The zoned crystals are typically more inclusion-rich than the pore-filling cements (Frank et al., 2008; Huggett et al., 2005; Larsen, 1994; Scheller et al., 2022). Although the term "guttulatic" was coined recently, this microfabric had already been described in numerous cold-water marine and lacustrine carbonate strata ranging from Cryogenian to modern in age (Fairchild et al., 2016; Rogov et al., 2021; Scheller et al., 2022; Selleck et al., 2007), many of which were identified as pseudomorphs after ikaite based on the morphology of large cm-scale crystals. The defining characteristics of guttulatic microfabric are closely linked to the paragenesis of ikaite stabilization. The pseudo-hexagonal to spherical crystals are consistent with initial transformation to vaterite and/or monohydrocalcite, both of which are commonly observed metastable phases in ikaite dehydration (Dahl & Buchardt, 2006; Ito, 1998; Last et al., 2013; Sánchez-Pastor et al., 2016; Shaikh, 1990; Tang et al., 2009). The generation of a porous microfabric followed by nucleation of pseudo-hexagonal to spherical crystals has also been captured by electron microscopy during ikaite transformation (Purgstaller et al., 2017; Sánchez-Pastor et al., 2016; Vickers et al., 2022). Overgrowths commonly contrast compositionally from cores (e.g., in terms of abundance of Mg, Fe, and inclusions), reflecting evolution of pore fluid compositions (Huggett et al., 2005; Scheller et al., 2022; Vickers et al., 2018). Finally, the cement-filled pore spaces between the crystals reflect the significant volume reduction associated with ikaite dehydration (Huggett et al., 2005; Jansen et al., 1987; Scheller et al., 2022; Shearman et al., 1989; Vickers et al., 2022). In summary, a large body of evidence suggests that guttulatic microfabric is a unique petrographic fingerprint of ikaite.

To test the hypothesis that Tonian climate was cool prior to the initiation of the Sturtian Snowball Earth glaciation, we examined petrographic fabrics in a suite of giant-ooid-bearing samples in the Tonian Beck Spring Dolomite (Death Valley area, CA, USA) that stratigraphically underlie Sturtian glacial diamictites (Figure 1). The Beck Spring Dolomite includes abundant microbial boundstone and giant ooid grainstone/packstone (Harwood & Sumner, 2011; Smith et al., 2016) deposited between ∼780 and 730 Ma in a low-latitude setting (0–15°N [Eyster et al., 2020], based on the interpretation that the Chuar and Pahrump Groups formed in adjacent basins during the Tonian [Dehler et al., 2017]). The overlying Kingston Peak Formation includes glacial diamictites interpreted to

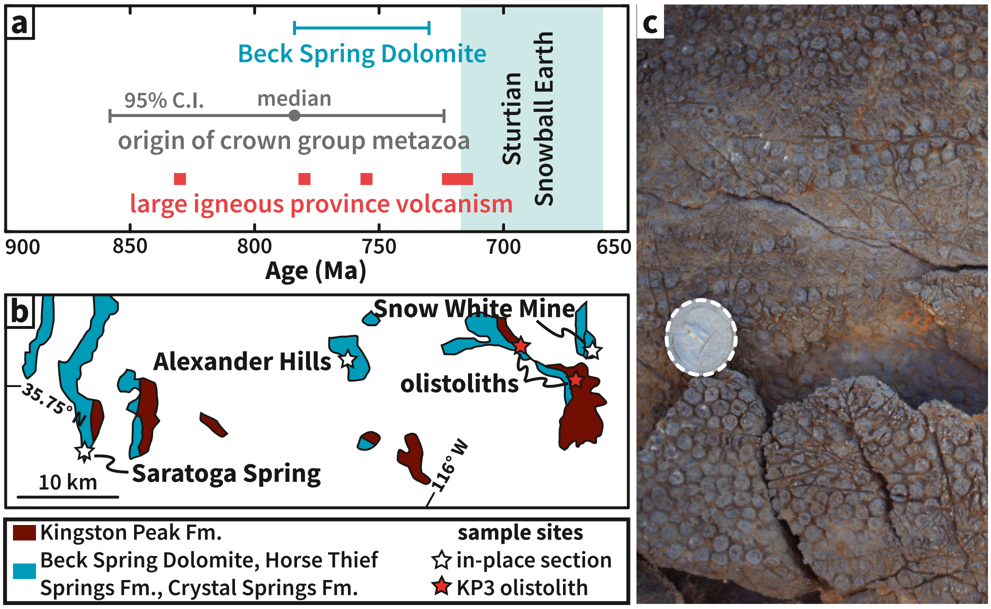

Figure 1. Overview of geological context of Beck Spring Dolomite. (a) Timeline of Beck Spring depositional age constraints (Smith et al., 2016), origin of crown group metazoa (including 95% confidence interval, C.I.) (Erwin et al., 2011), large igneous province volcanism thought to have driven Tonian cooling (Cox et al., 2016), and duration of Sturtian Snowball Earth (Rooney et al., 2015). (b) Simplified geologic map of Pahrump Group strata in the southern Death Valley area with sample sites. (c) Outcrop image of giant ooid facies from Saratoga Spring section (USA quarter, diameter 24.26 mm, for scale).

correlate with the Sturtian and Marinoan glaciations (Le Heron et al., 2014; Macdonald et al., 2013), although the up to 200-m-thick basal Kingston Peak unit, KP1, is comprised of siltstone and fine sandstone interpreted as non-glacial. The Beck Spring Dolomite has been interpreted by analogy as a Bahamas-like carbonate depositional environment (Gutstadt, 1968). Here, we document the occurrence of guttulatic fabrics within a suite of giant ooid grainstones and packstones from the Beck Spring Dolomite. Our observations provide the first direct evidence cold conditions at sea level in a low-latitude marine environment prior to the onset of the first Neoproterozoic Snowball glaciation.

2. Materials and Methods

We collected and analyzed a suite of giant ooid packstones and grainstones from five stratigraphic sections, including three in-place sections (Saratoga Spring, Alexander Hills, and Snow White Mine) and two large tabular blocks of Beck Spring Dolomite giant-ooid- and oncoid-bearing (oncoids are large coated grains that, unlike giant ooids, have crinkly irregular laminae interpreted as having formed due to microbial activity) grainstone beds that were eroded and redeposited as olistoliths entrained within the Kingston Peak diamictite (unit KP3) (Macdonald et al., 2013) (Figure 1). We compared the microfabrics and compositional characteristics of our Beck Spring Dolomite samples with analogous observations from a younger, better-preserved suite of ikaite pseudomorphs from the Oligocene Creede Formation. Creede Formation ikaites are characterized by macroscopic (cm-scale) bladed pseudomorphic crystals (Figure S1 in Supporting Information S1) and guttulatic microfabric (Larsen, 1994; Scheller et al., 2022) that formed in a high elevation, alkaline caldera lake in a cool climate (Gregory & Chase, 1992; Larsen, 1994; Wolfe & Schorn, 1989).

In-place Beck Spring Dolomite sections and Beck Spring olistoliths in the Kingston Peak Formation were sampled in November 2019, with a specific focus on facies with giant ooids and oncoids. For in-place sections, we focused on locating and sampling giant-ooid-bearing layers identified in detailed stratigraphic sections from previous work in Saratoga Spring (Smith et al., 2016), Alexander Hills (Harwood & Sumner, 2011; Smith et al., 2016), and Snow White Mine (Harwood & Sumner, 2011). As these sections document, giant ooids primarily occur in the uppermost Beck Spring Dolomite in the Saratoga Spring locality, while they are concentrated in the Middle Thrombolitic Member of the Beck Spring Dolomite in the Alexander Hills and Snow White Mine localities. The

10.1029/2022GL101903

Saratoga Spring locality is within Death Valley National Park and sampling in this site was performed under research permit DEVA-2019-SCI-0036. Olistolith sampling localities in Kingston Peak Formation unit KP3 focused on previously documented sites characterized by rounded boulders and tabular beds of giant ooid and oncoid grainstone/packstones in which microfossils have been documented (Corsetti et al., 2003). We collected 21 samples of facies characterized by giant ooids and/or oncoids and had polished thin sections prepared of 13 of these samples (Spectrum Petrographics, Vancouver, WA). Beck Spring Dolomite sample information is listed in Table S1 in Supporting Information S1.

We collected samples from the Airport Hill Creede Formation section (Larsen & Lipman, 2016) (N 37.82917°, W 106.9183°) (the site where the CCM-2 core was drilled) and Farmers Creek Trailhead section (Larsen & Lipman, 2016) (N 37.828°, W 106.889°) in June 2022. We also examined the Creede Formation in core CCM-2 at the USGS Core Research Facility in Denver, CO in June 2022, and collected two plugs from the core for thin section preparation. Thin sections were prepared of four representative Creede samples (Grindstone Laboratory, Portland, OR).

Thin sections were examined in plane- and cross-polarized transmitted light with a Zeiss Axio Imager M2 with 6 MP 33 fps Axiocam 506 color camera. Cathodoluminescence (CL) microscopy was performed with a Technosyn Luminoscope (cold-cathodoluminescence) operated at 14–16 kV, 400–500 μA, and 50 mTorr pressure with an Optronics Magnafire digital camera with a Peltier-cooled image sensor. Raman microspectroscopy maps were collected using a Horiba LabRAM HR Evolution Spectrometer with a 532 nm excitation laser at the CU Boulder Raman Microspectroscopy Lab to determine carbonate mineralogy. Elemental maps characterizing the distributions of Si, Ca, Mg, Mn, and Fe were collected on selected carbon-coated thin sections using a JEOL 8230 Superprobe at the CU Boulder Electron Microprobe (EMP) lab. Qualitative intensity maps without background corrections via wavelength dispersive X-ray spectrometry (WDS) were collected at 15 kV accelerating voltage, 18 nA beam current, and 18 ms dwell time.

3. Results

Transmitted light microscopy revealed the common occurrence of guttulatic microfabrics in intergranular pore spaces, along the edges of ooids, and within the cortices of oncoids in Beck Spring Dolomite samples (Figures 2a–2e). These fabrics are defined by ∼10–100 μm pseudohexagonal to rounded cores with zoned, rounded overgrowths and are remarkably similar in texture and scale to guttulatic fabrics from Creede Formation samples (Figures 2j and 2k), although the Creede Formation samples also include larger guttulatic crystals up to ∼500 μm in length. Zoned pseudohexagonal crystals from both formations occupy 24.6–31.2% of areas characterized by guttulatic microfabrics (Table S2 in Supporting Information S1), consistent with the 31.4% limit expected as a result of volume reduction Larsen (1994). We also observed alteration fabrics within Beck Spring Dolomite ooid cortices characterized by 50–200 μm circular to elliptical zones (Figures 2f and 2g) or irregular patches (Figures 2h and 2i) where finely-laminated cortical fabric has been replaced by sparry carbonate or silica cement. We interpret that these fabrics reflect cement-filled intraparticle porosity created as volume was lost during ikaite dehydration. Volume loss fabrics are also common in Creede Formation samples (Figure 2l).

Beck Spring Dolomite guttulatic fabrics are dominantly characterized by dull cathodoluminescence (Figures 3a–3d), with overgrowths punctuated by thin horizons characterized by yellow to red luminescence, indicating incorporation of Mn^{2+} and Fe^{2+}, respectively. Creede Formation guttulatic fabrics have similar cathodoluminescence characteristics (Figures 3e–3h); in these samples, presence of Mn^{2+} in some overgrowth layers is also indicated by higher fluorescence in Raman microspectroscopy (Figure 4h), which can be caused by the presence of trace transition metals (W. D. Bischoff et al., 1985). In both cases, variable incorporation of Mn^{2+} likely reflects shifts between relatively O_2-rich (dull luminescence, no Mn^{2+}) to more O_2-poor (yellow to red luminescence, incorporation of Mn^{2+} and then Fe^{2+}) conditions in pore waters during the formation of overgrowths (Hiatt & Pufahl, 2014), and parallels observations from a variety of other ikaite pseudomorphs (Huggett et al., 2005; Teichert & Luppold, 2013; Vickers et al., 2018).

Although Beck Spring Dolomite samples are now composed primarily of dolomite, Raman microspectroscopy and wavelength-dispersive X-ray spectroscopy reveal variable but lower Mg content in zoned overgrowths and patchy calcitic cements (Figures 4a–4d and Figures S2–S4 in Supporting Information S1), indicative of evolving pore water Mg/Ca during overgrowth formation. The preservation of delicate compositional zonation within

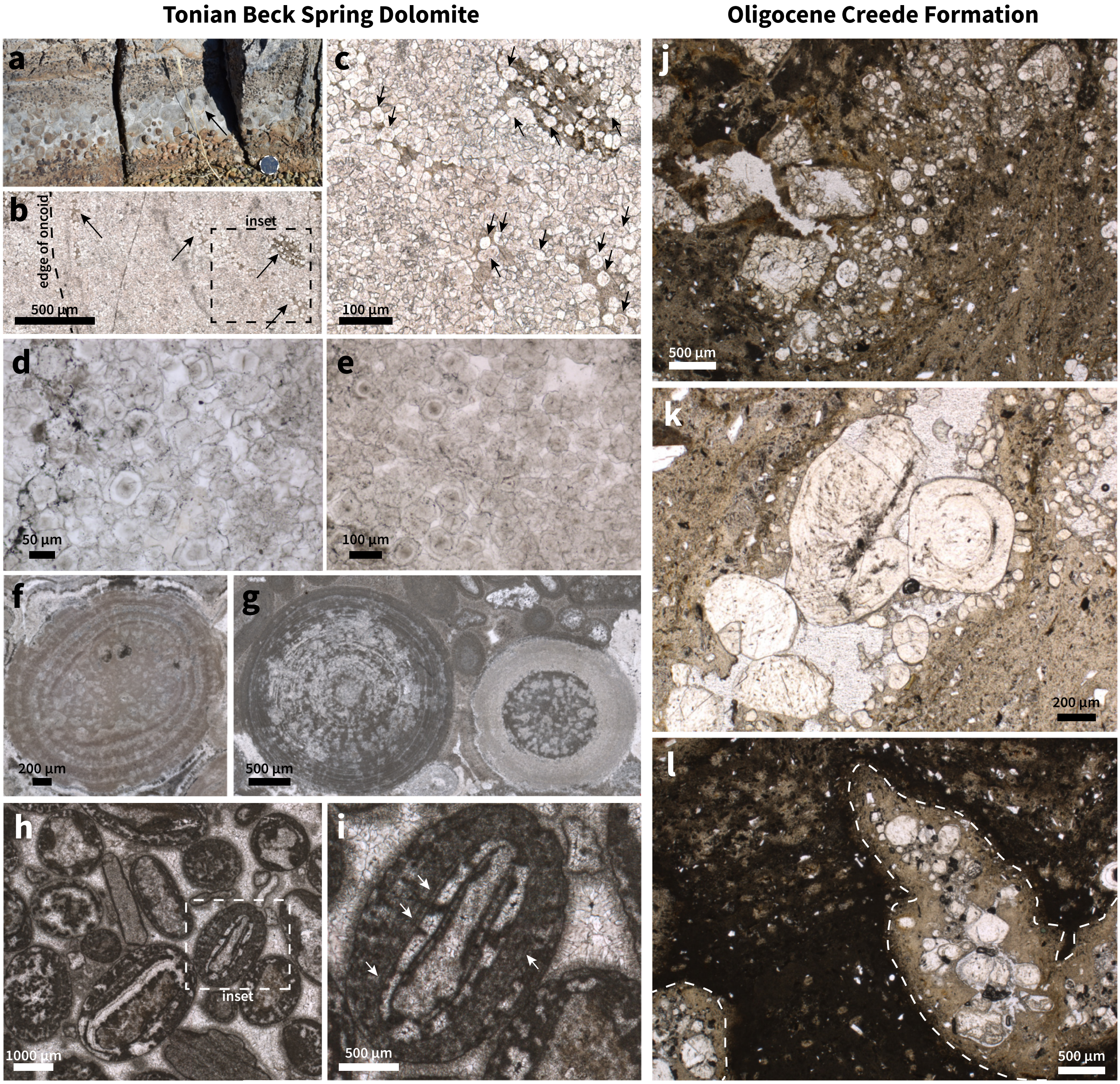

Figure 2. Transmitted light microscopy images of guttulatic microfabrics and other ooid cortical alteration fabrics in the Beck Spring Dolomite (a–i) and the Creede Formation (j–l). (a) Field photo of oncoid bed (arrow) in KP3 olistolith (USA quarter for scale). (b) Oncoid from bed shown in panel A with guttulatic microfabrics (arrows). (c) Magnified inset of panel B, abundant individual pseudohexagonal to rounded zoned crystals (some highlighted with arrows) within oncoid cortex. (d and e) Representative examples of guttulatic microfabrics characterized by pseudohexagonal to rounded crystals with zoned overgrowths, with spaces between crystals filled by sparry cement. (f–g) Circular to patchy alteration zones within giant ooid cortices. (h) Patchy replacement of finely laminated cortical fabrics (dark zones) by sparry cements (light zones). (i) Magnified inset of panel H, arrows highlight areas where laminated cortical fabric is preserved. (j and k) Representative images of Creede Formation guttulatic fabrics, characterized by some very large (~500 µm) guttulatic crystals and clusters of smaller (50–100 µm) rounded guttulatic crystals that are similar, with pore spaces between crystals filled with either dark micritic cement or clean, transparent sparry cement, similar to characteristics of panels (c–e). (l) Example of volume reduction fabric, in which guttulatic crystals fill only a fraction of the original ikaite crystal area (white dashed line).

guttulatic fabrics in Beck Spring samples suggests that dolomite, rather than calcite, pseudomorphically replaced vaterite and/or monohydrocalcite crystals during early diagenesis, consistent with other evidence of early dolomitization in the Beck Spring Dolomite (Shuster et al., 2018; Tucker, 1983). Creede Formation ikaite pseudomorphs are currently composed of calcite, but are also characterized by subtle variations in Mg content in the zoned overgrowths (Figures 4e–4i) reflecting variable pore water Mg/Ca. Contrasts in Mg content between

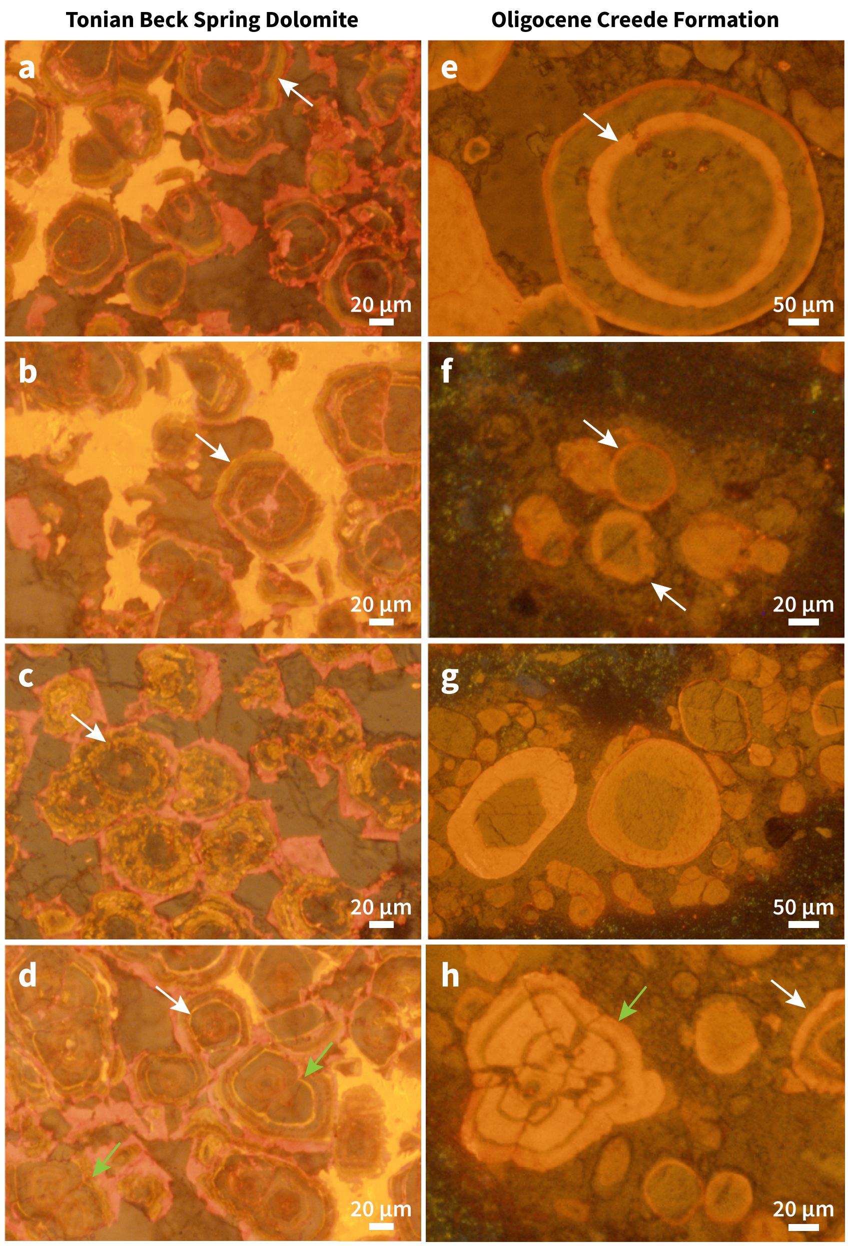

Figure 3. Cathodoluminescence microscopy images of guttulatic microfabrics in the Beck Spring Dolomite (a–d) and the Creede Formation (e–h). Crystals from both formations are typically characterized by dull luminescence in cores, with transitions to yellow luminescence in overgrowths (white arrows), indicating shifts in pore water redox state during early diagenesis resulting in enhanced incorporation of Mn^{2+}, and dull luminescence in surrounding cements. Beck Spring Dolomite samples also have a later, bright yellow cement that cross-cuts guttulatic crystals. Both sets of samples also include subpopulations of more complex crystals in which multiple pseudo-hexagonal crystals have grown into each other (green arrows).

guttulatic crystal cores and overgrowths are common among other well-characterized examples of ikaite pseudomorphs (Huggett et al., 2005; Scheller et al., 2022; Teichert & Luppold, 2013).

4. Discussion

Guttulatic microfabrics in Beck Spring Dolomite samples are similar in shape, size, and characteristic compositional variation to fabrics characterizing altered ikaites in the Oligocene Creede Formation and other examples from the literature (Scheller et al., 2022). We therefore interpret that Beck Spring Dolomite sediments were

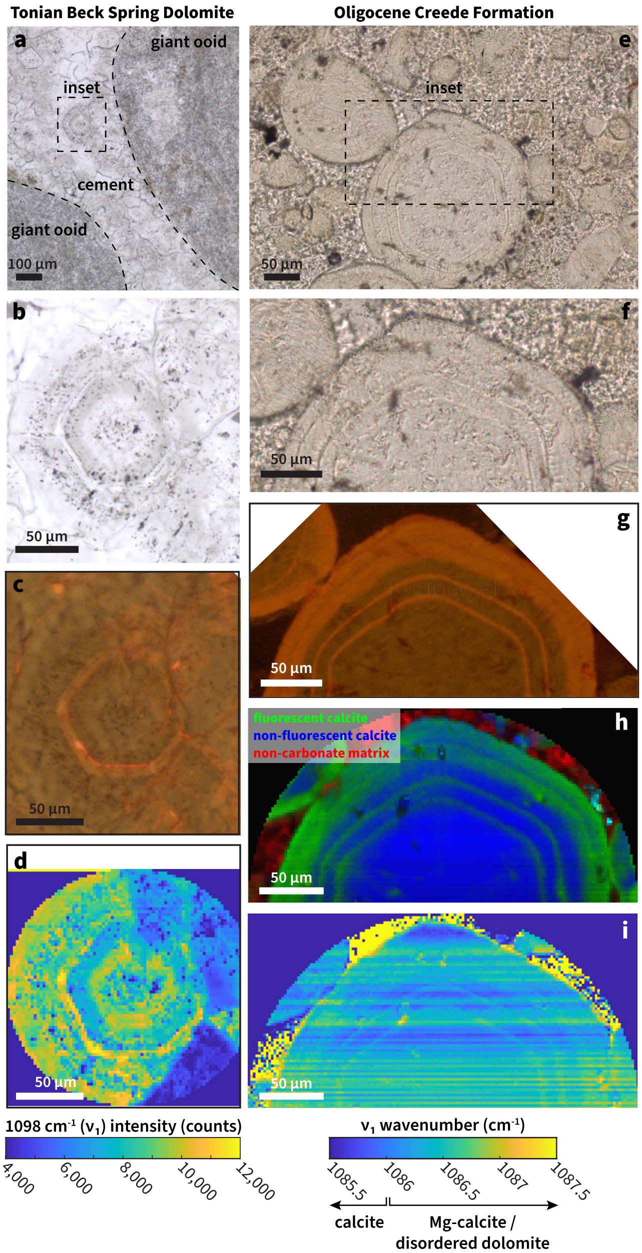

Figure 4. Comparisons of delicate compositional zonation preserved in guttulatic crystals in the Beck Spring Dolomite (a–d) and the Creede Formation (e–i). (a) Zoned pseudohexagonal guttulatic crystal in cement between giant ooid grains. (b–d) Magnified insets of panel (a) in transmitted light (b), cathodoluminescence (c), and Raman microspectroscopy (d). Panel (d) illustrates variations in intensity of the dolomite ν_1 peak that likely reflect differences in crystal orientation. (e) Zoned pseudohexagonal guttulatic crystal in the Creede Formation. (f–i) Magnified insets of panel (e) in transmitted light (f), cathodoluminescence (g), and Raman microspectroscopy (h–i). Panel h illustrates alternation of non-fluorescent (blue) and fluorescent (green) calcite in overgrowth that corresponds to the alternation of dull luminescence and yellow luminescence in panel (g). Panel (i) illustrates subtle variation in calcite ν_1 peak position reflecting variations in Mg content; these variations also correspond to zonation luminescence in panel (g). Horizontal features in panel (i) are artifacts of thermal instabilities in lab temperature during the analysis.

originally composed of ikaite. The occurrence of these microfabrics in both in-place sections and olistoliths require that ikaite precipitation occurred during Beck Spring time, rather than when Beck Spring blocks were reworked into Kingston Peak diamictites. The maximum temperature of ikaite precipitation observed in natural environments is 9°C (Field et al., 2017), providing an upper limit on the Beck Spring depositional temperature. Ikaite has formed at warmer temperatures in lab experiments, but only in conditions with exceptionally high alkalinities (pH > 9.3, alkalinity > 50 meq/kg [Stockmann et al., 2018; Tollefsen et al., 2020]) that are implausible for ancient seawater. Although recent petrographic analyses, modeling, and experiments have suggested that late Tonian seawater may have been much more alkaline than modern seawater (Roest-Ellis et al., 2021; Strauss & Tosca, 2020), the alkalinities required for ikaite nucleation at warm temperatures are still significantly more extreme than even these estimates. Furthermore, ikaite formed at warmer temperatures in experiments is rapidly replaced by calcite in <5 hr (Tollefsen et al., 2020), consistent with field observations of instability of ikaite in highly alkaline environments like Mono Lake at warmer temperatures (Council & Bennett, 1993; Shearman et al., 1989). It therefore seems unlikely that ikaite ooids of any size can form at warmer temperatures since not even highly alkaline, high phosphate waters can stabilize ikaite for the durations required for ooid growth (>1,000 years).

Our observations provide direct evidence that low-latitude shallow subtidal marine environments were cold millions of years prior to the onset of the Sturtian Snowball glaciation.

Guttulatic microfabrics in Beck Spring Dolomite giant ooid and oncoid grainstones support the hypothesis that some giant ooids could form as ikaite in a cold climate (Trower, 2020). However, our finding does not imply that all giant ooids (including, most notably, Cryogenian giant ooids that closely underlie Marinoan diamictites) formed in cold environments. Recent work on early Triassic giant ooids supported Trower's (2020) alternative hypothesis that giant ooids can also form in hot aragonite seas (Li et al., 2021). Cryogenian interglacial climate swung rapidly from a post-glacial greenhouse (Yang et al., 2017) into the Marinoan Snowball (Rooney et al., 2015), so either hot or cold climate could be viable explanations for Cryogenian giant ooid occurrences. More detailed petrographic characterization of Cryogenian giant ooids could therefore provide novel insight into how that <25 Myr period (Rooney et al., 2015) was split between hot and cold climates. As all ooids require wave action to form, if Tonian and/or Cryogenian giant ooids were composed of ikaite, they would represent a depositional environment that was cold but ice-free, albeit requiring less wave energy than aragonite ooids of similar size due to differences in mineral density and seawater viscosity (Figure S5 in Supporting Information S1). Furthermore, ikaite precipitation need not be restricted to ooids; the discovery of ikaite in deeper water or lower energy carbonate facies could also be used to constrain Tonian and Cryogenian climate.

The ~9°C maximum temperature constraint for the Beck Spring depositional environment is even colder than predicted for pre-Sturtian equatorial environments by climate models (Donnadieu et al., 2004). This supports the idea that global climate was in a cold state millions of years prior to the initiation of the Sturtian Snowball Earth. The formation of ikaite also constrains Tonian seawater chemistry because it requires elevated alkalinity (~6–10 meq/kg) (Trower, 2020) and, perhaps, high phosphate concentrations (J. L. Bischoff et al., 1993; Stockmann et al., 2018). Together, these paleoenvironmental conditions implied by the occurrence of ikaite are consistent with the hypothesis that enhanced weathering of Laurentian continental flood basalts drew down atmospheric CO_2, cooled Earth's climate, and delivered large fluxes of alkalinity and phosphate to the oceans long before the onset of Sturtian diamictite deposition (Figure 1a) (Cox et al., 2016; Donnadieu et al., 2004; Goddéris et al., 2003; Reinhard et al., 2017; Strauss & Tosca, 2020). However, given the uncertainty in age and depositional rate of the Beck Spring Dolomite, our observations cannot necessarily distinguish between long-term cooling as envisioned by some previous studies (Donnadieu et al., 2004; Goddéris et al., 2003; MacLennan et al., 2020) versus a shorter-term cooling event.

Our observations provide paleoclimate context for the vase-shaped microfossils and possible algal micro/macrofossils in Beck Spring Dolomite (Corsetti et al., 2003; Gutstadt & Schopf, 1969; Licari, 1978) and contemporaneous strata (Morais et al., 2017; Porter et al., 2003; Riedman et al., 2018; Strauss et al., 2014), which suggests that they were members of an ecosystem that was already accustomed to cold environments. In modern oceans, total biomass tends to be highest in coastal waters (Hatton et al., 2021; Jones et al., 2014; Laws et al., 2000) and this is also likely be true in the Precambrian (LaBarbera, 1978). The shift of shallow low-latitude coastal environments from warm to cold with high viscosity during the late Tonian may have led to a diverse set of adaptive strategies including complex multicellularity (Simpson, 2021) and terrestrialization in algal lineages (Žárský et al., 2022). Rocks of a similar age and formed within similar depositional conditions to the Beck Spring Dolomite may therefore be important to understanding the lifestyles of the earliest complex multicellular life, including crown group metazoans (Erwin et al., 2011) and green algae (Del Cortona et al., 2020), prior to the initiation of Sturtian Snowball Earth.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

All data, including light and CL microscopy images, Raman microspectroscopy and electron microprobe WDS maps, and field photos are archived at: https://doi.org/10.17605/OSF.IO/DC3U8. Physical samples are registered with IGSNs in the SESAR database (Table S1 in Supporting Information S1).

Acknowledgments

The authors thank Sarah Jamison-Todd, Boswell Wing, Stephanie Plaza-Torres, and KeMia Smith for assistance with fieldwork; David Budd for feedback on petrography; Eric Ellison for assistance with Raman microspectroscopy; Aaron Bell for assistance with electron microprobe analyses; Kathryn Snell for assistance with cathodoluminescence petrography; the USGS Core Research Center for access to the CCM-2 core; James Hagadorn and Peter Brannen for helpful discussions; and Paul Hoffman and Akshay Mehra for constructive reviews. Publication of this article was funded in part by the University of Colorado Boulder Libraries Open Access Fund.

References

Bischoff, J. L., Fitzpatrick, J. A., & Rosenbauer, R. J. (1993). The solubility and stabilization of ikaite ($CaCO_3$-$6H_20$) from 0° to 25°C: Environmental and paleoclimatic: Implications for thinolite tufa. *The Journal of Geology*, *101*(1), 21–33. https://doi.org/10.1086/648194

Bischoff, W. D., Sharma, S. K., & MacKenzie, F. T. (1985). Carbonate ion disorder in synthetic and biogenic magnesian calcites: A Raman spectral study. *The American Mineralogist*, *70*(5–6), 581–589.

Boch, R., Dietzel, M., Reichl, P., Leis, A., Baldermann, A., Mittermayr, F., & Pölt, P. (2015). Rapid ikaite ($CaCO_3 \cdot 6H_2O$) crystallization in a man-made river bed: Hydrogeochemical monitoring of a rarely documented mineral formation. *Applied Geochemistry: Journal of the International Association of Geochemistry and Cosmochemistry*, *63*, 366–379. https://doi.org/10.1016/j.apgeochem.2015.10.003

Buchardt, B., Israelson, C., Seaman, P., & Stockmann, G. (2001). Ikaite tufa towers in Ikka Fjord, southwest Greenland: Their formation by mixing of seawater and alkaline spring water. *Journal of Sedimentary Research*, *71*(1), 176–189. https://doi.org/10.1306/042800710176

Buchardt, B., Seaman, P., Stockmann, G., Vous, M., Wilken, U., Düwel, L., et al. (1997). Submarine columns of ikaite tufa. *Nature*, *390*(6656), 129–130. https://doi.org/10.1038/36474

Corsetti, F. A., Awramik, S. M., & Pierce, D. (2003). A complex microbiota from snowball Earth times: Microfossils from the Neoproterozoic Kingston Peak Formation, Death Valley, USA. *Proceedings of the National Academy of Sciences of the United States of America*, *100*(8), 4399–4404. https://doi.org/10.1073/pnas.0730560100

Council, T. C., & Bennett, P. C. (1993). Geochemistry of ikaite formation at Mono Lake, California: Implications for the origin of tufa mounds. *Geology*, *21*(11), 971–974. https://doi.org/10.1130/0091-7613(1993)021<0971:goifam>2.3.co;2

Cox, G. M., Halverson, G. P., Stevenson, R. K., Vokaty, M., Poirier, A., Kunzmann, M., et al. (2016). Continental flood basalt weathering as a trigger for Neoproterozoic Snowball Earth. *Earth and Planetary Science Letters*, *446*, 89–99. https://doi.org/10.1016/j.epsl.2016.04.016

Dahl, K., & Buchardt, B. (2006). Monohydrocalcite in the arctic Ikka Fjord, SW Greenland: First reported marine occurrence. *Journal of Sedimentary Research*, *76*(3), 460–471. https://doi.org/10.2110/jsr.2006.035

Dehler, C. M., Gehrels, G., Porter, S., Heizler, M., Karlstrom, K., Cox, G., et al. (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*, *129*(5–6), 607–624. https://doi.org/10.1130/b31532.1

Del Cortona, A., Jackson, C. J., Bucchini, F., Van Bel, M., D'hondt, S., Škaloud, P., et al. (2020). Neoproterozoic origin and multiple transitions to macroscopic growth in green seaweeds. *Proceedings of the National Academy of Sciences*, *117*(5), 2551–2559. https://doi.org/10.1073/pnas.1910060117

Dieckmann, G. S., Nehrke, G., Papadimitriou, S., Göttlicher, J., Steininger, R., Kennedy, H., et al. (2008). Calcium carbonate as ikaite crystals in Antarctic sea ice. *Geophysical Research Letters*, *35*(8), 129. https://doi.org/10.1029/2008gl033540

Donnadieu, Y., Goddéris, Y., Ramstein, G., Nédélec, A., & Meert, J. (2004). A "snowball Earth" climate triggered by continental break-up through changes in runoff. *Nature*, *428*(6980), 303–306. https://doi.org/10.1038/nature02408

Erwin, D. H., Laflamme, M., Tweedt, S. M., Sperling, E. A., Pisani, D., & Peterson, K. J. (2011). The Cambrian conundrum: Early divergence and later ecological success in the early history of animals. *Science*, *334*(6059), 1091–1097. https://doi.org/10.1126/science.1206375

Eyster, A., Weiss, B. P., Karlstrom, K., & Macdonald, F. A. (2020). Paleomagnetism of the Chuar Group and evaluation of the late Tonian Laurentian apparent polar wander path with implications for the makeup and breakup of Rodinia. *GSA Bulletin*, *132*(3–4), 710–738. https://doi.org/10.1130/b32012.1

Fairchild, I. J., Fleming, E. J., Bao, H., Benn, D. I., Boomer, I., Dublyansky, Y. V., et al. (2016). Continental carbonate facies of a Neoproterozoic panglaciation, north-east Svalbard. *Sedimentology*, *63*(2), 443–497. https://doi.org/10.1111/sed.12252

Field, L. P., Milodowski, A. E., Shaw, R. P., Stevens, L. A., Hall, M. R., Kilpatrick, A., et al. (2017). Unusual morphologies and the occurrence of pseudomorphs after ikaite ($CaCO_3 \cdot 6H_2O$) in fast growing, hyperalkaline speleothems. *Mineralogical Magazine*, *81*(3), 565–589. https://doi.org/10.1180/minmag.2016.080.111

Frank, T. D., Thomas, S. G., & Fielding, C. R. (2008). On using carbon and oxygen isotope data from glendonites as paleoenvironmental proxies: A case study from the Permian system of eastern Australia. *Journal of Sedimentary Research*, *78*(11), 713–723. https://doi.org/10.2110/jsr.2008.081

Goddéris, Y., Donnadieu, Y., Dessert, C., Dupré, B., Fluteau, F., François, L. M., et al. (2007). Coupled modeling of global carbon cycle and climate in the neoproterozoic: Links between Rodinia breakup and major glaciations. *Comptes Rendus Geoscience*, *339*(3), 212–222. https://doi.org/10.1016/j.crte.2005.12.002

Goddéris, Y., Donnadieu, Y., Nédélec, A., Dupré, B., Dessert, C., Grard, A., et al. (2003). The Sturtian "snowball" glaciation: Fire and ice. *Earth and Planetary Science Letters*, *211*(1), 1–12. https://doi.org/10.1016/s0012-821x(03)00197-3

Gregory, K. M., & Chase, C. G. (1992). Tectonic significance of paleobotanically estimated climate and altitude of the late Eocene erosion surface, Colorado. *Geology*, *20*(7), 581–585. https://doi.org/10.1130/0091-7613(1992)020<0581:tsopec>2.3.co;2

Gutstadt, A. M. (1968). Petrology and depositional environments of the Beck Spring Dolomite (Precambrian), Kingston Range, California. *Journal of Sedimentary Petrology*, *38*(4), 1280–1289.

Gutstadt, A. M., & Schopf, J. W. (1969). Possible algal microfossils from the late Pre-Cambrian of California. *Nature*, *223*(5202), 165–167. https://doi.org/10.1038/223165b0

Harwood, C. L., & Sumner, D. Y. (2011). Microbialites of the neoproterozoic Beck Spring Dolomite, Southern California: Beck Spring microbialites. *Sedimentology*, *58*(6), 1648–1673. https://doi.org/10.1111/j.1365-3091.2011.01228.x

Hatton, I. A., Heneghan, R. F., Bar-On, Y. M., & Galbraith, E. D. (2021). The global ocean size spectrum from bacteria to whales. *Science Advances*, *7*(46), eabh3732. https://doi.org/10.1126/sciadv.abh3732

Hiatt, E. E., & Pufahl, P. K. (2014). Cathodoluminescence petrography of carbonate rocks: A review of applications for understanding diagenesis, reservoir quality, and pore system evolution. In I. M. Coulson (Ed.), *Cathodoluminescence and its application to geoscience* (Vol. 45, pp. 75–96). Mineralogical Association of Canada.

Huggett, J. M., Schultz, B. P., Shearman, D. J., & Smith, A. J. (2005). The petrology of ikaite pseudomorphs and their diagenesis. *Proceedings of the Geologists' Association*, *116*(3), 207–220. https://doi.org/10.1016/s0016-7878(05)80042-2

Ito, T. (1996). Ikaite from cold spring water at Shiowakka, Hokkaido, Japan. *Journal of Mineralogy, Petrology and Economic Geology*, *91*(6), 209–219. https://doi.org/10.2465/ganko.91.209

Ito, T. (1998). Factors controlling the transformation of natural ikaite from Shiowakka, Japan. *Geochemical Journa*l, *32*(4), 267–273. https://doi.org/10.2343/geochemj.32.267

Jansen, J. H. F., Woensdregt, C. F., Kooistra, M. J., & van der Gaast, S. J. (1987). Ikaite pseudomorphs in the Zaire deep-sea fan: An intermediate between calcite and porous calcite. *Geology*, *15*(3), 245–248. https://doi.org/10.1130/0091-7613(1987)15<245:ipitzd>2.0.co;2

Jones, D. O. B., Yool, A., Wei, C.-L., Henson, S. A., Ruhl, H. A., Watson, R. A., & Gehlen, M. (2014). Global reductions in seafloor biomass in response to climate change. *Global Change Biology*, *20*(6), 1861–1872. https://doi.org/10.1111/gcb.12480

LaBarbera, M. (1978). Precambrian geological history and the origin of the Metazoa. *Nature*, *273*(5657), 22–25. https://doi.org/10.1038/273022a0

Larsen, D. (1994). Origin and paleoenvironmental significance of calcite pseudomorphs after ikaite in the Oligocene Creede Formation, Colorado. *Journal of Sedimentary Research*, *64*(3a), 593–603.

Larsen, D., & Lipman, P. (2016). Exploring the ancient volcanic and lacustrine environments of the Oligocene Creede caldera and environs, San Juan Mountains, Colorado. In S. M. Keller & M. L. Morgan (Eds.), *Unfolding the geology of the West: Geological Society of America field guide* (pp. 1–40). Geological Society of America.

Last, F. M., Last, W. M., Fayek, M., & Halden, N. M. (2013). Occurrence and significance of a cold-water carbonate pseudomorph in microbialites from a saline lake. *Journal of Paleolimnology*, *50*(4), 505–517. https://doi.org/10.1007/s10933-013-9742-6

Laws, E. A., Falkowski, P. G., Smith, W. O., Jr., Ducklow, H., & McCarthy, J. J. (2000). Temperature effects on export production in the open ocean. *Global Biogeochemical Cycles*, *14*(4), 1231–1246. https://doi.org/10.1029/1999gb001229

Le Heron, D. P., Busfield, M. E., & Prave, A. R. (2014). Neoproterozoic ice sheets and olistoliths: Multiple glacial cycles in the Kingston Peak Formation, California. *Journal of the Geological Society*, *171*(4), 525–538. https://doi.org/10.1144/jgs2013-130

Li, X., Trower, E. J., Lehrmann, D. J., Minzoni, M., Kelley, B. M., Schaal, E. K., et al. (2021). Implications of giant ooids for the carbonate chemistry of Early Triassic seawater. *Geology*, *49*(2), 156–161. https://doi.org/10.1130/g47655.1

Licari, G. R. (1978). Biogeology of the late pre-phanerozoic Beck Spring Dolomite of eastern California. *Journal of Paleontology*, *52*(4), 767–792.

Macdonald, F. A., Prave, A. R., Petterson, R., Smith, E. F., Pruss, S. B., Oates, K., et al. (2013). The Laurentian record of Neoproterozoic glaciation, tectonism, and eukaryotic evolution in Death Valley, California. *GSA Bulletin*, *125*(7–8), 1203–1223. https://doi.org/10.1130/b30789.1

Mackey, T. J., Jost, A. B., Creveling, J. R., & Bergmann, K. D. (2020). A decrease to low carbonate clumped isotope temperatures in cryogenian strata. *AGU Advances*, *1*(3). https://doi.org/10.1029/2019av000159

MacLennan, S. A., Eddy, M. P., Merschat, A. J., Mehra, A. K., Crockford, P. W., Maloof, A. C., et al. (2020). Geologic evidence for an icehouse Earth before the Sturtian global glaciation. *Science Advances*, *6*(24), eaay6647. https://doi.org/10.1126/sciadv.aay6647

Marland, G. (1975). The stability of $CaCO_3 \cdot 6H_2O$ (ikaite). *Geochimica et Cosmochimica Acta*, *39*(1), 83–91. https://doi.org/10.1016/0016-7037(75)90186-6

Morais, L., Fairchild, T. R., Lahr, D. J. G., Rudnitzki, I. D., William Schopf, J., Garcia, A. K., et al. (2017). Carbonaceous and siliceous Neoproterozoic vase-shaped microfossils (Urucum Formation, Brazil) and the question of early protistan biomineralization. *Journal of Paleontology*, *91*(3), 393–406. https://doi.org/10.1017/jpa.2017.16

Pauly, H. (1963). "Ikaite", a new mineral from Greenland. *Arctic*, *16*(4), 263–264. https://doi.org/10.14430/arctic3545

Porter, S. M., Meisterfeld, R., & Knoll, A. H. (2003). Vase-shaped microfossils from the Neoproterozoic Chuar Group, Grand Canyon: A classification guided by modern testate amoebae. *Journal of Paleontology*, *77*(3), 409–429. https://doi.org/10.1666/0022-3360(2003)077<0409:vmftnc>2.0.co;2

Purgstaller, B., Dietzel, M., Baldermann, A., & Mavromatis, V. (2017). Control of temperature and aqueous Mg^{2+}/Ca^{2+} ratio on the (trans-) formation of ikaite. *Geochimica et Cosmochimica Acta*, *217*, 128–143. https://doi.org/10.1016/j.gca.2017.08.016

Reinhard, C. T., Planavsky, N. J., Gill, B. C., Ozaki, K., Robbins, L. J., Lyons, T. W., et al. (2017). Evolution of the global phosphorus cycle. *Nature*, *541*(7637), 386–389. https://doi.org/10.1038/nature20772

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

Roest-Ellis, S., Strauss, J. V., & Tosca, N. J. (2021). Experimental constraints on nonskeletal $CaCO_3$ precipitation from Proterozoic seawater. *Geology*, *49*(5), 561–565. https://doi.org/10.1130/g48044.1

Rogov, M., Ershova, V., Vereshchagin, O., Vasileva, K., Mikhailova, K., & Krylov, A. (2021). Database of global glendonite and ikaite records throughout the Phanerozoic. *Earth System Science Data*, *13*(2), 343–356. https://doi.org/10.5194/essd-13-343-2021

Rooney, A. D., Macdonald, F. A., Strauss, J. V., Dudás, F. Ö., Hallmann, C., & Selby, D. (2014). Re-Os geochronology and coupled Os-Sr isotope constraints on the Sturtian snowball Earth. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(1), 51–56. https://doi.org/10.1073/pnas.1317266110

Rooney, A. D., Strauss, J. V., Brandon, A. D., & Macdonald, F. A. (2015). A Cryogenian chronology: Two long-lasting synchronous Neoproterozoic glaciations. *Geology*, *43*(5), 459–462. https://doi.org/10.1130/g36511.1

Sánchez-Pastor, N., Oehlerich, M., Astilleros, J. M., Kaliwoda, M., Mayr, C. C., Fernández-Díaz, L., & Schmahl, W. W. (2016). Crystallization of ikaite and its pseudomorphic transformation into calcite: Raman spectroscopy evidence. *Geochimica et Cosmochimica Acta*, *175*, 271–281. https://doi.org/10.1016/j.gca.2015.12.006

Scheller, E. L., Grotzinger, J. P., & Ingalls, M. (2022). Guttulatic calcite: A carbonate microtexture that reveals frigid formation temperatures. *Geology*, *50*(1), 48–53. https://doi.org/10.1130/g49312.1

Schrag, D. P., Berner, R. A., Hoffman, P. F., & Halverson, G. P. (2002). Continental arc volcanism as the principal driver of icehouse-greenhouse variability. *Geochemistry, Geophysics, Geosystems*, *3*(6), 1–21. https://doi.org/10.1029/2001gc000219

Schubert, C. J., Nürnberg, D., Scheele, N., Pauer, F., & Kriews, M. (1997). ^{13}C isotope depletion in ikaite crystals: Evidence for methane release from the Siberian shelves. *Geo-Marine Letters*, *17*(2), 169–174. https://doi.org/10.1007/s003670050023

Selleck, B. W., Carr, P. F., & Jones, B. G. (2007). A review and synthesis of glendonites (pseudomorphs after ikaite) with new data: Assessing applicability as recorders of ancient coldwater conditions. *Journal of Sedimentary Research*, *77*(11), 980–991. https://doi.org/10.2110/jsr.2007.087

Shaikh, A. M. (1990). A new crystal growth form of vaterite, CaCO3. *Journal of Applied Crystallography*, *23*(4), 263–265. https://doi.org/10.1107/s0021889890002485

Shearman, D. J., McGugan, A., Stein, C., & Smith, A. J. (1989). *Ikaite, $CaCO_3 \cdot 6H_2O$, precursor of the thinolites in the Quaternary tufas and tufa mounds of the Lahontan and Mono Lake Basins, western United States*. Geological Society of America Bulletin.

Shuster, A. M., Wallace, M. W., van Smeerdijk Hood, A., & Jiang, G. (2018). The tonian Beck spring dolomite: Marine dolomitization in a shallow, anoxic sea. *Sedimentary Geology*, *368*, 83–104. https://doi.org/10.1016/j.sedgeo.2018.03.003

Simpson, C. (2021). Adaptation to a viscous snowball Earth ocean as a path to complex multicellularity. *The American Naturalist*, *198*(5), 590–609. https://doi.org/10.1086/716634

Smith, E. F., MacDonald, F. A., Crowley, J. L., Hodgin, E. B., & Schrag, D. P. (2016). Tectonostratigraphic evolution of the c. 780–730 Ma Beck Spring Dolomite: Basin Formation in the core of Rodinia. *Geological Society, London, Special Publications*, *424*(1), 213–239. https://doi.org/10.1144/sp424.6

Stockmann, G., Tollefsen, E., Skelton, A., Brüchert, V., Balic-Zunic, T., Langhof, J., et al. (2018). Control of a calcite inhibitor (phosphate) and temperature on ikaite precipitation in Ikka Fjord, southwest Greenland. *Applied Geochemistry: Journal of the International Association of Geochemistry and Cosmochemistry*, *89*, 11–22. https://doi.org/10.1016/j.apgeochem.2017.11.005

Strauss, J. V., Rooney, A. D., Macdonald, F. A., Brandon, A. D., & Knoll, A. H. (2014). 740 Ma vase-shaped microfossils from Yukon, Canada: Implications for Neoproterozoic chronology and biostratigraphy. *Geology*, *42*(8), 659–662. https://doi.org/10.1130/g35736.1

Strauss, J. V., & Tosca, N. J. (2020). Mineralogical constraints on Neoproterozoic pCO_2 and marine carbonate chemistry. *Geology*, *48*(6), 599–603. https://doi.org/10.1130/g47506.1

Suess, E., Balzer, W., Hesse, K. F., Müller, P. J., Ungerer, C. A., & Wefer, G. (1982). Calcium carbonate hexahydrate from organic-rich sediments of the Antarctic shelf: Precursors of glendonites. *Science*, *216*(4550), 1128–1131. https://doi.org/10.1126/science.216.4550.1128

Sumner, D. Y., & Grotzinger, J. P. (1993). Numerical modeling of ooid size and the problem of Neoproterozoic giant ooids. *Journal of Sedimentary Petrology*, *63*(5), 974–982.

Tang, C. C., Thompson, S. P., Parker, J. E., Lennie, A. R., Azough, F., & Kato, K. (2009). The ikaite-to-vaterite transformation: New evidence from diffraction and imaging. *Journal of Applied Crystallography*, *42*(2), 225–233. https://doi.org/10.1107/s0021889809005810

Teichert, B. M. A., & Luppold, F. W. (2013). Glendonites from an Early Jurassic methane seep—Climate or methane indicators? *Palaeogeography, Palaeoclimatology, Palaeoecology*, *390*, 81–93. https://doi.org/10.1016/j.palaeo.2013.03.001

Thorie, A., Mukhopadhyay, A., Banerjee, T., & Mazumdar, P. (2018). Giant ooids in a Neoproterozoic carbonate shelf, Simla Group, Lesser Himalaya, India: An analogue related to Neoproterozoic glacial deposits. *Marine and Petroleum Geology*, *98*, 582–606. https://doi.org/10.1016/j.marpetgeo.2018.08.025

Tollefsen, E., Balic-Zunic, T., Mörth, C.-M., Brüchert, V., Lee, C. C., & Skelton, A. (2020). Ikaite nucleation at 35°C challenges the use of glendonite as a paleotemperature indicator. *Scientific Reports*, *10*(1), 8141. https://doi.org/10.1038/s41598-020-64751-5

Trower, E. J. (2020). The enigma of neoproterozoic giant ooids—Fingerprints of extreme climate? *Geophysical Research Letters*, *47*(4), 1280. https://doi.org/10.1029/2019gl086146

Trower, E. J., Bridgers, S. L., Lamb, M. P., & Fischer, W. W. (2020). Ooid cortical stratigraphy reveals common histories of individual co-occurring sedimentary grains. *Journal of Geophysical Research: Earth Surface*, *125*(7). https://doi.org/10.1029/2019jf005452

Trower,E.J.,Cantine,M.D.,Gomes,M.L.,Grotzinger,J.P.,Knoll,A.H.,Lamb,M.P.,etal.(2018).Activeooidgrowthdrivenbysedimenttransportinahigh-energy shoal, Little Ambergris Cay, Turks and Caicos Islands. *Journal of Sedimentary Research*, *88*(9), 1132–1151. https://doi.org/10.2110/jsr.2018.59

Trower, E. J., Lamb, M. P., & Fischer, W. W. (2017). Experimental evidence that ooid size reflects a dynamic equilibrium between rapid precipitation and abrasion rates. *Earth and Planetary Science Letters*, *468*, 112–118. https://doi.org/10.1016/j.epsl.2017.04.004

Tucker, M. E. (1983). Diagenesis, geochemistry, and origin of a Precambrian dolomite; the Beck Spring Dolomite of eastern California. *Journal of Sedimentary Research*, *53*(4), 1097–1119.

Tucker, M. E. (1992). The Precambrian–Cambrian boundary: Seawater chemistry, ocean circulation and nutrient supply in metazoan evolution, extinction and biomineralization. *Journal of the Geological Society*, *149*(4), 655–668. https://doi.org/10.1144/gsjgs.149.4.0655

Vickers, M. L., Vickers, M., Rickaby, R. E. M., Wu, H., Bernasconi, S. M., Ullmann, C. V., et al. (2022). The ikaite to calcite transformation: Implications for palaeoclimate studies. *Geochimica et Cosmochimica Acta*, *334*, 201–216. https://doi.org/10.1016/j.gca.2022.08.001

Vickers, M. L., Watkinson, M., Price, G. D., & Jerrett, R. (2018). An improved model for the ikaite-glendonite transformation: Evidence from the Lower Cretaceous of Spitsbergen, Svalbard. *Norwegian Journal of Geology*. https://doi.org/10.17850/njg98-1-01

Whiticar, M. J., & Suess, E. (1998). The cold carbonate Connection between Mono Lake, California and the Bransfield Strait, Antarctica. *Aquatic Geochemistry*, *4*(3), 429–454. https://doi.org/10.1023/a:1009696617671

Wolfe, J. A., & Schorn, H. E. (1989). Paleoecologic, paleoclimatic, and evolutionary significance of the Oligocene Creede flora, Colorado. *Paleobiology*, *15*(2), 180–198. https://doi.org/10.1017/s0094837300009350

Yang, J., Jansen, M. F., Macdonald, F. A., & Abbot, D. S. (2017). Persistence of a freshwater surface ocean after a snowball Earth. *Geology*, *45*(7), 615–618. https://doi.org/10.1130/g38920.1

Žárský, J., Žárský, V., Hanáček, M., & Žárský, V. (2022). Cryogenian glacial habitats as a plant terrestrialisation cradle—The origin of the anydrophytes and Zygnematophyceae split. *Frontiers in Plant Science*, *12*, 735020. https://doi.org/10.3389/fpls.2021.735020