Tropical shoreline ice in the late Cambrian: Implications for Earth's climate between the Cambrian Explosion and the Great Ordovician Biodiversification Event

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ABSTRACT

Middle to late Cambrian time (ca. 513 to 488 Ma) is characterized by an unstable plateau in biodiversity, when depauperate shelf faunas suffered repeated extinctions. This poorly understood interval separates the Cambrian Explosion from the Great Ordovician Biodiversification Event and is generally regarded as a time of sustained greenhouse conditions. We present evidence that suggests a drastically different climate during this enigmatic interval: Features indicative of meteoric ice are well preserved in late Cambrian equatorial beach deposits that correspond to one of the shelf extinction events. Thus, the middle to late Cambrian Earth was at least episodically cold and might best be considered a muted analogue to the environmental extremes that characterized the Proterozoic, even though cooling in the two periods may have occurred in response to different triggers. Such later Cambrian conditions may have significantly impacted evolution preceding the Ordovician radiation.

INTRODUCTION

Understanding the paleoclimatic context within which major evolutionary events have occurred is one of the most critical, yet most elusive, aspects of interpreting the history of life on Earth. Between the Cambrian Explosion and the Great Ordovician Biodiversification Event (GOBE) is a ~25 m.y. period of subdued diversification, variously termed the "Late Cambrian Plateau" (Bambach et al., 2004) or the "Dead Interval" (Miller et al., 2006). Middle and late Cambrian marine fauna had low diversity, dominated by trilobite, phosphatic brachiopod, and conodont communities, yet these faunas experienced high turnover rates (Bambach et al., 2004; Miller, 2004). Viewed from the perspective of calcareous seafloor sediments and their non-uniformitarian rheological properties, this time interval is remarkable in its resemblance to the Proterozoic (Sepkoski, 1982; Cowan and James, 1992; Grotzinger and James, 2000; Knoll, 2003). The similarity in seafloor character suggests that at least some environmental conditions that typified the Proterozoic, and that existed prior to the Cambrian radiation of metazoa, might have reemerged in middle to late Cambrian time, preceding the GOBE.

This resemblance may not be restricted to the nature of the seafloor. In this paper, we describe upper Cambrian features that indicate the presence of fresh-water ice at the Laurentian equator, suggesting that, like the Proterozoic, the latter half of the Cambrian was at least episodically globally cold.

Ice is indicated by extraordinary intraclasts in ancient beach deposits of the Furongian (501.0–488.3 Ma) Jordan Formation in the cratonic interior of North America (Fig. 1) (Runkel et al., 2007). The intraclasts preserve evidence of brittle-ductile-brittle changes in rheological behavior during their residence time in the paleo-swash zone—features identical to those caused by freeze-thaw-freeze cycles in modern beach sands at temperate latitudes. This evidence for freezing meteoric conditions near the Furongian paleoequator is in a stratigraphic interval that corresponds in timing to a global extinction that has long been postulated to have been triggered by a cryptic cold-water oceanographic event (Palmer, 1984).

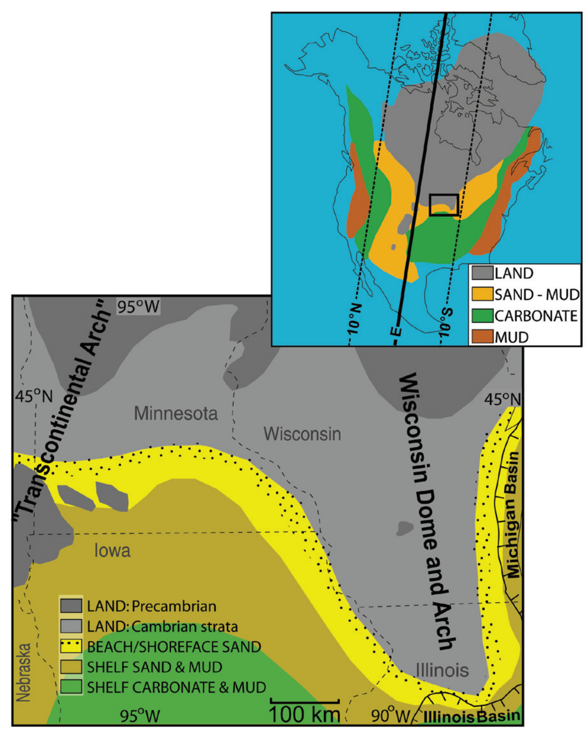

Figure 1. Location maps showing Laurentian late Cambrian facies belts and position relative to the equator (E) and regional tectonic and physiographic features of the cratonic interior. Modified from Runkel et al. (2007) with paleogeography of Laurentia from Cocks and Torsvik (2002).

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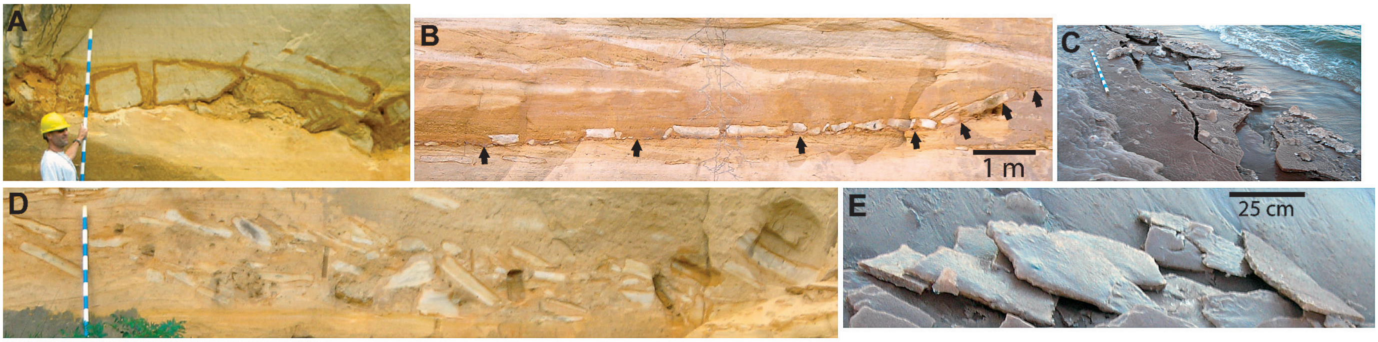
GSA Today, v. 20, no. 11, doi: 10.1130/GSATG84A.1



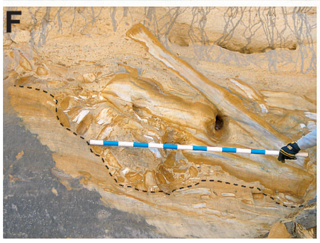


Figure 2. Large sandstone intraclasts of the Furongian Jordan Formation, Minnesota, USA, and ice-cemented sand clasts on modern, temperate, fresh-water shoreline of Lake Superior. (A) Intraclasts (up to 1.2 m in length) mantle a scour surface and are overlain by beach swash sands (late diagenetic iron oxide staining accentuates intraclast margins). (B–C) Examples of in situ brecciation (intraclast formation) by undercutting and collapse of hard (frozen) swash-zone sand in the Cambrian Jordan Formation (B) and the modern partially frozen, temperate fresh-water shoreline of Lake Superior (C). (D–E) Imbricated intraclasts in the Jordan Formation (D), and imbrication of frozen clasts along modern shoreline (E). (F) Intraclast conglomerate within a steeply channelized scour (dashed line along scour surface). Both the gray area in the lower left and branching streaks in upper part of photo are surface coating of dried, modern mud. Blue and white staff has 10 cm increments. Jordan Formation intraclasts in this and other figures are from section 12 of Runkel (1994), with UTM NAD83, Zone 15 coordinates 595174.486453 (UTME), 4872859.43211 (UTMN). Photographs and descriptions of modern ice-cemented sand are from the shoreline of Lake Superior at Park Point, Duluth area, Minnesota, USA. UTM NAD83, Zone 15 coordinates 572476.465496 (UTME), 5175832.45352 (UTMN).

Invocation of extreme cold, however, contradicts the long-held view that the middle to late Cambrian represents a sustained Greenhouse Earth episode (Berner, 1990). The greenhouse interpretation is based, in large part, on traditional paleoecological assumptions about shallow marine carbonate sediments, models of atmospheric carbon dioxide levels (Berner, 1990), and, recently, by extrapolation of controversial biogenic oxygen isotope data from the Lower Ordovician (Trotter et al., 2008). We revisit the applicability of characteristic middle through late Cambrian carbonate sediments to paleoclimatology and suggest that this interval of time was, at least episodically, and perhaps persistently, much colder than is commonly assumed. We also posit that this extraordinary climate mode may have had profound impacts on the evolution of Earth's early Paleozoic biosphere.

EVIDENCE FOR ICE

Unusual tabular sandstone intraclasts (Figs. 2A and 2B; Supplemental Data Fig. DR1A[1]) up to 1.5 m in length occur within a discrete stratigraphic interval of the Jordan Formation. These intraclasts resulted from synsedimentary cementation of intertidal sands in beach and tidal inlet environments (surf-swash zone and intertidal dune fields) that comprise the shallowest marine and estuarine facies preserved in this progradational cratonic sandstone (Runkel et al., 2007). Intraclasts typically occur in situ but can also occur ex situ: Rare pinstripe lamination of some intraclasts represents shore-adjacent aeolian lithofacies not otherwise preserved locally. Intraclasts of shallow-water origin also occur in deeper-water, finer-grained swaley cross-stratified facies deposited at fair-weather wave base, representing seaward transport of clasts by storms.

In surf- and swash-zone lithofacies of the Jordan Formation, intraclasts mantle low-angle, intrastratal truncation surfaces (Fig. 2B), locally displaying imbrication (Fig. 2D), or form conglomerates that fill steeply channelized storm scours (Fig. 2F). Where resting on low-angle scour surfaces, many intraclasts can be matched to their pre-brecciation original bed configuration, revealing an origin through undercutting and collapse (i.e., storm removal of loose sand from beneath a lithified sand layer) (Figs. 2B and 2C). Where filling steep-sided scours, intraclast orientations and compositions are typically more varied than in other settings. In intertidal dune lithofacies, intraclasts rest on foreset or set-bounding surfaces of decimeter to meter-scale dune cross-sets.

Intraclast abundance shows that synsedimentary cementation of sand was locally common along the paleo-coastline during deposition of this part of the Jordan Formation. However, none of that original cement remains. This interval of the Jordan is friable, and late diagenetic Fe-oxide cements (Fig. 2A) locally accentuate or cross-cut original depositional interfaces, including intraclast margins. Cross-bedding and lamination within intraclasts show that they started as centimeter- to decimeter-thick cemented horizons, whose tops were primary sedimentary interfaces, and whose sides resulted from brecciation. We refer herein to the "sides" of an intraclast as representing these broken edges, regardless of present-day orientation.

Intraclast aspect ratios range from 1:1 to 1:12 and their sides may be smooth or irregular, displaying wedge-shaped gaps that narrow toward intraclast interiors, or with intricate, highly rugose, millimetric filigree (Figs. 3A–3C, 3G, and 3H). Rare intraclasts are curviform with internal laminae that are concordant to overall intraclast morphology (Figs. 3J–3L). The host sandstone for

[1]GSA Supplemental Data item 2010290, supplemental photographs of modern and ancient ice-cemented intraclasts, is available online at www.geosociety.org/pubs/ft2010.htm. You can also request a copy from *GSA Today*, P.O. Box 9140, Boulder, CO 80301, USA; gsatoday@geosociety.org.

these curviform intraclasts is undeformed and cross-bedded, which reveals that the curviform shape was imparted to the intraclasts as the result of ductile deformation prior to the intraclasts being covered by migrating bedforms at the sediment-water interface (Fig. 4). Additionally, downward-branching burrows, similar to those made by polychaetes in modern coastal settings (Hertweck et al., 2007), pass from the host cross-bedded lithofacies into, and through, intraclasts (Fig. 5).

From these observations, we can reconstruct the synsedimentary and shallow subsurface rheological behavior of the intraclasts, and thus constrain characteristics of the occult cementing agent. Both brittle brecciation of intraclasts with high aspect ratios and preservation of delicate filigree edges under swash and storm conditions on a sandy beach require a strong, hard cementing agent. In contrast, curviform (bent) intraclasts are evidence of ductile behavior at the sediment surface. Likewise, burrows that pass from host sediment into and through buried intraclasts necessitate that the cementing agent had essentially disappeared (presenting no resistance to Cambrian burrowers) when the clasts were still within centimeters of the sediment-water interface. Bent intraclasts with wedge-shaped gaps that formed post-bending suggest that intraclast rheological behavior could evolve from brittle (initial brecciation) to ductile (bending) to brittle again (gap formation and preservation) during its time on the shoreline (Fig. 4).

These characteristics are indicative of ice as the cementing agent for this ancient sand, a relatively routine interpretation for sand intraclasts in glaciogenic deposits (Browne and Naish, 2003), but less commonly recognized in other ancient settings (Illich et al., 1972). Intraclast rheology, size and aspect ratios, and recurring features such as bent clasts, wedge-shaped gaps, and filigree are consistent with published descriptions of frozen sand clasts along modern temperate shorelines (Nielsen, 1988; Dillon and Conover, 1965) and are identical to examples we studied along today's Lake Superior shoreline (Figs. 2, 3, and Supplemental Data Fig. DR1 [see footnote 1]). Solidly frozen sand has a similar strength to weak Portland cement concrete (Andersland and Ladanyi, 2004), which accounts for brittle characteristics. During incipient freezing or thawing, however, thin films of water surround sand grains and allow for ductile behavior (Andersland and Ladanyi, 2004) that results in draping and deformation of clasts. Complex intraclast rheological histories, repeated transitions between ductile and brittle behavior, and, ultimately, the complete disappearance of the cement, even just below the sediment surface, would be expected in ice-cemented sediment, which is susceptible to small fluctuations in temperature near its freezing point.

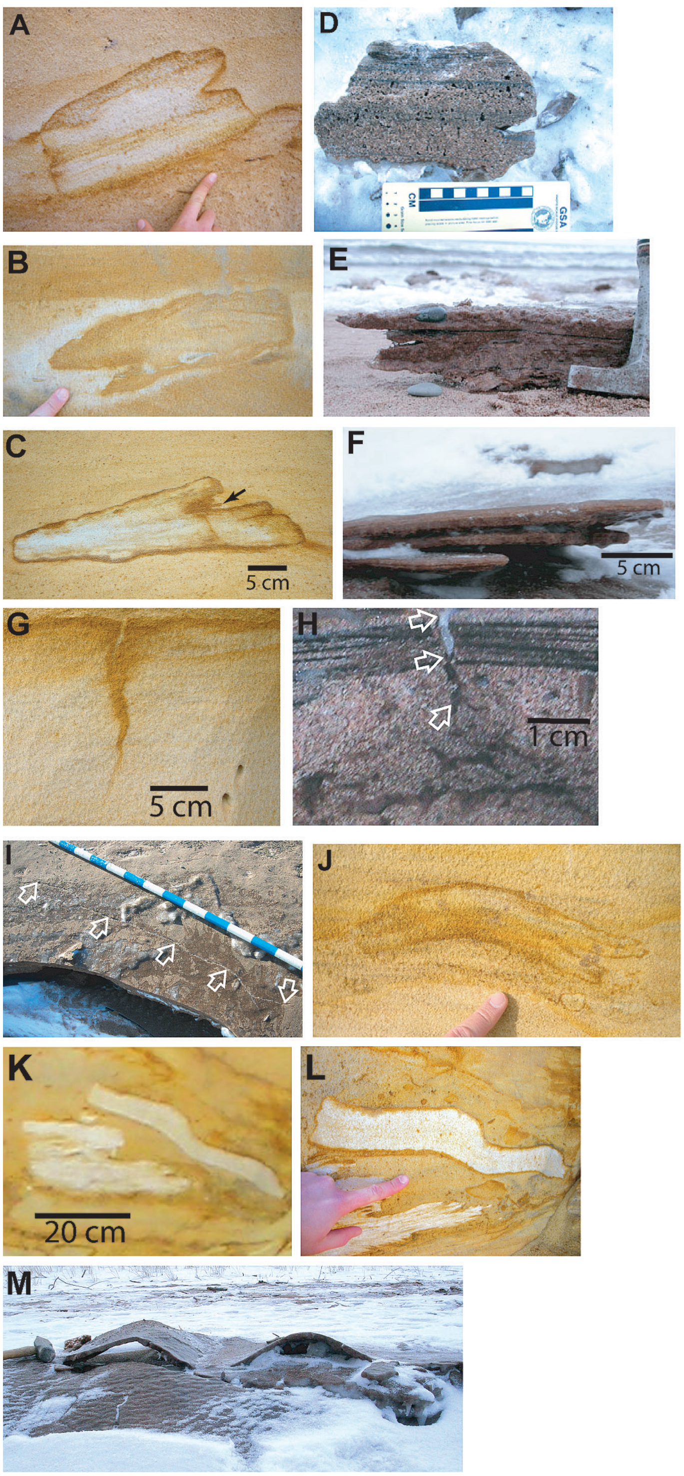


Figure 3. Comparison of morphologies that characterize Furongian intraclasts (left) with ice-cemented clasts on the modern partially frozen shoreline. (A–F) Lamination-parallel wedge-shaped gaps that taper toward clast interiors. Clast in (C) also displays preservation of fine-scale, delicate, millimetric filigree (arrow). Furongian clast-edge filigree follows foresets of a frozen toe of a paleodune form; modern clast-edge filigree follows frozen swash laminations; left edge of hammer handle in (E) is 2 cm vertically. (G–I) Lamination-perpendicular, partly penetrating cracks: (G–H) cross-sectional views of clast interior and upper margin of clasts; (I) plan view for modern example only (10 cm increments on staff). Such cracks form on the modern shoreline where a thawing, undercut, frozen sand layer partly fails and subsequently refreezes. (J–M) Curvilinear clasts: (J) intraclast with wedge-shaped gaps that opened up along laminations; (K–L) intraclast with contiguous curves. Oblique, closer view (L) shows that laminae within clast conform to clast margins, indicating curviform shape resulted from deformation (bending or folding) of an originally tabular clast, rather than having originated as a curviform-outlined cemented area of cross-laminated sand. Relationships of such deformed intraclasts to host sandstone matrix show that deformation occurred prior to burial by Furongian swash action. Clasts along modern shoreline (M) deform similarly in the swash zone by freeze-thaw processes. Circular end of hammer on left is 4 cm in diameter.

The strandline and estuarine paleoenvironments of intraclasts in the Jordan Formation implicate frozen freshwater as the cementing agent; there is no evidence of frozen Furongian sea water (e.g., "freeze-up" or "break-up" deposits from nearshore ice; Reinson and Rosen, 1982). Instead, it appears that these intraclasts formed as a result of local conditions specific to the interface between the marine and terrestrial realms, where near-surface sand was saturated with fresh (or perhaps brackish) water. Fresh or brackish-water saturation of intertidal sands would have permitted freezing at temperatures far above those required for saltwater. A frozen sandy shore adjacent to an ice-free surf or open estuary would be an ideal setting to generate and preserve storm-wave induced brecciation of large blocks of the frozen beach sand (Dillon and Conover, 1965) (Figs. DR1B and DR1C [see footnote 1]).

A LINK TO MASS EXTINCTION

The intraclasts indicative of frozen shoreline conditions appear to have a restricted distribution both spatially and temporally within lower Paleozoic deposits of the Laurentian cratonic interior. Among thousands of exposures of Cambrian and Ordovician sandy shoreline deposits in the region, spanning ~50 m.y., they are present only in a discrete interval of the Jordan Formation that encompasses parts of just two biozones (upper *Eoconodontus* and lowermost *Cordylodus proavus* conodont zones). They are common to abundant only in several outcrops representing the upper *Cambrooistodus minutus* to lowermost *Hirsutodontus hirsutus* conodont subzones (Runkel et al., 2007). This biostratigraphic position corresponds to the boundary between the Sunwaptan and Skullrockian Laurentian Stages, which records the initiation of the last of at least three middle and late Cambrian global mass extinction events that decimated shelf communities (Loch et al., 1993). In North America, these recurring extinction events are used to define biostratigraphic units known as "biomeres" (Palmer, 1984; Taylor, 2006). The cause of biomere mass extinctions has been debated for decades, but among the most enduring hypotheses for the "kill mechanism" is incursion of cold water onto continental shelves (Taylor, 2006; Loch et al., 1993). The persistence of the cold water theory is due largely to recognition that (1) "olenimorph" trilobites, otherwise known mostly from deep-water and high-latitude paleoenvironments, repopulated shelves after extinctions, presumably having migrated up from cold-water continental slope environments; and (2) sedimentary facies and geochemical analyses encompassing biomere intervals leave little room for other interpretations, such as eustatic sea level changes (with or without associated changes in water chemistry) or impact events (Taylor, 2006). The cold water hypothesis, however, has suffered from lack of widespread, unambiguous, direct or proxy evidence in the rock record, although coeval diastems and facies changes in carbonate sections (Loch et al., 1993) and

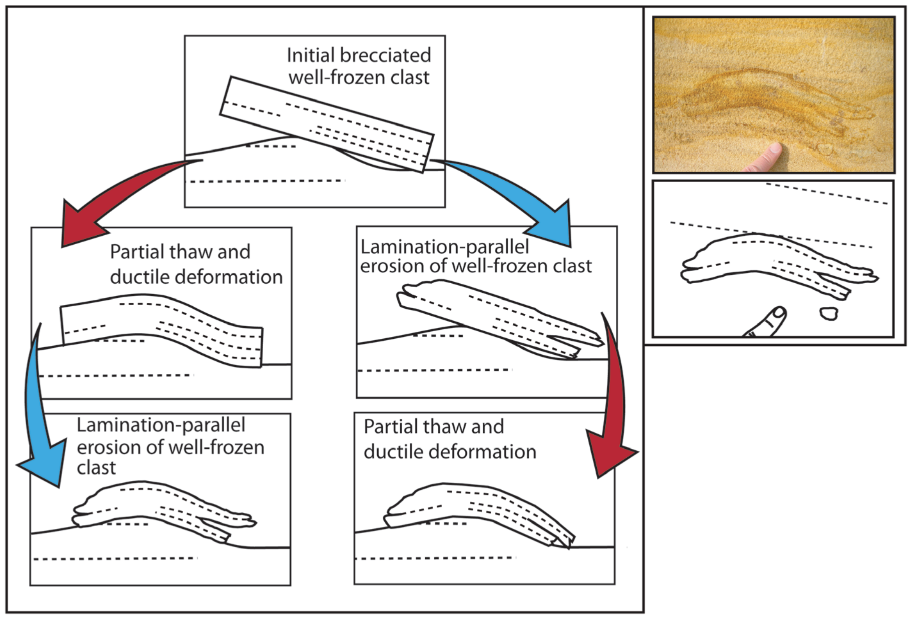


Figure 4. Constraints on evolution of intraclast rheological behavior shown by curviform intraclast with wedge-shaped gap (red arrows—partial thawing; blue arrows—refreezing). The sequence shown at left is the only way to achieve the ultimate configuration of deformed clast with observed wedge-shaped gap. Bending must occur prior to gap formation, because gap orientation requires a competent, but already curviform, clast. This evolution is suggestive of freeze-thaw-freeze (freeze to create original tabular clast that survives transport, partial thaw to then bend clast, and subsequent refreeze to create a competent clast that can support gap formation in this new position).

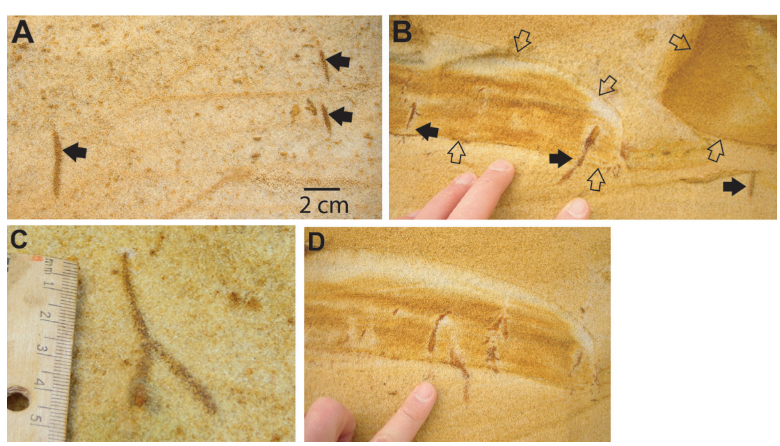


Figure 5. *Skolithos*(?) burrows (arrows) from intraclast host facies (diagenetic iron staining accentuates burrow) (A) and cutting intraclast margins (B) (solid arrows—burrows; open arrows—edges of intraclasts). (C–D) Branched burrows with similar relationships. Burrows that cross intraclast margins demonstrate that the cementing agent was no longer present after the clast was buried by sand in the swash zone but was still within reach of Cambrian shallow-depth burrowers.

negative carbon isotope excursions (Perfetta et al., 1999) at biomere boundaries have been cited as physical evidence for incursions of cold water onto shelves. Additionally, a mechanism to raise the oceanic thermocline without apparently changing sea level has been elusive. The freezing shoreline conditions we document here provide not only important physical evidence linking extinction to cold conditions, but also provide insight into the magnitude of their influence. Expression of freezing conditions on the Furongian beach requires atmospheric cooling, not simply a rise in the thermocline or a shift in ocean currents. Cold could have penetrated shelf waters from above, bringing freezing temperatures across well-circulated, wave-agitated vast epicontinental shelves and thus exterminating endemic faunas.

DISCUSSION

The former presence of ice cement is a routine interpretation for known glacial paleoenvironments, but it is much more problematic in the context of middle to late Cambrian paleogeographic and inferred paleoclimatic conditions that place Laurentia in tropical latitudes during a presumed Greenhouse Earth episode. Several lines of evidence are consistent with the widely held characterization of sustained warmth during later Cambrian time. This evidence, however, is more equivocal than that used to characterize paleoclimate in younger rocks. Temperature tolerances of Cambrian organisms are not well understood, and the relatively few measures of paleotemperature based on isotopes are highly controversial (Land, 1995; Shields and Kasting, 2007), as is the correlation between modeled atmospheric carbon dioxide levels and paleotemperature (Veiser et al., 2000). A paucity of confirmed glacial deposits, and overall rising and ultimately high sea level, indicate merely that the Cambrian Earth apparently did not experience the climatic conditions necessary for development of continental ice to the extent as seen in other times in Earth's history.

Perhaps the most commonly cited evidence for sustained warmth during the middle and late Cambrian is the observation that the Laurentian craton, at least at times, was fringed by extensive carbonate platforms with features such as ooids and microbial reefs (stromatolites and thrombolites) (Lochman-Balk, 1971) that are traditionally regarded as indicative of tropical or near-tropical conditions. Recent studies, however, have cast doubt on the requisite warm-water origin for ancient ooids (James et al., 2005a); modern microbialites are not restricted to tropical climes, and modern marine stromatolites bear only scant resemblance to their ancient counterparts (Riding, 1991; Grotzinger and Knoll, 1999). Investigation of modern cool-water carbonate sediments and early seafloor diagenetic processes (James et al., 2005b) shows that many middle and late Cambrian oolites bear some hallmarks of cool-water deposition: original calcitic mineralogies (Heller et al., 1980) and synsedimentary dissolution of aragonite on the seafloor (Wilkinson and Landing, 1978). Furthermore, irrespective of the possibly contentious re-interpretation of the paleoclimatological usefulness of oolite and stromatolite proposed here, such lithofacies are present only in discrete stratigraphic intervals of Cambrian sections, and, if "tropical" carbonate facies were indeed warmth-dependent, we suggest that relatively brief cooling events would be represented by other lithofacies, equivocal in their temperature tolerance (e.g., calcisiltites and thrombolites), or by diastems when carbonate production ceased. Such diastems and lithofacies changes are ubiquitous in strata that correlate to the sandstone intraclasts we describe herein, and several authors have suggested they reflect cold water conditions (e.g., Loch et al., 1993).

Unlike coeval pericratonic carbonate depositional systems that are prone to climate-controlled stratal hiatuses (Bathurst, 1987), progradation of the quartzose Jordan Formation would be little-affected by cold temperature. It was fed by a nearly limitless supply of sand from the deeply weathered Laurentian craton, resulting in an exceptionally complete record of time (Runkel et al., 2008). Furthermore, the cratonic strandline setting had a rare set of conditions favorable to capturing and preserving evidence of even brief episodes of freezing temperatures: Intraclasts were deposited in facies where (1) percolating shoreface fresh or brackish water would have frozen at temperatures much higher than those required for coeval seawater; (2) exposure of frozen sand along the paleo-beachface would have permitted alternating freeze-thaw conditions that provide distinctive evidence for the former presence of ice (i.e., syndepositional alternating changes in clast rheology); and (3) wave-induced brecciation and rapid post-storm burial by wave processes would have preserved the frozen intraclasts before cement loss (melting or sublimation) (Figs. DR1B and DR1C [see footnote 1]).

A global-scale climatic phenomenon triggering this discretely preserved equatorial freezing event is favored by paleomagnetic data that place the Laurentian cratonic interior in sustained southern tropical latitudes throughout middle and late Cambrian time (e.g., Cocks and Torsvik, 2002), rendering unlikely the possibility that freezing conditions are the result of rapid continental drift to high latitudes (i.e., true polar wander) (Kirschvink et al., 1997). This poses the question of whether middle and late Cambrian time was consistently much colder than previously recognized, with relatively minor cooling episodes leading to freezing equatorial conditions, or, instead, whether the equatorial ice interpreted here represents an episode of drastic cooling during an otherwise Greenhouse Earth. Oxygen isotopic studies of slightly younger (Lower Ordovician) conodont apatite (Trotter et al., 2008), as well as modeled atmospheric carbon dioxide levels (Berner, 1990), would appear to suggest the latter, if the debated use of those data as a measure of paleotemperature is regarded as reliable. We favor the former scenario and note that a number of reports have cited evidence from Laurentia and other continents consistent with a colder global Cambrian climate than widely assumed. This includes indications of continental glaciation specifically during the middle and late Cambrian, based on the magnitude and rate of eustatic sea level changes (e.g., Miller et al., 2005), and reputed, poorly dated glaciogenic sediments on some continents (Evans, 2003).

An overall cooler, later Cambrian Earth, or an unstable climate with dramatic swings, considered together with characteristic properties of carbonate seafloor sediment, is indicative of a reprise of select Proterozoic environmental conditions. However, the conditions that could have led to a cool later Cambrian Earth are no more apparent than they are for the Proterozoic, and the two periods may well have responded to different climatic drivers. Globally significant tectonic and paleogeographic boundary conditions that might have triggered Proterozoic "Snowball Earth" events (Evans, 2003) are inconsistent with Cambrian plate reconstructions and known tectonic activity. High obliquity (Williams, 2008) appears to be contraindicated by reconstructions of global paleoenvironments (e.g., Evans, 2006) and the necessity for a subsequent reduction in obliquity prior to the onset of exclusively circum-polar glaciation in the Late Ordovician. Furthermore, unlike the relatively long durations of global cooling required to produce a Proterozoic Snowball Earth, the Cambrian conditions we have documented require cooling only to the extent that tropical latitudes were briefly subjected to diurnal temperatures that varied a few degrees around freezing. This allows for consideration of short-term climate drivers, such as cometary impacts (Bendtsen and Bjerrum, 2002), which might leave little geochemical or sedimentologic evidence. Whatever the primary controls on Cambrian climate, global cooling may have been subdued compared to during the Proterozoic, because the Cambrian likely experienced higher solar luminosity, less-efficient burial of organic carbon due to greater Cambrian bioturbation, and more limited primary productivity due to lower levels of bioavailable iron and phosphorus (Hoffman et al., 1998).

Ice at the late Cambrian equator suggests that the climate can be more accurately characterized as a muted analogue to the episodically globally cold conditions of the Proterozoic, rather than as the first of several sustained Greenhouse Earth events of the Phanerozoic. Such an interpretation has significant implications for understanding interactions between climatic and biologic evolution during this critical part of Earth's history. It provides physical evidence for the long-postulated cold-water event that initiated a late Furongian global mass extinction and suggests the possibility that cooling events of this nature could have triggered earlier Cambrian mass extinctions. From a broader perspective, recognition of a cooler Earth during this time can provide additional constraints on recent hypotheses that link the climatic conditions of the Proterozoic and early Paleozoic to the origin and early evolution of metazoans. The reversion to Proterozoic-like conditions in the middle and late Cambrian is coincident with plateaued biodiversification and high extinction intensity following the Cambrian Explosion (Bambach et al., 2004), and the ultimate reemergence into the climate style of the Paleozoic is coincident with the GOBE and development of the shelly, filter-feeding benthic fauna that dominates the remaining Paleozoic record.

ACKNOWLEDGMENTS

Mentors for three of the authors were instrumental to this research. Earl McBride encouraged Runkel to consider the potential for ice as a cementing agent for Jordan Formation intraclasts. Noel James introduced Cowan to the cool-water carbonate realm. Bruce Wilkinson led a Michigan field trip during which he showed Fox examples of deformed sand intraclasts that were likely cemented by ice. Partial funding was provided through the Henrickson, Potts, and Bernstein funds at Carleton College and the State Special Appropriation to the University of Minnesota. Reviews by Paul Hoffman and editor Stephen Johnston improved the paper.

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Manuscript received 8 Oct. 2009; accepted 22 Feb. 2010. ✷