A Cenozoic-style scenario for the end-Ordovician glaciation

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The end-Ordovician was an enigmatic interval in the Phanerozoic, known for massive glaciation potentially at elevated CO2 levels, biogeochemical cycle disruptions recorded as large isotope anomalies and a devastating extinction event. Ice-sheet volumes claimed to be twice those of the Last Glacial Maximum paradoxically coincided with oceans as warm as today. Here we argue that some of these remarkable claims arise from undersampling of incomplete geological sections that led to apparent temporal correlations within the relatively coarse resolution capability of Palaeozoic biochronostratigraphy. We examine exceptionally complete sedimentary records from two, low and high, palaeolatitude settings. Their correlation framework reveals a Cenozoic-style scenario including three main glacial cycles and higher-order phenomena. This necessitates revision of mechanisms for the end-Ordovician events, as the first extinction is tied to an early phase of melting, not to initial cooling, and the largest δ13C excursion occurs during final deglaciation, not at the glacial apex.
S helf sedimentary architecture is controlled essentially by relative rates of base-level change and sediment supply1,2. The base level reflects the interplay between tectonics (subsidence, volume change at mid-oceanic ridges) and the orbitally tuned, glacio-eustatically driven, sea-level change. The rate of the latter, at tens of metres per 10^4–10^5 years, is one to three orders of magnitude greater than the tectonically driven sea-level change, at tens of metres per million years or less. The critical issue for analysing the stratigraphic record, therefore, is the correct assignment of depositional units to their appropriate temporal hierarchy alongside a given sea-level curve. Another consideration is the temporal significance of the observed or suspected hiatuses. Any stratigraphic record of ancient shelf deposits, and their isotopic or palaeontological proxies, inevitably samples only the discontinuous segments of a given sea-level curve3, which often are below the relatively coarse resolution correlation potential of Palaeozoic biostratigraphy4. Regardless, shelf deposits are the principal record that we have for pre-Mesozoic glaciations and they must therefore serve as stratigraphic archives for glacially driven basins, providing: subsidence was active; water depths at the onset of glaciation were moderately deep; and sediment supply was adjusted to subsidence rates. These preconditions are essential for the maintenance of significant water depths during glaciation, as any rapid shallowing would pre-empt the registration of subsequent glacio-eustatic events.

The end-Ordovician witnessed one of the three largest Phanerozoic glaciations with the development of continental-scale ice sheets5–7. This climatic event was postulated to have been initiated by massive weathering of fresh volcanic rocks8, tectonics and related plate migration9–11, high cosmic ray flux impacting cloud albedo12 or by a combination of the above13. The glaciation apparently coincided with highly14 or moderately10,15 elevated CO_2 levels, with large isotopic excursions (C, S, O, N, Nd), and with a major double-phased biological extinction event16,17,21. Yet the high palaeolatitude near-field sequences of extinction to the onset and termination of a single glaciation16,22,24–26, which often are below the relatively coarse resolution correlation potential of Palaeozoic biostratigraphy4. Regardless, shelf deposits are the principal record that we have for pre-Mesozoic glaciations and they must therefore serve as stratigraphic archives for glacially driven basins, providing: subsidence was active; water depths at the onset of glaciation were moderately deep; and sediment supply was adjusted to subsidence rates. These preconditions are essential for the maintenance of significant water depths during glaciation, as any rapid shallowing would pre-empt the registration of subsequent glacio-eustatic events.

The end-Ordovician glacial tempos. Within the context of glaciation, where eustasy is expected to control shallow shelf sequences5, our findings strongly suggest that the two independent regional scale frameworks and their correlation are robust and that the correspondence of the low- and high-order GSS records from dissimilar tectonic and environmental settings arises from glacio-eustatically fluctuating sea levels, the latter a consequence of waxing and waning of the western Gondwana ice sheet. We interpret the three low-order GSSs to be the signature of the three extensive glacial cycles (Latest Ordovician Glacial Cycles, LOGCs 1–3; Figs 2 and 3 and Supplementary Note). Note that our provisional numbering refers to the latest Ordovician, understood to informally include the highest Katian and the...
Hirnantian. This is in agreement with the views that ice sheets were extant already before the latest Katian\(^7\),\(^22\),\(^31\),\(^32\). Our first glacial cycle spans the upper Katian (LOGC 1), the second (LOGC 2) includes the uppermost Katian strata and most of the lower to middle part of Hirnantian and the third (LOGC 3) commences in the upper Hirnantian and ends in the lowermost Silurian. In our view, corroborated recently by Nd isotope studies\(^22\), the end-Ordovician glaciation could not have been restricted to a single short-lived glacial event, as earlier believed.

The minimum depositional time for the entire LOGC 1–3 succession is in excess of the Hirnantian duration (~1.4 ± 0.2 Myr\(^\text{22}\)), the latter encompassing about 60–90% of the LOGC 2 and some 40–80% of the LOGC 3. Assuming that all LOGCs are of about equal durations, a single LOGC corresponds to a 0.7–1.6 Myr time span. The embedded higher-frequency multiorer event stratigraphy is typical of orbitally controlled climatic oscillations that lead to recurring ice-sheet growth stages\(^34\), in agreement with the modelling results of Hermann et al.\(^35\). Note however that in contrast to the well-known, strongly asymmetric and shorter-term, Pleistocene glacial cycles\(^36\), our LOGCs show no abrupt deglaciations. They have a symmetric distribution of the high-order GSSs, as evident from the stacking patterns within the lower-order regressive to transgressive system tracts (TSTs). Long-lasting interglacials are expressed as condensed, maximum flooding stratigraphic intervals\(^7\) that account for significant portions of the overall duration of the studied time span (Fig. 3). Despite of some similarities to Quaternary glaciations\(^5\),\(^7\),\(^15\),\(^31\),\(^37\), the durations and internal organization of LOGCs argue for dissimilar glacial tempos and forcings. These Ordovician features and tempos more closely resemble the Oligocene climate patterns that were driven by a high-amplitude obliquity modulation at 1.2 Myr frequency\(^34\), resulting in a limited number of short-lived ice-sheet growth phases, our high-order GSSs, centred around the obliquity nodes\(^38\),\(^39\). Such high-frequency signals may hold some similarities to the metre-scale cycles described from other low-latitude areas and attributed to ~200 (ref. 40) or 40–130 kyr (ref. 32) frequency oscillations.

Assuming the analogy with the Oligocene climate is valid, we hypothesize that an orbital forcing responding to the amplitude modulation of the obliquity typifies glacial climate systems at relatively high CO2am levels. In such a scenario, the ice-sheet inception, driven by ice-albedo feedbacks, may have resulted from a dearth of exceptionally warm rather than a ubiquity of exceptionally cool summers\(^38\).

**Discussion**

Our sequence stratigraphic framework allows Hirnantian excursi (s) and extinction(s) to be revisited. The large positive carbon isotope excursions of the Palaeozoic, such as the Hirnantian Isotopic Carbon Excursion, HICE in LOGC 3 (refs 17,18,41–43), are often used as chronostratigraphic markers, albeit with no consensus model for their existence. Yet, the notion that the


\[ \delta^{13}C_{\text{carb}} \] signal of shelf carbonates is a direct reflection of the \[ \delta^{13}C_{\text{DIC}} \] of the globally uniform open ocean is clearly open to debate\(^{13,26}\) (Supplementary Discussion). Note that the magnitude and occurrences of such \(^{13}C\) enrichments depends on localized settings (for example, epeiric versus open ocean aquafacies\(^{22,44}\)) and is therefore related to depositional facies and not straightforwardly to a global signal. For example, the \[ \delta^{13}C_{\text{carb}} \] on the modern Bahamas Bank is considerably more positive than that of the open ocean\(^{45}\).

In addition, our revised chronology questions the paradigm of temporal relationships that link the position of the end-Ordovician glacial cycles, their tempos and biochemical events\(^{13,16–22,26}\). The first issue that arises is the identification and temporal range of the HICE itself. If it is understood as coeval with the large \(+ 4\%\) isotopic excursion, it has to be confined to a restricted time interval of a single high-order GSS within the end-Ordovician glaciation (Fig. 3), as posited by the Anticosti case study. If, on the other hand, understood as a \(^{13}C\) signal that commences in the latest Katian and ends in the latest Hirnantian, our results (Fig. 3 and Supplementary Table 1) show \(^{13}C\) enrichments in at least three stratigraphic positions, suggesting that HICE combines several excursions, thus challenging its validity as a high-resolution chronostratigraphic marker.

The Anticosti \[ \delta^{13}C_{\text{carb}} \] curve (Fig. 3) includes two main isotopic events. First, it is the well-known excursion in the Laframboise Mb. (\(+ 4\%\)) that is disconnected from a rising limb in the underlying strata by a major unconformity that we relate to the glacial maximum and to subaerial erosion in LOGC 3. Second, there is an earlier asymmetric excursion (\(+ 2\%\)) with its descending limb that is spanning the lower and middle parts of the Ellis Bay Fm. (LOG 2). There is also a lesser enrichment in the uppermost Vauréal Fm., associated with LOGC 1, which may form a third, subordinate excursion. Other putative (\(< 1\%\)) excursions, while present, are minor and difficult to interpret. This multi-peak isotope pattern at Anticosti Island questions the views of strictly synchronous signals, despite observations that a number of Hirnantian records worldwide—and potentially similar ‘wiggles’ in the carbon isotope record elsewhere—contain positive \[ \delta^{13}C \] spikes that appear isochronous\(^{17,24,46}\) within the correlation capabilities of the Palaeozoic bio- and/or
An apparent single peak may represent only disjointed parts (Fig. 4) of a hypothetically complete $\delta^{13}C_{\text{carb}}$ curve for just one of several repetitious LOGCs, or a composite signal from an artificially stacked section. Whatever the temporal extent of HICE, our sequence stratigraphic framework warrants reconsideration of the published ‘cause-and-effect’ scenarios for its origin. The rising limb of the $^{13}C$ excursion at the base of the Ellis Bay Fm. (Fig. 3) is associated with a highstand that follows the LOGC 1–2 transition, while its descending limb spans several high-frequency glacio-eustatic cycles within the late regressive to TSTs of the LOGC 2. In this case, there is therefore no apparent connection between eustasy and the $\delta^{13}C_{\text{carb}}$ curve. The simplest explanation is to see the LOGC 2 isotopic signal as that of regional epeiric water masses with their distinctive variations in $\delta^{13}C$ (ref. 44). In contrast, the subsequent, exceptionally high-amplitude excursion is within the TST of LOGC 3, and is associated with a drastic basin-scale change of facies caused by transition from glacial to...

**Figure 3 | Perspective of sequence stratigraphy.** Temporal correspondence between documented (chitinozoa54,55,59,60) or essentially inferred (graptolite) biostratigraphies and (a), the Anticosti Island succession with its related isotopic signal and faunal turnovers and (b), the Anti-Atlas succession with interpreted low-frequency sea-level changes and ice-sheet occurrences. A cycle hierarchy is developed that distinguishes LOGC1–3 (low-order, high-significance Late Ordovician Glacial Cycles represented by both coloured triangles and the thick, pale blue curve) from high-order cycles (thin, dark blue curve). LOGCs are bounded by major MFS (dotted lines). Blue shading highlights time intervals specifically characterized, or thought to be characterized by ice-sheet development stages. The ice-sheet development increased from the late Katian to the late Hirnantian, as suggested by glacioeustatic trends. The dashed blue curve is a representation of the early Silurian eustatic background. Black, dashed lines are the inferred Katian to Hirnantian and Hirnantian to Llandovery boundaries. (c) Representation of a potential time calibration is based on astronomical forcings dominated by 1.2 Myr amplitude modulation of obliquity cycles34 (see text for details). By analogy with the Cenozoic, the composite artificial curve was constructed by mixing high-frequency orbital cycles (‘ETP’ for eccentricity–tilt–climatic precession33) and here it is shown only to illustrate the distortion in the stratigraphic record. It results in condensed transgressive and overdeveloped lowstand intervals, relative to a linear timescale. The high- and highest-order glacial cycles likely correspond to such orbitally forced, high-frequency climatic oscillations. In contrast, during the long interglacials orbital forcing did not result in ice-sheet development and they have therefore a poorly differentiated record. The end-Ordovician includes short glaciation intervals with cumulative duration of perhaps a few hundred thousand years. The embedded isotopic and biological signals show up to three discrete isotopic events and two faunal turnovers (oblique-line shading), from the highest Katian to uppermost Hirnantian. The Hirnantian isotopic carbon excursion (HICE) is not restricted to the excursion associated with LOGC 3 at the top of the Ellis Bay Fm. The dashed pink curve is a representation of the Katian isotopic background.
warmer climates (reefs of the Laframboise Mb.). At a higher resolution, the excursion appears to be confined to the highstand of a high-order GSS (Fig. 4), thus peaking at times of rising sea levels associated with deglaciation. This coincidence is opposite to the postulated lowstand conditions that are essential in the ‘weathering’ scenario and the model can be discounted as a potential explanation. The ‘productivity’ and related ‘circulation pattern’ explanations could perhaps offer plausible alternatives, providing it can be demonstrated that the isotopic excursion is not facies dependent. Our highstand nadir of isotope excursion can then be consistent with the scenario that invokes carbon storage in the deeper parts of the shelf, albeit constrained—because of its high amplitude—to basinal, not global, scales (see box model in Supplementary Discussion and Supplementary Tables 2 and 3). In such a context, the particular highstand conditions favourable for the development of carbon excursions may arise at distinct locations during any high-order GSSs. If so, it is the short duration of contiguous high-order GSSs that give the impression of a synchronous, worldwide phenomenon during the LOGC 3 transgressive trends. For minor excursions, such as those in LOGC 1 or in the uppermost (below the unconformity) Ellis Bay Fm., we contend that our present-day knowledge of carbon isotope systematics does not permit unique diagnostics of causative factors and scenarios. We therefore desist from their interpretation. In summary, providing our sections represent sufficiently comprehensive archives of the latest Ordovician development, we dispute the apparent association of each LOGC with an individual isotopic excursion. At higher resolution, the relationship with sea-level history differs from case to case, indicating that it is not a unique forcing but likely a combination of processes that is involved in 13C enrichment.

Figure 4 | A detailed interpretation of the far-field LOGC 3 stratigraphic and isotopic record. (a) The main lithostratigraphic units on Anticosti Island, including the Laframboise Member, are shown with their representative depositional facies and related δ13C curve. They are separated by shoreline ravinement unconformities. The sequence stratigraphic interpretation differentiates low-order/high-significance regressive (orange and yellow triangle) and transgressive (purple triangle) system tracts. The corresponding first-order unconformity coincides with the base of the Laframboise Member. High-order cycles represented by white triangles are present in the LOGC 3 TST, which commences with the base of the Laframboise Member. (b) The same sequence in the ‘linear’ timescale perspective of this succession of depositional events. It includes relatively long depositional hiatuses (oblique-line shading). At Anticosti, the high-frequency glacio-eustatic sea level changes, similar to those recorded in the near-field glacial record of Morocco, are represented by unconformities coeval with the glacial maxima. One recorded interglacial event (Laframboise Mb.) is interpreted here as a single high-order GSS within the larger TST of LOGC 3. (c) An alternative view of the isotopic excursion, which includes the stratigraphic hiatuses. The δ13C record captures only disjointed segments of the isotope signal. In particular, the δ13C curve does not include values from the time interval that corresponds to the Hirnantian glacial climax. We suspect that the trend from background levels to the maximum in fact combines an initial rise that predates the glacial climax, the associated hiatus and the subsequent maximum that postdates the glacial climax. This maximum is developed mainly within the reefal limestones constituting the highstand facies of a particular high-order GSS.

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segments from the stratigraphic record, as must be the case for hiatus-dominated successions\textsuperscript{20}. The two phases of the Late Ordovician mass extinction that were documented worldwide in earlier studies\textsuperscript{17,18} are however confirmed also by our results on the Anticosti Island (Fig. 3 and Supplementary Fig. 2). Our correlation framework moreover indicates that these turnovers are relatively long-lasting time intervals that encompass several glacio-eustatic fluctuations of the high or highest GSSs in the Anti-Atlas record. Whether these turnovers originate from evolution specifically related to LOGC developments, or whether they only mirror a succession of stacked, quasi-instantaneous, pulses is beyond resolution of our data set, regardless of their potential combination within protracted, global events\textsuperscript{21,50}. The ensemble of our sections studied represents only a fraction of affected palaeohabitats and biota, and, as explained, sections that contain complementary palaeontological data cannot be readily correlated into our framework; our analyses thus likely undersamples the full biotic dynamics through this interval. Yet, our juxtaposition of extinction phases to glacial development suggests a more nuanced scenario than previously advocated (Fig. 3).

The older turnover, which has classically been associated with the onset of the Hirnantian glaciation at the base of the N. extraordinarius Biozone, spans an interval that includes LOGC 1 glaciation and the early LOGC 2 highstand. This turnover corresponds therefore mostly to the first major interglacial period. The models that are based on processes linked to glacial onset, such as the shrinkage of biotic ecospace, temperature decline or development (or the loss) of anoxia during falling sea level\textsuperscript{13,15,20,21}, are thus not compatible with this revised scenario. Instead, processes linked to deglaciation dynamics (for example, amplification of meltwater fluxes that enhance ocean stratification), or flooding of the shelves by relatively deep anoxic waters\textsuperscript{13,21,51}, appear to be more likely scenarios for this first turnover, but they are not applicable, as previously envisioned, for the second turnover. The second turnover that we recognize in LOGC 3 is an event traditionally assigned to the lower part of the N. persculptus Biozone. This extinction/recovery pattern affects mostly macrofauna in the Anticosti Island succession (Supplementary Fig. 2). The phytoplankton crisis, on the other hand, commenced beneath the regional unconformity (Fig. 4), that is before glacial climax of LOGC 3 (refs 42,52), suggesting that the second end-Ordovician faunal turnover may have been initiated already during the late Hirnantian ice-sheet waxing, thus casting doubt on a unique causative linkage that would have been confined to final deglaciation. Note nevertheless that the ubiquitous existence of worldwide hiatuses at that time makes any interpretation tentative.

While we appreciate the merits of a sophisticated model-driven approach, and welcome the impetus derived from it, the insights arising here from the application of basic geological methods underlie the need for detailed understanding of the rock record as well\textsuperscript{13}. In this contribution, temporal relationships of near-field underline the need for detailed understanding of the rock record arising here from the application of basic geological methods approach, and welcome the impetus derived from it, the insights any interpretation tentative.

The orbital controlled depositional record of a glacial interval will mostly be underrepresented in proven or suspected hiatuses. These may originate from nondeposition, subaerial or subglacial unconformities, transgressive post-glacial ravinement processes, mass movements or from erosion by bottom currents, the latter being particularly effective for the deeper parts of shelf basins. Due to the lack of Palaeozoic deep-sea records, the absolute timing and calibration of the Ordovician glaciation may remain enigmatic\textsuperscript{13}. We envision therefore that future progress in understanding the temporal, spatial and causal evolution of the Late Ordovician environmental record will have to rely on high-resolution methods that capture multi-tier sequence stratigraphy based on proxies already present in our high-resolution waiting scale. Our advances using these methods include: rejection of the earlier cause-and-effect scenarios for HICE(s), as these no longer fit with the revised context of glacial/ glacio-eustatic development; the suggestion that low-order LOGCs likely represent the 1.2 Myr long obliquity cycles that modulated ice-sheet dynamics, similar to scenarios proposed for the Oligocene; and the insight that the first Hirnantian extinction pulse, contrary to earlier studies, was linked to an intervening melting phase, not to the initial cooling phase of the end-Ordovician.

**Methods**

**GSSs.** Sequence stratigraphic correlation frameworks are based on visual correlations of marker beds along continuous exposures at the 10–30 km scale (Fig. 2) and on refined, regional scale, chitinozoan-based biostratigraphies for northern Gondwana\textsuperscript{54–58} and eastern Laurentia\textsuperscript{59,60}. This results in correlations that are not consistently different from lithostratigraphic schemes (Supplementary Figs 1 and 2). MFS and a variety of erosion surfaces have been delineated in the field. The MFS coincide with deeper, usually condensed, depositional conditions and serve as bounding surfaces for GSSs\textsuperscript{61}, ideally including a lower regressive system tract (RST) and an upper transgressive system tract (TST). Erosional surfaces correspond to glacial erosion surfaces (Morocco); subaerial unconformities reworked by transgressive ravinement processes (SR-U sensu Embry, 2009 (ref. 62); Anticosti); or sharp-based erosional surfaces punctuating regressive facies trends and ascribed in most cases to regressive surfaces of marine erosion (Anti-Atlas and Anticosti). We favour GSSs over Trangressive/Regressive\textsuperscript{62} (T–R), or depositional sequences\textsuperscript{63} because their bounding surfaces (MFS) better approximate late diachronous conditions and the diachronous brackets glacial cycles. In this scheme, a post-glacial highstand of an interglacial is represented by deposits that constitute the lower part of the subjacent sequence.

**Sequence hierarchy.** Stratigraphic surfaces have been assigned to a hierarchy of GSSs. The significance of facies shifts and/or their penetration into the basin are used as criteria to assess the relative magnitude of base-level falls in successive, mutliorder sequences. It results in a data-driven hierarchy\textsuperscript{22}, different from a predefined scheme based on a priori assumptions about sequences. The highest-order (low significance) GSSs display limited facies shifts, both in the basin and at basin edge. More significant are the high-order genetic sequences, which comprise several higher-order GSSs and/or include abrupt facies shifts associated with coeval, or at least suspected, erosion surfaces at basin edge. High-order sequences (high-order sequence) are made up of a suite of high-order sequences, the stacking pattern of which defines long-term RST and TST. They are bounded by the major MFS associated with severe condensation (for example, phosphogenesis in the Anti-Atlas). They include in their most regressive part (late RST or early TST) one or several important erosional surfaces such as the shoreline reworked unconformities, or glacial erosion surfaces in the upper Hirnantian in Morocco, which expand toward basin areas. This approach is often not appropriate for maximum flooding intervals characterized by relatively deep depositional conditions, where facies shifts are poorly deciphered. Here, an alternative, frequency-related, hierarchy is frequently applied\textsuperscript{22}. Base-level falls associated with glacial erosional surfaces are recognized on the basis of: their basinward extent at regional scale\textsuperscript{63} (Supplementary Fig. 1); the development/absence of well-organized subglacial shear zones that indicate fully
subglacial/marginal ice fronts. Maximum erosional depths are not considered to be a measure of the significance of a glacial surface. We are aware that such estimates reflect glacial extents rather than true ice-sheet volumes, but they do have significance when dealing with high- and low-order GSSs.

References

1. Jervey, M. T. in Sea Level Changes—An Integrated Approach Vol. 42 (eds Wilgus, C. K. et al.) 47–69 (Society of Economic Paleontologists and Mineralogists, Special Publication, 1988).

2. Catuneau, O. et al. Towards the standardization of sequence stratigraphy. Earth-Sci. Rev. 92, 1–33 (2009).

3. Mountain, G. S. in Continental Margin Sedimentation: From Sediment Transport to Sequence Stratigraph (eds Nittouer, C. A. et al.) 381–458 (International Association of Sedimentologists, Special Publication, Blackwells, 2007).

4. Sadler, P. M., Cooper, R. A. & Melchin, M. High-resolution, early Paleozoic (Ordovician-Silurian) time scales. GSA Bull. 121, 887–906 (2009).

5. Ghienne, J.-F., Le Heron, D., Moreau, J., Denis, M. & Deynoux, M. in Glacial Sedimentary Processes and Products Vol. 39 (eds Hambery, M. et al.) 295–319 (International Association of Sedimentologists, Special Publication, Blackwells, 2007).

6. Le Heron, D. P. & Craig, J. First-order reconstructions of a Late Ordovician Saharan ice sheet. J. Geol. Soc. 165, 19–29 (2008).

7. Loo, A. et al. The Late Ordovician glacio-eustatic record from a high latitude storm-dominated shelf succession: the Bou Ingarf section (Anti-Atlas, Southern Morocco). Palaeogeogr. Palaeoclim. Palaeoecol. 296, 332–358 (2010).

8. Lefebvre, Y., Servais, T., Francois, L. & Averbuch, O. Did a Katian large igneous province trigger the Late Ordovician glaciation? A hypothesis tested with a carbon cycle model. Palaeogeogr. Palaeoclim. Palaeoecol. 296, 309–319 (2010).

9. Herrmann, A. D., Patzkowsky, M. E. & Pollard, D. The impact of paleogeography, pCO2, poleward ocean heat transport, and sea level change on global cooling during the Late Ordovician. Palaeogeogr. Palaeoclim. Palaeoecol. 206, 59–74 (2004).

10. Nardin, E. et al. Modeling the early Paleozoic long-term climatic trend. Geol. Soc. Am. Bull. 123, 1181–1192 (2011).

11. Kump, L. R. et al. A weathering hypothesis for glaciation at high atmospheric pCO2 during the Late Ordovician. Palaeogeogr. Palaeoclim. Palaeoecol. 152, 173–187 (1999).

12. Shaviv, N. J. & Veizer, J. Celestial driver of Phanerozoic climate? Science 312, 133–135 (2006).

13. McElrath, L. M. The Late Ordovician glacial record of the Anti-Atlas, Morocco. Geol. Soc. Lond. Spec. Publ. 165, 182–195 (2000).

14. Brenchley, P. J. Annu. Rev. Earth Planet. Sci. 37, 152–165 (2009).

15. Harper, D. A. T., Hammarlund, E. U. & Rasmussen, C. M. O. End Ordovician extinctions: a coincidence of causes. Gondwana Res. 25, 1294–1307 (2013).

16. Holmden, C. et al. Nd isotope records of Late Ordovician sea-level change—Implications for glaciation frequency and global stratigraphic correlation. Palaeogeogr. Palaeoclim. Palaeoecol. 386, 131–144 (2013).

17. Sattler, O. E. & Whitinthong, J. L., Therem, J. N. & Craig, J. Calibrating the Late Ordovician glaciation and mass extinction by the eccentricity cycles of the Earth’s orbit. Geol. Soc. Lond. Spec. Publ. 312, 967–970 (2000).

18. McElhin, M. J. & Holmden, C. Carbon isotope chemostratigraphy in Arctic Canada: Sea-level forcing of carbonate platform weathering and implications for Hirnantian global correlation. Palaeogeogr. Palaeoclim. Palaeoecol. 238, 186–200 (2006).

19. Debroeye, A. et al. Physiopanlont dynamics across the Ordovician/Silurian boundary at low palaeolatitudes: Correlations with carbon isotopic and glacial events. Palaeogeogr. Palaeoclim. Palaeoecol. 312, 79–97 (2011).
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Author contributions

J.-F.G., M.-P.D. and A.L. and A.D., C.F., S.W. and J.V. compiled and generated field data, from the Anti-Atlas and the Anticosti Island, respectively. T.R.A.V. and F.P. and A.A. and E.A. generated biostratigraphic data for the Anti-Atlas and the Anticosti Island, respectively. S.W. and J.V. performed isotopic data and ran the C-cycle model. J.-F.G., A.D., T.R.A.V. and J.V. designed the research and wrote the paper.

Additional information

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