Long-lived glaciation in the Late Ordovician? Isotopic and sequence-stratigraphic evidence from western Laurentia

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ABSTRACT

The timing and causes of the transition to an icehouse climate in the Late Ordovician are controversial. Results of an integrated δ^{13}C and sequence stratigraphic analysis in Nevada show that in the Late Ordovician Chatfieldian Stage (mid-Caradoc) a positive δ^{13}C excursion in the upper part of the Copenhagen Formation was closely followed by a regressive event evidenced within the prominent Eureka Quartzite. The Chatfieldian δ^{13}C excursion is known globally and interpreted to record enhanced organic carbon burial, which lowered atmospheric $p\mathrm{CO}_2$ to levels near the threshold for ice buildup in the Ordovician greenhouse climate. The subsequent regressive event in central Nevada, previously interpreted as part of a regional tectonic adjustment, is here attributed in part to sea-level drawdown from the initiation of continental glaciation on Gondwana. This drop in sea level—which may have contributed to further cooling through a reduction in poleward heat transport and a lowering of $p\mathrm{CO}_2$ by suppressing shelf-carbonate production—signals the transition to a Late Ordovician icehouse climate $\sim$10 m.y. before the widespread Hirnantian glacial maximum at the end of the Ordovician.

Keywords: Late Ordovician, Eureka Quartzite, glaciation, carbon isotope, Nevada.

INTRODUCTION

The Late Ordovician glacial episode (Crowell, 1999) is anomalous in comparison with the late Paleozoic and late Cenozoic ice ages in that models and proxy data indicate high levels of atmospheric $p\mathrm{CO}_2$ at the time of glaciation ($\sim$14–16 times preindustrial levels; Crowley and Baum, 1995; Berner and Kothavala, 2001). However, it has also been recognized that because the precise timing and duration of ice buildup in the Ordovician remain uncertain, prior analyses may have missed a brief or earlier episode of $p\mathrm{CO}_2$ drawdown (Kump et al., 1995). A short-lived Late Ordovician glaciation ($\sim$1 m.y.) was proposed on the basis of correlation of a global eustatic drop with positive shifts in δ^{13}C and δ^{18}O in the terminal Hirnantian Stage (Brenchley et al., 1994). A more prolonged episode ($\sim$10 m.y.) beginning earlier in the Ordovician (Chatfieldian Stage) was argued on the basis of glaciogenic sediments from polar Gondwana (Hamoumi, 1999) and indicators of upwelling and moderate-amplitude, high-frequency sea-level fluctuations in low-latitude carbonate settings (Pope and Read, 1998; Pope and Steffen, 2003).

A long-lived Late Ordovician glaciation is consistent with recognition of a significant positive δ^{13}C excursion during the Chatfieldian Stage that preceded the well-known Hirnantian shift by $\sim$10 m.y. The Chatfieldian δ^{13}C shift of $\sim$+3‰ is smaller than the Hirnantian shift, but appears to likewise have global significance (Fig. 1; Ainsaar et al., 1999). Furthermore, the Chatfieldian excursion in marine carbonate also corresponds to a shift in the δ^{13}C of organic matter (Patzkowsky et al., 1997) and may signal a critical drop in $p\mathrm{CO}_2$ values to threshold levels for ice-sheet growth in the Late Ordovician greenhouse climate (Herrmann et al., 2003, 2004). In contrast, δ^{13}C evidence during the Hirnantian glacial maximum suggests that $p\mathrm{CO}_2$ began to rise again as land area available for silicate weathering was covered in ice (Kump et al., 1999).

A key test of the hypothesis of a prolonged (pre-Hirnantian) period of ice-sheet buildup is unresolved: is there evidence for a glacio-eustatic drop that coincides with the Chatfieldian δ^{13}C excursion and other sedimentary proxy indicators of global cooling (Hamoumi, 1999; Pope and Steffen, 2003)? A drop in sea level could provide a positive feedback for further cooling and ice buildup by reducing poleward oceanic heat transport (Herrmann et al., 2004) or by lowering $p\mathrm{CO}_2$ through suppression of shallow-water carbonate production (cf. Ridgwell et al., 2003). We present an integrated isotopic and sequence-stratigraphic study from central Nevada that suggests a prominent regressive event within the Eureka Quartzite, previously interpreted to represent local tectonic adjustments, was likely a response to glacio-eustasy.

GEOLOGIC SETTING AND BACKGROUND

Upper Ordovician strata in the Great Basin region represent the mature phase of the Cordilleran passive-margin (miogeoclinal) succession on the basis of the exponential form of the tectonic subsidence curve (e.g., Levy and Christie-Blick, 1991). Passive-margin subsidence was not disrupted on a regional scale until the Late Devonian Antler orogeny. In contrast with sections in eastern Laurentia affected by the Taconic orogeny (Holland and Patzkowsky, 1996), the rate of thermally controlled subsidence in the early Paleozoic of the Great Basin was continually decreasing, and eustatic sea level was beginning to play an increasingly important role in deposition (Bond et al., 1989). Subsidence was greatest in the outer-shelf settings of central Nevada (Finney et al., 1999) examined here (Fig. 1). Two sections in the Monitor and Antelope Ranges were selected for study because they provide key biostratigraphic tie points useful in global correlation (Harris et al., 1979; Finney et al., 1999). The presence of the *undatus-tenuis* conodont zones in the uppermost Copenhagen Formation allows for correlation with Chatfieldian sections east of the Transcontinental Arch (Harris et al., 1979).

METHODS AND RESULTS

The δ^{13}C values (Appendix DR1 and Table DR1[1]) were analyzed by using fine-grained micritic components drilled ($\sim$1 mg powder) from those parts of polished thin-section billets determined to be least altered, following standard petrographic examination (e.g., Saltzman, 2003). Although brachiopods or marine cements are considered most reliable, sequences examined here did not contain a suitable number of horizons with good preservation of such components. Confidence in micrite-based δ^{13}C curves is seen in comparisons with brachiopod-based curves that yield similar overall trends (e.g., Saltzman et al., 2000; Brenchley et al., 2003). Furthermore, δ^{18}O values in our sections (Table DR1 and Fig. DR1, cross plot of δ^{18}O and δ^{13}C, Fig. DR2, stratigraphic plot of δ^{18}O; see footnote 1) do not covary with δ^{13}C in the form expected if primary δ^{13}C values were reset during meteoric diagenesis.

The $\delta^{13}\mathrm{C}_{\mathrm{carb}}$ values for the Antelope Valley

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[1] GSA Data Repository item 2005014, Appendix DR1, Table DR1, and Figures DR1 and DR2, methods and stable isotope ($\delta^{13}\mathrm{C}_{\mathrm{carb}}$, $\delta^{13}\mathrm{C}_{\mathrm{org}}$, δ^{18}O) data, is available online at www.geosociety.org/pubs/ft2005.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

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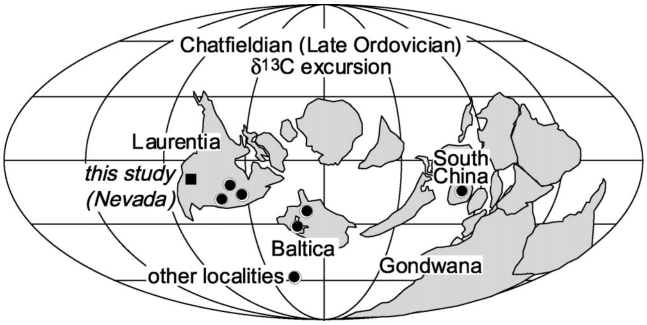

Figure 1. Paleogeographic map (after Scotese and McKerrow, 1990) showing position of study area in Nevada along with other localities that record Chatfieldian (late Mohawkian) positive δ^{13}C excursion (Patzkowsky et al., 1997; Ainsaar et al., 1999; Saltzman et al., 2003; Ludvigson et al., 2004).

Limestone of Whiterockian age are relatively steady at between −2‰ and 0‰ (Fig. 2). A positive shift documented in the overlying Copenhagen Formation reaches a peak of +3.7‰ in the *undatus-tenuis* conodont zone (Harris et al., 1979). We also analyzed 12 Copenhagen samples for $\delta^{13}C_{org}$ after they were reacted completely with HCl and combusted in a furnace attached to a continuous-flow isotope-ratio mass spectrometer, and although the conodont alteration indices for central Nevada (≥3) indicate high alteration temperatures (≥100 °C), our values (∼−27‰ to −26‰; Table DR1 [see footnote 1]) are within a range consistent with prior work (e.g., Patzkowsky et al., 1997).

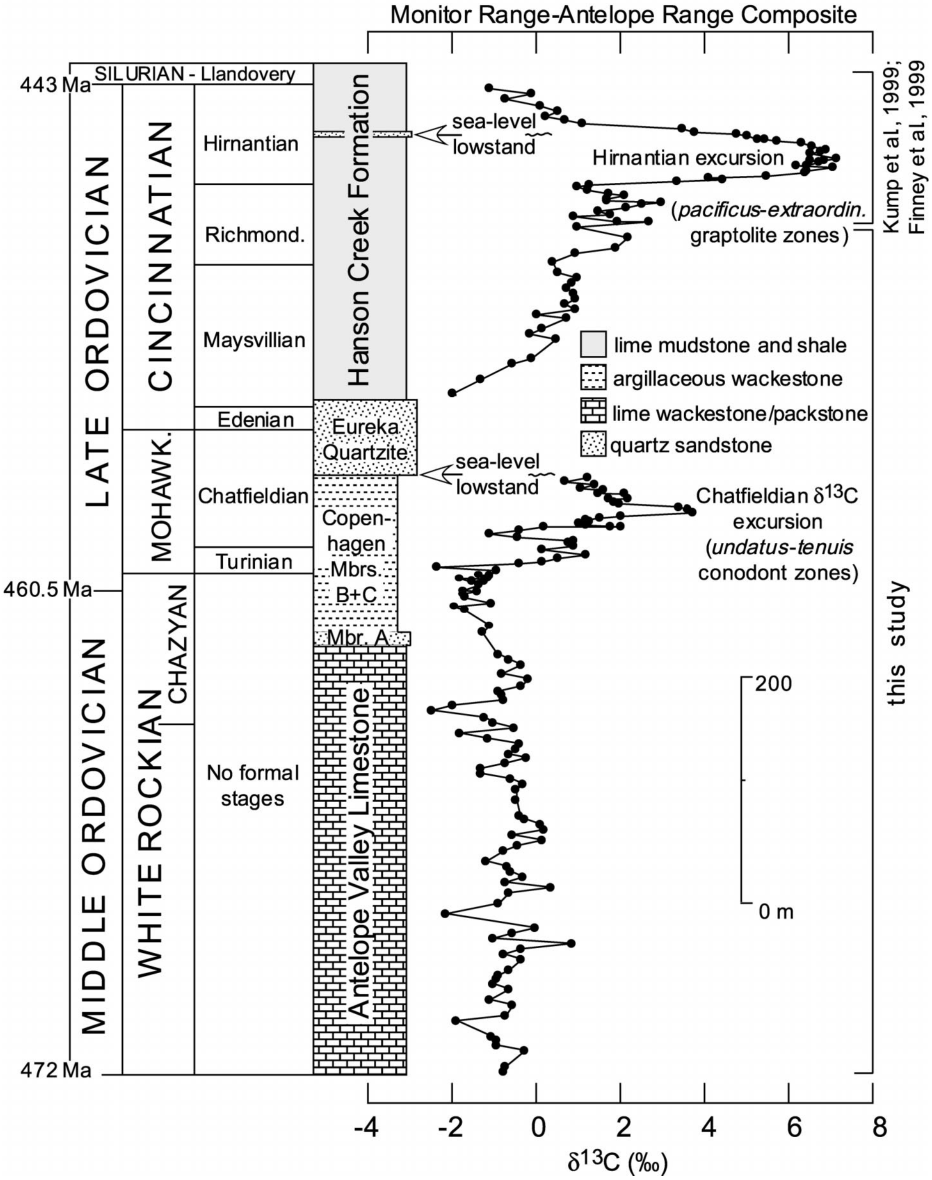

Figure 2. Plot of δ^{13}C and simplified measured section for Monitor Range–Antelope Range composite. Late Ordovician (sensu Webby et al., 2004) stages and biostratigraphic zones are based on Harris et al. (1979) and Finney et al. (1999).

DISCUSSION

Isotope Stratigraphy

The $\delta^{13}C_{carb}$ data from the Copenhagen Formation in Nevada record a positive excursion in the Chatfieldian Stage (middle Mohawkian; Fig. 2) that can be correlated with δ^{13}C peaks observed in eastern Laurentian sections through the use of the *undatus-tenuis* conodont zones (Patzkowsky et al., 1997; Ludvigson et al., 2004). This shift has also been correlated to sections in Estonia (Ainsaar et al., 1999), Sweden, and south China by using the *tvaerensis* conodont and *clingani* graptolite zones (Fig. 1; Saltzman et al., 2003). Global and regional correlations of the Chatfieldian δ^{13}C excursion are also bolstered by K-bentonite stratigraphy (Ainsaar et al., 1999), and its widespread occurrence indicates a significant paleoceanographic event ∼10 m.y. prior to the end of the Ordovician (Fig. 3).

The ∼+3‰ Chatfieldian shift in $\delta^{13}C_{carb}$ was interpreted to reflect a period of enhanced organic carbon burial in (1) rapidly subsiding foreland basins during the Taconic orogeny by Patzkowsky et al. (1997) or (2) other oceanic regions of increased production and preservation (Ainsaar et al., 1999). Although dark organic-rich shales have also been described in the Whiterockian (e.g., Finney, 1986), these older units do not coincide with high δ^{13}C values and may represent condensed sections rather than elevated carbon burial on a global scale. In the expanded section in eastern Laurentia sampled by Patzkowsky et al. (1997) for both $\delta^{13}C_{carb}$ and $\delta^{13}C_{org}$, the Chatfieldian $\delta^{13}C_{carb}$ excursion is also associated with a decrease in the difference between carbonates and organic matter (Δ^{13}C), which suggests that enhanced C_{org} burial resulted in drawdown of pCO_2 (Fig. 3; Kump and Arthur, 1999). Furthermore, Patzkowsky et al. (1997) observed the decrease in Δ^{13}C in the late stages of the $\delta^{13}C_{carb}$ excursion and proposed that organic burial began under highly elevated pCO_2 levels and gradually fell to near ∼8–10 times current levels and into the range of sensitivity for phytoplankton. Such low levels are near the likely threshold in pCO_2 necessary to initiate glaciation in an Ordovician greenhouse climate (Herrmann et al., 2003, 2004). Available $\delta^{13}C_{org}$ data from Nevada are consistent with the results of Patzkowsky et al. (1997) in that the preexcursion (*bicornis* zone) values in Jacobson et al. (1995) average −29‰ to −30‰, whereas our data from the Copenhagen Formation yield ^{13}C-enriched values of ∼−26‰ (Fig. DR2 and Table DR1;

see footnote 1). However, the relatively high degree of thermal alteration in the Great Basin region makes detailed reconstructions of the timing of changes in $\Delta^{13}C$ less reliable, and future study and comparison with the results of Patzkowsky et al. (1997) from eastern Laurentia should focus on less deeply buried sections.

A decline in $p\text{CO}_2$ brought about by organic carbon burial during the Chatfieldian $\delta^{13}C$ excursion (Fig. 3) would have augmented any initial drawdown in the Ordovician associated with the Taconic uplift (e.g., Kump et al., 1999). Indirect evidence for rapid weathering of young basaltic rocks during the early phases of the Taconic may be found in the Sr isotope curve of Shields et al. (2003), which shows a prominent shift toward nonradiogenic values in the several million years (late Whiterockian and early Mohawkian) that led up to the Chatfieldian $\delta^{13}C$ excursion (Fig. 3). A pre-Hirnantian cooling step is a likely consequence of enhanced silicate weathering and high organic carbon burial and may explain the pronounced sedimentologic (i.e., widespread chert and phosphorite deposition; Pope and Steffen, 2003) and faunal changes (Holland and Patzkowsky, 1996) beginning in the early Chatfieldian (Fig. 3). Does the regressive event within the Eureka Quartzite that follows the Chatfieldian $\delta^{13}C$ excursion in central Nevada represent the initiation of continental ice buildup during this cooling episode?

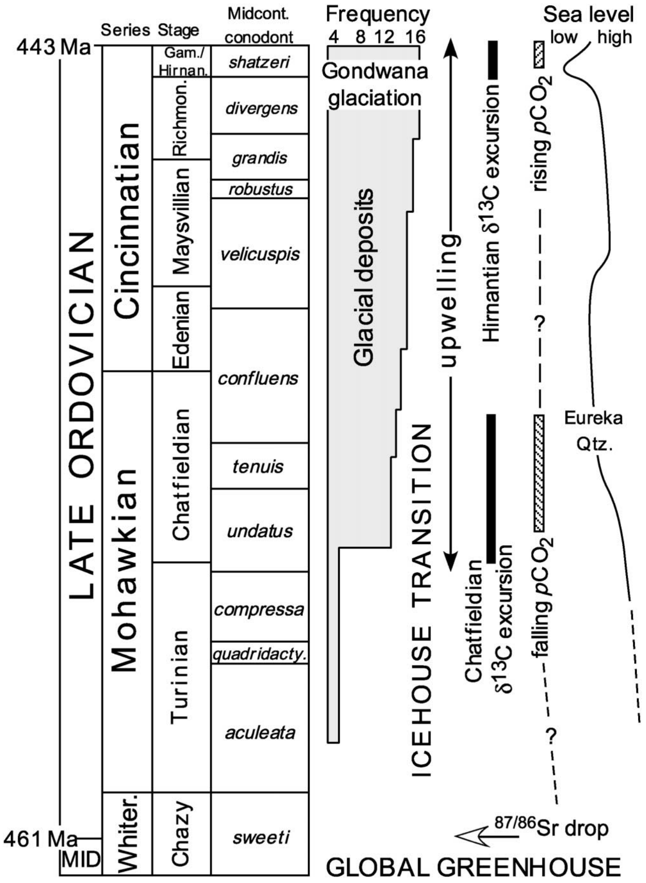

Figure 3. Generalized time chart depicting Middle to Late Ordovician greenhouse to icehouse transition, and relative timing of isotopic and stratigraphic events. Glacial deposits (Frakes et al., 1992) and upwelling (Pope and Steffen, 2003) are plotted alongside simplified eustatic curve and $\delta^{13}C_{carb}$ excursions (black bars). Period of rising and falling $p\text{CO}_2$ (striped bars) are based on $\delta^{13}C_{carb}$-$\delta^{13}C_{org}$ data in Patzkowsky et al. (1997) and Kump et al. (1999). Chatfieldian fall in $p\text{CO}_2$ reflects organic carbon burial, and Hirnantian rise signals decreased silicate weathering rates due to ice-sheet expansion (“weathering hypothesis”). Sr isotope drop is after Shields et al. (2003).

Sequence Stratigraphy

The $\delta^{13}C$ excursion in the upper Copenhagen (Fig. 2) is truncated by a sequence boundary at the contact with the Eureka Quartzite. This Chatfieldian sequence boundary is regionally represented by an intra-Eureka contact (e.g., Zimmerman and Cooper, 1999) and likely marks a regressive pulse superimposed on the long-term (second order) Sauk regression. The Sauk regression spread vast amounts of quartz sand over exposed carbonate platforms throughout North America, which formed the St. Peter Sandstone on the craton and lower part of the Eureka Quartzite (equivalent to the Copenhagen) elsewhere in the Great Basin (Ross et al., 1989) during a period of ~10 m.y. in late Whiterockian and early Mohawkian time (Mussman and Read, 1986). However, because interior North America was reflooded by advancing Tippecanoe seas in the early Mohawkian (Turinian; Ludvigson et al., 2004), the Chatfieldian regressive event that we observe in central Nevada may also be entirely younger than the classically defined Sauk-Tippecanoe sequence boundary. The abrupt nature of the progradation of quartz sand into outer shelf environments represented by the Copenhagen-Eureka transition thus seems to require a separate explanation that is consistent with a third-order sequence boundary. Local tectonic uplift is one possibility, and Cooper and Keller (2001) documented the importance of periodic movement on the ‘‘Las Vegas arch’’ in southern Nevada during the Early to Middle Ordovician. Glacial eustasy provides the most plausible alternative, and in order to determine the relative roles of local vs. global factors in the Copenhagen-Eureka transition, correlative sequences must be examined outside the Great Basin.

Equivalent strata that record the Chatfieldian $\delta^{13}C$ excursion in eastern Laurentia are characterized by relative sea-level rise as a result of flexural subsidence during the Taconic uplift (Patzkowsky et al., 1997). This subsidence event locally overwhelmed eustatic drops that formed prominent sequence boundaries in less rapidly subsiding basins (Holland and Patzkowsky, 1996). Farther west in Laurentia, in the continental-margin facies of Oklahoma, a major Chatfieldian sea-level fall was also interpreted as eustatic by Finney (1986). In Baltica, which represents a separate continental block (Fig. 1) that was undergoing relative tectonic quiescence at this time (Nielsen, 2004), the Chatfieldian $\delta^{13}C$ excursion in middle Caradocian strata of Estonia coincides with a lowstand of sea level that brought fine-grained siliciclastic materials out over the carbonate platform (Ainsaar et al., 1999). In the Oslo area, a conspicuous lowstand during the latest *Diplograptus foliaceus* zone (Nielsen, 2004) can also be correlated with the sea-level drop in Estonia and the Chatfieldian regressive event in central Nevada (Fig. 3), consistent with glacio-eustasy as the driving mechanism.

IMPLICATIONS AND CONCLUSIONS

Study of a Late Ordovician (Chatfieldian) succession in Nevada shows that a positive $\delta^{13}C$ excursion in the upper Copenhagen Formation was closely followed by a regressive event within the prominent Eureka Quartzite. The Chatfieldian $\delta^{13}C$ excursion is a global event and may signal enhanced organic carbon burial that lowered atmospheric $p\text{CO}_2$ to levels near the threshold for ice buildup in the Ordovician greenhouse climate. If confirmed to be eustatic in future investigations, the subsequent sea-level fall we observe may have provided a positive feedback for further cooling and ice buildup either by reducing poleward oceanic heat transport (Herrmann et al., 2004) or by lowering $p\text{CO}_2$ in response to the suppression of shallow-water carbonate production in a Late Ordovician ocean that did not have a compensating mechanism for buffering ocean carbonate-ion concentrations (cf. Ridgwell et al., 2003). The evidence for a widespread Chatfieldian $\delta^{13}C$ excursion and eustatic drop further supports the notion that the transition to an Ordovician icehouse climate occurred ~10 m.y. before the widespread Hirnantian glaciation, ending a long greenhouse period in Earth history that extended back to the Neoproterozoic (Hoffman et al., 1998).

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