Earliest Carboniferous cooling step triggered by the Antler orogeny?

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ABSTRACT

We report a large, positive, carbon isotope excursion in the Kinderhookian Stage of the Lower Mississippian in North America and propose that the excursion is linked to the Antler orogeny. The δ13C excursion reaches +7.1‰ in the upper part of the Joana Limestone in southeast Nevada and correlates with peaks recorded in Europe and elsewhere in North America. This isotopic shift, one of the largest known Phanerozoic δ13C events, is found within the upper part of the Siphonodella isosticha–Upper crenulata conodont Zone; its formation coincided with a time of rapid subsidence of the Joana platform within the Antler foreland basin. We interpret the large changes in δ13C values to reflect enhanced organic carbon burial rates in response to tectonic deepening followed by creation of a restricted water mass at depth in the Antler foredeep and other foredeeps of similar age. The presence of a large δ13C excursion in the upper part of the S. isosticha Zone is consistent with a late Kinderhookian (Tournaissian) glacial episode.

Keywords: carbon isotope, carboniferous, Antler, Kinderhookian, glaciation.

INTRODUCTION

Evidence for a sustained period of glaciation during the late Paleozoic includes the well-known tillsites on Gondwana continents and cyclothemtic deposition in Eurameria (Veivers and Powell, 1987). The main period of ice-sheet development lasted from the middle Carboniferous into the Permian, although uncertainty remains concerning the precise timing of the earliest glacial advances that are notoriously difficult to date (Crowell, 1995). Mii et al. (1999) used evidence for enrichments in heavy carbon and oxygen isotopes to suggest that Carboniferous glaciation may have begun as early as the Kinderhookian. However, these isotopic shifts are only poorly known on a global scale, and their significance for estimates of ice-sheet development lasted from the middle Carboniferous into the Permian, although uncertainty remains concerning the precise timing of the earliest glacial advances that are notoriously difficult to date (Crowell, 1995). Mii et al. (1999) used evidence for enrichments in heavy carbon and oxygen isotopes to suggest that Carboniferous glaciation may have begun as early as the Kinderhookian. However, these isotopic shifts are only poorly known on a global scale, and their significance for estimates of changes in global temperature and ice volumes (as seen in δ18O data) and atmospheric CO2 drawdown (recorded in δ13C values) is unclear.

The causes of this late Paleozoic greenhouse-icehouse transition are also widely debated and center on the relative importance of tectonic versus biological factors and their influence on atmospheric CO2 levels and global temperatures (Crowell, 1995). Veivers and Powell (1987) suggested that orogenic uplift at midlatitudes associated with the formation of the supercontinent Pangaea may have triggered the late Paleozoic ice age, in part by providing high-altitude regions that served as the locus of large ice sheets. Berner (1990) recognized the critical role that the evolution of vascular land plants likely played in the Permian-Carboniferous glaciation through their intensification of chemical weathering rates and enhancement of organic carbon burial. Positive δ13C values in marine carbonates during the Permian-Carboniferous are taken as evidence for high rates of organic carbon burial in coal swamps; these high rates are thought to have played a role in drawdown of atmospheric CO2 levels and glaciation (Berner, 1990).

Here we report evidence for a major, positive, δ13C excursion to +7‰ in the Early Carboniferous (Kinderhookian)—one of the largest known Phanerozoic δ13C events—and suggest a link with the low-latitude Antler orogenic belt and rapid subsidence in the foreland of western Nevada. Our focus on δ13C values in investigating Early Carboniferous paleoclimates is based in part on the good correlation between positive shifts in both δ13C and δ18O and the main episodes of glaciation in the Late Ordovician and middle Carboniferous (Brenchley et al., 1994; Mii et al., 1999), as well as modeling experiments linking high rates of organic carbon burial to drawdown of atmospheric CO2 and global cooling (Berner, 1990; Gibbs et al., 1997).

METHODS AND DATA

Stable isotope (δ13C and δ18O) analyses of Carboniferous brachiopods have yielded consistent results from time-equivalent stratigraphic intervals on separate continents (Bruckschen and Veizer, 1997; Mii et al., 1999), but brachiopods are commonly not continuously available for high-resolution chemostratigraphy. This is the case in much of the Kinderhookian and Osagean intervals targeted in this study, and we have selected fine-grained, micritic components as an alternative. Several authors have demonstrated that δ13C values are essentially rock buffered during the diagenetic processes that typically affect marine carbonates (Banner and Hanson, 1990). For example, an excursion in Upper Cambrian rocks is particularly robust and has survived dolomitization (Saltzman et al., 1998; Glumac and Walker, 1998) and even Mississippi Valley–type mineralizing fluids (He, 1995). Preservation of secular trends in δ13C from dominantly micritic limestones of Late Ordovician (Kump et al., 1999) and Late Devonian age (Wang et al., 1996) has also been demonstrated. Micrites for this study were micropneumated from polished slabs by using a microscope-mounted drill assembly. Analytical error for δ13C and δ18O was ±0.04‰. We report stable isotope results from southeast Nevada that make up one of the clearest well-dated sections of Kinderhookian carbonates in North America.

Joana Limestone, Southeast Nevada

In eastern Nevada and western Utah, the Joana Limestone (Kinderhookian and earliest Osagean) displays thickness and facies trends attributable to deposition in a foreland-basin setting during the Antler orogeny (Giles, 1996). We studied a particularly thick section of the Joana in the eastern Parahangat Range, southeast Nevada (Fig. 1), where it can be sub-Veevers and Powell (1987) suggested that orogenic uplift at midlatitudes associated with the formation of the supercontinent Pangaea may have triggered the late Paleozoic ice age, in part by providing high-altitude regions that served as the locus of large ice sheets. Berner (1990) recognized the critical role that the evolution of vascular land plants likely played in the Permian-Carboniferous glaciation through their intensification of chemical weathering rates and enhancement of organic carbon burial. Positive δ13C values in marine carbonates during the Permian-Carboniferous are taken as evidence for high rates of organic carbon burial in coal swamps; these high rates are thought to have played a role in drawdown of atmospheric CO2 levels and glaciation (Berner, 1990).

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divided into three distinct facies associations: a lower unit (10 m thick) of fossiliferous wackestone and calcareous shale that disconformably overlie the Famennian Pilot Shale; a middle unit (35 m thick) of massive, cliff-forming, crinoidal packstone and peloidal grainstone; and an upper succession (200 m thick) of predominantly dark-colored, fetid wackestone and argillaceous lime mudstone (Fig. 2). The Joana Limestone is overlain by fine-grained siliciclastic rocks of the Chainman Shale.

At the base of the Joana Limestone (Fig. 2), the δ13C values are near 0‰ and climb to a peak of +7.1‰ toward the middle of the formation within the dark-colored, fetid wackestone facies. This shift is constrained by conodont collections to occur within the upper part of the upper Kinderhookian Siphonodella isosticha—Upper crenulata Zone (Fig. 2; Singler, 1992). A second rise above +6‰ appears to occur within the lower Osagean Gnathodus typicus Zone, on the basis of a collection containing a single specimen of G. typicus M2 (Fig. 2; Singler, 1992). The δ13C values then fall back toward +4‰ in strata between the collection containing G. typicus M2 and a younger horizon containing Gnathodus cuneiformis, which is also diagnostic of the G. typicus Zone (Singler, 1992). The accompanying δ18O trends show a positive shift from values between –4‰ and –7‰e to values between –3‰e and –2‰e near the δ13C peak of +7‰.1

CORRELATIONS AND DISCUSSION
Carbon Isotope Stratigraphy

The δ13C curves for the Early Carboniferous were published by Bruckschen and Veizer (1997) for western Europe and by Mii et al. (1999) for the Midcontinent of North America. These curves show distinct peaks in the upper Kinderhookian (middle Tournaisian), which suggests that the shift we recognize in the upper part of the S. isosticha Zone in Nevada (Joana Limestone) may have global significance (Fig. 3). Mii et al.’s (1999, p. 965) “brief and curious peak” to values >+6‰ (Fig. 3) comes from brachiopods

1GSA Data Repository item 200040. Plots of carbon and oxygen isotopic trends, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/drpint.htm.

![Figure 2. δ13C (PDB—Peedee belemnite) results from Lower Mississippian Joana Limestone, Pahranagat Range, southeastern Nevada (see Fig. 1). Arrows indicate diagnostic conodont collections documented in Singler (1992), which place δ13C peak (to +7.1‰) within S. isosticha Zone.](image-url)
Other factors to consider in the mechanism for the large positive $\delta^{13}C$ excursion include the extremely high sedimentation rates determined for rapidly subsiding flysch troughs during this time, which may have contributed to high rates of organic carbon burial by rapidly sequestering organic matter beneath the oxic zone of the sediment column (Derry et al., 1992). For example, Link et al. (1996) documented >3 km of sediments deposited during the $S. isosticha$ Zone in central Idaho and estimated sedimentation rates as high as 1400 m/my. during that time. Organic-rich deposition in both proximal and distal parts of Antler-type forelands could have been further enhanced if the accretionary prism (e.g., Roberts Mountains allochthon) was partly subaerially exposed and served as a source of locally high nutrient fluxes (particularly if colonized by land plants); however, this notion appears unlikely based on Giles (1996) indication that the allochthon was still submerged in the late Kinderhookian.

**IMPLICATIONS FOR THE TIMING OF LATE PALEOZOIC GLACIATION**

The positive $\delta^{13}C$ shifts during the late Kinderhookian (time scales of ~10^6 yr) in this study may signal episodes of enhanced burial of isotopically light ($^{12}C$ enriched) organic matter in the global oceans (e.g., Arthur et al., 1987). Episodes of high rates of organic carbon burial may be expected to result in drawdown of atmospheric CO2 and lead to global cooling (Vincent and Berger, 1985; Brenchley et al., 1994). This logic supports Mii et al.’s (1999) suggestion that glaciation began in the late Kinderhookian and is also consistent with their evidence for a positive shift in $\delta^{18}O$, which was recognized by Bruckschen and Veizer (1997) in western Europe. The physical evidence for glaciation is seemingly in conflict with this view from isotopic proxies, although we would argue that the available evidence does not rule out a late Kinderhookian glacial advance (Crowell, 1995). For example, Hunicken et al. (1986) and Garzanti and Sciumnach (1997) showed that late Paleozoic glacial deposits in South America and Tibet, respectively, are at or above a conodont fauna that correlates with the terminal zone of the Famennian ($S. isosticha$ Zone; G. Klapper, 1999, oral commun.). These authors assigned the glacial deposits to the Famennian (the South American deposits) and Visean (the Tibetan deposits; equivalent to part of the Osagean), although a Kinderhookian (Tournaisian) age is equally plausible for both occurrences.

The Carboniferous global sea-level curve of Ross and Ross (1988) also can accommodate a glacial episode in the Tournaisian. Two prominent regressions occurred during the middle to late Kinderhookian: one at the Kinderhookian-Osagean boundary and a second within the Kinderhookian. Although the eustatic signal is complicated in Nevada by the Antler orogeny (Giles, 1996), Silberling et al. (1997) placed a major sequence boundary at the Kinderhookian-Osagean boundary in the upper Joana (elsewhere in Nevada and Utah) and suggested that eustasy was the major control on large-scale depositional sequences in the distal foreland. The Sr isotope curve of Bruckschen et al. (1995) indicates a shift to more radiogenic ratios near the Kinderhookian-Osagean boundary (superimposed on a longer term decline) that could reflect increased continental weathering during sea-level fall; however, tighter biostratigraphic controls will be necessary to evaluate the significance of Sr isotope ratios in the context of Tournaisian paleoceanography.

**CONCLUSIONS**

A major positive $\delta^{13}C$ excursion to +7‰ in Lower Carboniferous (upper Kinderhookian) marine carbonate is recognized in Nevada and correlates with previously recognized excursions in Utah, Iowa, and Belgium (Fig. 3). This event may have been related to collisional tectonics at low latitudes (Antler orogeny) that resulted in the creation of deep-marine foreland basins with restricted water masses (Fig. 4). High organic carbon burial in rapidly subsiding foreland basins was likely a contributing factor in the onset of the late Paleozoic ice age, which has previously been attributed to...
uplift at midlatitudes (Veevers and Powell, 1987) and organic carbon burial in terrestrial coal swamps associated with the rise of vascular land plants (Berner, 1990).

The 4.7% excursion in the late Kinderhookian is one of the largest in the Phanerozoic and provides important evidence for the highly volatile nature of Paleozoic seawater δ13C ratios (Brenchley et al., 1994; Wang et al., 1996; Saltzman et al., 1998; Azmy et al., 1998). Whereas these previously identified positive excursions all appear to be associated in time with the major biotic crises of the Paleozoic, the Early Mississippian δ13C changes do not show a close coincidence with extinctions. Prominent mass extinctions occurred at the Devonian-Carboniferous and Tournaisian-Visean boundaries (Webster and Groessens, 1990; Ziegler and Lane, 1987), but are not obviously linked with the large excursions in δ13C values that we observe. Further investigation should better constrain the timing of these changes in carbon cycling in the Early Carboniferous with evidence for changes in tectonic uplift, sea level, and faunal diversity.

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Earliest Carboniferous cooling step triggered by the Antler orogeny?: Comment and Reply

COMMENT

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Saltzman et al. (2000) presented an impressive data set showing a pronounced positive excursion in carbon-isotope values that commences in the upper Kinderhookian upper Siphonodella isosticha conodont zone within a limestone section in southern Nevada. They proposed that this isotopic anomaly might correlate with the Antler orogeny, development of the Antler foreland, and sequestration of organic carbon in the sedimentary fill of this foreland. This interpretation is not supported, however, by the nature and age of the initial Mississippian deposits in the typical part of this foreland in Nevada and Utah that is adjacent to the trace of the type Roberts Mountains thrust. Conceivably, the observed δ13C anomaly could signal establishment of some other older and very large along-strike segment of the Antler foreland now made cryptic by terrane dispersion, but the magnitude of the reported carbon-isotope anomaly is so large as to suggest a global cause rather than a local one.

Among the oldest strata of the typical Mississippian Antler foreland, the rhythmically bedded upper (or Harris Canyon) member of the Joana Limestone characterizes the western part of the Sadlick sequence (Fig. 1 here; Silberling et al. 1997) and is best interpreted primarily as a deep-subtidal tempestite, which would not be expected to be extraordinarily rich in organic carbon. Its total thickness never exceeds 200 m and is generally much less than this, and only its lower part is as old as late Kinderhookian. Apparent foredeep equivalents of the upper Joana are the spiculitic-radiolarian lime mudstones included in the Island Mountain Formation (Nichols and Silberling, 1995) forming the basal part of the Diamond Range sequence (Fig. 1; Silberling et al., 1997). They might have had higher total organic carbon values, but they range from only a few tens of meters to no more than 200 m in thickness. A simple mass balance shows the problem with the proposed scenario. If the total mass of carbon in the Mississippian ocean was similar to that of the modern ocean, then increasing the δ13C of the world ocean from +2‰ to +6‰ (Saltzman, 2000, Fig. 3) would have required that −15‰ of the ocean’s δ13C or −6 × 1013g C (Holland, 1978, Table 6-7) be sequestered in the Antler foredeep (assuming δ13Corg = −21‰) during the late Kinderhookian. To explain the observed carbon-isotope anomaly, a relatively large basin, 1000 km × 200 km in area, would have to contain 570 m of sediment averaging 2% total organic carbon, an unrealistically high value.

Only in the thick, mostly pelitic, foredeep deposits of the Dale Canyon Formation, which forms the bulk of the Diamond Range sequence, could significant amounts of organic carbon have been buried. Possibly, synorogenic, pelitic foredeep deposits correlative with even the lower Joana Limestone of the Morris sequence might occur in proximal, Antler-disrupted parts of the Dale Canyon Formation (Fig. 1). However, the widespread, thin, open-marine platform carbonate rocks of the Morris sequence bear no evidence of flexural tectonic control of their deposition, and Kinderhookian conodonts from the Diamond Range sequence reported in the literature as being older than the upper S. isosticha zone are commonly associated with Devonian forms and can be interpreted as having been reworked from the Morris sequence (Nichols and Silberling, 1995). In the back-buige area, the rocks showing the most pronounced effects of restriction and partly hyposaline deposition, and most suggestive of flexural topographic relief, are those of the Osagean to Meramecian (mid-Mississippian) Needle Siltstone or Woodman Formation in the upper part of the Sadlick sequence (Fig. 1). Incipient development of the typical segment of the Antler foreland may have commenced during the late Kinderhookian, but generation of a major Mississippian foredeep related to Antler orogenesis, and deposition of the thick, mainly pelitic, potentially carbon-rich deposits of the Dale Canyon Formation within the Diamond Range sequence, may not have begun until the Osagean—too late to explain the carbon-isotope excursion reported by Saltzman et al. (2000).

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Figure 1. Schematic cross section along belt A–A′ across eastern Nevada and western Utah showing strata deposited in Antler foreland before, during, and after Mississippian Roberts Mountains thrusting, Diamond Range and Sadlick sequences are interpreted to be correlative with one another and to be principal Mississippian deposits recording thrust-related flexural tectonics. Vertical exaggeration about ×250. Adapted from Silberling et al. (1997).
Silberling, Jewell, and Nichols raise important points concerning the carbon storage capacity and age estimates of Antler foreland basin deposits in Nevada and Utah which bear on the interpretation of a large $\delta^{13}C$ ($+7\%e$) peak recorded in carbonates of late Kinderhookian and early Osagean age in North America and western Europe (Saltzman et al., 2000). The steady-state isotopic mass balance for a $\delta^{13}C$ shift of $\pm 4\%e$ to $5\%e$ indicates at least a 50% to 70% increase in fraction of carbon buried as organic matter ($f_{\text{org}}$); if we use average Phanerozoic values for masses and fluxes of carbon in Kump and Arthur (1999) and a 2 m.y. duration for the $\delta^{13}C$ event, this translates into roughly $1.5 \times 10^{19} \text{g}$ of excess carbon sequestered in the global oceans (or terrestrial biosphere). This likely represents a maximum value for excess carbon storage (compare with the number of $6 \times 10^{18} \text{g}$ used by Silberling et al.), reflecting the relatively large total carbon burial flux used by Kump and Arthur (1999) as compared to others (e.g., four times larger than the value in Shackleton, 1987). Note that these calculations assume constant values for $\delta^{13}C$ of the riverine input and the photosynthetic discrimination factor, $\delta^{13}C_{\text{carb}} = \delta^{13}C_{\text{org}}$. The challenge, which is not unique to this Lower Mississippian $\delta^{13}C$ event, is to try to account for the excess carbon burial ($10^{18}$ to $10^{20} \text{g C}$) in sedimentary basins worldwide.

Calculation of carbon storage potential, using best estimates of the dimensions of the basin fill ($1000 \text{km} \times 200 \text{km}$) and likely total organic carbon values of $<1\%$ for the ~200-m-thick late Kinderhookian and early Osagean sequences in Nevada and Utah, gives only a fraction of this number (~$1 \times 10^{18} \text{g C}$; 15% of Silberling et al.’s value). This calculation is in accord with our (Saltzman et al., 2000) conclusion that the presence of additional “Antler”-type basins of equivalent age elsewhere in Euramerica are needed to produce a portion of the $\pm 4\%e$ to $5\%e$ global $\delta^{13}C$ shift. Several such basins have been recognized along the length of the Cordilleran margin, from Idaho to the Yukon, including the organic-rich Exshaw Formation in British Columbia, the thick (~900 m), coarse clastics of the Tuttle Formation that crop out over a large area (~750 km × 500 km) of northwestern Yukon, the District of Mackenzie, and east-central Alaska; and the ~500 m “black clastic” unit of the Earn Group in the southern Yukon (Gordey et al., 1987; Smith et al., 1993). The very thick (up to 3 km) accumulations of proximal terrigenous clastics in the Pioneer Mountains of central Idaho (Link et al., 1996), which appear to be similar to what Silberling and others describe as the potentially organic-rich Diamond Range sequence in Nevada, are reasonably well dated to the late Kinderhookian S. isostichica conodont zone, and thus provide key evidence for a rapidly subsiding basin that formed during the $\delta^{13}C$ excursion outside of the Nevada-Utah foreland and within which significant amounts of organic matter were likely buried rapidly below the oxic zone of the sediment column. Furthermore, I am aware of no detailed biostratigraphic information that precludes an early Osagean age for potentially organic-rich parts of the Dale Canyon Formation, consistent with the $\delta^{13}C$ peak ($>+6\%e$) in the upper part of the Joana Limestone in the Pahranagat Range that is dated to the typicus conodont zone. Clearly, more detailed information concerning the ages, basin fill dimensions, and total organic carbon values for all “Antler”-type deposits in Euramerica (including the Diamond Range and Joana sequences) is needed to better estimate how much carbon was buried during the time of the carbon isotope excursion, and this work is in progress.

If the potential for carbon storage in basins globally during the late Kinderhookian and early Osagean falls short of the number required by isotopic mass balance, as Silberling et al. seem to suspect, and I am inclined to agree with, based on preliminary calculations using the fluxes in Kump and Arthur (1999), then we must look to alternative hypotheses for $\delta^{13}C$ isotopic enrichment, or question the validity of the steady-state values for masses and fluxes of carbon in the early Carboniferous. Indeed, the target value of $10^{19}$ to $10^{20} \text{g C}$ we seek to account for would be an overestimate if the total throughput of carbon was significantly less in the Early Mississippian (i.e., lower rates of volcanism and riverine carbon input), or if the increase in $\delta^{13}C$ resulted in part from a positive shift in the carbon isotopic composition of the riverine flux in response to a relative increase in global carbonate weathering. Enhanced carbonate weathering worldwide is consistent with evidence for a sea-level drop (glacio-eustatic?) near the Kinderhookian-Osagean boundary in Euramerica. These remain largely untested ideas, but are clearly worth exploring in the context of the greenhouse-icehouse transition of the middle to late Paleozoic and its possible relation to collisional tectonics and carbon cycling.

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