

Earliest Carboniferous cooling step triggered by the Antler orogeny?

Matthew R. Saltzman*
Luis A. González

Department of Geoscience, University of Iowa, Iowa City, Iowa 52242, USA

Kyger C Lohmann Department of Geological Sciences, University of Michigan, Ann Arbor, Michigan 48104, USA

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 $\delta^{13}\text{C}$ excursion reaches +7.1‰ in the upper part of the Joana Limestone in southeast Nevada and correlates with peaks recognized in Europe and elsewhere in North America. This isotopic shift, one of the largest known Phanerozoic $\delta^{13}\text{C}$ 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 $\delta^{13}\text{C}$ 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 $\delta^{13}\text{C}$ excursion in the upper part of the *S. isosticha* Zone is consistent with a late Kinderhookian (Tournaisian) 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 tillites on Gondwana continents and cyclothem deposition in Euramerica (Veevers 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 changes in global temperature and ice volumes (as seen in $\delta^{18}\text{O}$ data) and atmospheric CO_2 drawdown (recorded in $\delta^{13}\text{C}$ 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 CO_2 levels and global temperatures (Crowell, 1995). Veevers and Powell (1987) suggested that orogenic uplift at midlatitudes associated with the formation of the supercontinent Pangea 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 $\delta^{13}\text{C}$ 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 CO_2 levels and glaciation (Berner, 1990).

Here we report evidence for a major, positive, $\delta^{13}\text{C}$ excursion to +7‰ in the Early Carboniferous (Kinderhookian)—one of the largest known Phanerozoic $\delta^{13}\text{C}$ events—and suggest a link with the low-latitude Antler orogenic belt and rapid subsidence in the foreland of western North America. Our focus on $\delta^{13}\text{C}$ values in investigating Early Carboniferous paleoclimates is based in part on the good correlation between positive shifts in both $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ 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 CO_2 and global cooling (Berner, 1990; Gibbs et al., 1997).

METHODS AND DATA

Stable isotope ($\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) 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 $\delta^{13}\text{C}$ 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 $\delta^{13}\text{C}$ 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 microsampled from polished slabs by using a microscope-mounted drill assembly. Analytical error for $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ was $\leq 0.04\text{‰}$. We report stable isotope results from southeastern Nevada that make up one of the thickest 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 Pahrnagat Range, southeast Nevada (Fig. 1), where it can be sub-

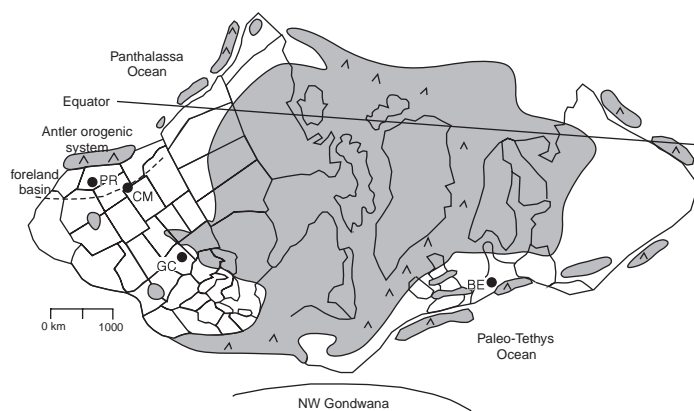


Figure 1. Early Carboniferous paleogeography (Kinderhookian–early Osagean or Tournaisian) after Witzke (1990), showing localities discussed in text. Filled circles (PR—Pahrnagat Range, Nevada; GC—Gilmore City, Iowa; CM—Crawford Mountains, Utah; BE—Dinant basin, Belgium) are sites that display large, positive, $\delta^{13}\text{C}$ changes in upper Kinderhookian carbonates (see Figs. 2 and 3). Land areas are shaded; carets indicate tectonically active areas.

*E-mail: matthew-saltzman@uiowa.edu.

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divided into three distinct facies associations: a lower unit (10 m thick) of fossiliferous wackestone and calcareous shale that disconformably overlies 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 $\delta^{13}\text{C}$ 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 $\delta^{13}\text{C}$ 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 $\delta^{18}\text{O}$ trends show a positive shift from values between –4‰ and –7‰ to values between –3‰ and –2‰ near the $\delta^{13}\text{C}$ peak of +7.1‰.¹

CORRELATIONS AND DISCUSSION

Carbon Isotope Stratigraphy

The $\delta^{13}\text{C}$ 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/drprint.htm.

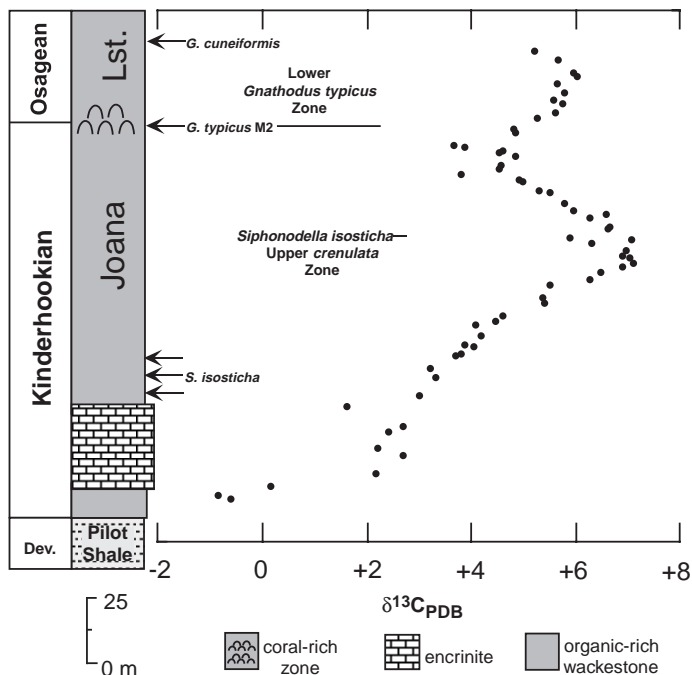


Figure 2. $\delta^{13}\text{C}$ (PDB—Peedee belemnite) results from Lower Mississippian Joana Limestone, Pahrnagat Range, southeastern Nevada (see Fig. 1). Arrows indicate diagnostic conodont collections documented in Singler (1992), which place $\delta^{13}\text{C}$ peak (to +7.1‰) within *S. isosticha* Zone.

in the upper Kinderhookian Gilmore City Formation in northern Iowa (Fig. 1), which contains the *S. isosticha* Zone (Webster and Groessens, 1990). In western Europe, Bruckschen and Veizer's (1997) $\delta^{13}\text{C}$ excursion to values >+6‰ (Fig. 3) occurs within the Tn 3a faunal zone of the middle Tournaisian, which correlates with the upper part of the *S. isosticha* Zone in Nevada (Webster and Groessens, 1990). Additional evidence for a late Kinderhookian positive $\delta^{13}\text{C}$ excursion comes from studies of the Lodgepole Limestone in Utah and Wyoming (Fig. 3; Budai et al., 1987), which has been shown to contain abundant *S. isosticha* Zone conodonts (Chen et al., 1994). Resolution of this excursion into two distinct peaks on either side of the Kinderhookian-Osagean boundary (in the upper part of the *S. isosticha* Zone and lower part of the *G. typicus* Zone) seems possible based on the basis of the curve from the Joana Limestone (Fig. 3); however, the final determination must await more detailed sampling in other regions for both carbon isotopes and conodonts.

The potential significance of the +7‰ $\delta^{13}\text{C}$ excursion in the upper part of the *S. isosticha* Zone (and perhaps in the lowermost *G. typicus* Zone) is underscored by the fact that global excursions of this magnitude are known from only one other interval during the Phanerozoic, in the Late Ordovician (Brenchley et al., 1994; Kump et al., 1999). An event of this magnitude in the Late Silurian (Azmy et al., 1998) may yet prove global as well. The following discussion focuses on possible causes of the large seawater $\delta^{13}\text{C}$ excursion in the latest Kinderhookian.

Relationship to the Antler Orogeny

We suggest that events associated with the Antler orogeny can in part explain the $\delta^{13}\text{C}$ excursion observed in the late Kinderhookian. Conodont collections from flysch and adjacent platform-carbonate sequences in the Antler foreland basin in the western United States date the major period of subsidence associated with the Antler orogeny to the *S. isosticha* Zone (Johnson and Pendergast, 1981; Giles, 1996; Link et al., 1996). Regional analysis of the Antler system by Giles (1996) suggests that subsidence occurred in response to thrust loading and the emplacement of the Roberts Mountains allochthon and drove a tectonically induced relative sea-level rise during deposition of the upper Joana Limestone in the foreland. We suggest that this regional deepening generated a restricted water mass at depth and allowed the accumulation of organic carbon in the upper Joana that ultimately drove the oceans toward increasingly positive $\delta^{13}\text{C}$ values (Fig. 4). The allocation emplacement also created a silled basin, which further contributed to restricted circulation. The laminated, organic-rich mudstone and wackestone in the Joana indicate deep water, and model results in the Cretaceous foreland basin in North America have shown that where seaway depths were >300 m oxygen deficiencies could be maintained even during the most severe storms (Jewell, 1993). The presence of “Antler”-type foreland basins filled with organic carbon-rich deposits farther north into Canada (Savoy, 1992) suggests that similarly stratified water masses likely existed outside of Nevada during the Kinderhookian (perhaps also including the partly coeval Marathon foreland basin) and may have contributed to the late Kinderhookian $\delta^{13}\text{C}$ excursion.

In addition to high levels of organic carbon burial in Antler-type forelands, the increases in $\delta^{13}\text{C}$ during the late Kinderhookian may track periods of enhanced carbonate weathering associated with glacio-eustatic falls and tectonic uplift, as outlined by Kump et al. (1999) for the events of the Late Ordovician. This possibility is supported by evidence for large, craton-derived carbonate-clast turbidite fans (Tripson Pass Formation) that constitute the early sediment fill of the Antler foreland basin in Nevada and indicate that forebulge uplift (Fig. 4) and erosion of the thick lower Paleozoic platform carbonate succession were occurring in the Kinderhookian (Frye and Giles, 1997). Additional evidence for a major interval of carbonate erosion can be found farther north in Idaho, where Link et al. (1996) described calciclastic turbidite deposits (Drummond Mine Limestone) interpreted to have been derived from the carbonate platform to the east.

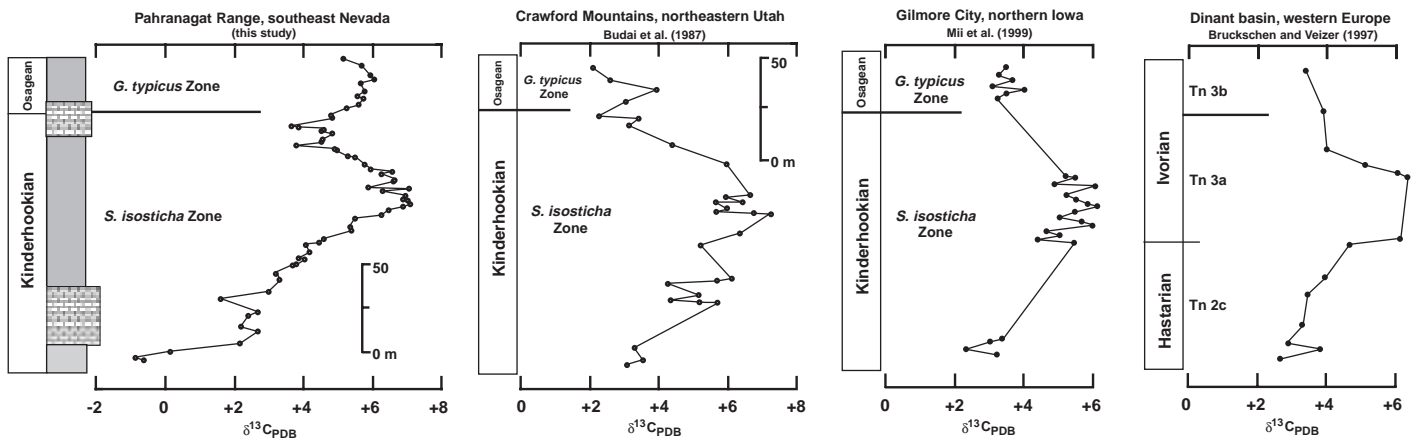


Figure 3. $\delta^{13}\text{C}$ (PDB—Peedee belemnite) results from Joana Limestone, southeastern Nevada, plotted against time-equivalent data sets from Iowa (Gilmore City Formation), Utah (Lodgepole Limestone), and Belgium (see Fig. 1). Line of correlation is top of *S. isosticha* Zone. Nevada and Utah data sets are essentially bulk-rock analyses, whereas Iowa and Belgium data sets represent brachiopod calcite. No scale is given for Iowa and Belgium data sets, and measured section can only be approximated from information in Mii et al. (1999) and Bruckschen and Veizer (1997).

Other factors to consider in the mechanism for the large positive $\delta^{13}\text{C}$ 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/m.y. 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 $\delta^{13}\text{C}$ shifts during the late Kinderhookian (time scales of $\sim 10^6$ yr) recognized 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 CO_2 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 $\delta^{18}\text{O}$, 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 Sciunnach (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 (*Siphonodella praesulcata* Zone; G. Klapper, 1999, oral commun.). These authors assigned the glacial deposits to the Famennian (the South American deposits) and Viséan (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 $\delta^{13}\text{C}$ 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

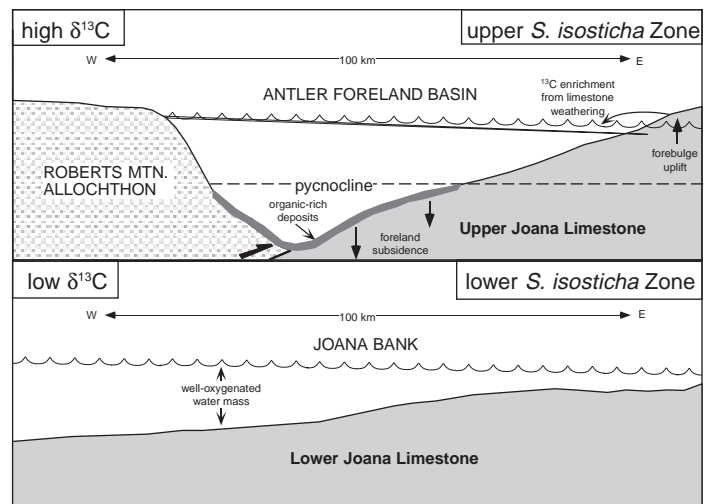


Figure 4. Schematic model relating positive $\delta^{13}\text{C}$ excursion in upper *S. isosticha* Zone to Antler orogeny and formation of restricted water mass at depth in Antler foreland basin. See text for discussion.

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 +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 $\delta^{13}\text{C}$ 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 $\delta^{13}\text{C}$ 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 $\delta^{13}\text{C}$ 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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REFERENCES CITED

- Arthur, M. A., Schlanger, S. O., and Jenkyns, H. C., 1987, The Cenomanian-Turonian oceanic anoxic event: II. Palaeoceanographic controls on organic-matter production and preservation, *in* Brooks, J., and Fleet, A. J., eds., Marine petroleum source rocks: Geological Society [London] Special Publication 26, p. 401–420.
- Azmy, K., Veizer, J., Bassett, M. G., and Copper, P., 1998, Oxygen and carbon isotopic composition of Silurian brachiopods: Implications for coeval seawater and glaciations: Geological Society of America Bulletin, v. 110, p. 1499–1512.
- Banner, J. L., and Hanson, G. N., 1990, Calculation of simultaneous isotopic and trace element variations during water-rock interaction with applications to carbonate diagenesis: *Geochimica et Cosmochimica Acta*, v. 54, p. 3123–3137.
- Berner, R. A., 1990, Atmospheric carbon dioxide levels over Phanerozoic time: *Science*, v. 249, p. 1382–1386.
- Brenchley, P. J., Marshall, J. D., Carden, G. A. F., Robertson, D. B. R., Long, D. F. G., Meidla, T., Hints, L., and Anderson, T. F., 1994, Bathymetric and isotopic evidence for a short-lived Late Ordovician glaciation in a greenhouse period: *Geology*, v. 22, p. 295–298.
- Bruckschen, P., and Veizer, J., 1997, Oxygen and carbon isotopic composition of Dinantian brachiopods: Palaeoenvironmental implications for the Lower Carboniferous of western Europe: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 132, p. 243–264.
- Bruckschen, P., Bruhn, F., Veizer, J., and Buhl, D., 1995, $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic evolution of Lower Carboniferous seawater: Dinantian of western Europe: *Sedimentary Geology*, v. 100, p. 63–81.
- Budai, J. M., Lohmann, K. C., and Wilson, J. L., 1987, Dolomitization of the Madison Group, Wyoming and Utah overthrust belt: *American Association of Petroleum Geologists Bulletin*, v. 71, p. 909–924.
- Chen, X., Derewetzyk, A. N., and Webster, G. D., 1994, Evaluation of the Kinderhookian-Osagean (Lower Mississippian) boundary in the Cordillera, western United States, *in* Embry, A. F., et al., eds., Pangea: Global environments and resources: Canadian Society of Petroleum Geologists Memoir 17, p. 877–890.
- Crowell, J. C., 1995, The ending of the late Paleozoic ice age during the Permian Period, *in* Scholle, P. A., et al., eds., The Permian of northern Pangea: Volume I: Paleogeography, paleoclimates, stratigraphy: Berlin, Springer-Verlag, p. 62–74.
- Derry, L. A., Kaufman, A. J., and Jacobsen, S. B., 1992, Sedimentary cycling and environmental change in the late Proterozoic: Evidence from stable and radiogenic isotopes: *Geochimica et Cosmochimica Acta*, v. 56, p. 1317–1329.
- Frye, M. C., and Giles, K. A., 1997, The Early Mississippian Tripson Pass submarine fan complex, northeastern Nevada: Detritus derived from the forebulge margin of the Antler foreland basin: Geological Society of America Abstracts with Programs, v. 29, no. 6, p. 273–274.
- Garzanti, E., and Sciunnach, D., 1997, Early Carboniferous onset of Gondwanian glaciation and neo-Tethyan rifting in South Tibet: *Earth and Planetary Science Letters*, v. 148, p. 359–365.
- Gibbs, M. T., Barron, E. J., and Kump, L. R., 1997, An atmospheric $p\text{CO}_2$ threshold for glaciation in the Late Ordovician: *Geology*, v. 25, p. 447–450.
- Giles, K. A., 1996, Tectonically forced retrogradation of the Lower Mississippian Joana Limestone, Nevada and Utah, *in* Longman, M. W., and Sonnenfeld, M. D., eds., Paleozoic systems of the Rocky Mountain region: Denver, Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, p. 145–164.
- Glumac, B., and Walker, K. R., 1998, A Late Cambrian positive carbon-isotope excursion in the southern Appalachians: Relation to biostratigraphy, sequence stratigraphy, environments of deposition, and diagenesis: *Journal of Sedimentary Research*, v. 68, p. 1212–1222.
- He, Z., 1995, Sedimentary facies and variation of stable isotope composition of Upper Cambrian to Lower Ordovician strata in southern Missouri: Implications for the origin of MVT deposits, and the geochemical and hydrological features of regional ore-forming fluids [Ph.D. thesis]: Rolla, University of Missouri, 124 p.
- Hunicken, M. A., Goncalves, M., and Lemos, V. B., 1986, Devonian conodonts from the upper Amazon Basin, northwestern Brazil, *in* McMillan, N. J., et al., eds., Devonian of the world, Volume III: Calgary, Alberta, Canadian Society of Petroleum Geologists, p. 479–483.
- Jewell, P. W., 1993, Water-column stability, residence times, and anoxia in the Cretaceous North American seaway: *Geology*, v. 21, p. 579–582.
- Johnson, J. G., and Pendergast, A., 1981, Timing and mode of emplacement of the Roberts Mountains allochthon, Antler orogeny: Geological Society of America Bulletin, v. 92, p. 648–658.
- Kump, L. R., Arthur, M. A., Patzkowsky, M. E., Gibbs, M. T., Pinkus, D. S., and Sheehan, P. M., 1999, A weathering hypothesis for glaciation at high atmospheric $p\text{CO}_2$ during the Late Ordovician: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 152, p. 173–187.
- Link, P. K., Warren, I., Preacher, J. M., and Skipp, B., 1996, Stratigraphic analysis and interpretation of the Mississippian Copper Basin Group, McGowan Creek Formation, and White Knob Limestone, south-central Idaho, *in* Longman, M. W., and Sonnenfeld, M. D., eds., Paleozoic systems of the Rocky Mountain region: Denver, Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, p. 117–144.
- Mii, H., Grossman, E. L., and Yancey, T. E., 1999, Carboniferous isotope stratigraphies of North America: Implications for Carboniferous paleoceanography and Mississippian glaciation: Geological Society of America Bulletin, v. 111, p. 960–973.
- Ross, C. A., and Ross, J. R. P., 1988, Late Paleozoic transgressive-regressive deposition, *in* Wilgus, C. K., et al., eds., Sea-level changes: An integrated approach: Society of Economic Paleontologists and Mineralogists Special Publication 42, p. 227–247.
- Saltzman, M. R., Runnegar, B., and Lohmann, K. C., 1998, Carbon-isotope stratigraphy of the pteropodid biomere in the eastern Great Basin: Record of a global oceanographic event during the Late Cambrian: Geological Society of America Bulletin, v. 110, p. 285–297.
- Savoy, L. E., 1992, Environmental record of Devonian-Mississippian carbonate and low-oxygen facies transitions, southernmost Canadian Rocky Mountains and northwesternmost Montana: Geological Society of America Bulletin, v. 104, p. 1412–1432.
- Silberling, N. J., Nichols, K. M., Macke, D. L., and Trappe, J., 1997, Upper Devonian–Mississippian stratigraphic sequences in the distal Antler foreland of western Utah and adjoining Nevada: U.S. Geological Survey Bulletin 1988-H, 33 p.
- Singler, C. S., 1992, Carbonate petrology and conodont biostratigraphy of the Mississippian carbonate unit, East Pahrangat Range, Lincoln County, Nevada [M.S. thesis]: Pullman, Washington State University, 107 p.
- Veevers, J. J., and Powell, M., 1987, Late Paleozoic glacial episodes in Gondwanaland reflected in transgressive-regressive depositional sequences in Euramerica: Geological Society of America Bulletin, v. 98, p. 475–487.
- Vincent, E., and Berger, W., 1985, Carbon dioxide and polar cooling in the Miocene: The Monterey hypothesis, *in* Sundquist, E. T., and Broecker, W. S., eds., The carbon cycle and atmospheric CO_2 : Natural variations Archaean to present: American Geophysical Union Geophysical Monograph 32, p. 455–468.
- Wang, K., Geldsetzer, H. H. J., Goodfellow, W. D., and Krouse, H. R., 1996, Carbon and sulfur isotope anomalies across the Frasnian–Famennian extinction boundary, Alberta, Canada: *Geology*, v. 24, p. 187–191.
- Webster, G. D., and Groessens, E., 1990, Conodont subdivision of the Lower Carboniferous: *Courier Forschungsinstitut Senckenberg*, v. 130, p. 31–40.
- Witzke, B. J., 1990, Palaeoclimatic constraints for Palaeozoic palaeolatitudes of Laurentia and Euramerica, *in* McKerrow, W. S., and Scotese, C. R., eds., Palaeozoic palaeogeography and biogeography: Geological Society [London] Memoir 12, p. 57–73.
- Ziegler, W., and Lane, H. R., 1987, Cycles in conodont evolution from Devonian to Mid-Carboniferous, *in* Aldridge, R. J., ed., Palaeobiology of conodonts: Chichester, Ellis Horwood Limited, p. 147–163.

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COMMENT

N.J. Silberling

Consulting Geologist, 1235 Estes Street, Lakewood, Colorado 80215, USA

Paul W. Jewell

Department of Geology & Geophysics, University of Utah, Salt Lake City, Utah 84112, USA

K.M. Nichols

Consulting Geologist, 1235 Estes St., Lakewood, Colorado 80215, USA

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 $\delta^{13}\text{C}$ 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

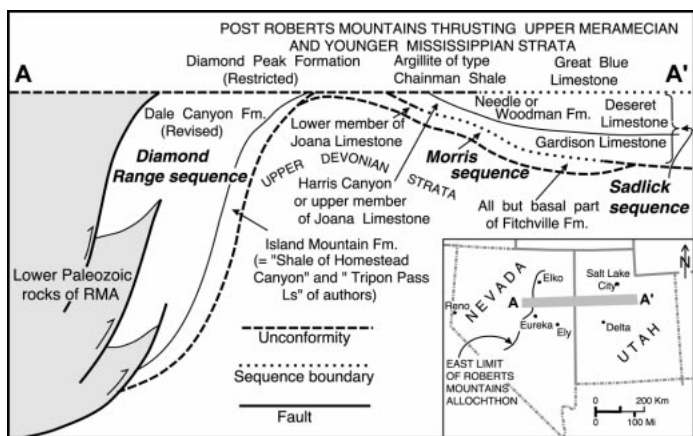


Figure 1. Schematic cross section along belt A–A' across eastern Nevada and western Utah showing strata deposited in Antler foreland before, during, and after Mississippian Roberts Mountains thrusting. Diamond Range and Sadlick sequences are interpreted to be correlative with one another and to be principal Mississippian deposits recording thrust-related flexural tectonics. Vertical exaggeration about $\times 250$. Adapted from Silberling et al. (1997).

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 $\delta^{13}\text{C}$ of the world ocean from $+2\text{‰}$ to $+6\text{‰}$ (Saltzman, 2000, Fig. 3) would have required that $\sim 15\%$ of the ocean's ^{12}C or $\sim 6 \times 10^{18}\text{g C}$ (Holland, 1978, Table 6-7) be sequestered in the Antler foredeep (assuming $\delta^{13}\text{C}_{\text{org}} = -21\text{‰}$) during the late Kinderhookian. To explain the observed carbon-isotope anomaly, a relatively large basin, $1000\text{ km} \times 200\text{ km}$ 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-bulge 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).

REFERENCES CITED

- Holland, H.D., 1978, *The chemistry of the atmospheres and oceans*: New York, Wiley Interscience, 351 p.
- Nichols, K.M. and Silberling, N.J., 1995, Initial foredeep deposits of the mid-Mississippian episode of Antler flexural-loading tectonics in the vicinity of Eureka, Nevada, in Hansen, M.W., and Trexler, J.H., Jr., eds., *Mississippian source rocks in the Antler basin and associated structural and stratigraphic traps*: Reno, Nevada Petroleum Society 1995 Fieldtrip Guidebook, p. 87–96.
- Saltzman, M.R., González, L.A., and Lohmann, K.C., 2000, Earliest Carboniferous cooling step triggered by the Antler orogeny?: *Geology*, v. 28, p. 347–350.
- Silberling, N.J., Nichols, K.M., Trexler, J.H., Jr., Jewell, P.W., and Crosbie, R.A., 1997, Overview of Mississippian depositional and paleotectonic history of the Antler foreland, eastern Nevada and western Utah, in Link, P.K., and Kowallis, B.J., eds., *Proterozoic to Recent stratigraphy, tectonics, and volcanology, Utah, Nevada, southern Idaho, and central Mexico* [Geological Society of America, 1997 Annual Meeting Field Trip Guidebook], Brigham Young University Geology Studies, v. 42, pt. 1, p. 161–196.

REPLY

Matthew R. Saltzman*

Department of Geological Sciences, Ohio State University,
Columbus, Ohio 43210, USA

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 $\delta^{13}\text{C}$ (+7‰) 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 $\delta^{13}\text{C}$ shift of $\pm 4\text{‰}$ – 5‰ indicates at least a 50% to 70% increase in fraction of carbon buried as organic matter (f_{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 $\delta^{13}\text{C}$ event, this translates into roughly 1.5×10^{20} 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 6×10^{18} 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 $\delta^{13}\text{C}$ of the riverine input and the photosynthetic discrimination factor, $\delta^{13}\text{C}$ ($= \delta^{13}\text{C}_{\text{carb}} - \delta^{13}\text{C}_{\text{org}}$). The challenge, which is not unique to this Lower Mississippian $\delta^{13}\text{C}$ event, is to try to account for the excess carbon burial (10^{18} to 10^{20} 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 $\sim 200\text{-m}$ -thick late Kinderhookian and early Osagean sequences in Nevada and Utah, gives only a fraction of this number ($\sim 1 \times 10^{18}$ 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 $\pm 4\text{‰}$ – 5‰ global $\delta^{13}\text{C}$ 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 ($\sim 900 \text{ m}$), coarse clastics of the Tuttle Formation that crop out over a large area ($\sim 750 \text{ km} \times 500 \text{ km}$) of northwestern Yukon, the District of Mackenzie, and east-central Alaska; and the $\sim 500 \text{ m}$ "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. isosticha* conodont zone, and thus provide key evidence for a rapidly subsiding basin that formed during the $\delta^{13}\text{C}$

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 $\delta^{13}\text{C}$ peak ($>+6\text{‰}$) in the upper part of the Joana Limestone in the Pahrangat 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 ^{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} 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 $\delta^{13}\text{C}$ 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.

REFERENCES CITED

- Gordey, S.P., Abbott, J.G., Tempelman-Kluit, D.J., and Gabrielse, H., 1987, "Antler" clastics in the Canadian Cordillera: *Geology*, v. 15, p. 103–107.
- Kump, L.R., and Arthur, M.A., 1999, Interpreting carbon-isotope excursions: Carbonates and organic matter: *Chemical Geology*, v. 161, p. 181–198.
- Link, P.K., Warren, I., Preacher, J.M., and Skipp, B., 1996, Stratigraphic analysis and interpretation of the Mississippian Copper Basin Group, McGowan Creek Formation, and White Knob Limestone, south-central Idaho, in Longman, M.W., and Sonnenfeld, M.D., eds., *Paleozoic systems of the Rocky Mountain region: Denver, Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists*, p. 117–144.
- Saltzman, M.R., Gonzalez, L.A., and Lohmann, K.C., 2000, Earliest Carboniferous cooling step triggered by the Antler orogeny?: *Geology*, v. 28, p. 347–350.
- Shackleton, N.J., 1987, The carbon isotope record of the Cenozoic: History of organic carbon burial and of oxygen in the ocean and atmosphere, in Brooks, J., and Fleet, A.J., eds., *Marine petroleum source rocks: Geological Society [London] Special Publication 26*, p. 423–434.
- Smith, M.T., Dickinson, W.R., and Gehrels, G.E., 1993, Contractual nature of Devonian-Mississippian Antler tectonism along the North American continental margin: *Geology*, v. 21, p. 21–24.

*E-mail: saltzman.11@osu.edu.