Silurian δ13C stratigraphy: A view from North America

Matthew R. Saltzman* Department of Geological Sciences, Ohio State University, Columbus, Ohio 43210, USA

ABSTRACT

Three positive shifts in $\delta^{13}C$ are recognized in well-dated carbonate successions in North America and can be confidently correlated with shifts in the Baltic region by using conodont and graptolite zonations. The $\delta^{13}C$ excursions reach distinct peaks of +3‰ to +4‰ at the ends of the *amorphognathoides* and *siluricus* conodont zones and within the *ludensis* graptolite zone. The three events are associated with the most significant extinction horizons in the Silurian and occur near clastic-carbonate transitions that mark eustatic or oceanographic changes. The magnitudes of the two oldest $\delta^{13}C$ peaks compare well with the Baltic region; however, the end-*siluricus* excursion reaches far greater values of as much as +11‰ in Sweden, likely reflecting local modification of the global seawater signature.

Keywords: Silurian, carbon isotope, Oklahoma, Nevada, sea level, extinction.

INTRODUCTION

Over the past five years, an impressive string of independent publications has documented large fluctuations in carbonate carbon isotope ($\delta^{13}C$) values in the Wenlockian and Ludlovian Series of the Silurian in Europe (Wenzel and Joachimski, 1996; Kaljo et al., 1997; Bickert et al., 1997; Azmy et al., 1998; Wigforss-Lange, 1999). The three positive $\delta^{13}C$ excursions apparent in these studies are not distributed randomly within the Silurian successions, but instead appear to be closely linked with the major biotic, climatic, and eustatic events of the time period (Quinby-Hunt and Berry, 1991; Johnson, 1996; Barrick, 1997; Berry, 1998; Jeppsson, 1998). A close correlation between the $\delta^{13}C$ excursions and positive shifts in $\delta^{18}O$ is also observed in brachiopod studies, compelling some to conclude that glacial episodes likely occurred later in the Silurian than has been revealed by the geologic evidence (e.g., Kump et al., 1999). However, because the $\delta^{13}C$ shifts are thus far well documented only from the Baltic region, their global significance and causal links with climatic and biotic events of the Silurian world remain intriguing yet untested possibilities.

The purpose of this paper is to present the first high-resolution carbonate $\delta^{13}C$ curves from the Silurian of North America that can be tied to recognized faunal boundaries and sea-level changes worldwide by using conodont and graptolite biostratigraphic zonations. The samples come from two of the most well-dated and continuously exposed Silurian sections in North America: Pete Hanson Creek II in central Nevada and Highway 77 in southern Oklahoma (Fig. 1). These sections are complementary in the sense that Pete Hanson Creek II represents one of the thickest Silurian sequences worldwide in which both conodont and graptolite faunas have been described (Berry and Murphy, 1975; Klapper and Murphy, 1975), and the Highway 77 section is among the most densely sampled and well-studied Silurian conodont successions in the world (Barrick and Klapper, 1976, 1992). As a result of this richness of biostratigraphic information, both sections figure prominently in the development of the Global Composite Standard for the Silurian Period using the statistical method of graphic correlation (Kleffner, 1995); in addition, the Highway 77 section serves as the primary source of information in the Silurian $^{87}Sr/^{86}Sr$ curve (Ruppel et al., 1996). The biostratigraphic and geochemical framework in place in Nevada and Oklahoma allows for the highest possible confidence level in making direct comparisons with the previously examined Baltic successions and provides evidence for the global significance of Silurian $\delta^{13}C$ shifts.

SILURIAN δ13C DATA

In order to generate high-resolution curves, $\delta^{13}C$ values were derived from micritic limestones drilled from fresh rock surfaces (Saltzman et al., 2000a, 2000b). Powders were roasted under vacuum at 380 °C to remove volatile contaminants, and samples were reacted with 100% phosphoric acid at 75 °C in an online carbonate preparation line connected to a Finnigan Mat 251 mass spectrometer. The analytical precision based on duplicate analyses and on multiple analyses of NBS19 was ≤0.04‰.

Highway 77 Section

The Highway 77 road cut in the Arbuckle Mountains of Oklahoma provides nearly complete exposures of Silurian strata in parts of the Cochrane, Clarita, and Henryhouse Formations (Fig. 2). The Cochrane consists of skeletal wackestone and packstone that yield conodonts of the *celloni* zone. The Clarita is divided into the Prices Falls Member, a thin shaly unit containing the distinctive *Pterospathodus amorphognathoides* zone conodont fauna, and an upper Fitzhugh Member, a skeletal wackestone and argillaceous mudstone unit containing faunas of the *ranuliformis, amsdeni, stauros,* and *crassa* zones. The Henryhouse consists of marlstone and wackestone that yield faunas of the *crassa, ploeckensis, siluricus, snajdri, eosteinhornensis,* and *detorta* zones. The $\delta^{13}C$ values increase from −2‰ in the lower Cochrane to +4‰ in the Clarita, before decreasing steadily to a low in the lowermost Henryhouse (Fig. 2). They increase again to a distinct peak of +3.5‰ at 5 m above the base of the Henryhouse. Values then decrease to a new baseline of ∼+1‰ and are

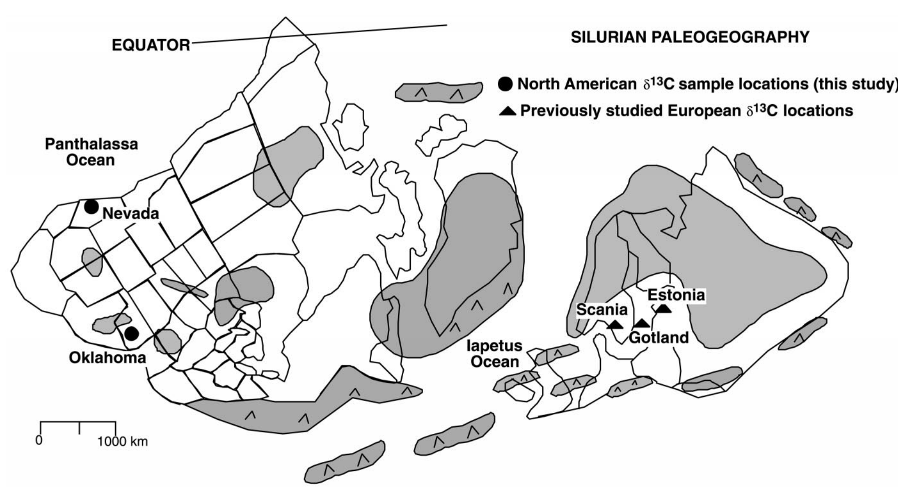

Figure 1. Map (after Witzke, 1990) showing positions of Pete Hanson Creek II section in central Nevada and Highway 77 section in southern Oklahoma, and previously studied localities in Europe discussed in text. Shading is land, triangle pattern is mountains.

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

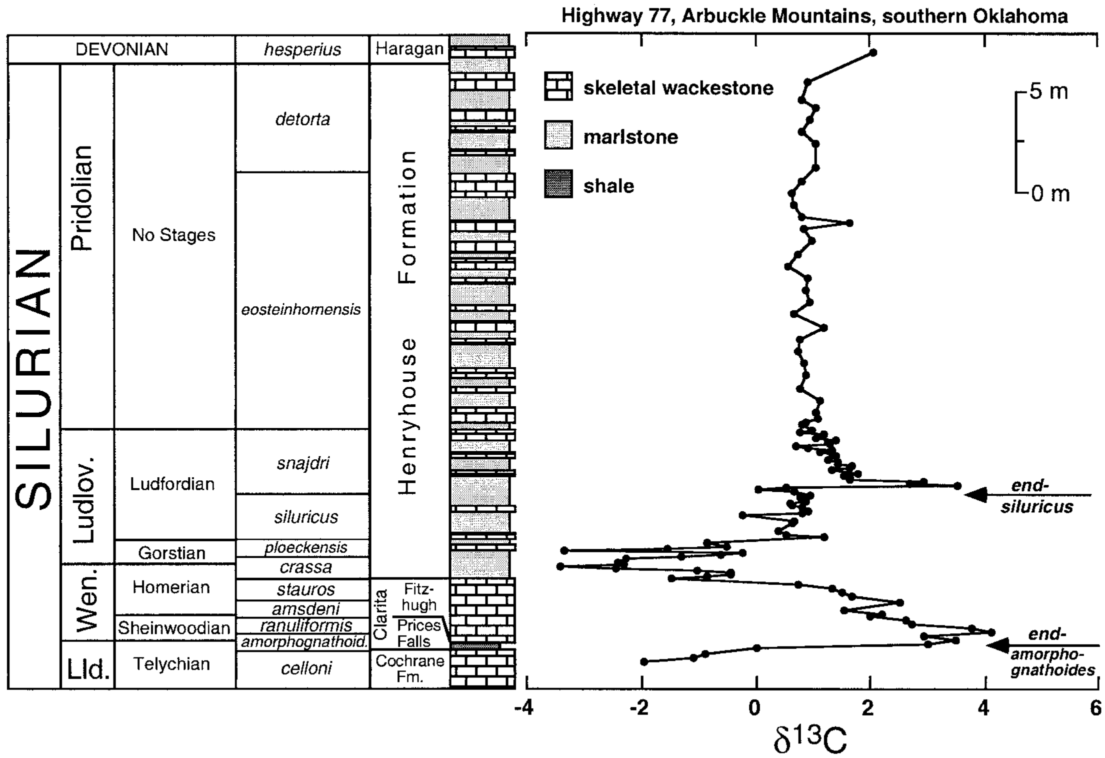

Figure 2. Integrated $\delta^{13}C$ and conodont biostratigraphy (Barrick and Klapper, 1976, 1992) and generalized measured section for Highway 77 section. Arrows point to end-*siluricus* and end-*amorphognathoides* zone $\delta^{13}C$ excursions.

notably stable for the remainder of the Ludlovian and Pridolian[1].

Pete Hanson Creek II Section

A thick late Llandoverian through Pridolian section (Roberts Mountains Formation) is exposed along Pete Hanson Creek in the Roberts Mountains of central Nevada and exhibits a unique association of graptolites and conodonts (Berry and Murphy, 1975; Klapper and Murphy, 1975). The Roberts Mountains Formation consists of argillaceous wackestone and marlstone, and minor pelletal grainstone and skeletal packstone. Unlike the condensed and easily accessible Highway 77 section, discontinuous biostratigraphic sampling at Pete Hanson Creek precludes precise placement of zonal boundaries. Nonetheless, key zonal indicators are present and allow for correlation with Highway 77 and the global standard (Fig. 3). The $\delta^{13}C$ values reach three distinct positive intervals of ~+3‰ in the lower, middle, and upper parts of the Roberts Mountains Formation. The peaks appear to interrupt a steadily rising $\delta^{13}C$ baseline, from −1‰ near the base of the formation to +1‰ at the top (Fig. 3) (see footnote 1).

DISCUSSION

The combined data from Highway 77 in Oklahoma and Pete Hanson Creek II in Nevada provide the first evidence that the Silurian Period in North America was characterized by three carbonate $\delta^{13}C$ excursions, the same number of events recognized in Europe. The following discussion utilizes the interrelationship of globally traceable graptolite and conodont biostratigraphic zones to demonstrate the intercontinental correlation of these $\delta^{13}C$ peaks (Fig. 4) and serves to underscore the close temporal link between the excursions

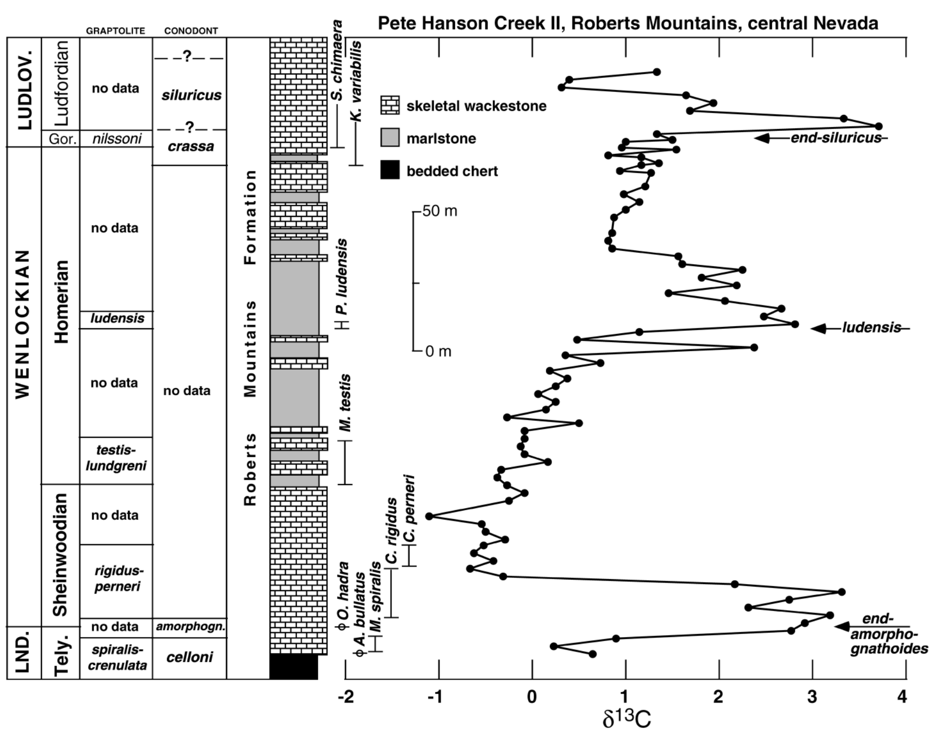

Figure 3. Integrated $\delta^{13}C$ and conodont-graptolite biostratigraphy (Berry and Murphy, 1975; Klapper and Murphy, 1975) and generalized measured section for Pete Hanson Creek II section. Arrows point to end-*siluricus, ludensis,* and end-*amorphognathoides* zone $\delta^{13}C$ excursions. Question marks at boundaries of *siluricus* zone indicate uncertainty in fossil range data and zonal determinations.

[1]GSA Data Repository item 2001081, $\delta^{13}C$ and $\delta^{18}O$ data, 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/ft2001.htm.

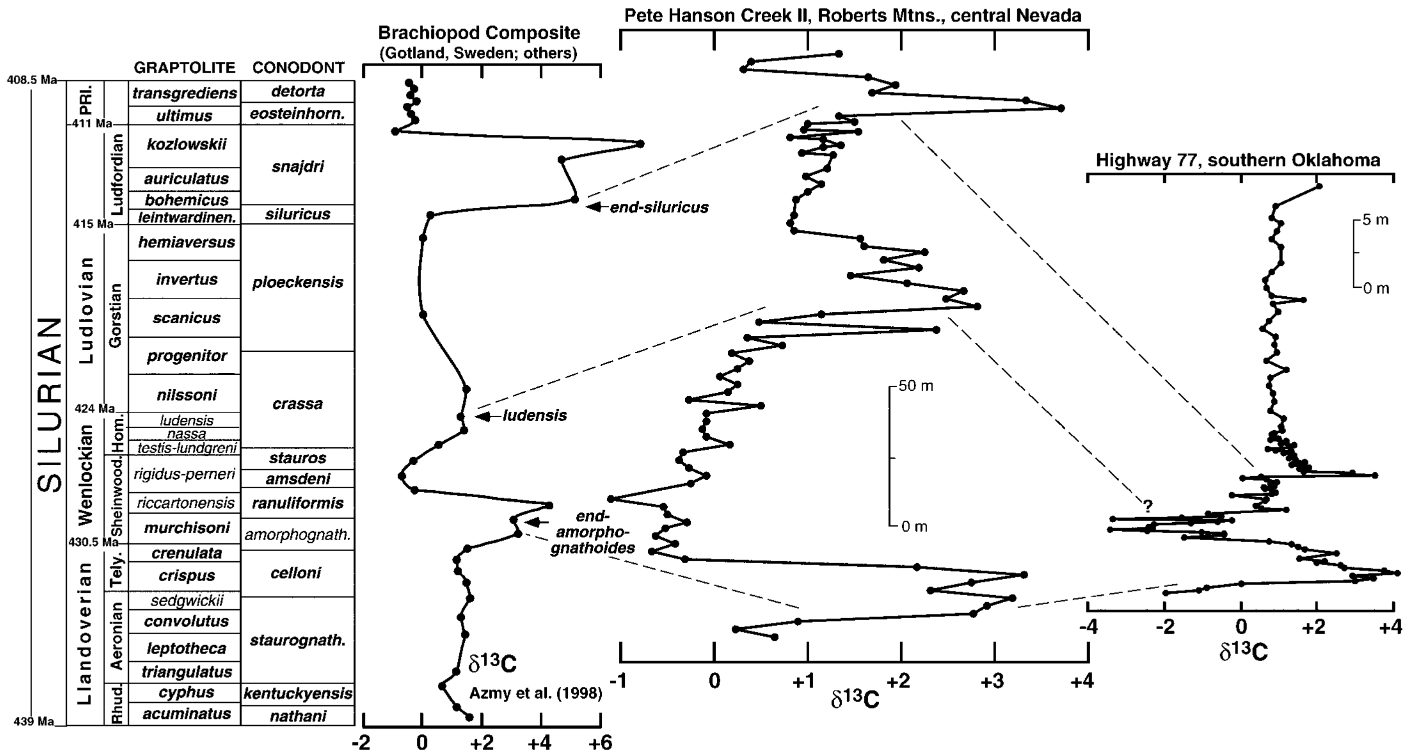

Figure 4. Correlation of Silurian $\delta^{13}C$ shifts between North America and Europe using compiled curve of Azmy et al. (1998), which is based primarily on brachiopod calcite data from Gotland, Sweden.

and the three major biological and eustatic events of the Silurian.

Ireviken (End-*amorphognathoides*) Event

The oldest of the three Silurian $\delta^{13}C$ excursions can be shown to correlate between North America and Europe on the basis of strata bearing the distinctive faunal elements of the *amorphognathoides* conodont zone (Fig. 4). In North America, the rising limb of the positive $\delta^{13}C$ shift is dated to the *amorphognathoides* zone by collections containing (1) *P. amorphognathoides* along with the zonally restricted *Pterospathodus procerus* and *Ozarkodina hadra* in the Prices Falls at Highway 77 (Fig. 2) (Barrick and Klapper, 1976), and (2) *O. hadra* in the lower part of the Roberts Mountains Formation at Pete Hanson Creek (Fig. 3). In Europe, a correlative shift is dated to the *amorphognathoides* zone based on specimens of the name giver along with *P. procerus* in the lower Riga Formation of Estonia (Kaljo et al., 1997; Loydell et al., 1998) and in the base of the Upper Visby Formation in Gotland, Sweden (Jeppsson, 1998; Bickert et al., 1997). Thus, within the current level of biostratigraphic resolution, the onset of the $\delta^{13}C$ excursion is synchronous between North America and Europe, and perhaps Australia (Talent et al., 1993).

The $\delta^{13}C$ excursion that began in the *amorphognathoides* zone peaks at ~+4‰ in the overlying *ranuliformis* zone in Oklahoma, Gotland, and Estonia, and thus cuts across a distinct faunal boundary marking the most significant conodont extinction event in the Silurian—known as the Ireviken (end-*amorphognathoides*) event (Talent et al., 1993; Jeppsson, 1998)—which also marks turnover among graptolites, brachiopods, and trilobites (Chatterton et al., 1990). The Ireviken event coincides with a profound change in the pattern of sedimentation, from the shale-dominated units of the *amorphognathoides* zone worldwide to the pure carbonates of the overlying *ranuliformis* zone, that has been interpreted to reflect the largest magnitude eustatic event of the entire Silurian (Johnson, 1996; Barrick, 1997). This lithologic change and conodont extinction event are unambiguously reflected in southern Oklahoma at the transition between the shaly Prices Falls Member of the Clarita Formation and the pure carbonates of the Fitzhugh Member (Fig. 2). Jeppsson (1998) proposed an alternative hypothesis in which the drop-off in shale deposition reflects a change from humid to dry climatic conditions rather than eustasy. It would thus appear that the trigger for the extinctions and associated $\delta^{13}C$ excursion was related to a eustatic highstand or the transition to a humid climate, both of which could alter oceanic circulation patterns sufficiently to bring anoxic, nutrient-laden waters into the habitat zones of conodonts and graptolites (Quinby-Hunt and Berry, 1991), and increase $\delta^{13}C$ through some combination of enhanced oceanic surface-water production (Wenzel and Joachimski, 1996), increased organic matter burial (Azmy et al., 1998), and advection of ^{13}C-enriched surface waters (Bickert et al., 1997).

Late Wenlockian (*ludensis*) Event

Evidence for a late Wenlockian $\delta^{13}C$ excursion in North America comes from the Pete Hanson Creek section in Nevada, where a shift to ~+3‰ is dated to the *ludensis* graptolite zone (Fig. 3) (Berry and Murphy, 1975). In Europe, sections in Gotland and the Anglo-Welsh basin (Corfield et al., 1992) show a seemingly broader Wenlockian $\delta^{13}C$ excursion spanning the *ludensis* zone as well as the overlying and underlying *lundgreni, nassa,* and *nilssoni* zones (Fig. 4), and a section in Estonia records a shift that is no older than the *nassa* zone (Kaljo et al., 1997). The shift is truncated or missing in southern Oklahoma at a cryptic disconformity (Fig. 2; Barrick, 1997). Despite significant uncertainties in the timing and anatomy of this Wenlockian $\delta^{13}C$ event that preclude a more detailed consideration at this time, it appears to share important similarities with the Ireviken event in that the late Wenlockian marks a major faunal crisis when the graptolites nearly became extinct (Berry, 1998).

Pentamerid (End-*siluricus*) Event

The youngest of three $\delta^{13}C$ excursions in the Silurian peaks at values near +4‰ in the middle Ludlovian of North America and is associated with the third major faunal event of the Silurian known as the Pentamerid, or end-*siluricus*, event (Talent et al., 1993). The $\delta^{13}C$ excursion is most precisely dated at Highway 77 (Fig. 2), where closely spaced conodont collections yield *P. siluricus* (one of the most distinctive of all Paleozoic conodont species) and clearly delineate an extinction event at the transition to the overlying *snajdri* zone (Barrick and Klapper, 1992); peak $\delta^{13}C$ values are recorded ~30 cm above this faunal transition. In Nevada, an ~+4‰ excursion in the Ludlovian is less well dated by multiple horizons bearing *Kockelella variabilis* and an older, pre-*siluricus* age cannot be ruled out at this time (Fig. 3). In Gotland (Fig. 4) and Sweden (Wigforss-Lange, 1999), this $\delta^{13}C$ event peaks just above the end of the *siluricus* zone, and in Latvia (Kaljo et al., 1997), the event spans time equivalent graptolite zones (post-*leintwardinensis*) of the Ludfordian Stage.

The $\delta^{13}C$ excursion at the end of the *siluricus* zone is unique among the three events because previous investigations identifying the shift in the Baltic region (Wenzel and Joachimski, 1996; Bickert et al., 1997; Azmy et al., 1998; Wigforss-Lange, 1999) and Australia (Andrew et al., 1994) suggest a much larger shift of +8‰ to +12‰, compared with North America (Fig. 4). Despite evidence for extreme $\delta^{13}C$ values, the pattern of correlation with a prominent clastic-carbonate transition and extinction is indistinguishable from the end-*amorphognathoides* event (Jeppsson, 1998) and suggestive of a common origin. The most likely explanation for the large variance in the magnitude of the end-*siluricus* shift is local enhancement of a global $\delta^{13}C$ excursion related to nutrient cycling and reservoir effects in highly productive regions of the surface mixed layer (e.g., Murphy et al., 2000). This is supported by the considerable $\delta^{13}C$ variation observed for this event in the Baltoscandian basin; shallow-water sequences dominated by oncolites (+11‰ in Scania and +8‰ in Gotland; Wigforss-Lange, 1999) are much heavier than deeper water sequences (+5‰ in Latvia; Kaljo et al., 1997). An alternative hypothesis, that the large $\delta^{13}C$ peak is missing at a major hiatus in North America, is not consistent with evidence for relatively continuous deposition and an absence of prominent subaerial exposure surfaces in Nevada and Oklahoma. Further study is warranted because values as high as +12‰ have not been recorded for any other time in the Paleozoic, nor has any previously identified $\delta^{13}C$ excursion shown such enormous interbasinal variation (Kump et al., 1999; Saltzman et al., 2000a, 2000b).

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