ABSTRACT
Three positive shifts in δ¹³C 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 δ¹³C excursions reach distinct peaks of +5‰ 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 δ¹³C 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 (δ¹³C) 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 δ¹³C 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 δ¹³C excursions and positive shifts in δ¹⁸O 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 geological evidence (e.g., Kump et al., 1999). However, because the δ¹³C 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 δ¹³C 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 ⁸⁷Sr/⁸⁶Sr 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 δ¹³C shifts.

SILURIAN δ¹³C DATA
In order to generate high-resolution curves, δ¹³C values were derived from micritic lime-
stones 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 re-acted 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 Clarita 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 Pierospathodus amor phognathoides zone conodont fauna, and an upper Fitzhugh Member, a skeletal wackestone and argillaceous mudstone unit containing faunas of the ranuliforms, 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 δ¹³C 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

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notably stable for the remainder of the Ludlovian and Pridolian.  

**Pete Hanson Creek II Section**

A thick late Llandoveryan 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 δ¹³C 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 δ¹³C 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 δ¹³C 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 δ¹³C peaks (Fig. 4) and serves to underscore the close temporal link between the excursions.

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Footnote 1: GSA Data Repository item 2001081, δ¹³C and δ¹⁸O data, is available on request from Documents Secretary, GSA, PO. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2001.htm.
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 Pterosphathodus 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 Robert’s 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 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, 1998), 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 $\sim +3\%$ 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 δ13C 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 δ13C 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 Kockeletella 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 δ13C event peaks just above the end of the siluricus zone, and in Latvia (Kaljo et al., 1997), the event spans time equivalent graphitite zones (post-leinwardinitis) of the Ludfordian Stage.

The δ13C 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 Aus-
tralia (Andrew et al., 1994) suggest a much larger shift of +8‰ to +12‰, compared with North America (Fig. 4). Despite evidence for extreme δ13C values, the pattern of correlation with a prominent clastic-carbonate transition and extinction is indistinguishable from the end-amorphophagoides 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 δ13C excursion related to nutrient cycling and reservoir effects in highly productive regions of the surface mixed layer (e.g., Murphy, 2000). This is supported by the considerable δ13C variation observed for this event in the Baltoscandi-
an basin; shallow-water sequences dominated by oncinites (+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 hy-
thesis, that the large δ13C peak is missing at a major hiatus in North America, is not consistent with evidence for relatively continuous deposition and an absence of prominent sub-
aerial exposure surfaces in Nevada and Oklahoma. Further study is warranted because values as high as +12‰ have not been re-
corded for any other time in the Paleozoic, nor has any previously identified δ13C excursion shown such enormous interbasinal variation (Kump et al., 1999; Saltzman et al., 2000a, 2000b).

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