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# First record of the Hirnantian (Upper Ordovician) $\delta^{13}$C excursion in the North American Midcontinent and its regional implications

STIG M. BERGSTRÖM*‡, MATTHEW M. SALTZMAN* & BIRGER SCHMITZ†

*Department of Geological Sciences, The Ohio State University, Columbus, Ohio 43210, USA
†Department of Geology, GeoBiosphere Science Center, Lund University, Sölvegatan 12, SE-223 62 Lund, Sweden

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**Abstract –** The most prominent of the two major global $\delta^{13}$C excursions in the Ordovician, the Hirnantian $\delta^{13}$C excursion (HICE), which is previously recorded from the uppermost Ordovician in a few sections in Nevada, Quebec, Arctic Canada, Baltoscandia, Scotland and China, is documented for the first time from the North American Midcontinent. Samples through the Girardeau Limestone and Leemon Formation in Missouri and Illinois show elevated $\delta^{13}$C values of + 4 ‰ to + 5 ‰. Although not determined precisely, the beginning of the HICE is likely to be in the upper part of the Orchard Creek Shale, and it ends in the upper Leemon Formation. Being extraordinarily useful chronostratigraphically, the presence of the HICE makes it possible to provide a firm dating of the study interval, whose age has long been controversial. Comparison between the study sections and coeval HICE sequences in North America and Europe show striking similarities, especially in sea-level history, indicating that major local lowstands reflect eustatic sea-level changes. A comparison with Hirnantian diamictite successions in North and South Africa and Argentina suggests that these lowstands correspond to two major Gondwanan glacial episodes.

Keywords: carbon isotope excursion, Hirnantian, Upper Ordovician, Missouri–Illinois, Gondwana glaciation, sea-level changes.

## 1. Introduction

During the last two decades, documentations of the carbon isotope variations in ancient seawater have become a new frontier in local and regional chemostratigraphic research on Ordovician sedimentary rocks. Two prominent, widely distributed, $\delta^{13}$C excursions have so far been documented to be present in the Upper Ordovician Global Series (Webby *et al.* 2004). The oldest one, which is in the North American Chatfieldian Stage (Hatch *et al.* 1987; Ludvigson *et al.* 1996, 2004; Saltzman *et al.* 2003; Young, Saltzman & Bergström, 2004), was first recorded in the Guttenberg Member of the Decorah Formation in Iowa. It has subsequently been found to be quite widespread in North America as well as in coeval strata in northern Europe (Ainsaar, Meidla & Martma, 1999; Ainsaar, Meidla & Tinn, 2004; Saltzman *et al.* 2003; Young, Saltzman & Bergström, 2005). Furthermore, our ongoing studies suggest that it is also present in China and hence, it is likely to have a global distribution. In recent years, this $\delta^{13}$C excursion has commonly been referred to as the Guttenberg isotopic carbon excursion, abbreviated GICE.

An even more widely recorded prominent $\delta^{13}$C excursion is present in the uppermost Ordovician Hirnantian Stage and is now known from several sections in North America (see, e.g. Orth *et al.* 1986; Long, 1993; Ripperdan, Cooper & Finney, 1998; Finney *et al.* 1999; Brenchley *et al.* 1994, 1997, 2003; Melchin, Holmden & Williams, 2003; Brenchley, 2004) as well as in Europe (Marshall & Middleton, 1990; Middleton, Marshall & Brenchley, 1991; Brenchley *et al.* 1994, 1997; Brenchley, Carden & Marshall, 1995; Marshall *et al.* 1997; Underwood *et al.* 1997; Marshall & Brenchley, 1998; Brenchley & Marshall, 1999; Kaljo *et al.* 1999, 2001, 2004*a*,*b*; Brenchley, 2004; Ainsaar, Meidla & Martma, 2004; Ainsaar, Meidla & Tinn, 2004; Männik *et al.* 2004; Meidla *et al.* 2004) and China (Wang *et al.* 1993*b*; Wang, Chatterton & Wang, 1997). The literature on the distribution and cause(s) of this $\delta^{13}$C excursion, which is known as the Hirnantian isotopic carbon excursion, abbreviated HICE, is growing rapidly and a consensus is emerging that it is associated with the Gondwana glaciation. Extensive research shows that this excursion has a global distribution and occupies a biostratigraphically well-defined interval in the graptolite and chitinozoan zone successions (Finney *et al.* 1999; Soufiane & Achab, 2000; Melchin, Holmden & Williams, 2003; Kaljo *et al.* 2004*a*,*b*). As noted by Brenchley *et al.* (2003), it is of extraordinary significance for local and regional high-resolution chronostratigraphy. However, at the present time this usefulness is restricted by the fact that this excursion has so far been investigated at relatively few localities, although these are distributed over four continental plates.

Thus far, the North American records of the HICE are from the Great Basin in Nevada (Finney *et al.* 1999),

‡ Author for correspondence: stig@geology.ohio-state.edu

Anticosti Island in Quebec (Orth *et al.* 1986; Long, 1993; Brenchley *et al.* 2003), northwestern Canada (Wang *et al.* 1993*a*) and the Canadian Arctic (Melchin, McCracken & Oliff, 1991, 2003; Melchin, Holmden & Williams, 2003). The only hint that a geochemical C anomaly might be present in the vast region of the North American Midcontinent has been a record of very high $CO_2$ values in goethite from the Hirnantian Neda Formation in Illinois (Yapp & Poths, 1992). A likely reason why the HICE has previously not been recorded anywhere in the central portion of the North American continent is that Hirnantian strata are missing over most of this region, the uppermost Ordovician and lowermost Silurian being cut out by a prominent unconformity (Berry & Boucot, 1970; Bergström & Boucot, 1988). This is the case in the classic succession of the Cincinnati area in Ohio, Indiana and Kentucky (Grahn & Bergström, 1985), which is the type area of the Cincinnatian Series, the Upper Ordovician in the North American series classification. In this respect, the succession in the Appalachian Mountains in eastern North America may at least locally be more complete stratigraphically than in the Midcontinent. However, the Appalachian uppermost Ordovician consists of sandstones and other clastic rocks that are very poorly fossiliferous and hence incompletely controlled biostratigraphically. An exception to this is a succession with a *Hirnantia* fauna found by Neuman (1968) in Maine, which is the only record of this typical latest Ordovician shelly fauna in the entire Appalachians from Alabama to Newfoundland (Bergström & Boucot, 1988).

It has long been known that the Upper Ordovician/Lower Silurian sequence in the Upper Mississippi Valley in Missouri, Illinois and Iowa is more complete stratigraphically than elsewhere in the Midcontinent, but the precise age of the formations in the systemic boundary interval has remained controversial and the subject of very different interpretations. In an effort to find out if carbon isotope ($\delta^{13}C$) chemostratigraphy could solve the long-standing age problems in the Upper Ordovician/Lower Silurian succession in this region, reconnaissance sampling for $\delta^{13}C$ work was carried out in 2002. This produced positive results which were first briefly reported by Bergström, Saltzman & Ausich (2003). This first recorded occurrence of the HICE in the North American Midcontinent was from the succession in southeastern Missouri but subsequent work has revealed the presence of this excursion also in coeval strata in southwesternmost Illinois. These localities (Fig. 1) are approximately halfway between the previously recorded occurrences in Nevada and Quebec, which are separated by a distance of more than 8000 km. The purpose of the present paper is to describe this geographically quite isolated $\delta^{13}C$ excursion record and discuss its global chronostratigraphic and palaeoceanic ramifications.

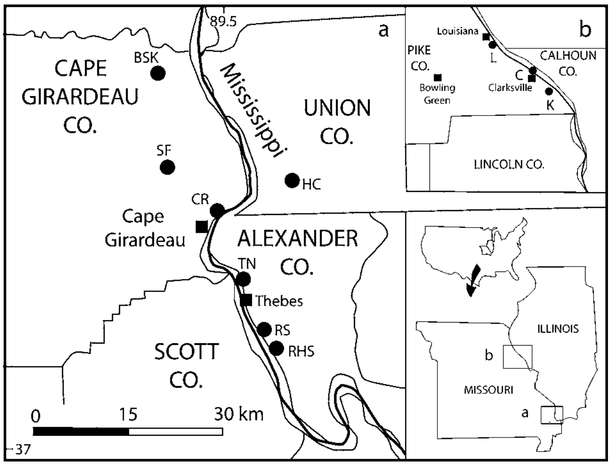


Figure 1. Sketch-map showing location of study localities in (a) the Cape Girardeau region and (b) Pike County, in Missouri and adjacent parts of Illinois. RHS – Rock Springs Hollow S; RS – Rock Springs; TN – Thebes N; CR – Cape Rock; SF – Short Farm; BSK – Blue Shawnee Creek; HC – Harrison Creek; K – Kissenger; C – Clarksville; L – Louisiana. For precise geographic location of these sites, see Appendix 1.

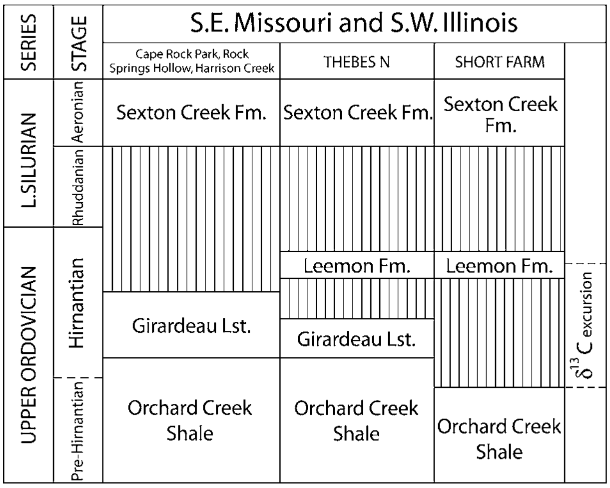


Figure 2. Stratigraphic diagram showing relations of latest Ordovician and Early Silurian formations in Missouri and adjacent parts of western Illinois. Note that based on $\delta^{13}C_{carb}$ evidence, the uppermost Orchard Creek Shale is of Hirnantian age. In this figure, as in other figures, vertical ruling indicates non-deposition.

## 2. Stratigraphic framework

The Ordovician outcrop area in the Upper Mississippi Valley is a classical region in North America for the study of Ordovician sedimentary rocks and faunas. For a comprehensive review of the Upper Ordovician sequence in Minnesota, Iowa and Wisconsin, see Sloan (1987) and for that in Missouri, see Thompson (1991).

Uppermost Ordovician rocks crop out in two areas of eastern Missouri and adjacent parts of Illinois (Fig. 1). In the southeastern outcrop area, which centres in Cape Girardeau County, the uppermost Ordovician includes two shallow-water carbonate formations (Fig. 2), the

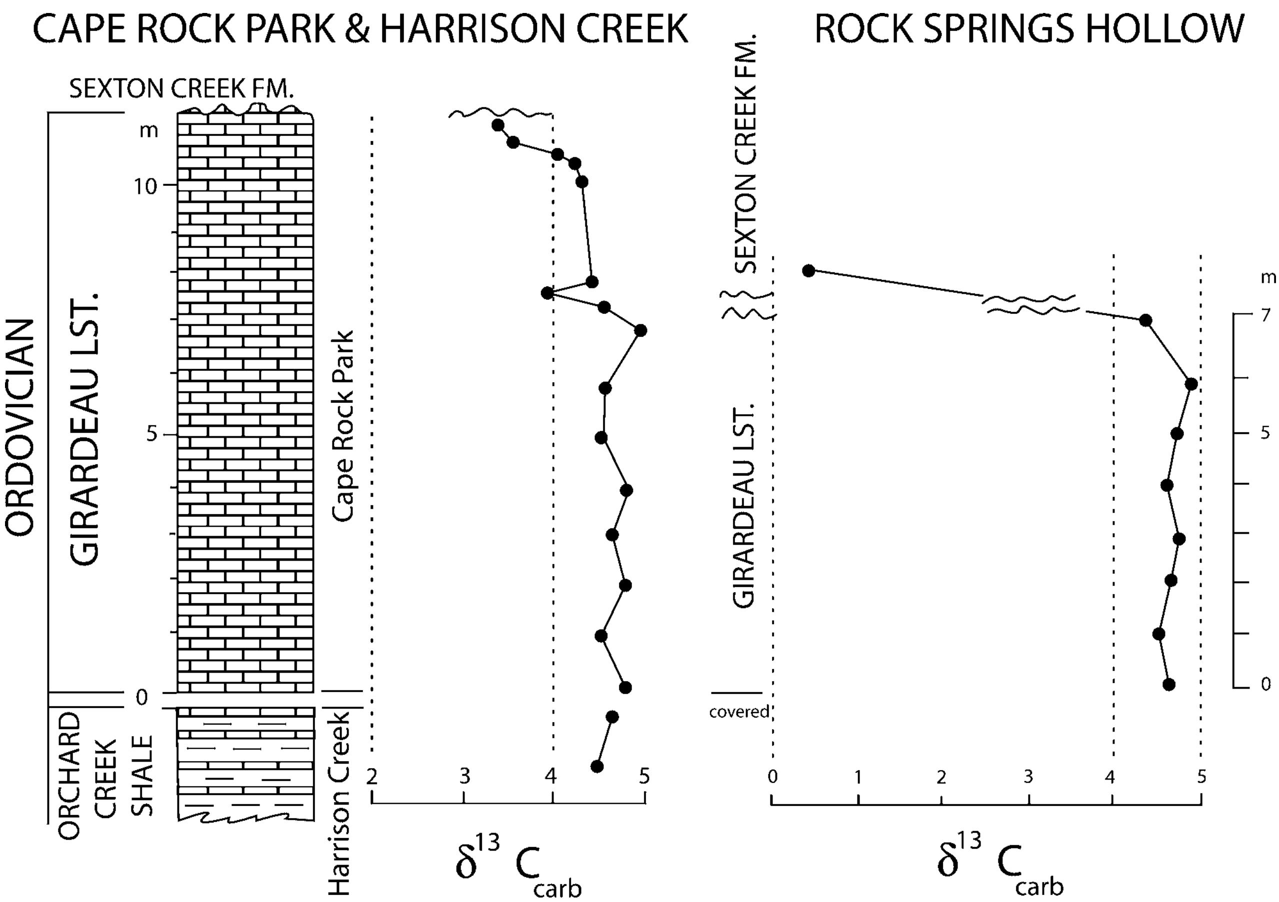


Figure 3. Stratigraphic location of samples and the $\delta^{13}C$ curve for the Cape Rock and Rock Springs sections. Note that the samples from the uppermost Orchard Creek Shale in the Cape Rock columnar section are from Harrison Creek.

Girardeau Limestone and the Leemon Formation (Thompson & Satterfield, 1975; Amsden, 1974, 1986, 1988). These units are also exposed across the Mississippi River in Alexander County in Illinois. In the northeastern outcrop area in Missouri, which is in Pike County, the topmost part of the Ordovician succession includes two thin shallow-water carbonate units, the Noix Oolite and the Cyrene Limestone.

The moderately large shelly faunas collected from the Girardeau Limestone and the Leemon Formation, as well as from the Noix Oolite and the Cyrene Limestone (Savage, 1910, 1913; Amsden, 1974, 1986, 1988; McAuley & Elias, 1990; Young & Elias, 1995), show affinities to the widespread *Hirnantia* fauna at the genus level but they do not contain the brachiopod and trilobite species assemblage typical of that fauna (Rong, 1984), and accordingly, their biostratigraphic significance has remained somewhat uncertain. Conodonts of Ordovician aspect have been described from these units by Satterfield (1971), Thompson & Satterfield (1975) and McCracken & Barnes (1982) and these, as well as the shelly fossils, were interpreted by Amsden & Barrick (1986, 1988) as indicating a latest Ordovician (Hirnantian) age. However, the currently available fossil evidence is not very conclusive regarding the precise age of these formations.

## 3. Stratigraphic successions at the collecting localities

### 3.a. Lithology and stratigraphic sequences

The Girardeau Limestone and the Leemon Formation are exposed in several natural outcrops in the area around Cape Girardeau, Missouri, and across the Mississippi River in southwestern Illinois. We have investigated all the important outcrops, and the location of the study sections is shown in Figure 1 and described in Appendix 1. For schematic stratigraphic columns of the study sections showing sample locations and lithology, see Figures 3–6.

The Girardeau Limestone ranges up to 10–12 m in thickness and is a lithologically uniform succession of light grey to bluish, fine-grained, locally cherty, somewhat irregularly bedded limestone with many thin interbeds of yellowish-weathering grey shale (Thompson, 1991). Shelly fossils are generally sparse except in a few beds. Conodonts are extremely rare in the Girardeau Limestone (Satterfield, 1971) and the known fauna is monospecific, consisting only of the distinctive species *Noixodontus girardeauensis* (Satterfield, 1971).

The Leemon Formation, which ranges in thickness from 0 to 7 m, rests disconformably on the Girardeau Limestone (Fig. 2) with the contact marked at some

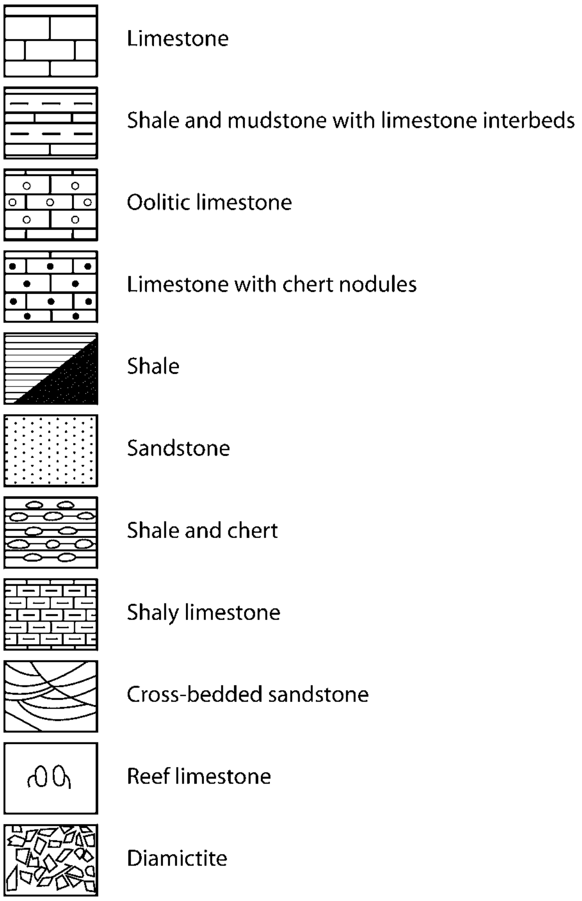


Figure 4. Explanation of lithological patterns used in stratigraphic columns in the figures of the present paper.

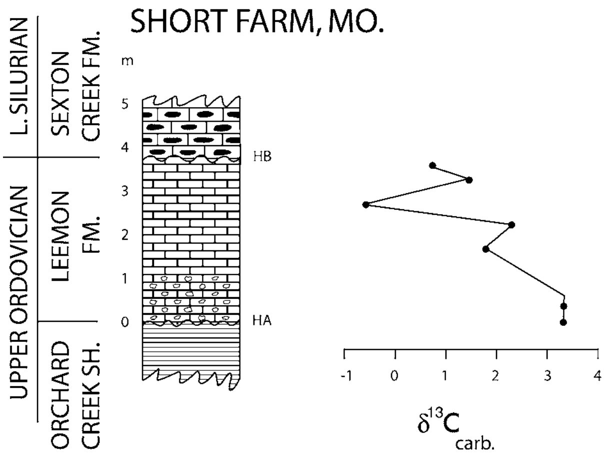


Figure 5. Columnar section, sample locations and $\delta^{13}$C curve from the Short Farm section.

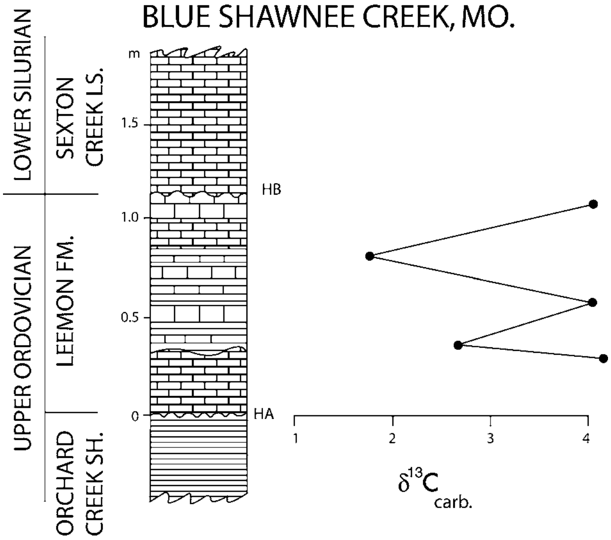


Figure 6. Columnar section, sample locations and $\delta^{13}$C curve from the Blue Shawnee Creek section.

sections, such as that at Thebes N (Amsden, 1986), by a conglomerate containing clasts of the Girardeau Limestone. This indicates that the Girardeau Limestone was lithified prior to the deposition of the Leemon Formation. At some localities, such as its type section at Short Farm (Fig. 5) and along Blue Shawnee Creek (Fig. 6), the Girardeau Limestone is missing due to pre-Leemon erosion, and the Leemon Formation rests directly on the Orchard Creek Shale. The Leemon Formation differs from the Girardeau Limestone in being oolitic, much more fossiliferous, more coarse-grained, and being cross-bedded locally. It appears to represent a higher-energy environment than the Girardeau Limestone. The Leemon Formation is unconformably overlain by the middle Llandoverian Sexton Creek Formation. At some localities, such as the Girardeau Limestone type section at Cape Rock Park, the Harrison Creek section and the Rock Springs Hollow section, the Leemon Formation is missing and the Sexton Creek Formation rests disconformably directly on the Girardeau Limestone (Figs 2, 3).

### 3.b. Girardeau Limestone sample sites

Samples for $\delta^{13}$C analysis were collected from this unit at four localities (Fig. 1), including: its type section along the east side of the Mississippi River at Cape Rock Park (Thompson, 1991); the natural outcrop in the waterfalls of Orchard Creek just above the road bridge at Rock Springs Hollow (Rock Springs section); a natural outcrop on the hillside at the southern end of the cut of the abandoned railroad 1.6 km south of Thebes, here referred to as Rock Springs Hollow S; and from the thin and eroded development of the Girardeau Limestone on the river bottom along the east side of the Mississippi River about 1.6 km north of Thebes (Thompson, 1991), a locality here referred to as Thebes N. In addition, two samples were collected from the uppermost part of the Orchard Creek Shale beneath the bluffs of the Girardeau Limestone along Harrison Creek just east of the Hill Road bridge 22 km northeast of Thebes (Harrison Creek section). For schematic sections and location of the Girardeau samples, see Figure 3.

### 3.c. Leemon Formation sample sites

Samples for $\delta^{13}C$ analysis were obtained from the Leemon Formation type section at Short Farm (Amsden, 1974, 1986; McAuley & Elias, 1990; Thompson, 1991), from the east bank of Blue Shawnee Creek (Thompson, 1991), and from the outcrop on the river bottom along the east side of the Mississippi River 1.6 km north of Thebes (Amsden, 1974) (Thebes N). For schematic columnar sections of the Lemon Formation at Short Farm and Blue Shawnee Creek, and the location of samples, see Figures 5, 6.

## 4. Laboratory results and the $\delta^{13}C$ excursion

All rock samples were subjected to standard laboratory treatment to obtain $\delta^{13}C$ values.

This included microdrilling of the rock samples to produce carbonate powders. At the American labs, the powders were subsequently heated for 1 hour at 380 °C to remove volatile contaminants, and then reacted with 100 % $H_3PO_4$ at 72 °C in a Finnigan Kiel extraction system coupled directly to a Finnigan MAT 251 mass spectrometer. At the Swedish laboratory, the rock powder was roasted in vacuum at 400 °C and the isotopic analyses performed with a VG Prism Series II mass spectrometer attached to an Isocarb preparation system. For 12NBS-19 standards in a carousel with 12 samples the mean $\delta^{13}C$ value and standard deviation was $1.96 \pm 0.02$. Calibration to PDB was via NBS-19 ($\delta^{13}C = 1.95$ ‰ Vienna PDB).

Most of the samples through the Girardeau Limestone at Cape Rock and Rock Springs have $\delta^{13}C$ values between + 4 and + 5 ‰ (Fig. 3). The highest 2 m of the formation has values of + 3 to + 4 ‰ at Cape Rock Park. Because the basal contact of the formation is currently not exposed at these sections, limestone interbeds in shaly strata that appeared to represent the topmost Orchard Creek Shale were sampled at Thebes N, Rock Springs Hollow S and Harrison Creek. The Thebes N samples were not calcareous enough to yield useful $\delta^{13}C$ data, but those from Rock Springs Hollow S and Harrison Creek showed $\delta^{13}C$ values between + 4 and + 5 ‰. There are at least two possible explanations for these high $\delta^{13}C$ values. The most likely one is that the beginning of the excursion is below the sampled interval with limestone interbeds in the upper 2–3 m of the Orchard Creek Shale. The other possibility is that the shaly strata that look like the Orchard Creek Shale in these sections are lithologically transitional strata between the Girardeau Limestone and the Orchard Creek Shale that are coeval with the lower part of the Girardeau Limestone at its type locality at Cape Rock Park. Similar lithological relations have been suggested to exist between the Powder Mill Hollow, Alexander County, Illinois and Cape Rock Park sections by Satterfield (1971, fig. 1). This explanation is not likely to apply to the Harrison Creek section, where the shale is overlain by a thick development of the Girardeau Limestone. Unfortunately, apart from the Thebes N outcrop, there are currently no outcrops through the entire Orchard Creek Shale in the Cape Girardeau region.

High $\delta^{13}C$ values (> 3‰) were obtained from the lower part of the Leemon Formation at Short Farm (Fig. 5) and the Blue Shawnee Creek (Fig. 6) exposures. However, in the upper part of the unit at the former locality, the $\delta^{13}C$ values decrease rapidly to below 0 in the uppermost part of the formation. We interpret this decline as representing a return to pre-HICE values and the end of the HICE excursion. Based on the information now available, the HICE appears to start in the uppermost Orchard Creek Shale, and range through the Girardeau Limestone and the lower Leemon Formation to end in the upper part of the latter unit. The combined total thickness of the excursion interval in the Girardeau Limestone and the Leemon Formation is approximately 15 m. This should be taken as a minimum value because the conspicuous erosional disconformity between the Girardeau Limestone and the Leemon Formation is likely to reflect a currently indeterminable, but probably significant, gap in the preserved stratigraphic succession. Based on the data now at hand, the HICE excursion in the Girardeau Limestone–Leemon Formation succession can be pieced together in a composite curve as shown in Figure 7. It may be of interest to note that the $\delta^{18}O$ values of the studied samples are generally round + 4 and do not show any clear trend. It appears, as is commonly the case elsewhere, that they have been digenetically affected.

## 5. Chronostratigraphic significance of HICE

### 5.a. The Cape Girardeau region

The relations between the HICE and biostratigraphic standard units have been well established in key sections elsewhere in the world, especially in the Great Basin of Nevada (Ripperdan, Cooper & Finney, 1998; Finney *et al.* 1999) and Estonia (Kaljo *et al.* 1999, 2001, 2004*a*,*b*; Brenchley *et al.* 2003). For our discussion we use curves based on $\delta^{13}C_{carb}$ because there is evidence that the shape of curves based on $\delta^{13}C_{org}$ may in some cases differ substantially from those based on $\delta^{13}C_{carb}$ (cf. Patzkowsky *et al.* 1997, fig. 2; Melchin, Holmden & Williams, 2003, fig. 1), although the stratigraphic range of the excursion is closely similar. In the Monitor Range, Nevada composite section curve (Finney *et al.* 1999, fig. 3), the HICE begins in the uppermost part of the *Paraorthograptus pacificus* Zone and ends somewhere in the middle-upper part of the *Normalograptus persculptus* Zone. Recent international decisions define the base of the global Hirnantian Stage as coinciding with the base of the *Normalograptus extraordinarius* Zone, which overlies the *P. pacificus* Zone. The top of the Hirnantian Stage,

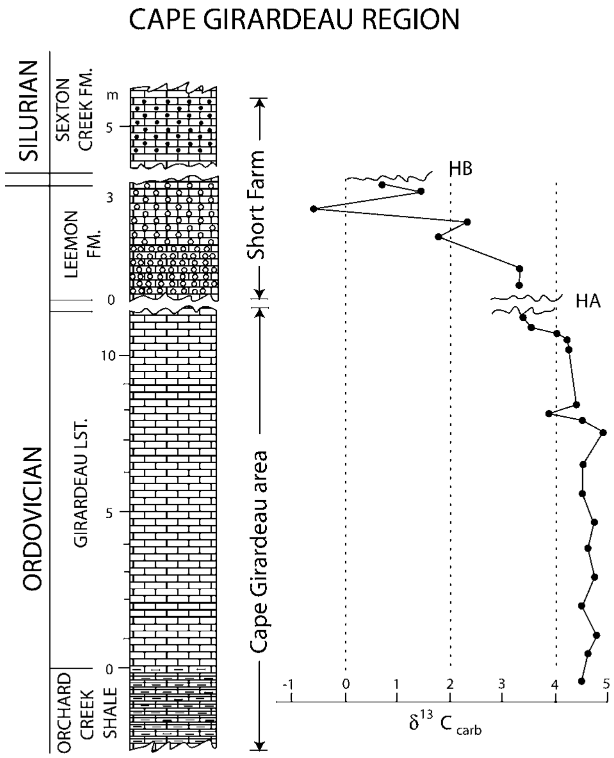


Figure 7. Composite Hirnantian $\delta^{13}C_{carb}$ curve for the Cape Girardeau region based on the Harrison Creek, Cape Rock Park and Short Farm sections. Note that the level of the beginning of the HICE has not yet been established but is somewhere in the Orchard Creek Shale. The magnitude of the gap in the HICE curve between the Girardeau Limestone and Leemon Formation is not determined but is not believed to be significant in terms of the general shape of the curve.

and the base of the Silurian System, are currently defined to be at the base of the *Parakidograptus acuminatus* Zone (Finney, 2004). Based on the reasonable assumption that the range of the Missouri–Illinois HICE curve is approximately the same as that in Nevada, the new chemostratigraphic evidence conclusively solves the problem of the much-disputed age of the Girardeau Limestone and the Leemon Formation. These units are not Silurian in age as suggested by several past studies (see, e.g. Weller & Ekblaw, 1940; Pryor & Ross, 1962; Templeton & Willman, 1963), nor Richmondian (Twenhofel *et al.* 1954; Brower, 1973), but Hirnantian (latest Ordovician) as previously suggested by Amsden (1974, 1986, 1988) based on brachiopods and Satterfield (1971) and Barrick (1986, 1988) based on conodonts. This is also consistent with the recent report (Männik, 2001) of *Noixodontus girardeauensis* from the Hirnantian succession in Estonia, where this species ranges from just below and into the HICE interval. This characteristic conodont is typical of the Girardeau Limestone–Leemon Formation interval, as well as the coeval Keel Limestone of Oklahoma, the Cason Oolite of Arkansas (Barrick, 1986) and the Noix Oolite of northeastern Missouri (McCracken & Barnes, 1982). It may be the only conodont currently known to be essentially restricted to the Hirnantian.

Figure 7 provides a summary of the stratigraphic classification of the study sequence and the Missouri–Illinois HICE based on the present study.

#### 5.b. Pike County

In Pike County in northeastern Missouri (Fig. 1b), the Noix Oolite and the Cyrene Formation contain shelly fossils interpreted by Amsden (1974) to be of Hirnantian age, as well as *Noixodontus girardeauensis* and several other typical Ordovician conodonts. These formations have been considered equivalents of the Girardeau–Leemon interval in southeastern Missouri (Amsden & Barrick, 1986) but the biostratigraphic evidence has been somewhat inconclusive. Samples from these units at several localities (see Appendix 1) did not show any trace of a Hirnantian excursion, all $\delta^{13}C$ values being –1 or lower. It appears likely that these very low values reflect post-deposition diagenetic change of the carbon isotope.

### 6. HICE and eustatic sea-level changes

#### 6.a. Cape Girardeau region

Based on their lithologies and shelly faunas, the studied units in the Hirnantian succession in Missouri and southwestern Illinois were deposited in shallow, and at times apparently very shallow, water. Furthermore, this is likely to have been a stable cratonic environment in the central part of the North American continent, and therefore it can be expected that this sedimentary succession would more closely record changes in sea level than deeper-water sequences in tectonically active regions in the distal portions of the craton. Hence, a sea-level curve (Fig. 8) based on the study succession is likely to be of more than local significance in terms of eustatic sea-level changes. In order to assess the possible existence of such eustatic sea-level changes, we compare our curve with curves from comparable sites elsewhere, especially on other continents.

As noted above, in the basal part of the study succession, the uppermost Orchard Creek Shale, which was probably laid down in relatively deep water, grades into the shallow-water Girardeau Limestone without evidence of a depositional break. We interpret this gradual shallowing in the depositional environment as representing the early phase of the global regression that is generally thought to be caused by the Hirnantian glaciation in Gondwana (Brenchley *et al.* 2003). Sea-level changes during the deposition of the Girardeau Limestone are not very clearly recorded in its lithologically relatively uniform succession, although the general decrease of shaly interbeds in the upper part of the unit may be interpreted as indicating a progressive shallowing.

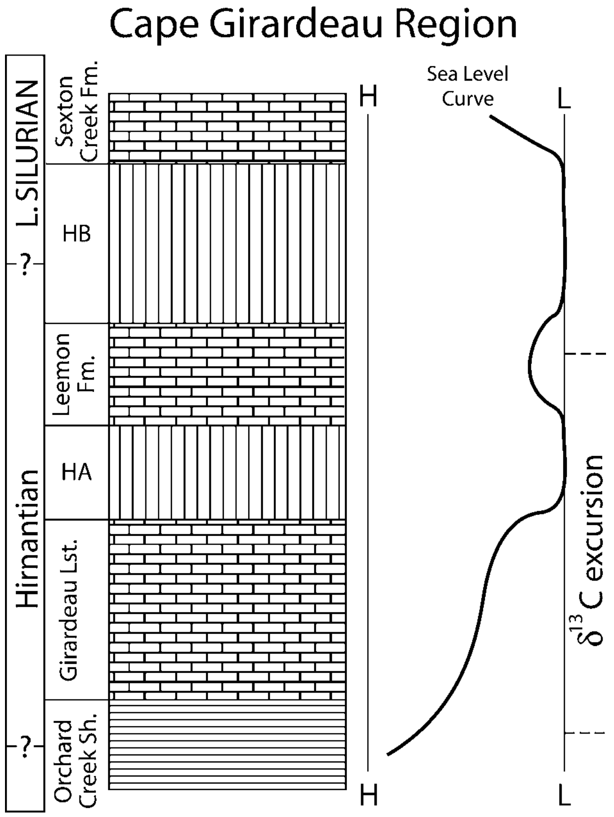


Figure 8. Preliminary Hirnantian sea-level curve for the Cape Girardeau region. Note the two major stratigraphic gaps, referred to as HA and HB, respectively, which correspond to significant sea-level lowstands. The precise length of these lowstands is unknown, although the latter is the longest. Based on chemostratigraphy, the upper limey part of the Orchard Creek Shale is likely to represent an early phase of the Hirnantian regression.

The local presence of a conglomerate with pebbles of the Girardeau Limestone in the basal part of the overlying Leemon Formation (Amsden, 1986), along with the fact that apparent pre-Leemon erosion has resulted in greatly variable thickness, and even local absence, of the Girardeau Limestone, indicates a significant sea-level lowstand. It was evidently associated with emersion causing erosion locally of the deposited Girardeau strata. This lowstand is here referred to as Lowstand HA (Fig. 8).

Lowstand HA was followed by a minor transgression and deposition of the thin oolitic Leemon Formation in very shallow water. The deposition of this unit was followed by a long period of non-deposition that extended to the middle Llandoverian transgression, when the Sexton Creek Formation was laid down. This period is here referred to as Lowstand HB. That this period of non-deposition was quite substantial in terms of erosion is shown by the fact that locally, the Sexton Creek Formation rests disconformably directly on the Orchard Creek Shale, with all the Girardeau Limestone and Leemon Formation apparently having been eroded away. Because of this regression and associated erosion, it is difficult to assess whether the Leemon Formation was deposited as a blanket-type unit, or was formed only in shallow depressions on a somewhat irregular surface of the older sediments. At any rate, its moderately diverse fauna indicates normal-marine salinity and absence of distribution barriers to marine deposition areas elsewhere. The Sexton Creek Formation and coeval strata (Brassfield Limestone, etc.) represent the initial Silurian transgression over much of the eastern Midcontinent, earliest Silurian (Rhuddanian) strata evidently being missing regionally.

If the two major lowstands recognized in the study succession were not caused by local epeirogenic movements and rather represent glacially induced eustatic sea-level changes, it should be possible to identify these lowstands in other successions, especially those laid down in shallow to moderately deep water. Stratigraphically strongly condensed deep-water successions such as those at Dob's Linn, southern Scotland (Underwood *et al.* 1997) and those near Yichang on the Yangtze Platform in China (Wang *et al.* 1993*b*, Wang, Chatterton & Wang, 1997) are less likely to record sea-level changes of the magnitude represented by those in the early–middle Hirnantian. Here we compare the Missouri–Illinois successions with sequences deposited in relatively shallow water at Monitor Range, Nevada, on western Anticosti Island, Quebec, and in Estonia, Sweden and the Oslo region, southeastern Norway. We also make a comparison with the somewhat deeper water succession at Vinini Creek, Nevada (Finney *et al.* 1999).

#### 6.b. Nevada

The conspicuous erosion surface at the 187 m level in the Hanson Creek Limestone succession in the Copenhagen Canyon, Monitor Range, section and recorded as a sea-level lowstand by Finney *et al.* (1999) is located in the middle of the downturn in the $\delta^{13}C$ curve (Fig. 9) and occupies a position similar to the Lowstand HA. That this erosion surface is not unique is shown by the fact that similar erosion surfaces are present in other Nevada successions, such as that at the 79 m level in the Lone Mountain sequence (Finney *et al.* 1999). Furthermore, the disconformable contact between the Hanson Creek Limestone and the overlying Silurian Roberts Mountain Formation in these successions might be an expression of Lowstand HB.

In the deeper-water Vinini Creek succession (Finney *et al.* 1999), the HA Lowstand is not identified but the HB Lowstand separates the Vinini Formation from the Aeronian Elder Formation (Fig. 9).

#### 6.c. Anticosti Island, Quebec

In the Pt Laframboise section on western Anticosti Island (Fig. 10), the contact between the Ellis Bay and Becscie formations, which coincides with a sharp

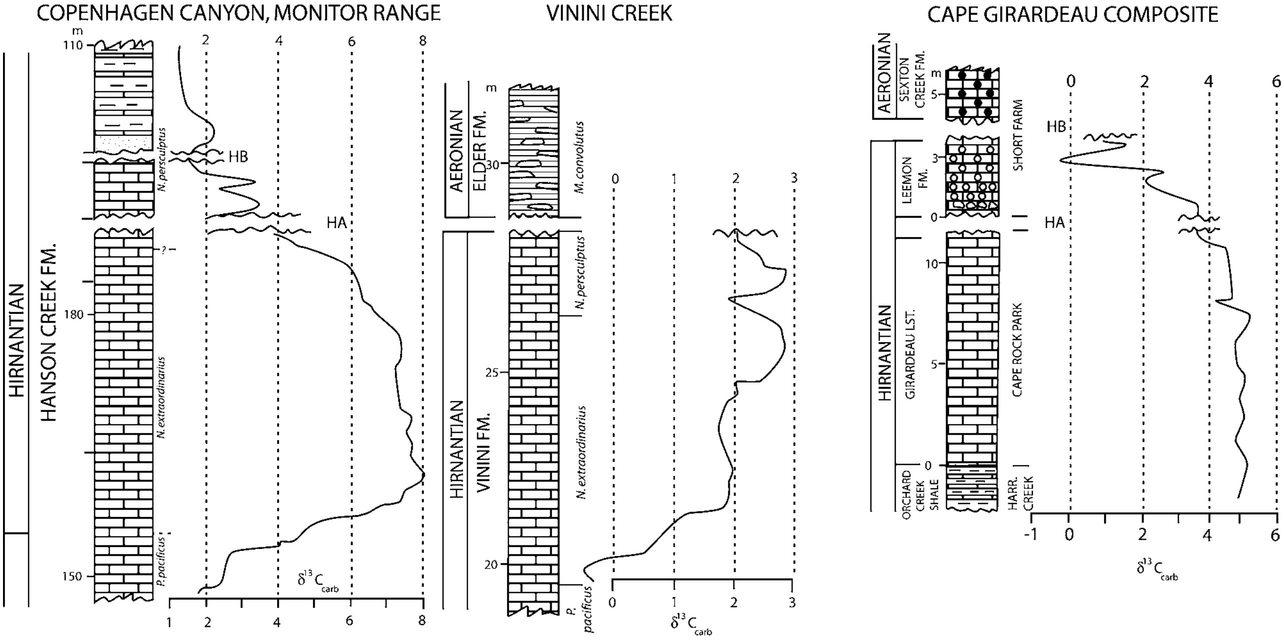


Figure 9. Comparison between the Copenhagen Canyon and Vinini Creek $\delta^{13}C_{carb}$ curves (after Finney *et al.* 1999) and that of the Cape Girardeau region. Note the similarity in the position of lowstands HA and HB between the Copenhagen Canyon and Cape Girardeau successions.

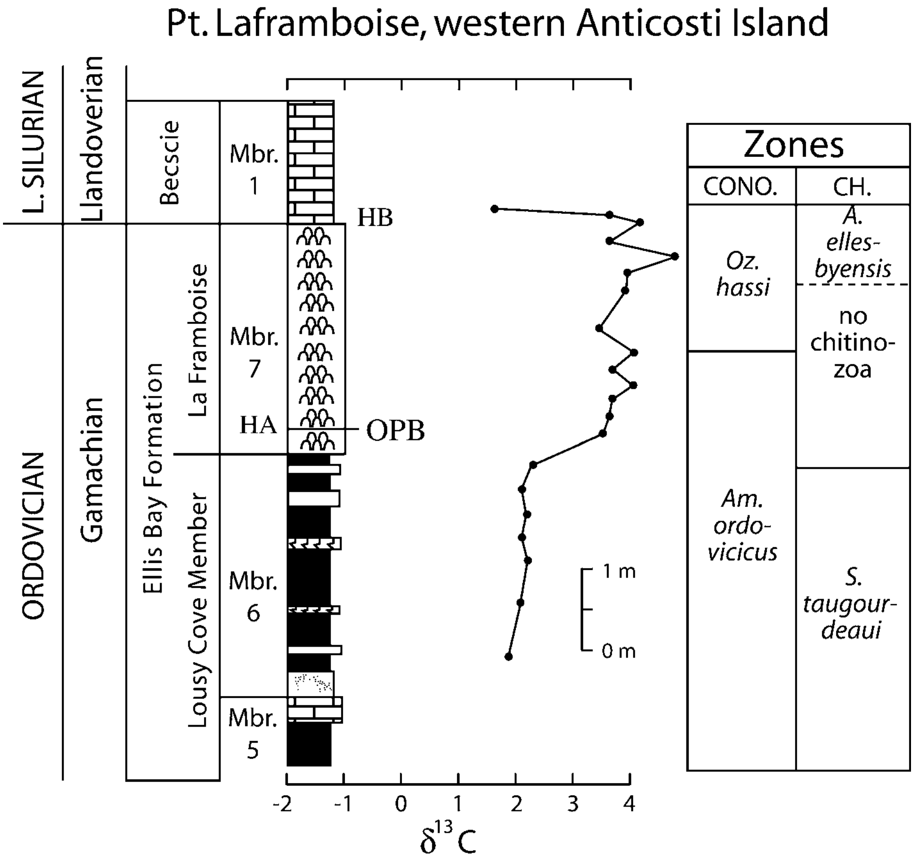


Figure 10. Columnar section and $\delta^{13}C_{carb}$ curve from the Pt Laframboise section on western Anticosti Island (M. Saltzman, unpub. data). Judging from the chemostratigraphy, the base of the Hirnantian is below the Oncolite Platform Bed (OPB) near the base of Member 7 of the Ellis Bay Formation. The sharp truncation at the top of the HICE curve suggests the presence of a significant stratigraphic gap, corresponding to Lowstand HB, at the base of Member 1 of the Becscie Formation. The Oncolite Bed Platform near the base of the La Framboise Member may represent another gap corresponding to Lowstand HA. Conodont and chitinozoan zones are based on McCracken & Barnes (1981) and Soufiane & Achab (2000), respectively.

truncation of the $\delta^{13}$C curve, is probably disconformable (Brenchley *et al.* 2003), although lithological evidence for this is inconclusive. This sharp truncation of the HICE curve suggests the presence of a significant stratigraphic gap, which is at about the same stratigraphic level as Lowstand HB. The presence of such a gap is consistent with the fact that the excursion interval in this section is only about 3 m thick in a succession where the thickness of stratigraphic units is usually several times as large as in coeval shallow-water sequences elsewhere. Interestingly, according to Melchin, Holmden & Williams (2003), the upper part of the Ellis Bay Formation contains graptolites of the *Normalograptus persculptus* Zone, indicating a late Hirnantian age for that part of the formation. This also suggests that a major part of the HICE is coeval with the lower part of the latter graptolite zone. Furthermore, the level of the beginning of the HICE suggests that the base of the Hirnantian Stage is below the level of the Oncolitic Platform Bed (OPB) near the base of the biohermal buildups that began to be formed at the base of Member 7 of the Ellis Bay Formation. This Oncolitic Platform Bed, which occurs all over the island, clearly represents an important shallowing episode. The fact that the HICE curve shows a conspicuous sudden upturn at this level suggests the presence of a gap in the succession. The presence of such a gap is also suggested by the fact that the base of the *Ozarkodina hassi* Conodont Zone, which is at the FAD of the zone index, corresponds to a level in the middle of the HICE curve at Pt Laframboise, whereas in Nevada (Finney *et al.* 1999), this level is near the top of the HICE curve. This gap may well be an expression of Lowstand HA. Based on brachiopods, Copper (1999) placed the base of the Hirnantian at the base of the Ellis Bay Formation, that is, at a substantially lower stratigraphic level than suggested by the chemostratigraphy. However, we consider his brachiopod evidence inconclusive because the taxa listed from the lower and middle part of the Ellis Bay Formation do not include the species diagnostic of the *Hirnantia* fauna.

Petryk (1981) distinguished five regressive–transgressive cycles in the uppermost Vaureal and Ellis Bay formations and correlated these with glacial episodes in North Africa. Based on our chemostratigraphy, only the last of these cycles would be of Hirnantian age, and hence, his correlation of the other cycles with North African Hirnantian glacial episodes would seem to be questionable unless there were such episodes also in pre-Hirnantian time.

#### 6.d. Estonia

In the several platform sections described from Estonia (Fig. 11), the HICE is well developed through the Baltic Porkuni Stage (Kaljo *et al.* 2001, 2004*a*). The base of this stage is at approximately the same stratigraphic level as that of the global Hirnantian

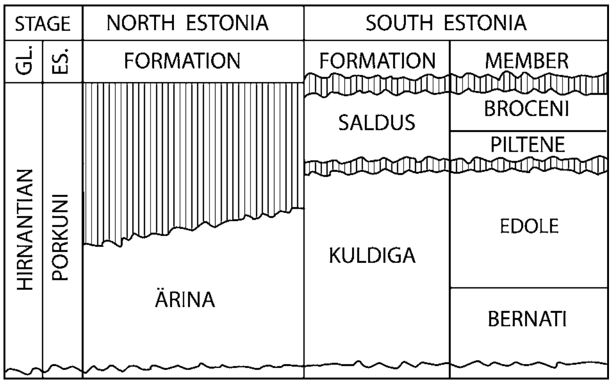


Figure 11. Stratigraphic diagram showing major units in the Hirnantian Stage of Estonia. Note the large stratigraphic gap in the upper Hirnantian in northern Estonia and the two, much smaller, gaps in the stratigraphically much more complete succession in southern Estonia. (Slightly modified from Kaljo *et al.* 2001, fig. 2).

Stage. The Porkuni Stage contains biostratigraphically diagnostic chitinozoans and the *Hirnantia* brachiopod fauna. The fact that the HICE curve is truncated at the top of the Porkuni Stage, at a level marked by a conspicuous lithic and faunal change, may be taken as an indication of a gap in the succession (cf. Brenchley *et al.* 2003, fig. 13) corresponding to at least a part of the latest Ordovician *Normalograptus persculptus* Graptolite Zone. That such a gap is present in northern Estonia appears certain (Kaljo *et al.* 2001, fig. 2; Fig. 11). The stratigraphically more complete, deeper-water, Hirnantian succession in southern Estonia has two gaps, both in the upper Hirnantian (Fig. 11). These could correspond to the HA and HB lowstands. If so, the Edole Member of the Kuldiga Formation and Saldus Formation would correlate with the Girardeau Limestone and the Leemon Formation, respectively. Interestingly, the Saldus Formation is partly oolitic and sandy, as is the Leemon Formation. Also, based on the HICE curve, the Bernati Member would correlate with at least the upper portion of the Orchard Creek Shale. As a whole, the stratigraphy and its relation to the HICE curve are remarkably similar to those of the Cape Girardeau region and the Copenhagen Canyon (Figs 9, 12).

#### 6.e. Sweden

The only published $\delta^{13}$C data from Hirnantian successions in Sweden are from the Siljan region in the Province of Dalarna (Marshall & Middleton, 1990; Middleton, Marshall & Brenchley, 1991; Brenchley *et al.* 1997). These studies show that the topmost part of the Boda Limestone mounds have $\delta^{13}$C values of up to + 6.6, indicating the presence of the HICE. This topmost Ordovician is separated from overlying Lower Silurian (Aeronian Stage) shales and limestones by a prominent stratigraphic gap corresponding to at least the lowermost Silurian Rhuddanian Stage, hence the

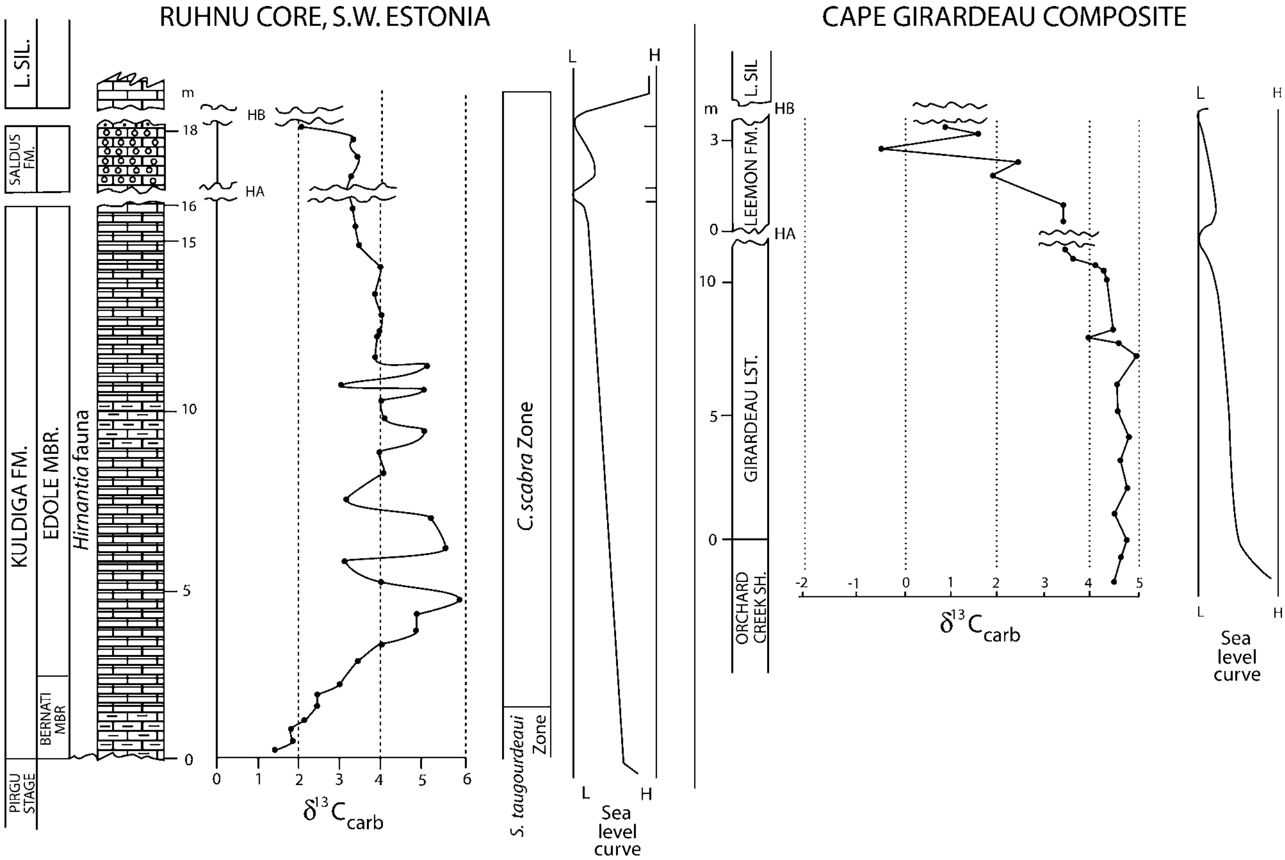


Figure 12. Stratigraphy and $\delta^{13}C_{carb}$ curve through the Hirnantian Stage of the Ruhnu drill core from southwestern Estonia (redrawn from Kaljo *et al.* 2001, fig. 4) compared to that of the Cape Girardeau region. Chitinozoan zones from Brenchley *et al.* (2003). For location of this drill-site, see Kaljo *et al.* (2001, fig. 1). Note that the disconformities at the base and the top of the Saldus Formation appear to correspond the HA and HB lowstands, respectively, in the Cape Girardeau region. Based on the HICE, the Edole Member seems to correspond to the Girardeau Limestone, and the Saldus Formation to the Leemon Formation.

interval corresponding to the HB Lowstand. The level of the HA Lowstand has not yet been identified in the mound succession, although it cannot presently be ruled out that it is represented by the currently biostratigraphically poorly dated top of the Boda Limestone buildups.

No $\delta^{13}C$ work has yet been carried out in the classical Hirnantian outcrops in the Province of Västergötland in southern Sweden. In this region, the Hirnantian is represented by the Loka Formation that includes a lower and upper mudstone member and a middle limestone member (Bergström, 1968; Stridsberg, 1981; Bergström & Bergström, 1996). The middle member is a warm-water (bahamitic), in places oolitic, cross-bedded and conglomeratic limestone (Stridsberg, 1981) that contains relatively abundant corals and other fossils. In view of the fact that this shallow-water deposit is the only documented occurrence of a bahamitic limestone in the Swedish Upper Ordovician, it appears very odd that it was deposited during a period of glaciation, and this calls for an explanation.

The lower contact of this limestone member is sharp; in the important Mt Kinnekulle succession it is marked by a conglomerate (Waern, 1948), and in the equally significant sequence on Mt Ålleberg, the contact is a distinct discontinuity surface (Bergström, 1968). Hence, in both these successions, as well as in others (Stridsberg, 1981), there is evidence of a depositional break and a stratigraphic gap at the base of the limestone member. This stratigraphic gap can be interpreted to represent the HA Lowstand. If so, the overlying limestone member would reflect the following minor transgression and be coeval with the Leemon Formation in the Cape Girardeau region and the oolitic Saldus Formation in Estonia. In this interpretation, the warm-water nature of this member would be consistent with the fact that it was deposited during an interglacial between two major Hirnantian glaciations.

The upper mudstone member of the Loka Formation is disconformably overlain, at least in the Kinnekulle succession (Waern, 1948), by a transgressive black shale (referred to as the Kallholn Shale by Bergström & Bergström, 1996) that contains graptolites of earliest Llandovery age (*Parakidograptus acuminatus* Zone). Because the latest Ordovician *Normalograptus persculptus* Zone has not been recognized, there may be a gap at the systemic boundary corresponding to the HB Lowstand.

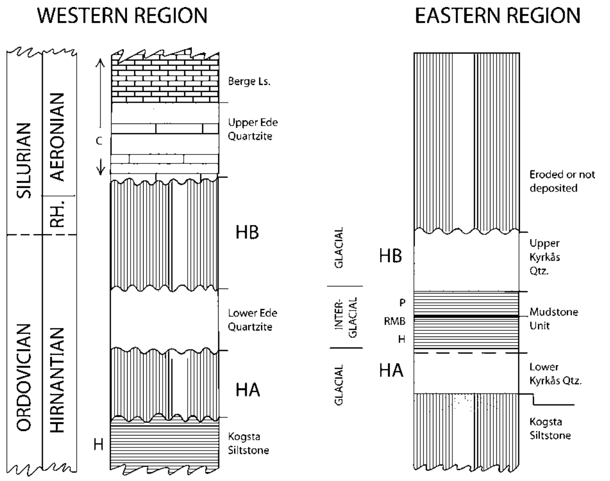


Figure 13. Schematic comparison of the latest Ordovician–Early Silurian succession in the western and eastern regions of the Province of Jämtland, north-central Sweden. The HA and HB lowstands are interpreted to correspond to prominent stratigraphic gaps in the western region and to shallow-water sandstones in the eastern region. The Lower Ede Quartzite was deposited during an interglacial minor highstand that is also reflected in the deeper-water mudstone unit in the eastern region. Note that the two illustrated sections have a very different thickness ($< 10$ m and $> 90$ m in the western and eastern regions, respectively), and the shown thickness of individual lithological units is not to scale. Also note that the precise age of the top of the Lower Ede Quartzite remains undetermined, although it is probably latest Ordovician. For lithological details and other data, see Dahlqvist (2004). C – conodonts; H – Hirnantian marofossils; P – *Normalograptus persculptus* graptolite fauna; RMB – Rusty Marker Bed of Dahlqvist (2004); Rh – Rhuddanian Stage.

The Upper Ordovician–Lower Silurian successions in the Province of Jämtland, north-central Sweden, are of special interest in the present discussion. In that region, this interval is represented by two geographically separated and lithologically rather different sequences. As recently described (Dahlqvist, 2004; Dahlqvist & Calner, 2004; Dahlqvist & Bergström, 2005), the Hirnantian sequence in the western region includes the Kogsta Siltstone, the upper part of which contains Hirnantian shelly fossils. This unit is unconformably overlain by the Ede Quartzite that consists of two parts, the Lower and the Upper Ede Quartzite, which are separated by an unconformity (Fig. 13). Whereas the Lower Ede Quartzite appears unfossiliferous, the Upper Ede Quartzite has produced conodonts of the early–middle Aeronian *Pranognathus tenuis* Zone (Dahlqvist & Bergström, 2005). We interpret the prominent sub-Ede unconformity as representing the HA Lowstand and the Lower Ede Quartzite as deposited during the following highstand that would make this unit coeval with the North American Leemon and Estonian Saldus formations. The marked unconformity between the Lower and Upper Ede Quartzite reflects the HB Lowstand. The following transgression and deposition of the Upper Ede Quartzite is coeval with the base of the post-HB Lowstand succession in several parts of the world, for instance, in parts of the North American Midcontinent (Dahlqvist & Bergström, 2005).

In the eastern region, the Kogsta Siltstone is overlain, with gradational contact, by the Kyrkås Quartzite (Fig. 13) that represents two depositional sequences (Dahlqvist, 2004), each of which reflects a shallowing from a deeper-water mudstone to a shallow-water sandstone. The mudstone in the lower part of the upper depositional sequence contains a Hirnantian shelly fauna which is followed by an interval with *Normalograptus persculptus* and other graptolites of that graptolite zone. Although no unconformities similar to those in the western region have been recognized in the Kyrkås Quartzite, we interpret the sandstones in the lower depositional sequence as reflecting the early Hirnantian regression and the HA Lowstand, the overlying deeper-water, fossiliferous mudstones as deposited during an interglacial and to be coeval with the Leemon highstand. The superjacent shallow-water sandstones of the upper depositional cycle are interpreted to be a product of the following HB eustatic lowstand during the second glacial period. No post-Kyrkås sedimentary rocks are known in the region and if deposited, they have been eroded away.

The simplest explanation for the apparent absence of the HA Lowstand unconformity is that in the eastern region, the water depth in the depositional environment of the Kogsta Siltstone was greater than in the western region, resulting in deposition of the upper Kogsta Siltstone and lower Kyrkås Quartzite in a continuous sequence without emersion during the early Hirnantian regression. In the absence of fossils in most of the unit, the age of the Kyrkås Quartzite has long been controversial but the results of the present study are consistent with Dahlqvist's (2004) suggestion, which was based on sedimentological indications, that the entire Kyrkås Quartzite is of Hirnantian age. It is also of interest to note that, apart from the absence of diamictites, the Kyrkås lithological succession is remarkably similar to the Gondwana Hirnantian sequences discussed below.

### 6.f. Norway

In many well-exposed outcrops in the Oslo region, Hirnantian successions show conspicuous regional variations in both lithology (Brenchley & Newall, 1980) and $\delta^{13}C$ chemostratigraphy (Kaljo *et al.* 2004*b*). In the Hirnantian sequence on Hovedøya (Brenchley *et al.* 1997; Brenchley & Marshall, 1999), the HICE starts in a few-metres-thick fine-grained sandstone in the uppermost part of the Husbergøya Formation (Fig. 14), a formation that otherwise consists of calcareous mudstones. Based on the $\delta^{13}C$ curve and the recent redefinition of the base of the Hirnantian Stage, this sandstone ought to be referred to the Hirnantian

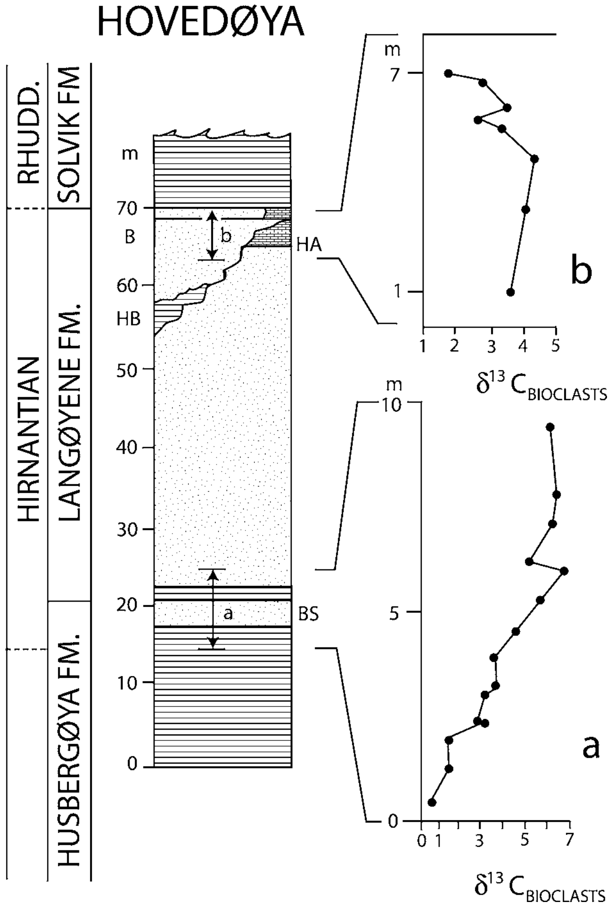


Figure 14. The Hirnantian succession on Hovedøya in the Oslo area, Norway, and $\delta^{13}$C curves from the lower and upper part of the Langøyene Formation (modified from Brenchley & Marshall, 1999, figs 1, 2). Apart from a relatively prominent limestone bed, the entire succession consists of shallow-water sandstones and subordinate mudstones. Note the conspicuous channelling, marked HB, which indicates a lowstand that probably corresponds to the HB Lowstand in the Upper Mississippi Valley. The HA Lowstand may correspond to an interval below the prominent limestone bed. BS – Brown Sandstone.

Stage, not the subjacent Rawtheyan Stage, as has been the practice in several recent papers (e.g. Brenchley & Marshall, 1999).

The overlying, locally more than 50 m thick, Langøyene Formation (Fig. 14) is dominated by regressive calcareous sandstones and mudstones containing the *Hirnantia* fauna. The top part of the Langøyene Formation includes a locally 4–6 m thick oolitic limestone, which is overlain by a thin transgressive sandstone (Spjeldnaes, 1957). It seems logical to suggest that this prominent oolitic limestone, which is widespread in the Oslo region and contains corals as well as the important conodont *Ozarkodina oldhamensis* (S. M. Bergström, unpub. data), represents the same period of unusual carbonate deposition as the middle limestone member of the Loka Formation in Västergötland.

Following the interpretation of the nature of the middle limestone member of the Loka Formation in Västergötland, we suggest that the oolitic limestone bed on Hovedøya was formed during the same minor interglacial highstand as the Leemon Formation in the Cape Girardeau region and the Saldus Formation in Estonia. This is consistent with its position in the upper part of the HICE curve (Fig. 14). In this interpretation, the HA Lowstand would be represented in the succession just below the oolitic limestone bed.

This oolitic limestone, as well as underlying sandstones, are cut by locally up to 13 m deep tidal channels (Brenchley & Newall, 1980) that in places contain clasts of the oolitic limestone. This indicates that the channels were formed subsequent to the lithification of the oolite. The channelling reflects a very significant lowstand that may correspond to part of the HB Lowstand. According to Brenchley & Marshall (1999), the channels were filled with sediments during a subsequent minor sea-level rise during the latest Hirnantian that corresponds to a slight fall in the $\delta^{13}$C values (Fig. 14). This minor highstand may reflect the beginning of the post-glacial melting of the Gondwanan ice sheets.

The lower part of the overlying Solvik Formation, which rests disconformably on the Langøyene Formation, contains sparse graptolites identified as *Normalograptus transgrediens* by Howe (1982), a species that in the well-studied Scanian succession occurs just above the *N. persculptus* Zone (Koren', Ahlberg & Nielsen, 2003). The latest Hirnantian *N. persculptus* Zone has not been positively identified by means of diagnostic fossils in the Oslo region. Judging from its position relative to the HICE curve in Nevada, it may correspond to the upper part of the Langøyene Formation and a possible gap in the succession below the Solvik Formation.

As is suggested by these regional comparisons, it seems possible to recognize the HA and HB lowstands in shallow-water successions far away from Missouri–Illinois, hence supporting the idea that they represent eustatic sea-level changes. The eustatic drop in sea level during the Gondwana glaciation has been estimated to have been 60–100 m (Brenchley *et al.* 1994), or even as much as 150 m (Ross & Ross, 1992, fig. 1). The lithology of the Orchard Creek Shale in the study area suggests deposition in relatively deep water, but probably not much more than 100 m. The unusual deposition of marine sediments, rather than emersion and non-sedimentation, in this region during the regression in Hirnantian time may well be due to the considerable pre-Hirnantian depth of the basin. In other regions of the Midcontinent, such as the Cincinnati area, the pre-Hirnantian water depth was much less, resulting in emersion and non-deposition during the Hirnantian regressions. Alternatively, but less likely, a period of renewed subsidence of the depositional

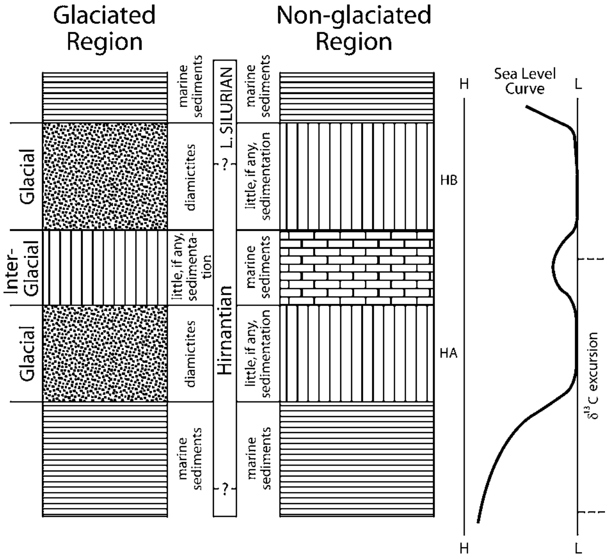


Figure 15. Simplified diagram showing relations between the eustatic sea-level curve, glacial episodes (indicated by diamictite occurrences), stratigraphic gaps, and periods of deposition in non-glaciated regions (corresponding to interglacials).

basin in the Missouri–Illinois area may explain this occurrence of Hirnantian sediments.

## 7. Relation to Gondwana glacial successions

### 7.a. Hirnantian diamictite occurrences and their significance in Gondwana

Several recent studies have provided conclusive evidence of the existence of a significant glacial period in Gondwana during Hirnantian time. Late Ordovician diamictites are quite widespread across North Africa and in much of South America, and such sediments have been recognized locally also in southern and central Europe, the Arabian Peninsula and South Africa (Caputo & Crowell, 1985; Young, Minter & Theron, 2004). Because very large amounts of water were trapped in the huge continental ice sheets, these glaciations were associated with a considerable sea-level drop, estimated to be of the order of 60–100 m (Brenchley & Newall, 1980; Brenchley *et al.* 1994), or perhaps even more (Ross & Ross, 1992). A eustatic regression of this magnitude would result in an emersion and the development of a conspicuous stratigraphic gap in the cratonic marine shallow-water successions. That is, glacial periods indicated by the formation of regionally distributed diamictites should correspond to regional regressions in non-glaciated, isostatically stable regions, especially those with shallow-water environments (Fig. 15).

Establishing the precise age of these diamictite deposits is obviously of critical importance in any attempt to assess the relations between the Hirnantian glaciation events and the eustatic sea-level history. Such an assessment might seem relatively simple, but several problems make it more complicated and uncertain than might appear at first sight. First, because diagnostic fossils are absent in many diamictites, it is in some cases difficult, or impossible, to fix their age more closely than Hirnantian. Second, the fact that carbonate rocks are very rare in the Gondwana Hirnantian successions makes it not feasible to use $\delta^{13}C_{carb}$ chemostratigraphy, and as far as we are aware, no HICE curve has been published from Africa or South America. The only $\delta^{13}C$ values recorded from Hirnantian strata in these regions are from a few brachiopod shells at two localities in the Precordillera of Argentina (Marshall *et al.* 1997). Third, if marine fossils are absent, it might be difficult to establish with certainty if a particular diamictite unit is of continental or marine origin. In the former case, it is likely to represent a significant lowstand but in the latter case, it may be more difficult to interpret it in terms of eustatic sea-level history. Fourth, the significance of conspicuous disconformities in a diamictite succession is not always clear in terms of sea-level history, particularly in dominantly continental successions. Such disconformities may reflect local epeirogenic movements, glacier advance–retreat, lack of deposition due to interstadials or even interglacials, or a period of erosion/non-deposition due to other reasons. Fifth, post-glacial isostatic rebound during and after deglaciation events may be considerable, and in some cases even greater than the eustatic sea-level rise, resulting in a relative sea-level fall locally. Such a scenario is well illustrated by the fact that the Holocene glacial rebound in north-central Sweden, as measured above the present sea level, locally amounts to as much as 285 m (Lindström, Lundqvist & Lundqvist, 2000), hence several times as large as the post-glacial eustatic sea-level rise. Regardless of these potential problems, it is of interest to examine how the geological evolution of Hirnantian successions in Gondwana compares with those of the study sections in North America and northern Europe. For this, we have selected one well-studied sequence in North Africa and one in Argentina.

### 7.b. Africa

In two important papers, Legrand (1995, 2003) showed the difficulties involved in dating precisely much of the Upper Ordovician successions in North Africa. Stratigraphically diagnostic fossils are scarce or absent in many of these clastic sequences, which furthermore differ markedly in lithological succession between different outcrop areas.

In the Anti-Atlas succession in Morocco (Fig. 16), which is one of the best-known successions, the lower Hirnantian is represented by the Lower Sandstone Formation of the Second Bani Group (Hamoumi, 1999, fig. 1; 2003), which locally carries a diverse *Hirnantia* shelly fauna and chitinozoans of the *T. elongata* Zone (Paris, 1990; Paris *et al.* 1995; Bourahrouh, Paris & Elaouad-Debbaj, 2004). This formation is overlain,

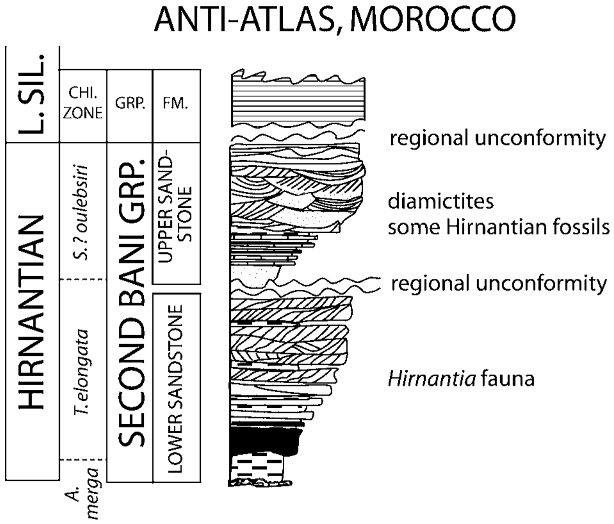


Figure 16. Schematic diagram (after Hamoumi, 1999) showing the Hirnantian succession in Anti-Atlas, Morocco. The regional disconformity separating the Lower and Upper Sandstone formations may correspond to an interglacial separating two main glacial periods. Chitinozoan zones after Bourahrouh, Paris & Elaouad-Debbaj (2004). Note that the occurrence of the *S.? oulebsiri* Zone has not yet been firmly established in this section but data from other North African successions suggest that the base of this zone is at the base of the Upper Sandstone Formation.

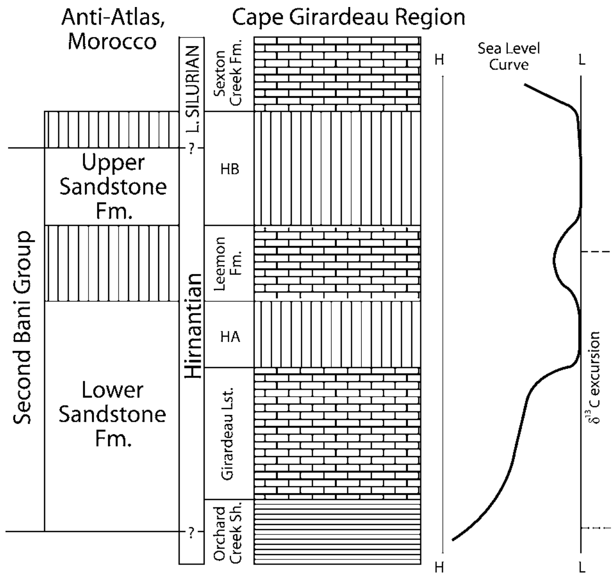


Figure 17. Schematic comparison between the successions in Anti-Atlas and the Cape Girardeau region and the inferred eustatic sea-level curve.

with a marked disconformity, by the diamictite-bearing Upper Sandstone Formation of the Second Bani Group, which is of glacial–marine origin. This unit contains some *Hirnantia* fossils (Destombes, Hollard & Willefert, 1985) and, in its basal part, chitinozoans that probably represent the *S.? oulebsiri* Zone (Bourahrouh, Paris & Elaouad-Debbaj, 2004). Overlying this clastic unit are transgressive shales of latest Ordovician–Early Silurian age. Based on the presence of the *Hirnantia* shelly fauna and the chitinozoans, both these sandstone formations can be inferred to be of marine origin. Hamoumi (1999, fig. 1; 2003) interpreted the disconformity at the base of the Upper Sandstone Formation as reflecting a significant lowstand. According to Bourahrouh, Paris & Elaouad-Debbaj (2004, fig. 1), the uppermost part of the Lower Sandstone Formation was deposited during a sea-level lowstand minimum. Sutcliff *et al.* (2000) recognized the disconformity as a subglacial erosion surface separating two ice growth cycles. Moreau *et al.* (2004) suggested that this disconformity was formed during an extensive flooding event and ice retreat during an interglacial. Ghienne (2003) published a more complex interpretation based on studies in the Taoudeni Basin in West Africa where he recognized four glacial cycles. The first two of these appear to represent that of the Lower Sandstone Formation and the last two that of the Upper Sandstone Formation. El-ghali (2005) described a similar succession in SW Libya in which he identified two glacial depositional sequences separated by an erosion surface and deltaic sandstones interpreted to have been formed during a glacial retreat. In another recent study, Young, Minter & Theron (2004) showed that a succession in South Africa is very similar to that in North Africa in that it has two diamictites separated by a thin unit of striated and cross-bedded sandstone and a thin mudstone. This mudstone is overlain by the upper diamictite. On top of this unit is the well-known Soom Shale, which contains an important fauna of latest Hirnantian age.

The regional disconformity between the Lower and Upper Sandstone formations is located between two significant diamictite successions, which are likely to have been associated with eustatic lowstands. In view of this, the suggestion by Moreau *et al.* (2004) that the disconformity might indicate an interglacial highstand seems reasonable, although this highstand might have been of rather modest magnitude.

We interpret the eustatic shallowing scenario shown by the Girardeau Limestone and overlying stratigraphic gap as reflecting the gradual ice buildup corresponding to the Lower Sandstone Formation with maximum regression during the HA Lowstand (Fig. 17). The deposition of the Leemon Formation could reflect an interglacial highstand between the Lower and Upper Sandstone formations. The following glacial advance, which has been interpreted by some as the most important one in North Africa, would correspond to the HB Lowstand in the Missouri–Illinois region. The fact that there is a stratigraphic gap in large areas of North Africa between the top of the Upper Sandstone Formation and overlying Silurian shales (Legrand, 1995, 2003, figs 2, 3) indicates that the post-glacial melting of the ice sheets might have extended into the latest Hirnantian. Alternatively, there might have been another glacial period in the latest Ordovician–earliest

Silurian, but firm evidence for this has not been presented from Gondwana. In summary, it would seem that the Lower Sandstone Formation is equivalent to the Girardeau Limestone, and possibly the upper Orchard Creek Shale, as well as Lowstand HA, the presumed interglacial highstand to the Leemon Formation, and the Upper Sandstone Formation to at least part of the HB Lowstand (Fig. 17). The same explanation may be applied to the succession in South Africa. This scenario supports the idea that the sea-level changes recognized in the Missouri–Illinois study sections are glacio-eustatic and not due to local tectonism.

#### 7.c. South America

Occurrences of Hirnantian and Early Silurian diamictites are widespread geographically in South America (Caputo & Crowell, 1985; Grahn & Caputo, 1992), but many of these have not been precisely dated, and some of those referred to the Hirnantian may be of Early Silurian age. One of the most easily accessible, well-dated and carefully studied Hirnantian diamictite successions is exposed along Don Braulio Creek in the Villicum Range in the Precordillera of western Argentina (Peralta & Baldis, 1992; Astini, 1993; Astini & Buggisch, 1993; Peralta & Carter, 1990, 1999; Peralta, 2003).

In this classical section (Fig. 18), the Hirnantian Don Braulio Formation rests with a conspicuous unconformity on the substantially older, siliciclastic, marine, non-glacial La Cantera Formation. In sections south of Don Braulio Creek, this stratigraphic gap is partly filled by the non-glacial La Pola Formation, which consists of mudstones, sandstones and coarse-grained debris flows laid down in a high-energy shelf environment (Peralta, 2003). Although not yet precisely dated, this formation lacks the *Hirnantia* fauna and is most likely of pre-Hirnantian age.

The Lower Member of the Don Braulio Formation at its type section is a 15–20 m thick diamictite containing some Hirnantian fossils as well as extensive but shallow channels filled with conglomerates (Fig. 18). The uppermost part of this member is a coarse conglomerate that with a sharp upper contact separates the Lower Diamictite Member from the overlying Fossiliferous Mudstone and Sandstone Member. Based on its lithology and the presence of diamictites and the shallow-water *Hirnantia* fauna, the latter member appears to have been deposited in relatively shallow water during a glacial period. Although Beresi (1992, fig. 4) interpreted the contact between these members as reflecting a change from a glacio-eustatic lowstand to a sea-level highstand, the presumed sea-level rise was probably of only modest size.

Based on its stratigraphic position, the interval of this glacio-eustatic lowstand could correspond to that of the Girardeau Limestone and the HA Lowstand in the Cape Girardeau region. The sharp contact at the top of the conglomerate may represent a disconformity and gap in the succession corresponding to the Leemon Formation. The overlying shallow-water, partly diamictitic, Fossiliferous Mudstone and Sandstone Member may be coeval with the Upper Sandstone Formation of the Second Bani Group in Anti-Atlas and the upper diamictite in South Africa. Significantly, Marshall *et al.* (1997) recorded $\delta^{13}C$ values as high as $+4.3$ from four brachiopod shells from the lowermost part of the Fossiliferous Mudstone and Sandstone Member in the Don Braulio section, and similar values from the same interval in the nearby La Pola outcrop, indicating the presence of the HICE. This member grades into

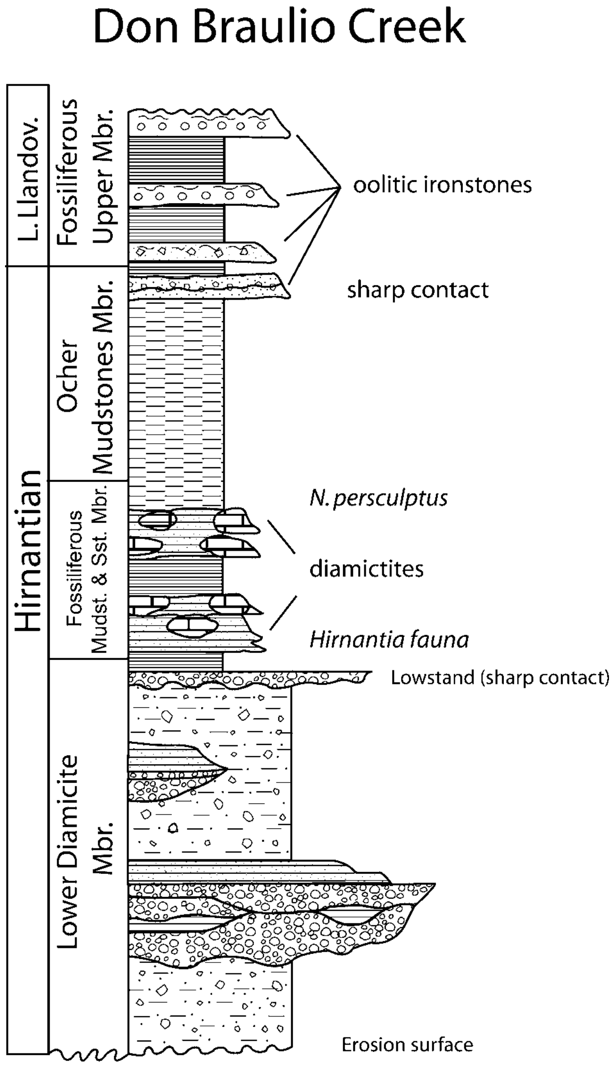


Figure 18. The Hirnantian succession of the Villicum Range in Argentina (after Peralta, 2003). The sharp contact with conglomerate separating the two diamictite units may correspond to the unconformity between the Upper and Lower Sandstone formations of the Second Bani Group in Anti-Atlas. The presence of the HICE is indicated by brachiopod-based $\delta^{13}C$ values as high as $+4.3$ that are recorded from the lowermost Fossiliferous Mudstone and Sandstone member (Marshall *et al.* 1997).

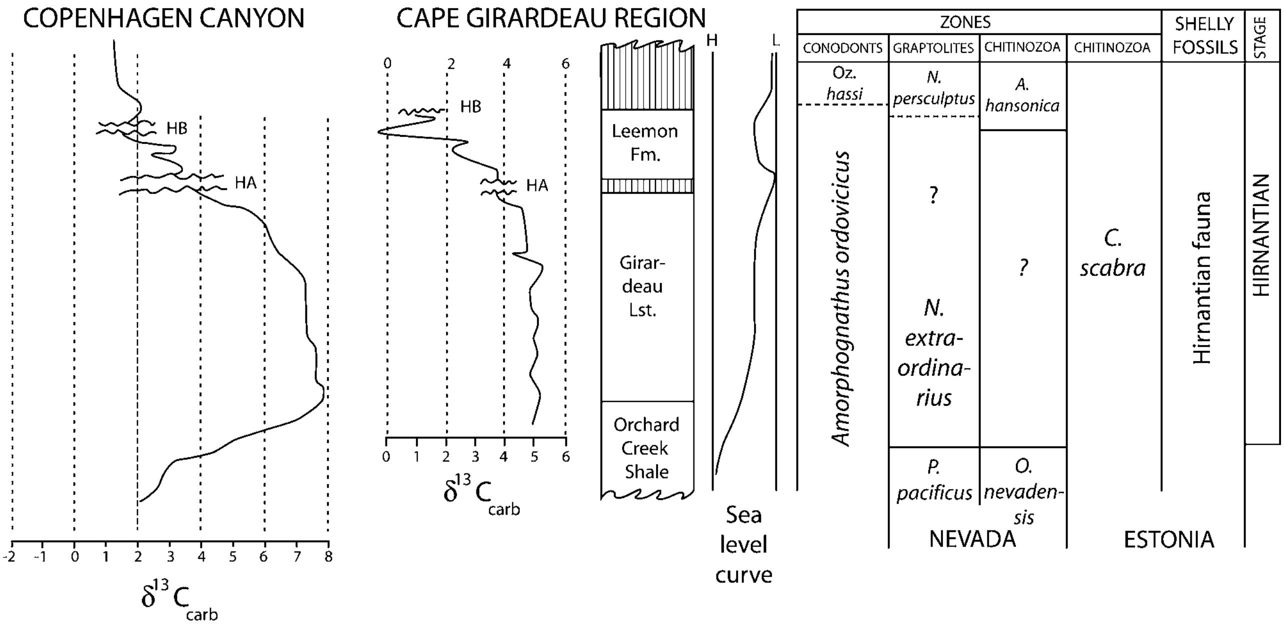


Figure 19. Summary diagram showing inferred relations between $\delta^{13}C_{carb}$ and eustatic sea-level curves, and lithostratigraphic and biostratigraphic units. Copenhagen Canyon graptolite and chitinozoan biostratigraphy after Finney *et al.* (1999) and Soufiane & Achab (2000), respectively. Estonian biostratigraphy after Brenchley *et al.* (2003).

the so-called Ocher Mudstones Member, which includes yellowish, very poorly fossiliferous, bioturbated mudstones of presumed post-glacial origin. This unit is disconformably overlain by the Fossiliferous Upper Member, which is composed of fine-grained sandstones, shales, siltstones and oolitic ironstones, and is dated, by means of graptolites (Peralta, 2003), as Early, but not earliest, Llandoverian (Peralta, 2003). The apparent gap at the base of this unit could correspond to the HB Lowstand in Missouri–Illinois. Hence, also this succession shows similarity to that in Missouri–Illinois in terms of apparent sea-level changes. It is also of interest to note the similarity between the Hirnantian successions in Anti-Atlas and Argentina, including the important disconformity of possible interglacial nature in the middle of the diamictite interval. In the Don Braulio succession, this disconformity is marked by a conglomerate with a sharp upper contact (Peralta & Carter, 1999), whereas in Anti-Atlas, the contact between the Lower and Upper Sandstone is a prominent glacially striated surface (Hamoumi, 2003).

It is obvious that in the absence of detailed biostratigraphic and chemostratigraphic control, this North American–Gondwanan comparison is necessarily very preliminary and subject to reassessment when more precise data are available. However, if the length of the Hirnantian Stage is no more than 0.5–1 Ma (Brenchley *et al.* 1994), the proposed correlations are unlikely to be very far off. They offer support to the idea that the Hirnantian lowstands recognized in Missouri–Illinois are indeed global glacio-eustatic events that can be traced into important Gondwanan successions in both North Africa and South America.

## 8. Relations between the $\delta^{13}C$ and sea-level curves, biozones, glacial periods and the study succession

The biostratigraphically well-controlled $\delta^{13}C_{carb}$ curve from the Nevada successions (Finney *et al.* 1999) and the $\delta^{13}C_{org}$ curves from the shale successions in southern Scotland (Underwood *et al.* 1997) and the Yangtze Platform in China (Wang *et al.* 1993*b*; Wang, Chatterton & Wang, 1997) show that the HICE starts in the very uppermost *Normalograptus pacificus* Zone, that is, just below the base of the Hirnantian as this global stage is currently defined. The increase in $\delta^{13}C$ values is associated with a eustatic sea-level drop that appears to be coeval with the initial formation of ice sheet deposits as represented by the Lower Sandstone Formation in Anti-Atlas in North Africa and the lower part of the Don Braulio Formation in Argentina. The Girardeau Limestone was deposited during this lowstand (Fig. 19) and much of this unit is probably coeval with the *Normalograptus extraordinarius* Zone. Unfortunately, the relationship between the HICE curve and the graptolite zonation is poorly constrained at Copenhagen Canyon where graptolites are missing in the excursion interval. However, data from Vinini Creek, where the top of the HICE is not documented, indicate that the base of the *N. persculptus* Zone is well down from the top of the excursion interval. This is consistent with the position of the base of the *N. persculptus* Zone in relation to the $\delta^{13}C_{org}$ curve at Dob's Linn (Underwood *et al.* 1997).

The rapid rise in the $\delta^{13}C$ curve in the lower *N. extraordinarius* Zone in Nevada and southern Scotland to uniformly high values is not yet documented in

Missouri–Illinois, where the curve is flat with + 4 to + 5 ‰ excursion values from the lowermost sampled levels in the Orchard Creek Shale to the highest levels of the Girardeau Limestone. This suggests that the lowermost part of the *N. extraordinarius* Zone may correspond to the topmost portion of the Orchard Creek Shale rather than to the basal part of the Girardeau Limestone. At any rate, we interpret the Girardeau Limestone as laid down during a pronounced sea-level lowstand caused by the first period of Gondwana glaciation. The Leemon Formation was deposited during the following interglacial(?) minor sea-level highstand, which in North Africa is marked by a moderate ice retreat and a regional disconformity. It corresponds to the upper portion of the $\delta^{13}$C excursion curve and the uppermost *N. extraordinarius* Zone and/or the lowermost *N. persculptus* Zone. The second, and according to some authors most important, period of Gondwana glaciation occurred in the lowermost *N. persculptus* Zone and is marked by a large stratigraphic gap in the Missouri–Illinois sequence. The abrupt return to base line values of some excursion curves may reflect this glacial period and associated non-deposition. In stratigraphically complete successions, the gradual return of the HICE curve to pre-excursion values takes place higher in the *N. persculptus* Zone but its precise time relation to deglaciation events and the associated sea-level rise requires further study.

The presence of the well-known *Hirnantia* fauna has been used almost globally for the recognition of Hirnantian strata, including the diamictite successions in Gondwana. As noted by several recent authors (see, e.g. Harper & Rong, 1995; Sutcliffe *et al.* 2001, fig. 2B; Rong, Chen & Harper, 2002), the *Hirnantia* fauna appears near the base of the global Hirnantian Stage, but it disappears gradually from about the middle Hirnantian with some fauna elements surviving into the lowermost Silurian. This fauna may be particularly typical of strata corresponding to the *N. extraordinarius* Zone, but the fact that this fauna occurs with *N. persculptus* itself in Sweden (Bergström & Bergström, 1996) indicates its presence in at least the lower part of this graptolite zone.

No chitinozoans are known from the Cape Girardeau region, and the excursion interval at Copenhagen Canyon has not produced diagnostic taxa (Soufiane & Achab, 2000). The extensive chitinozoan work carried out in Estonia shows (Kaljo *et al.* 2001, 2004*a*; Brenchley *et al.* 2003) the HICE to start in the upper *S. taugourdeaui* Zone and range through the *C. scabra* Zone (Fig. 12). The latter zone is correlated with the *T. elongata* Zone in the glaciogenic Second Bani Group of Morocco (Soufiane, Achab & Asselin, 1999). The *S. taugourdeaui* Zone is also recognized in the lowermost excursion interval in western Anticosti Island (Fig. 10), where the *A. ellesbayensis* Zone is coeval with the uppermost part of the excursion (Soufiane & Achab, 2000).

The various relations discussed above are summarized in Figure 19.

## 9. Concluding remarks

The present paper is the first report based on an ongoing large project on various aspects of the global Hirnantian $\delta^{13}$C isotopic excursion (HICE) in North America, northern Europe and east Asia, full details of which will be published elsewhere. The principal results of this study may be summarized as follows:

(1) For the first time, the HICE is recorded from sections in the North American Midcontinent. These sections, which are located in southeastern Missouri and southwestern Illinois, show elevated $\delta^{13}C_{carb}$ values of + 4 to + 5 ‰ in a stratigraphic interval from the uppermost part of the Orchard Creek Shale through the Girardeau Limestone to near the top of the Leemon Formation. Older and younger strata that bracket this interval typically show $\delta^{13}C_{carb}$ values of + 1 ‰ or less.

(2) The new chemostratigraphic data prove conclusively the existence of Hirnantian rocks in the study area, and confirm recent age datings based on brachiopods and conodonts.

(3) Two prominent stratigraphic gaps in the Missouri–Illinois study successions are interpreted to represent eustatic lowstands. A comparison between the Mississippi Valley successions and coeval shallow-water successions in Nevada, Quebec, Estonia, Sweden and Norway shows clear similarities in sea-level changes. The chemostratigraphic data at hand suggest that in several of the successions discussed, the latest Hirnantian (much of the *N. persculptus* Zone) is missing. If initially deposited, it was eroded away during the latest Hirnantian–earliest Silurian lowstand (HB).

(4) A comparison between the northern hemisphere successions and Hirnantian glacial successions in Morocco and Argentina suggests that diamictite units correspond to eustatic lowstands and the development of stratigraphic gaps in cratonic successions, hence supporting the idea that major eustatic changes in sea level during the Hirnantian were primarily glacially controlled.

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**Appendix 1. Location of the study sections in Missouri and Illinois**

Map references refer to U.S. Geological Survey 1:24 000 topographic quadrangle maps.

(1) *Cape Rock.* Along the east side of Cape Rock Park about 3 km north of Cape Girardeau, Cape Girardeau County, Missouri. Cape Girardeau Quadrangle.

Natural exposures of nearly the entire thickness of the Girardeau Limestone in low bluffs along the west side of the Mississippi River. Topmost part of the Girardeau Limestone, as well as the lower part of the overlying Sexton Creek Formation, are exposed in cuts along the St Louis and San Francisco railroad just above the river bank outcrops. Basal contact of the Girardeau Limestone with the underlying Orchard Creek Shale is currently not exposed, even at very low river water level. Girardeau Limestone sampled.

References: Thompson & Satterfield (1975), Thompson (1991).

(2) *Thebes N.* East side of the Mississippi River about 1.6 km north of Thebes, Alexander County, Illinois, Thebes-Missouri Quadrangle.

Wide outcrops (at low river water level) of the Orchard Creek Shale, Girardeau Limestone and Leemon Formation on the exposed river bottom in the eastern half of the river channel. All units sampled.

References: Amsden (1974), Thompson & Satterfield (1975), Thompson (1991).

(3) *Rock Springs.* In the waterfalls of Orchard Creek, 2.6 km SSE of Thebes, Alexander County, Illinois. Thebes Quadrangle.

These well-exposed outcrops through the virtually entire Girardeau Limestone start under the Rock Springs Hollow Road bridge across Orchard Creek at Rock Springs Hollow. The Girardeau Limestone/Sexton Creek Formation contact was not identified with certainty but the latter unit crops out in the creek a short distance upstream from the top of the waterfalls. Girardeau Limestone and basal Sexton Creek Formation sampled.

Reference: Although the section has been mentioned in the literature (Savage, 1913; Weller & Ekblaw, 1940), no detailed description has been published.

(4) *Harrison Creek.* Along the south side of Harrison Creek, about 0.05 km SSE of bridge across Plank-Hill Road (Rte 608) and its intersection with Rte 264 about 22 km NE of Thebes. Jonesboro, Illinois, Quadrangle.

Topmost Orchard Creek Shale is exposed in the south creek bank, and is overlain by Girardeau Limestone exposed in high and steep bluffs along the south side of the creek from the shale outcrop downstream (west) for several hundred metres. Topmost Orchard Creek Shale sampled.

Reference: Section mentioned in Weller & Ekblaw (1940) but no detailed description published.

(5) *Rock Springs Hollow S.* Hillside exposure in ravine just east of south end of cut along the abandoned Missouri–Pacific railroad 4.3 km SSE of Thebes and 1.6 km SSE of Rock Springs Hollow Road. Thebes Quadrangle.

About 1.5 m of Girardeau Limestone underlain by a less completely exposed, about 1.5 m thick, succession of shaly rocks with limestone interbeds, lithologically similar to the topmost Orchard Creek Shale. These rocks were sampled.

Reference: As far as we know, this outcrop has never been described in detail although it was mentioned and its location figured by Kolata & Guensburg (1979).

(6) *Short Farm.* Outcrop in waterfalls along small creek 0.1 km east of Short Farm and about 0.25 km east of State Route W, 3.5 km west of Leemon, Cape Girardeau County. Cape Girardeau NE Quadrangle.

This is the type locality of the Leemon Formation that here rests disconformably directly on the Orchard Creek Shale. The basal portion of the Leemon Formation contains clasts of the Girardeau Limestone. The latter was apparently eroded away completely prior to the deposition of the Leemon Formation. The Leemon Formation was sampled.

References: Amsden (1974), Thompson (1991).

(7) *Blue Shawnee Creek* (also known as *New Wells*). In Blue Shawnee Creek, 0.8 km east of New Wells, Cape Girardeau County. Neelys Landing Quadrangle, Missouri–Illinois.

Outcrop of Leemon Formation on the bottom and along the banks of the creek about 0.2 km upstream of the Highway C bridge across the creek. This unit overlies disconformably the Orchard Creek Shale and is disconformably overlain by the Sexton Creek Formation at this locality. The Leemon Formation was sampled.

References: Amsden (1974), McAuley & Elias (1990).

(8) *Clarksville.* Cut along west side of Highway 79 just north of Clarksville, Pike County, Missouri. Clarksville, Missouri and Illinois Quadrangle. Long outcrop of the Noix Oolite overlain by the Bowling Green Dolomite. Both units sampled.

Reference: Amsden (1974).

(9) *Louisiana* (also known as *Clinton Spring*). Outcrop of Noix Oolite, Bryant Knob Formation and Bowling Green Dolomite in wooded hill slope on west side of Highway 79 just north of Clinton Spring at south edge of Louisiana. Louisiana, Missouri–Illinois Quadrangle. Noix Oolite and Bryant Knob Limestone sampled.

Reference: Amsden (1974).

(10) *Kissenger*. Outcrop along west side of Highway 79, at Kissenger Hill and just south of spring, about 7 km south of Clarksville. Clarksville, Missouri and Illinois Quadrangle.

Noix Oolite, Bryant Knob Formation and Bowling Green Dolomite exposed in small cliff above the road ditch. The first two formations were sampled.

Reference: Amsden (1974).