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# First documentation of the Ordovician Guttenberg $\delta^{13}C$ excursion (GICE) in Asia: chemostratigraphy of the Pagoda and Yanwashan formations in southeastern China

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**Abstract –** The only published $\delta^{13}C$ data from the Ordovician of China are from the Lower and Upper Ordovician, and only the latter records include a significant excursion, namely the Hirnantian excursion (HICE). Our recent chemostratigraphic work on the Upper Ordovician (Sandbian–Katian) Pagoda and Yanwashan formations at several localities on the Yangtze Platform and Chiangnan (Jiangnan) slope belt has resulted in the recognition of a positive $\delta^{13}C$ excursion that has values of $\sim +1.5$ ‰ above baseline values. This excursion starts a few metres above a stratigraphic interval with *B. alobatus* Subzone conodonts as well as graptolites of the *N. gracilis* Zone. The distinctive conodonts *Amorphognathus* aff. *Am. ventilatus* and *Hamarodus europaeus* first occur at, or very near, the excursion interval. Because these conodonts appear in the stratigraphic interval of the Guttenberg $\delta^{13}C$ excursion (GICE) in Estonia, we identify the Chinese excursion as the GICE. This is the first record of the GICE in the entire Asian continent. It confirms that GICE is a global excursion and provides an illustration of how $\delta^{13}C$ chemostratigraphy, combined with new biostratigraphic data, solves the problem of the previously controversial age of the Pagoda Formation and how this classical stratigraphic unit correlates with the Baltoscandian and North American successions.

Keywords: Upper Ordovician, Guttenberg carbon isotope excursion, GICE, conodonts, Pagoda Formation, China.

## 1. Introduction

Extensive recent research, especially in northern Europe and North America, has confirmed the usefulness of $\delta^{13}C$ chemostratigraphy for both local and long-range correlations of Lower Palaeozoic rocks. Seven significant positive $\delta^{13}C$ excursions have been recognized (Fig. 1) in the Middle and Upper Ordovician (Darriwilian through Hirnantian Global Stages), and recent investigations (Bergström *et al.* 2007*b*) suggest that at least six of these excursions can be traced across the Atlantic from North America to Baltoscandia. The currently best known, and most investigated, among these excursions are the early Katian Guttenberg excursion (GICE) and the latest Ordovician Hirnantian excursion (HICE). Both of these excursions have been documented from a considerable number of localities in North America (see, e.g. Finney *et al.* 1999; Brenchley *et al.* 1997, 2003; Saltzman *et al.* 2003; Melchin, Holmden & Williams, 2003; Saltzman & Young, 2005; Ludvigson *et al.* 2004; Young, Saltzman & Bergström, 2005: Bergström, Saltzman & Schmitz, 2006; Bergström *et al.* in press; Barta *et al.* 2007) and northern Europe (see, e.g. Marshall & Middleton, 1990; Middleton, Marshall & Brenchley, 1991; Brenchley *et al.* 1994, 1997; Ainsaar, Meidla & Martma, 1999, 2004; Kaljo *et al.* 2004; Kaljo, Martma & Saadre, 2007; Schmitz & Bergström, 2007). The HICE has also been recorded in China (Wang *et al.* 1993; Wang, Chatterton & Wang, 1997; Chen *et al.* 2006*a*), and in the Subpolar Ural region of Russia (Männik *et al.* 2004), but we are not aware of any previous record of the GICE from any locality within the vast Asian continent.

For several years we have carried out chemostratigraphic and biostratigraphic studies of the Pagoda, Linhsiang and Yenwashan formations in the Yangtze Platform and Chiangnan (Jiangnan) belt in southeastern China (Fig. 2). Our principal study localities are: the stratigraphically upper continuation of the Huangnitang GSSP section, Zhejiang (Chen *et al.* 2006*b*), which represents the Chiangnan (Jiangnan) slope belt; the natural outcrop along the path on the hillside above Xiaotan village, Hexian, and outcrops at Beigongli, Jingxian, both sites being located in Anhui near the eastern margin of the Yangtze Platform; the inactive quarry on the hill slope above the Puxihe River near the ends of prominent bridges across a tributary of the Puxihe River about 29 km N of Yichang, Hubei; and an inactive quarry at Baiguowan, Donggongsi, near Zunyi, Guizou. Both the latter sites are situated in a more central portion of the Yangtze Platform. For more detailed locations of these sites, see the legend

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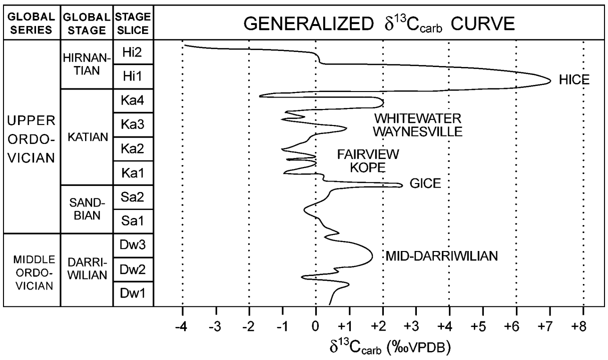


Figure 1. Recently recognized positive $\delta^{13}C$ excursions in the Upper Ordovician (Katian and Hirnantian Global Stages) and the upper Middle Ordovician (Darriwilian Global Stage). Note the stratigraphic position of the Guttenberg excursion (GICE) in the lower Katian Stage. The figure is modified from Bergström *et al.* (2008).

of Figure 2. Together, these sections may be viewed as representing a depositional environmental transect from the slope to the centre of the platform. Based on stratigraphically continuous sampling of these successions, we have assembled detailed conodont data from all the platform localities, and $\delta^{13}C$ values are now available from the Huangnitang, Xiaotan, Beigongli and Puxihe sections. We plan to present most of the conodont data in a separate paper and the focus of the present contribution is the $\delta^{13}C$ chemostratigraphy.

One important result of these investigations is the discovery (Bergström *et al.* 2007*a*) of a significant positive $\delta^{13}C$ excursion that we identify as the GICE, based on detailed conodont biostratigraphy. The recognition of the GICE in China not only confirms that this is a global excursion, but it also has major implications for the interpretation of the previously uncertain chronostratigraphic relations between a classic interval in the Chinese Ordovician succession and the Baltoscandic and North American successions. The purpose of the present report is to describe the isotopic record of this $\delta^{13}C$ excursion, as well as the basic conodont biostratigraphy, in some selected sections in southern China, and to assess their significance for detailed correlations based on biostratigraphy and chemostratigraphy between the Chinese successions and coeval strata in Baltoscandia and North America. Also, we discuss a possible occurrence of the GICE in the Tarim Basin in northwesternmost China.

## 2. Stratigraphic framework

To clarify the stratigraphic context of the $\delta^{13}C$ excursion interval, we will first briefly review the lithostratigraphy and biostratigraphy of the upper Sandbian and lower Katian successions, which include the Pagoda Formation and associated strata on the Yangtze Platform and its adjacent regions. The general stratigraphy in the study area is illustrated in Figure 3. The stage terminology used in this paper follows the recently ratified global stage terminology (cf. Bergström *et al.* 2006, 2008).

### 2.a. Lithostratigraphy

In the Yangtze Platform succession, most of the Sandbian Stage is represented by the Miaopo Formation, a black to dark grey graptolitic shale that is less than 5 m thick at most localities. In some sections, there are a small number of thin interbeds of argillaceous limestone, particularly in the upper part of the unit.

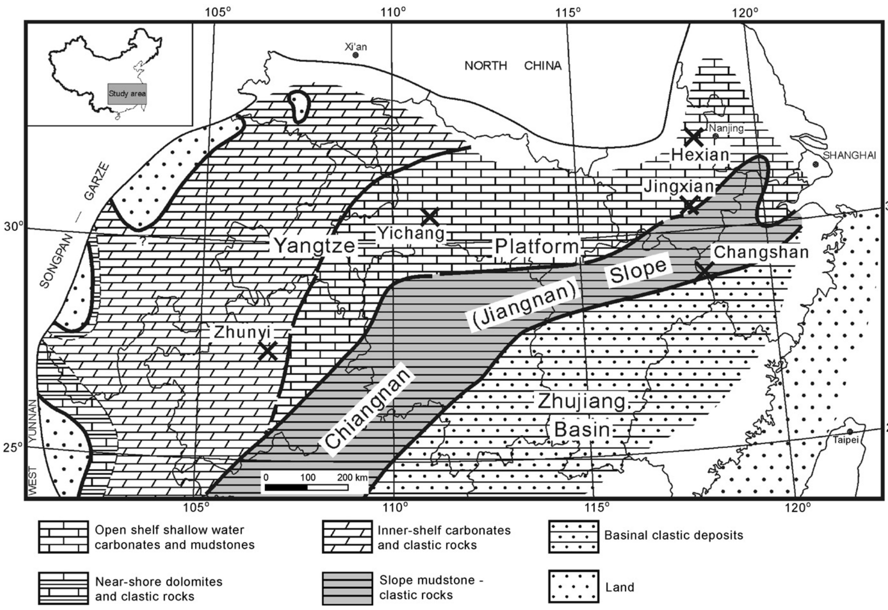


Figure 2. Sketch-map of the Yangtze Platform and adjacent regions in China showing early Late Ordovician (Katian) facies belts and the locations of the study localities, which are marked by X. The Huangnitang section is situated 5 km SW of the Changshan County town; that of Xiaotan is 30 km N of the Hexian County town; that of Beigongli is 25 km E of the Jinxian County town; that of Puxihe is 29 km N of Yichang City; that of Baiguowan, Donggongsi is 10 km N of Zhunyi City.

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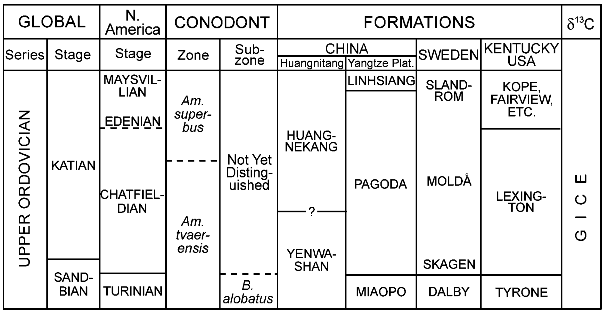


Figure 3. Stratigraphic chart showing late Sandbian and early–middle Katian formations in the Yangtze Platform region and their correlation to the Swedish (Fjäcka) and Kentucky successions based on biostratigraphy and chemostratigraphy.

The Miaopo Formation is restricted to three major areas on Yangtze Platform (Chen & Qui, 1986; Zhan & Jin, 2007, fig. 36), which have been interpreted to represent deeper-water intracratonic basins on the otherwise rather flat carbonate platform. In other parts of the platform deposition of limestones prevailed. These carbonate rocks are now referred to as the Datianba Formation (Nanjing Institute of Geology & Palaeontology, 1974). The conodont fauna of the latter unit is virtually identical to that of the Miaopo Formation (Hao Shougang, unpub. M.S. thesis, Peking Univ., 1981; An, 1987; Chen *et al.* 1995; Zhang, 1998) and these units are considered correlatives. Although abundant and taxonomically diverse graptolites dominate the fauna of the Miaopo Formation, it also contains many brachiopods, trilobites, ostracodes and conodonts.

The Miaopo Formation is conformably overlain by the Pagoda Formation, which is 5–60 m thick and covers thousands of square kilometres on the Yangtze Platform. It has the character of a blanket-type deposit but there are some indications, also from our study, that this unit is somewhat diachronous across its vast distribution area (Chen *et al.* 1995). The dominant lithology is a light-grey to purple, medium to thick-bedded, limestone, but locally the unit contains thin partings of green shale. A striking, and much discussed, lithological feature in many sections is the presence of abundant shrinkage cracks in the limestone that are filled by calcareous muds. Although fossils are not abundant at most sites, the Pagoda Formation has yielded a relatively diverse fauna of trilobites, brachiopods, and other shelly fossils, among which nautiloid cephalopods are particularly prominent. The depositional environment of this extremely widespread deposit has been the subject of vastly different interpretations, ranging from shallow subtidal to water depths of several hundred metres (Zhan & Jin, 2007). It appears that the prevailing current opinion is that it is a relatively deep water, rather than shallow water, deposit which is consistent with the distinctive deep/cold water character of its conodont fauna.

The Pagoda Formation is overlain, apparently conformably, by the Linhsiang Formation. This 1–25 m thick unit includes medium- to thick-bedded, nodular, impure limestones and thin mudstone beds. It contains a diverse shelly fauna and a conodont fauna that is very similar to that of the underlying Pagoda Formation. The Linhsiang Formation is overlain by the Wufeng Formation, a very widespread black graptolite shale that is at most localities about 5 m thick and ranges to the base of the Hirnantian Stage. It contains the taxonomically most diverse graptolite fauna known in the upper Katian anywhere in the world (Chen *et al.* 2005).

### 2.b. Biostratigraphy

The Miaopo Formation contains a taxonomically diverse graptolite fauna of the globally distributed *N. gracilis* Zone (Chen *et al.* 1995). The graptolite species association typical of the overlying *C. bicornis* Zone has been recorded only from the Shuanjiakou section in Hunan (Liu & Fu, 1989; Wang, Chen & Erdtmann, 1992) that represents the Chiangnan (Jiangnan) slope belt. The lower part of the Miaopo Formation has yielded diverse conodonts of the *Pygodus anserinus* Zone (Ni & Li, 1987; An, 1987), which is in good biostratigraphic agreement with the graptolites. At several localities, calcareous, non-graptolitiferous, beds in the very uppermost part of the formation have yielded specimens of the conodont subzone index species *Baltoniodus alobatus* (in older Chinese literature referred to as *Prioniodus lingulatus*; see, e.g. An, 1987). The *B. alobatus* Subzone, which has been the youngest subzone of the *Amorphognathus tvaerensis* Zone in the Atlantic conodont zone classification scheme (Bergström, 1971, 2007), elsewhere corresponds to the middle–upper part of the *C. bicornis* Zone in the standard Pacific graptoplite zone succession.

It should be noted that in Baltoscandia, the top of the range of *B. alobatus* Subzone is well below the top of the *Am. tvaerensis* Zone, and in recent years, this post-*B. alobatus* interval of the *Am. tvaerensis* Zone has in Estonia been recognized as the *Amorphognathus ventilatus* Zone (see, e.g. Männik, 2003, 2004). At the present time, we do not know whether the *B. alobatus* Subzone is restricted to the uppermost Miaopo Formation or if it extends into the lowermost part of the overlying Pagoda Formation.

The Pagoda and Linhsiang formations have not produced biostratigraphically diagnostic graptolites, but both of these units contain a moderately diverse conodont fauna (An, 1987; Ni & Li, 1987), which seems to be quite similar at all study localities. The conodont species association represents the relatively deep-water *Hamarodus–Dapsilodus–Scabbardella* biofacies of Sweet & Bergström (1984). To illustrate the general composition of the conodont fauna of the Pagoda Formation, the conodont species ranges through the unit in the Puxihe section are shown in Figure 4. As far as we are aware, this is the first published diagram illustrating in some detail the conodont species succession through the Pagoda Formation.

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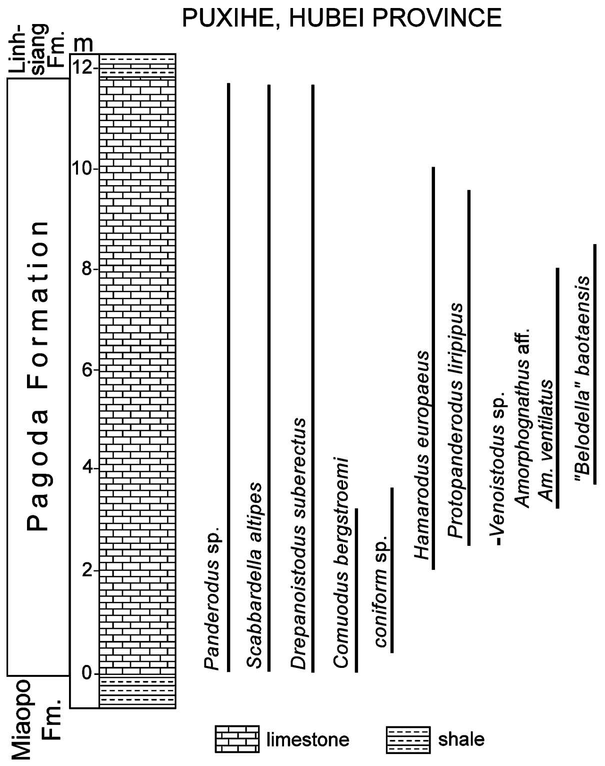


Figure 4. Conodont species ranges in the Pagoda Formation in the Puxihe section. Note the occurrence of the biostratigraphically important species *Amorphognathus* aff. *Am. ventilatus* near the base of the Pagoda Formation.

A biostratigraphically significant, and geographically widespread, species that first appears within the Pagoda Formation, and is common in many samples, is *Hamarodus europaeus*. An (1987, p. 81) recognized a *H. europaeus* Zone in the Pagoda Formation, and other authors (see Chen *et al.* 1995) have distinguished an *Am. superbus–H. europaeus* Zone, but it is outside the present account to discuss the merits of these rather loosely defined zone classifications. Nevertheless, it is appropriate to note that in Sweden, *H. europaeus* appears near the end of the GICE interval. This is slightly higher stratigraphically in relation to the GICE than is the case in our Chinese study sections, where this species first occurs near the middle of the GICE interval. However, the conodont fauna of most of the GICE interval in Sweden is sparse and includes mainly biostratigraphically non-diagnostic coniform taxa (Bergström, 2007), and it is quite possible that the currently known FAD of *H. europaeus* in Sweden is slightly younger stratigraphically than is the case elsewhere.

Specimens of the zone index *Amorphognathus superbus* have been reported from the upper Pagoda Formation at several localities (An, 1987), but its precise range within the unit remains unknown. This is also the case with the reported occurrences of the morphologically characteristic and biostratigraphically useful species *Amorphognathus complicatus*. Specimens of *Amorphognathus* occur in some of our Pagoda samples but we have not yet recovered positively identifiable specimens of *Am. superbus* or *Am. complicatus*.

A sample from a level 2.5 m above the base of the Pagoda Formation in the Puxihe section has yielded several M elements of an *Amorphognathus* species that appears morphologically indistinguishable from specimens from the Mòjcza Limestone of Poland referred to as *Am.* aff. *Am. ventilatus* by Dzik (1999, pl. 1, figs 6–10, 13–20). Based on direct comparison with Estonian specimens kindly supplied by Dr P. Männik, the Chinese specimens are also similar to the morphotype identified as *Amorphognathus ventilatus* by Männik (2003, 2004) and Männik & Viira (2005). *Amorphognathus ventilatus* was first described from significantly younger (late Katian; *Am. ordovicicus* Zone) strata (Ferretti & Barnes, 1997) than the early Katian units yielding the Polish and Estonian specimens. The species *Am. ventilatus* was based solely on M elements and the other elements of its apparatus have not been recognized in the type collection. According to Dzik (1999, fig. 3), the Polish representatives of the dextral Pa elements have the extra postero-lateral process characteristic of *Am. tvaerensis.* This feature is unknown in stratigraphically younger representatives of the genus, such as *Am. complicatus, Am. superbus* and *Am. ordovicicus,* and it would be surprising if it reappeared in *Am. ventilatus*. In view of this, we believe that unquestioned reference of the early Katian specimens to *Am. ventilatus* may be premature. Pending a needed taxonomic revision of *Amorphognathus*, in the present paper we use the designation *Am.* aff. *Am. ventilatus* for the early Katian morphotype. Obviously, the taxonomic problems of this early Katian morphotype do not affect its stratigraphic utility.

The occurrence of this species in the Pagoda Formation is particularly important because it belongs to a plexus of rapidly evolving platform conodonts with great biostratigraphic utility. Both in Poland (Dzik, 1999) and Estonia (Fig. 5; see Männik 2003, 2004; Männik & Viira, 2005), *Am.* aff. *Am. ventilatus* has a very short stratigraphic range. Its range in the Estonian Mehikoorma (421) core is compared to that in the Puxihe section in Figure 5. Significantly, its first appearance datum (FAD) is just above the peak $\delta^{13}C$ values of the GICE curve in both China and in Estonia. The presence of this conodont species in the $\delta^{13}C$ excursion interval at Puxihe provides strong evidence that the Chinese $\delta^{13}C$ excursion is indeed the GICE.

Another conodont of potential stratigraphic significance is *Protopanderodus insculptus*, which appears in the upper Pagoda Formation at some localities and also is present in many samples from the overlying Linhsiang Formation. In North America, this species is not known below the upper part of the *Amorphognathus superbus* Zone, but it has recently been reported (although not figured) from what appears to be a much lower stratigraphic level in the well-known Upper Ordovician section along Mirny Creek in northeastern Siberia (Zhang & Barnes, 2007). As a whole, the Pagoda–Linhsiang conodont fauna is so closely similar to those of the early–middle Katian Skagen, Moldå and Slandrom formations in Sweden (Bergström, 2007)

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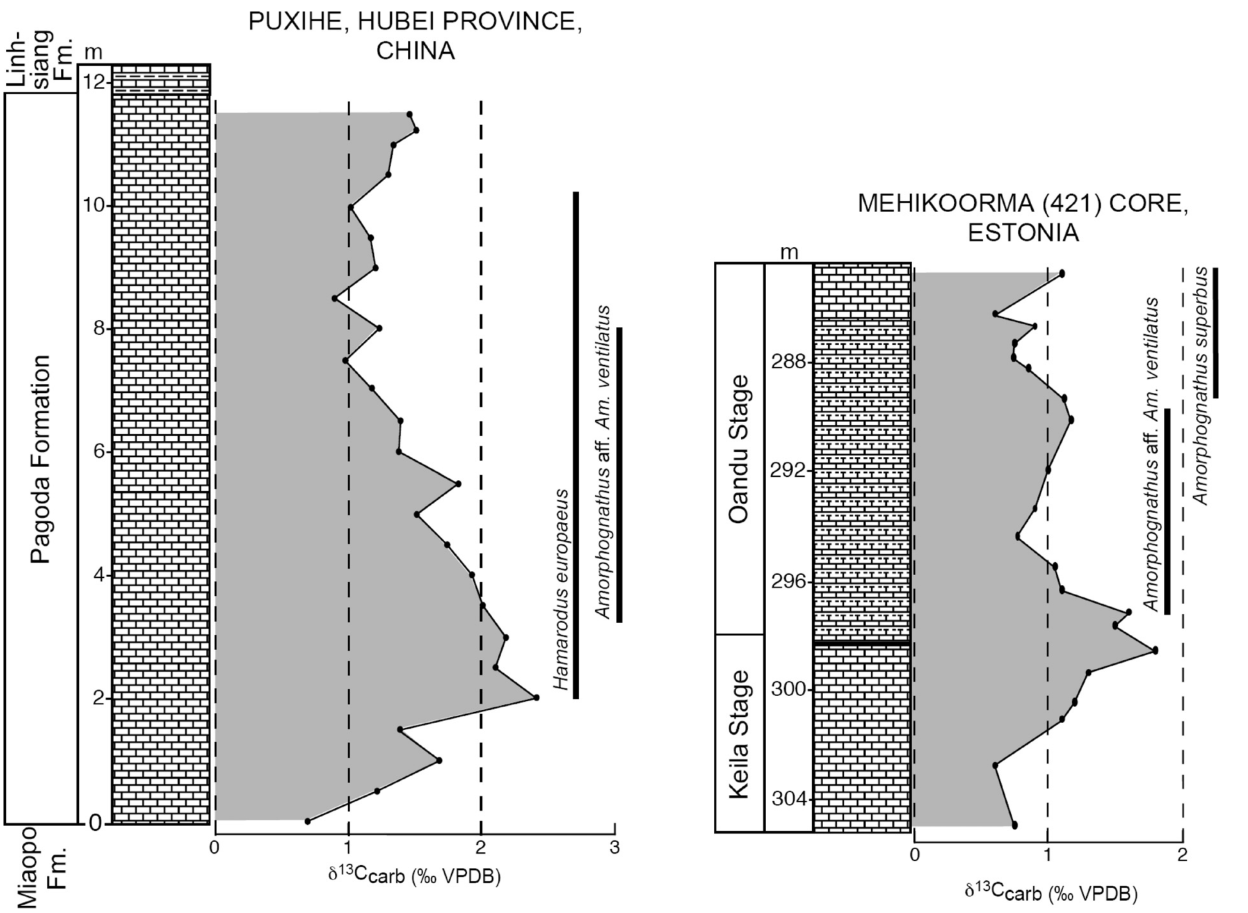


Figure 5. Stratigraphic chart illustrating the range of *Amorphognathus* aff. *Am. ventilatus* in relation to the GICE in the Puxihe section and the Mehikoorma (421) drill core, Estonia. The Estonian biostratigraphy and chemostratigraphy are based on Männik & Viira (2005) and Martma (2005), respectively. Note the close similarity in the first appearance datum (FAD) of this conodont species between the two sections. For explanation of lithological patterns in the stratigraphic columns, see Figure 4. The pattern in the 286.4–298.5 m interval in the Estonian drill-core denotes dolomitic marl with lenses and interbeds of carbonate.

that there is little doubt that they represent the same stratigraphic interval, which is consistent with the $\delta^{13}$C chemostratigraphy (cf. Fig. 3).

## 3. $\delta^{13}$C chemostratigraphy

### 3.a. Sample preparation and isotopic analyses

The lab preparation and isotopic analyses of the limestone samples followed the standard procedures described in Bergström, Saltzman & Schmitz (2006) and Schmitz & Bergström (2007).

### 3.b. Chemostratigraphy of the study sections

Figure 6 summarizes the chemostratigraphy of the four Chinese study sections as well as that of important sections in Sweden and Kentucky.

The Huangnitang section represents a deeper-water slope environment. In most of the Yenwashan Formation, the $\delta^{13}$C baseline values are between +0.5 ‰ and +1 ‰, but in the uppermost 2–3 m of the formation, the $\delta^{13}$C values increase to near +2 ‰. We interpret this excursion, which is of admittedly rather small magnitude, as the GICE. At the present time, there is no reliable biostratigraphic control of the upper part of the Yenwashan Fomation, but conodonts of the *Pygodus anserinus* Zone and the *B. alobatus* Subzone of the *Am. tvaerensis* Zone have been recorded from the lower part of the formation (An, 1987). This suggests that this interval is partially equivalent to the Miaopo Formation. It should also be noted that very recently, the *Nemagraptus gracilis* graptolite fauna was recorded from the top part of the Hulo Formation just below the base of the Yenwashan Formation at Huangnitang (Chen *et al.* 2006*b*). The available biostratigraphic data are consistent with the idea that the identified GICE interval in the upper part of the Yenwashan Formation is coeval with the GICE interval in the Pagoda Formation on the Yangtze Platform. The shape of the $\delta^{13}$C curve suggests that only the lower part of the excursion is present in the Yenwashan Formation and, provided there is no stratigraphic gap at the formational boundary, we expect that the upper part of the GICE is represented in the lower part of the overlying Huangnekang Formation, the $\delta^{13}$C chemostratigraphy of which has not yet been investigated.

The Xiaotan (Hexian) and Beigongli (Jinxian) sections in Anhui represent sites near the eastern platform margin, the latter site being the one closest to

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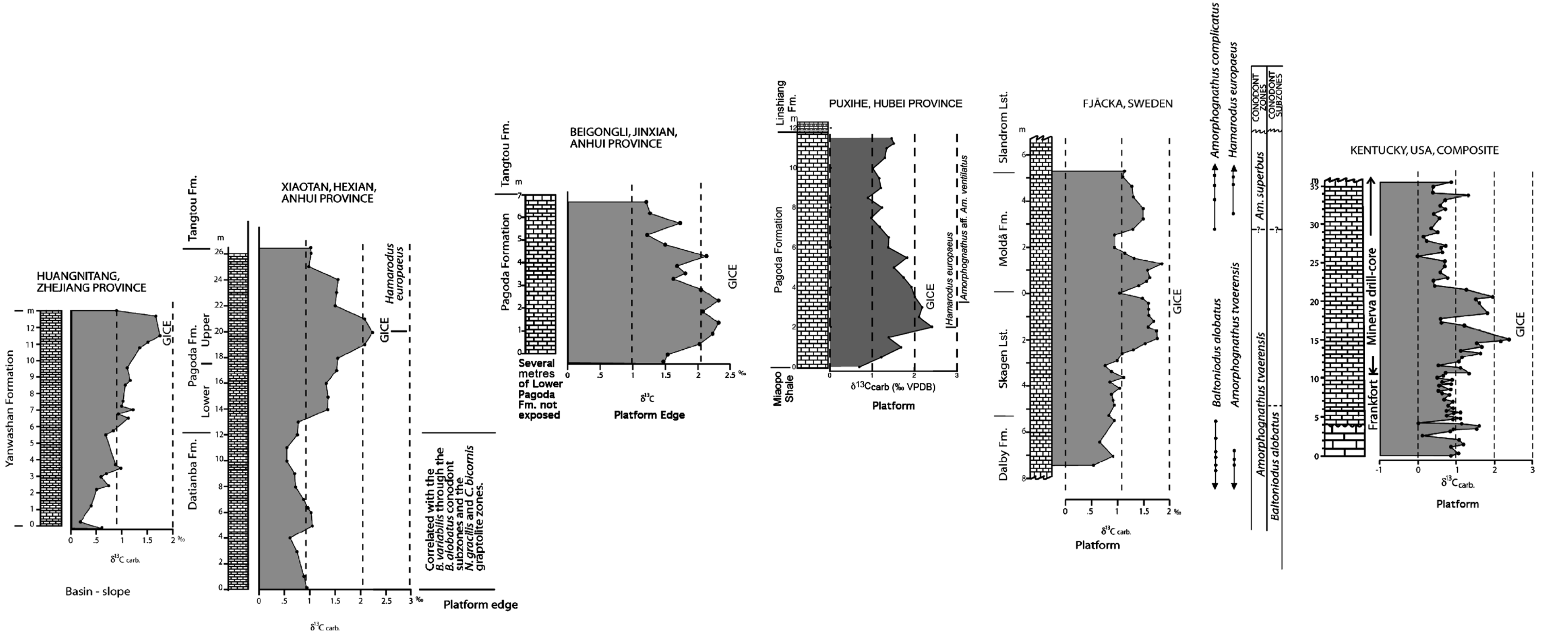


Figure 6. Correlation diagram based on $\delta^{13}C$ chemostratigraphy and biostratigraphy showing the inferred relations between Chinese, Swedish and Kentucky formations. Note that the baseline and peak $\delta^{13}C$ values are very similar in the illustrated sections. Also note that the GICE occupies a stratigraphically lower position in the Pagoda Formation in the central part of the Yangtze Platform (Puxihe section) than along the platform margin (Xiaotan and Beigongli sections). The Yanwashan Formation has frequently been correlated with the Pagoda Formation (Chen *et al.* 1995), but the $\delta^{13}C$ chemostratigraphy suggests that only its upper part is likely to be coeval with a part of the latter formation. The first appearance levels of key conodonts are shown by short horizontal lines in the Xiaotan and Puxihe sections. For explanation of lithological patterns in the stratigraphic columns, see Figure 4. The limestone pattern in the lower 4 m of the Kentucky column denotes the thick-bedded limestone of the Tyrone Formation.

the Chiangnan (Jiangnan) slope belt. At the former site there was in the past a complete exposure of the approximately 14 m thick Pagoda Formation and an exposed thickness of about 12 m of the underlying Datianba Formation. Unfortunately, recent farming activities have resulted in much of the formerly excellent outcrop now being covered. At Xiaotan, the $\delta^{13}$C baseline $\delta^{13}$C values are $\sim +0.5$ ‰ in the upper Datianba Formation and shift toward more positive values through the lower Pagoda Formation, with $\delta^{13}$C values reaching a maximum of $\sim +2.3$ ‰ in the middle Pagoda Formation near the level of the first appearance of *H. europaeus*. We interpret this excursion as the GICE. The $\delta^{13}$C values return to baseline values in the upper part of the Pagoda Formation. The thickness of the excursion interval is about 10 m.

Several metres of the lower Pagoda Formation are covered in the Beigongli section, but the $\delta^{13}$C data from the current exposure shows that an excursion identified as the GICE is present in the same interval of the Pagoda Formation, and reaches the same peak values, as at Xiaotan. Interestingly, the Beigongli GICE curve appears to have an incipient two-peak shape that approaches its appearance in many GICE localities in North America and northern Europe (cf. the curves from the Fjäcka and Kentucky successions shown in Fig. 6). The incompletely exposed excursion interval at Beigongli has a thickness of about 5 m.

The entire Pagoda Formation, as well as immediately underlying and overlying strata, are excellently exposed at the Puxihe Quarry N of Yichang in Hubei (Fig. 7). As in the other study sections, the $\delta^{13}$C baseline values are $\sim +1$ ‰ and the GICE excursion peak values a little more than $+2$ ‰. However, as shown in Figure 6, the interval of GICE is present in the lower, rather than the upper, part of the Pagoda Formation. This is consistent with the appearance of *Hamarodus europaeus* and *Amorphognathus* aff. *Am. ventilatus* at 1.5 and 2.5 m, respectively, above the base of the formation. This suggests that the base of the Pagoda Formation is somewhat diachronous from the platform margin to the central part of the platform. The significance of the presence of the biostratigraphically important species *A.* aff. *Am. ventilatus* just above the peak of the excursion has been discussed in Section 2.b.

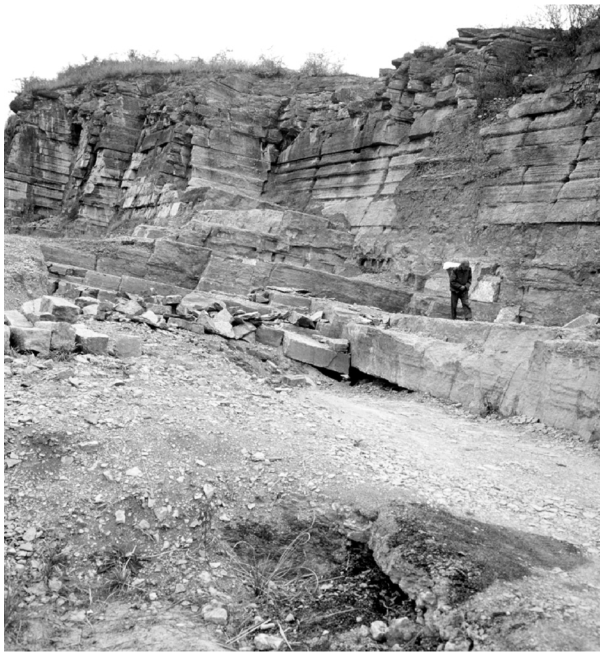

Figure 7. The exposure of the entire Pagoda Formation at the Puxihe Quarry near Puxihe River about 29 km N of Yichang, Hubei. Note the black shale of the Miaopo Formation at the bottom of the quarry and the nodular, thin-bedded limestone of the Linhsiang Formation at the top of the quarry wall. The Pagoda Formation is about 11.5 m thick at this locality.

### 3.c. Regional chemostratigraphic correlation

Based primarily on $\delta^{13}$C chemostratigraphy, the suggested stratigraphic relations between the Chinese study sections, the Fjäcka section in Sweden and the composite Kentucky section in the USA are shown in Figure 6. As shown in this figure, the correlation of the $\delta^{13}$C curves between these geographically widely separated regions appears straightforward and consistent with the conodont biostratigraphy. It is appropriate to note that because of pronounced faunal differences, it is currently not possible to correlate directly between China and Kentucky by means of conodont biostratigraphy, but such a correlation is possible between Baltoscandia and Kentucky. Interestingly, the base of the Pagoda Formation on the Yangtze Platform appears to be broadly at the same stratigraphic level as the base of the Skagen Formation in Sweden and the base of the Lexington Limestone in Kentucky. At least in the Puxihe section, the Miaopo/Pagoda Formation contact, although lithologically distinct, appears gradational, as is the case with the Dalby/Skagen formational contact in Sweden. However, the Tyrone/Lexington Formation contact in Kentucky is marked by a prominent unconformity that represents the M4/M5 sequence boundary of Holland & Patzkowsky (1996). Although there is little doubt that the studied Chinese and Baltoscandian depositional environments below and into the GICE interval represent a shallowing episode, those in Kentucky and several other North American regions (Oklahoma, Upper Mississippi Valley, New York State–Ontario; cf. Bergström *et al.* in press; Barta *et al.* 2007) seem to be the opposite and reflect an early phase of a transgression. Hence, the relations between the GICE and eustasy are not straightforward and require further study.

## 4. Possible occurrence of the GICE in the Tarim Basin succession

As noted above, the present study is the first to positively identify the GICE in China. However, there is a published $\delta^{13}$C record that suggests that this $\delta^{13}$C excursion may be present in another part of China. This record can be found in an internationally

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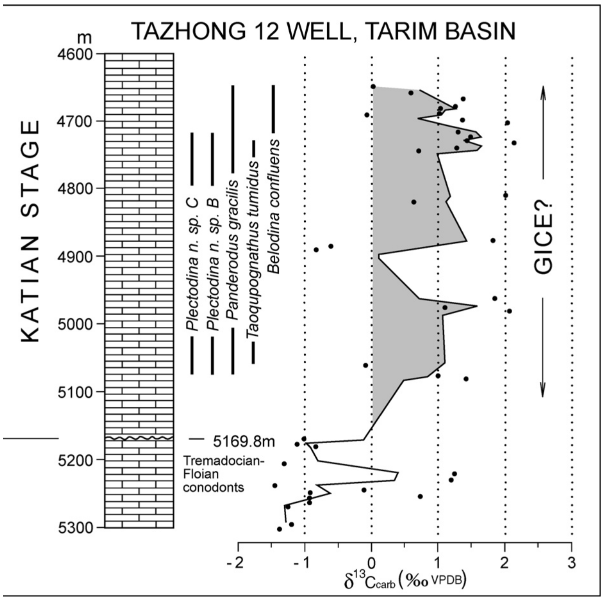


Figure 8. $\delta^{13}$C curve through the thick Ordovician succession of the Tazong 12 well in the Tarim Basin based on sample data from Jiang *et al.* (2001). To illustrate the excursion in a smoother curve, three-point average $\delta^{13}$C values were used to construct the isotope curve. The GICE is interpreted to be in the remarkably thick interval between approximately 4700 m and 5100 m. For explanation of the lithological pattern in the stratigraphic column, see Figure 4.

widely overlooked pioneer study of carbon, strontium and oxygen isotopes in marine carbonates from the important Ordovician succession of the Tarim Basin in Xinjiang, northwesternmost China, by Jiang *et al.* (2001). In this investigation they presented $\delta^{13}$C data from 86 samples collected from four drill-cores in the Tazhong region in the Tarim Basin. Unfortunately, their report includes very few biostratigraphic data that can be used for assessing the precise age of their samples. A few conodont species suggest a Tremadocian–Floian (Early Ordovician) age for their stratigraphically oldest samples, most of which show baseline $\delta^{13}$C values of $< +1$ ‰. However, many samples from a stratigraphically younger interval in the Tazhong 12 and Tazhong 29 drill-cores show $\delta^{13}$C excursion values of $\sim +2$ ‰ (Fig. 8), which are comparable with those of the GICE in the Pagoda Formation recorded above. The few conodont and coral species listed from this interval by Jiang *et al.* (2001) are not useful for precise biostratigraphic dating, but Zhao, Zhang & Xiao (2000) reported *Plectodina* n. sp. B, *Pl.* n. sp. C, *Panderodus gracilis* and *Taoqupognathus tumidus* from the suggested excursion interval in the Tazhong 12 drill-core. Slightly higher stratigraphically, these conodont species are followed by *Belodina confluens*. The evolutionary stage of the two *Plectodina* species is comparable to that of *Pl. aculeata* and related *Plectodina* taxa that first appear in the North American Midcontinent succession in strata of late Sandbian age just below the GICE interval (Bergström & Sweet, 1966). Significantly, in the latter region, *B. confluens* first occurs just above the GICE interval (Young, Saltzman & Bergström, 2005). The morphologically distinctive and stratigraphically short-ranging species *Taoqupognathus tumidus* was first described from the *Dicranograptus kirki* Zone (Ea3) in southeastern Australia (Trotter & Webby, 1994). The precise international correlation of this graptolite zone is somewhat problematic, although Williams (1982) considered it to correspond to the upper *Dicranograptus clingani* Zone and lower *Pleurograptus linearis* Zone in northern Europe. It should also be noted that in another well, the Tazhong 29 well, Zhao, Zhang & Xiao (2000) recorded *Dicranograptus* cf. *clingani resicis* from the excursion interval. Assuming that this graptolite is correctly identified, it is indicative of the *Dicranograptus clingani* Zone (Williams & Bruton, 1983), a graptolite zone that contains most of the GICE in Baltoscandia (Bergström *et al.* 2004, fig. 4). Hence, these limited biostratigraphic data suggest that the Tazhong $\delta^{13}$C excursion is comparable in age to that of the GICE in North America and northern Europe. However, the biostratigraphically incomplete data at hand do not exclude the possibility that this excursion rather represents the slightly younger Kope $\delta^{13}$C excursion of Bergström *et al.* (2007*b*), even if we believe that the evidence now available favours the identification of the excursion as the GICE. Clearly, more detailed chemostratigraphic and biostratigraphic studies are needed in this remote part of China to confirm fully the presence of this intriguing isotopic perturbation in the carbon isotope cycle.

## 5. Conclusions

The principal results of the present study may be summarized as follows:

(1) For the first time, the early Katian $\delta^{13}$C excursion known as the GICE is documented from eastern Asia, where it is recorded from several sections of the Pagoda and Yanwashan formations on the Yangtze Platform and the Chiangnan (Jiangnan) slope belt in southeastern China.

(2) In terms of conodont biostratigraphy, this excursion occurs in the same stratigraphic interval as in Baltoscandia. This interval can be correlated with the global early Katian Stage, as well as with the early part of the North American Chatfieldian Stage.

(3) The discovery of the GICE in the Chinese Ordovician succession confirms that the GICE was a global perturbation of the carbon cycle, and in this respect it is comparable with the latest Ordovician Hirnantian excursion (HICE).

(4) The Pagoda Formation is one of the most distinctive, well-known and geographically widespread formations in the Ordovician of China, but its precise age and international correlation have remained uncertain. The new evidence from $\delta^{13}$C chemostratigraphy and conodont biostratigraphy constrains the age of most of the formation, although the age of its topmost part still remains uncertain. There are also strong

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indications that the Pagoda Formation is somewhat diachronous across the Yangtze Platform, but further studies are needed to assess this interpretation fully.

(5) Somewhat inconclusive data suggest that the GICE may be recognized also in the subsurface of the Tazhong area in the Tarim Basin in northwesternmost China.

(6) The present study illustrates the usefulness of $\delta^{13}C$ chemostratigraphy for precise correlations over ultra-long distances. It confirms that in the Upper Ordovician, not only the HICE but also the GICE is a unique global correlation tool that can be successfully employed for clarification of stratigraphic relationships that are difficult, if not impossible, to work out using ordinary biostratigraphic methods.

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