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Global Upper Ordovician correlation by means of $\delta^{13}C$ chemostratigraphy: implications of the discovery of the Guttenberg $\delta^{13}C$ excursion (GICE) in Malaysia

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Abstract – Apart from a single study of the early Katian $\delta^{13}C$ chemostratigraphy in two regions in China, no investigations of the Sandbian and Katian chemostratigraphy have been published from anywhere in Asia. A recent study of the conodont biostratigraphy of the classical Ordovician succession on Langkawi Islands, peninsular Malaysia, showed the presence there of strata coeval with those having the Guttenberg Carbon Excursion (GICE) on the Yangtze Platform. In an effort to establish for the first time the presence of this widespread $\delta^{13}C$ excursion in southern Asia, a series of samples from the upper part of the Kaki Bukit Formation was isotopically analysed. This resulted in the discovery of a conspicuous $\delta^{13}C$ excursion with peak values of ∼ 2 ‰ above the baseline values. The excursion is located just above the *Baltoniodus alobatus* Subzone and near the level of the first appearance of *Hamarodus europaeus*, hence the same stratigraphic position as the GICE on the Yangtze Platform. Using the GICE, the Malaysian study interval is closely correlated with the GICE intervals at three localities representing an approximately 23 000 km long transect from Malaysia across Baltoscandia to central North America. This shows the usefulness of $\delta^{13}C$ chemostratigraphy to clarify previously obscure stratigraphic relationships between geographically very widely separated localities.

Keywords: Ordovician, GICE, $\delta^{13}C$ chemostratigraphy, China, Malaysia, North America, Baltoscandia.

1. Introduction

Some of the southernmost occurrences of Ordovician rocks in Asia occur in peninsular Malaysia (Hamada *et al*. 1975). The presence of Ordovician strata in this region was established as late as 1955 (Jones, 1968), and despite the various investigations that have been carried out in the ensuing years (for summaries, see, for instance, Jones, 1968, 1981; Hamada *et al.* 1975 and Cocks, Fortey & Lee, 2005), many aspects of the geology of these deposits remain incompletely known. Some of the most important and most studied occurrences of Ordovician strata in peninsular Malaysia are situated on the Langkawi Islands just off the coast in the northwesternmost part of the country (Fig. 1). The palaeontology and stratigraphy of the Langkawi Islands Ordovician succession, which ranges in age from the Tremadocian to the Hirnantian, have been investigated by, among others, Kobayashi (1959*a*,*b*), Jones (1961, 1968, 1981), Hamada *et al*. (1975) and Kobayashi & Hamada (1978). For a useful recent review, including the new stratigraphic nomenclature used herein, see Cocks, Fortey & Lee (2005). In this region, a succession of mainly carbonate rocks, which is estimated to have a thickness of more than 1 km, is now classified as the Kaki Bukit Formation. It contains a sparse and not very diverse shelly fauna as well as conodonts. Pioneer work on the conodonts was published by Igo & Koike (1967), based on a very small number of samples. More recent records of Floian conodonts have been published by Metcalfe (1980) and Laurie & Burrett (1992). Recently, using 40 systematically collected samples from the top 150 m of the Kaki Bukit Formation, Agematsu, Sashida & Ibrahim (2008) provided a modern reappraisal of the conodont biostratigraphy of this interval. Judging from that study, and that of Laurie & Burrett (1992), the major part of Kaki Bukit Formation, perhaps as much as the lower 1 km, is of Early to early Middle Ordovician (Tremadocian to Dapingian) age, whereas the presence of Darriwilian and early Sandbian strata remains to be fully documented.

Agematsu, Sashida & Ibrahim (2008) showed that the late Sandbian and Katian conodont species successions exhibit a striking similarity to those in the interval of the globally distributed Guttenberg $\delta^{13}C$ excursion (GICE) in the Pagoda Formation of the Yangtze Platform in southern China as recorded by Bergström *et al*. (2009*b*). This gave us the impetus to examine the $\delta^{13}C$ chemostratigraphy in the Malaysian succession. The purpose of this report is to present the results of this study, which is the first of its kind carried out on Lower Palaeozoic rocks in southernmost Asia. Despite the limited scope of this pioneer project, the chemostratigraphic data obtained markedly improve

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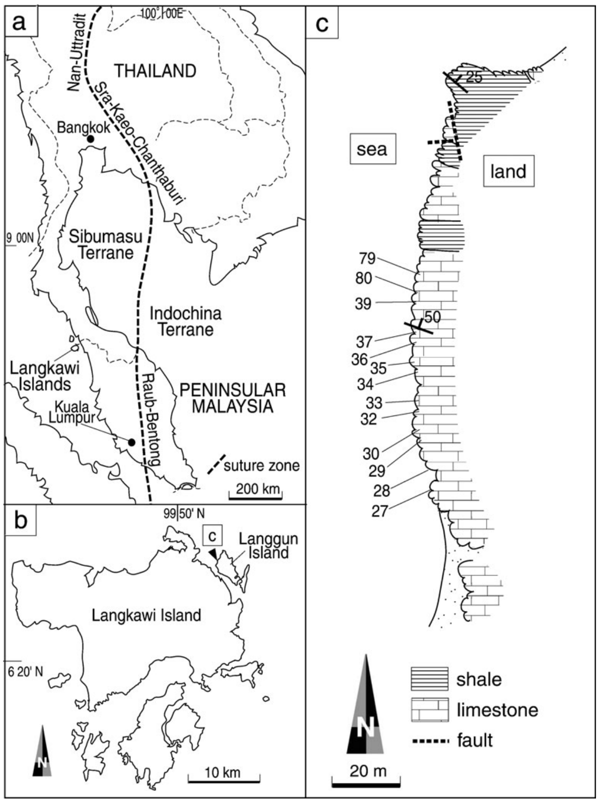

Figure 1. Maps showing the location of the study section on Langgun Island, Langkawi Islands, northwesternmost Malaysia. As shown in (c), the investigated section is along the northwestern shore of Langgun Island. Numbers refer to samples collected for conodont research and used in the present study. Map slightly modified from Agematsu, Sashida & Ibrahim (2008).

our understanding of the international, previously very incompletely known, stratigraphic relations of the study succession. The new information also confirms the idea that the GICE is a globally distributed perturbation in the Ordovician carbon cycle.

2. Geological framework

In terms of location of continental blocks, islands located and seas, the Ordovician palaeogeography of what is now southern and southeastern Asia differed conspicuously from today's geography. According to recent interpretations, in the presumably relatively large region between the giant continent of Gondwana and the smaller Siberian and Baltic plates, there were several terranes that were separated by moderately wide oceanic areas (for recent discussions, see Cocks, Fortey & Lee, 2005; Agematsu *et al*. 2007). Two of these smaller, but nevertheless substantial, terranes were the Sibumasu and Indochina blocks that in terms of present day geography extend from Yunnan in southern China and Vietnam and Laos, respectively (Cocks, Fortey & Lee, 2005, fig. 1). These blocks are today separated by a prominent suture zone known as the Raub-Bentong suture in peninsular Malaysia and the Sra-Kae-Chanthaburi suture in Thailand (Fig. 1a).

In most respects, especially in terms of lithology and fauna, the Ordovician geology differs greatly between these blocks. Whereas most of the Sibumasu successions consist of relatively shallow-water, little deformed, cratonic sediments including prominent carbonate units, coeval Indochina terrane strata are dominated by siliciclastic, mostly more or less tectonized, partly metamorphosed, poorly fossiliferous rocks with ophiolites. Jones (1968, figs 2, 3) interpreted the former rocks as representing miogeosynclinal shelf and basin deposits and the latter as eugeosynclinal basinal strata. In his interpretation, the western shallow-water shelf region was separated from the eastern deeper-water region by a geanticline consisting mostly of argillaceous rocks and volcanic rocks. In a more recent, very different, interpretation, the Sibumasu and Indochina terranes are regarded as separate land masses, which were separated by deep sea regions (see, for instance, Agematsu, Sashida & Ibrahim, 2008, fig. 7). However, as noted by Cocks, Fortey & Lee (2005), many features in the Lower Palaeozoic palaeogeography of this region remain obscure.

Ordovician rocks of the Sibumasu block are exposed in several areas from northwestern Thailand southward through the western part of peninsular Malaysia (Agematsu *et al.* 2007, fig. 1, and references therein). Perhaps the best known, and most studied, of these occurrences is on the Langkawi Islands in northwesternmost peninsular Malaysia (for informative maps and description, see Jones, 1968, 1981). The focus of the present investigation is an Upper Ordovician (Sandbian–Katian) section in this region.

3. Samples and biostratigraphy

The present chemostratigraphic research is based on limestone samples used for conodont work by Agematsu, Sashida & Ibrahim (2008) that were collected from exposures along the shore of the northwestern side of Langgun Island (= Palau Langgun of Jones, 1968; Langgon Island of Igo & Koike, 1967; Langoon Island of Agematsu, Sashida & Ibrahim, 2008). This section, which is situated on an island off the northeastern corner of Langkawi Island (Fig. 1), has previously been studied by Igo & Koike (1967) and Jones (1968). For this investigation, we used samples 27–30, 32–37, 39, 80 and 79 of Agematsu, Sashida & Ibrahim (2008), which provided suitable material for $\delta^{13}C_{carb}$ analysis. Other samples collected by these authors had been completely dissolved for conodonts. The geographic and stratigraphic locations of these samples are shown schematically in Figures 1 and 2, respectively.

As is a necessity for any study of this type, the samples are tied into an adequate biostratigraphic framework. The best biostratigraphic control of the study succession is provided by the conodonts as described by Agematsu, Sashida & Ibrahim (2008). To clarify the conodont biostratigraphic framework, the significant conodont taxa and their importance

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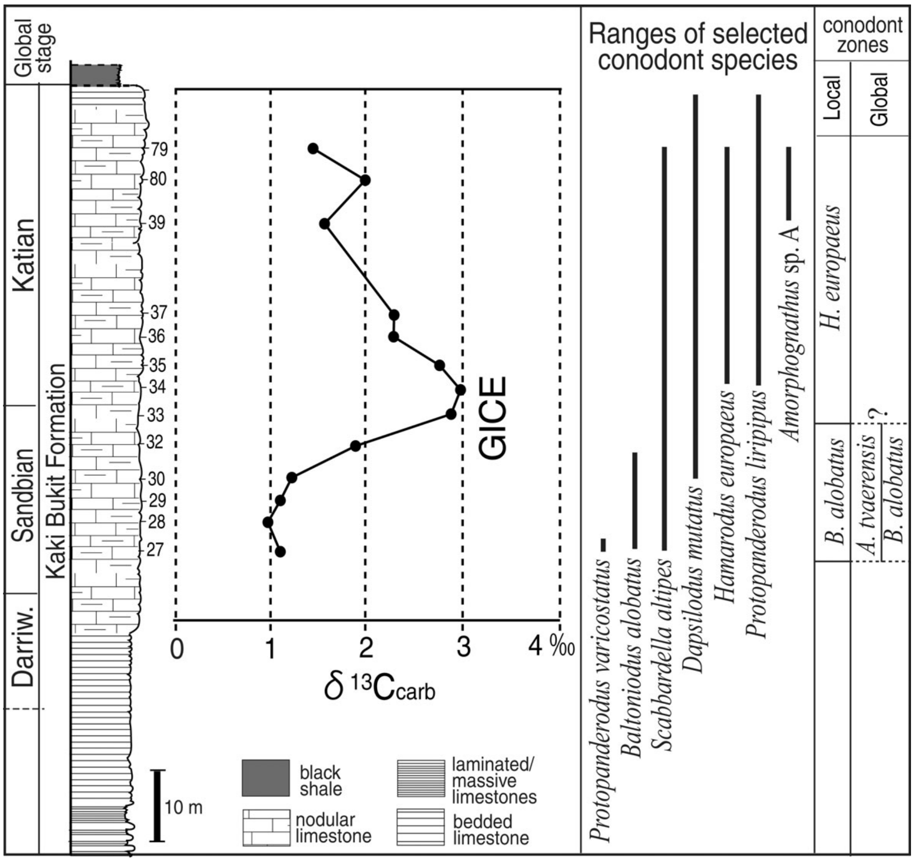

Figure 2. $\delta^{13}C_{carb}$ curve and vertical ranges of important conodont taxa in the late Sandbian–early Katian part of the Kaki Bukit Formation on Langgun Island. Note the conspicuous increase in $\delta^{13}C$ values from baseline values of $\sim$+1 ‰ to excursion values of $\sim$+3 ‰, which is followed by a gradual decline toward baseline values in the uppermost part of the formation. Darriw. – Darriwilian. As mentioned in the text, Darriwilian strata are still incompletely documented in the study area.

are briefly discussed below. For vertical distribution data, see Figure 2. Unless noted otherwise, we use the global stage terminology recently ratified by the International Commission on Stratigraphy (for a review, see Bergström *et al.* 2009*a*).

The conodont faunas from the lowermost portion of the Kaki Bukit Formation include *Cordylodus* sp. and other taxa indicating a Tremadocian age. Overlying strata yield Floian–Darriwilian(?) faunas that show similarities to tropical zone faunas from Australia and China (Agematsu, Sashida & Ibrahim, 2008). Analysis of these faunas is outside the scope of this study, which is centred on the uppermost Sandbian–Katian portion of the Kaki Bukit Formation.

Among the taxa present in this interval, *Dapsilodus mutatus, Protopanderodus liripipus* and *Scabbardella altipes* are relatively long-ranging and hence of limited value for detailed biostratigraphic correlation. The two latter species appear near the base of the early Sandbian *Amorphognathus tvaerensis* Zone in Sweden (Bergström, 2007), whereas *Dapsilodus mutatus* occurs already in Darriwilian strata (Zhang, 1998). Of greater biostratigraphic significance is *Baltoniodus alobatus*. The Malaysian specimens compare favourably with those identified as *Baltoniodus alobatus* (= *Baltoniodus* or *Prioniodus linguatus* in An, 1987 and some older Chinese papers) from the uppermost Miaopo Formation and coeval strata of the Yangtze Platform. In having a platform-like posterior process with a rounded lateral expansion, the Pb element of this morphotype is closely similar to the Pb element of the typical *Baltoniodus alobatus* from Baltoscandia (Bergström, 1971, pl. 2, figs 4, 5). However, at least some of the Langkawi Islands M elements have an unusually long denticulate posterior process (Agematsu, Sashida & Ibrahim, 2008, fig. 11:12a, b), a feature not seen in the mostly fragmentary Baltoscandic specimens. Other Malaysian M elements, such as that figured by Agematsu, Sashida & Ibrahim (2008, fig. 11:13a), appear indistinguishable from the Baltoscandic specimens. Based on the fact that as far as is known, this species is restricted to the *Baltoniodus alobatus* Subzone of the *Amorphognathus tvaerensis* Zone (Bergström, 1971, 2007), we conclude that the interval of samples 27–30 of Agematsu, Sashida & Ibrahim (2008) represents this conodont subzone, which is of late Sandbian age. Importantly, this subzone is in China and Baltoscandia located slightly below the level of the beginning of the GICE (Männik & Viira, 2005; Bergström *et al.* 2009*b*).

Another conodont species of biostratigraphic significance in the Langkawi Islands succession is *Hamarodus europeus*. This species is known from the *Amorphognathus superbus* and *A. ordovicicus* zones

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at many localities in Baltoscandia (Bergström, 2007) and has also been recorded from sections elsewhere in Europe (see, for instance, Serpagli, 1967; Orchard, 1980; Dzik, 1994; Ferretti & Barnes, 1997), but in North America, it has been safely identified only from Nevada (Sweet, 2000). Although used as a zone fossil in China (An, 1987; Ni & Li, 1987), Thailand (Agematsu *et al*. 2007) and recently in peninsular Malaysia (Agematsu, Sashida & Ibrahim, 2008), the fact that it ranges through virtually the entire Katian Stage (Bergström, 2007) greatly reduces its value for correlation of a particular stratigraphic interval. Nevertheless, the first appearance of this morphologically distinctive species appears to be at essentially the same stratigraphic level in Baltoscandia, Poland (Dzik, 1994), China (Bergström *et al*. 2009*b*, fig. 6) and Malaysia, namely in the uppermost *Amorphognathus tvaerensis* Zone as this zone was originally defined by Bergström (1971).

The few available Langkawi Islands specimens of the biostratigraphically important genus *Amorphognathus* are unfortunately not identifiable to species. Stratigraphically similar occurrences of specimens of this genus are known from the Pagoda Formation of the Yangtze Platform, China (An, 1987; Ni & Li, 1987; Bergström *et al.* 2009*b*). A specimen that apparently represents a dextral Pa element of *Amorphognathus superbus* was recorded (as *Amorphognathus* sp.) from an approximately coeval horizon in the Pa Kae Formation of southern Thailand by Agematsu *et al*. (2007, fig. 13:1a, b). However, additional specimens are clearly needed to establish the species identity of the morphotype(s) from the Langkawi Islands succession.

As a whole, the Sandbian–Katian conodont fauna recorded by Agematsu, Sashida & Ibrahim (2008) from the Kaki Bukit Formation is closely similar not only to that of the Pagoda Formation but also to that of the upper Pa Kae Formation. The latter fauna was recorded from the type section of the formation in outcrops near the Khlong Husi Ba River about 50 km N of Langkawi Islands. The rich trilobite fauna from reddish-weathering limestones in the top 50 m of the formation at this locality described by Fortey (1997) shows a striking similarity to that of the Pagoda Formation. Based on the ranges of key conodonts, such as *Hamarodus europaeus* and *Amorphognathus superbus,* this top part of the Pa Kae Formation would appear to correspond to the lower to middle part of the Pagoda Formation at the Puxihe Quarry. Hence, there is excellent agreement between the evidence furnished by conodonts and trilobites regarding the biostratigraphic relations between the Pa Kae and Pagoda successions.

4. $\delta^{13}C_{carb}$ chemostratigraphy

4.a. Sample preparation

Powdered, homogenized bulk-rock samples were analysed for $^{13}C/^{12}C$ and $^{18}O/^{16}O$ ratios at the Stable Isotope Laboratory, Department of Geology, Copenhagen University. The samples were dissolved in vacuum in 100 % phosphoric acid at 25 °C. The carbon dioxide evolved was analysed in a Finnigan-MAT 250 mass spectrometer. The results are reported in per mil (‰) deviations from the V-PDB (Vienna-Pee Dee Belemnite) standard. Reproducibility is better than ±0.03 for $\delta^{13}C$ and ±0.05 for $\delta^{18}O$ expressed as ±σ (standard deviation) for ten identical samples. Only the $\delta^{13}C$ results are presented herein.

4.b. The Langkawi Islands $\delta^{13}C_{carb}$ curve

The results of analysis of 13 limestone samples from an approximately 60 m thick interval of nodular limestone in the upper Kaki Bukit Formation are plotted in the $\delta^{13}C$ curve shown in Figure 2. The stratigraphically lowermost four samples (samples 27–30) show $\delta^{13}C$ values of ∼+1 ‰ that we interpret as baseline values. The sample 32 shows a significantly higher $\delta^{13}C$ value of +1.9 ‰, which represents the beginning of the excursion, the peak values of which range up to +3 ‰ in the samples 33–35. The excursion peak is followed by a gradual decline in $\delta^{13}C$ values to ∼+2 ‰ or less in the following samples 36, 37, 39, 80 and 79. Further studies are needed to clarify if the $\delta^{13}C$ curve returns to the previous baseline values of ∼+1 ‰ in the uppermost part of the Kaki Bukit Formation from which no samples were available. Importantly, the excursion peak values are in the approximately 10 m thick interval between the stratigraphically highest occurrence of *Baltoniodus alobatus* (sample 31) and the first appearance of *Hamarodus europaeus* (sample 34). Although the available conodont biostratigraphic evidence is not very extensive, it shows that the $\delta^{13}C$ excursion is present within an interval that is slightly younger than the *Baltoniodus alobatus* Subzone of the *Amorphognathus tvaerensis* Zone.

The conodont species succession around the excursion interval in the Malaysian study succession is virtually identical to that in the GICE interval on the Yangtze Platform of China (Bergström *et al.* 2009*b*) (Fig. 3) and there are also close similarities to that of the corresponding excursion interval in Baltoscandia (Bergström *et al*. 2004, 2009*b*; Männik &Viira, 2005; Barta *et al.* 2007). In North America and Baltoscandia, the excursion interval is in the topmost part of the *Amorphognathus tvaerensis* Zone (Young, Saltzman & Bergström, 2005). Although conclusive biostratigraphic evidence is not yet available, the data at hand clearly suggest that the excursion interval on the Langkawi Islands is of this age and hence, that the $\delta^{13}C$ excursion represents the GICE. This is the first documentation of the GICE in any part of Asia outside China.

5. Regional comparisons

In a recent paper, Bergström *et al.* (2009*b*) described the $\delta^{13}C$ chemostratigraphic relations in the GICE

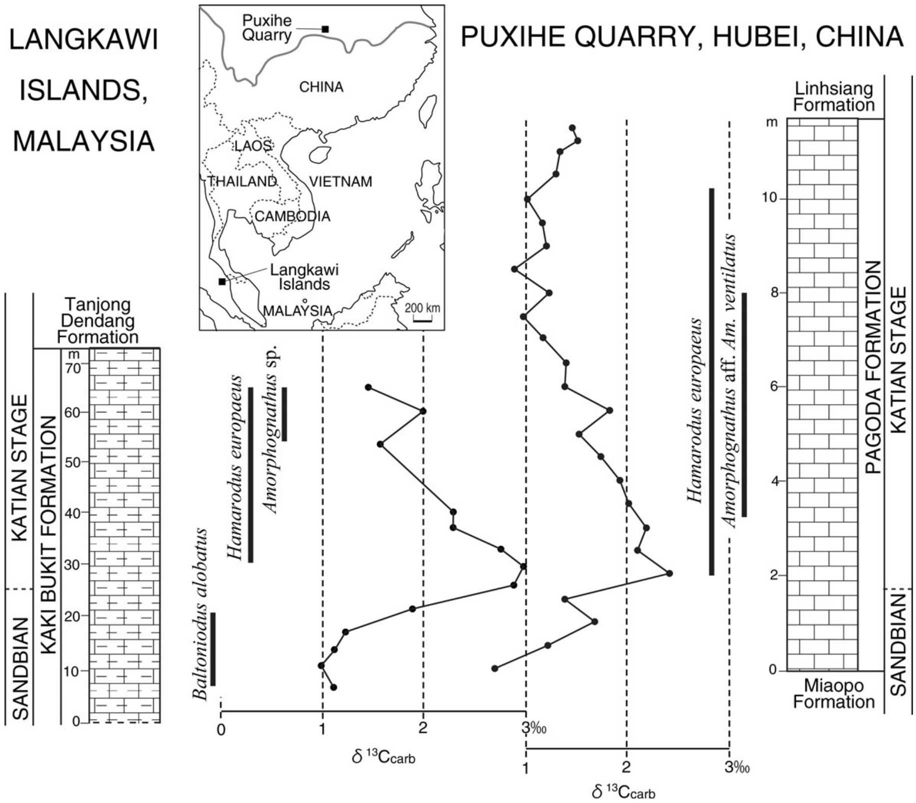

Figure 3. Comparison of $\delta^{13}C_{carb}$ curves and the vertical distribution of important conodont taxa between Langkawi Islands and the Puxihe Quarry, Hubei Province, China. The data from Puxihe Quarry are from Bergström *et al.* (2009*b*) and the conodont data from Langkawi Islands are from Agematsu, Sashida & Ibrahim (2008). Inset map shows the very long distance (approximately 2800 km) between the Langkawi Islands and the Puxihe Quarry. Note the close similarity in the shape of the curves and in the ranges of important conodont taxa which suggest that the study interval in the Kaki Bukit Formation corresponds to the uppermost Miaopo Formation and lower Pagoda Formation at the Puxihe Quarry.

interval between the Yangtze Platform, Sweden, and Kentucky in North America. As an expansion of that study, it is appropriate to examine how the Malaysian $\delta^{13}C$ curve can be correlated with the GICE curves from not only the Yangtze Platform but also those from Baltoscandia and North America. For such a comparison, we use GICE curves from the Fjäcka section, Province of Dalarna, central Sweden (Bergström *et al.* 2004, 2010; Barta *et al.* 2007), the Dexter Quarry–Roaring Brook composite section, Jefferson and Lewis counties, New York State, USA (Barta *et al*. 2007), and the McGregor Quarry, Clayton County, State of Iowa, USA (Ludvigson *et al*. 2002). As illustrated in Figure 4, Baltoscandia and North America were widely separated geographically from peninsular Malaysia in Katian time, whereas the latter region is thought to have been situated relatively close to the Yangtze Platform. The transect from Langkawi Islands to Iowa illustrated in Figure 5 represents a distance of as much as approximately 23 000 km in terms of today's geography.

5.a. Puxihe Quarry, China

In terms of both conodont biostratigraphy and $\delta^{13}C$ chemostratigraphy, the succession of the Miaopo Formation and Pagoda Formation on the Yangtze Platform offers a remarkably close parallel to the study interval in the upper Kaki Bukit Formation. The conodont species sequence from the *Baltoniodus alobatus* Subzone in the upper Miaopo Formation into the *Hamarodus europaeus* interval in the Pagoda Formation at the Puxihe Quarry (Bergström *et al.* 2009*b*, fig. 4) is virtually identical to that in the upper Kaki Bukit Formation (Fig. 3). Also, the appearance of an unidentified species of *Amorphognathus*, in all likelihood the same species as in the Pagoda Formation, is only slightly higher stratigraphically in the Langkawi Islands succession. However, in view of the general scarcity of conodont specimens in the Malaysian study interval and the fact that elements of *Amorphognathus* are relatively rare, it is quite likely that additional collecting may extend the range of this species somewhat downward to approach its level of appearance in the Yangtze Platform section.

As shown in Figure 3, the shape of the $\delta^{13}C$ curve through the study interval in the Kaki Bukit Formation is very similar to that in the Pagoda Formation at the Puxihe Quarry. The baseline values are ∼+1 ‰ in both successions, and the rapid increase in $\delta^{13}C$ values near the last occurrence of *Baltoniodus alobatus* to peak values close to the level of first occurrence of *Hamarodus europaeus* is almost identical. A slight difference is that the peak values of the Malaysian section are ∼+3 ‰, whereas they are only < 2.5 ‰ at the Puxihe Quarry. Interestingly, the stratigraphic thickness of the $\delta^{13}C$

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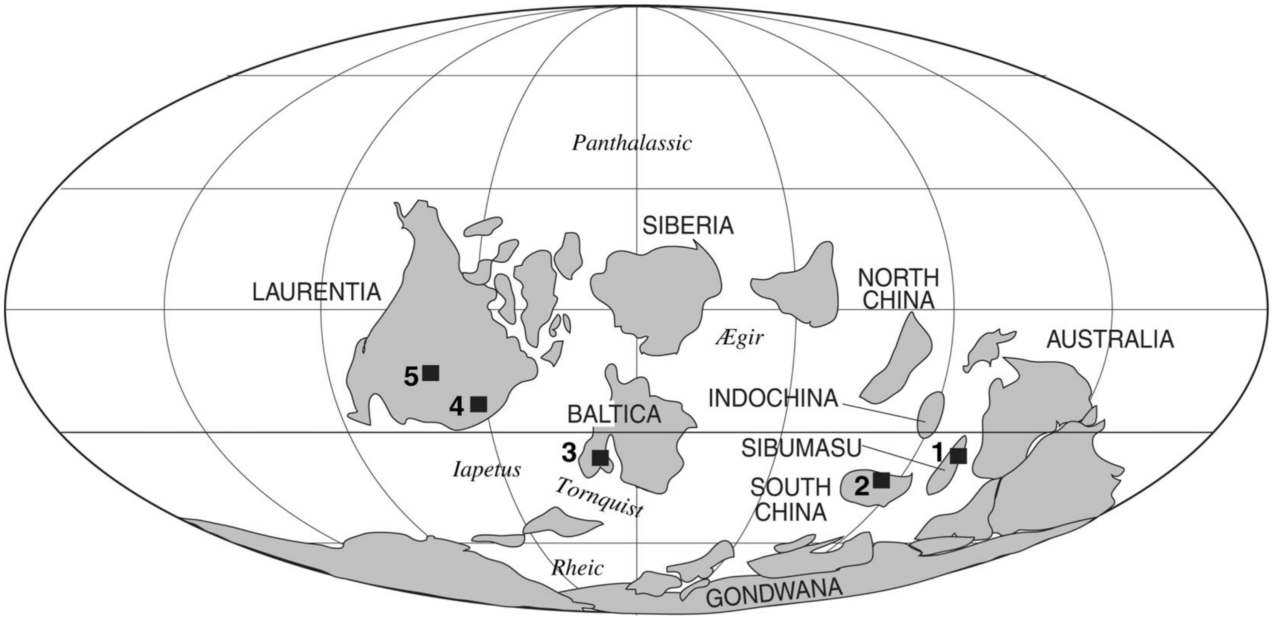

Figure 4. Sketch-map showing Katian (Upper Ordovician) inferred positions of major continental plates (modified after Agematsu, Sashida & Ibrahim, 2008) and the palaeogeographic location of the Malaysian, Chinese, Swedish and North American localities discussed in the text. Note that the South China and Sibumasu plates are interpreted not to have been very widely separated at this time and to have been located at about the same latitude as southern Baltoscandia, which is consistent with the similarity of the Katian conodont faunas from these three regions. The conodont faunas of the North American localities, which were situated at significantly lower latitudes in Ordovician time, are strikingly different and represent the Midcontinent Province. Locality designations (black squares): 1 – Langkawi Islands, Malaysia; 2 – Puxihe Quarry, Hubei Province, China; 3 – Fjäcka, Sweden; 4 – New York State, USA; 5 – McGregor Quarry, Iowa, USA.

peak interval is > 30 m in the Kaki Bukit Formation but only about 10 m in the Pagoda Formation, which indicates a significantly higher rate of net deposition in the Malaysian succession.

The extraordinary close agreement in both biostratigraphy and $\delta^{13}C$ chemostratigraphy between these two sections clearly indicates that the studied succession in the upper Kaki Bukit Formation is an equivalent to the uppermost Miaopo Formation and lower half of the Pagoda Formation at the Puxihe Quarry. Although no shaly strata similar to those of the Miaopo Formation have been recorded from the Langkawi Islands succession, part of the excursion interval in the Kaki Bukit Formation exhibits close lithological similarity to the Pagoda Formation (cf. Agematsu, Sahida & Ibrahim, 2008, fig. 4 with Zhan & Jin, 2007, fig. 37). Interestingly, in the case of the peak GICE interval, the precision of this long-range correlation appears to be < 2 m in terms of the Chinese succession. As suggested by the $\delta^{13}C$ chemostratigraphy, the Pagoda Formation is to some extent diachronous across the Yangtze Platform (Bergström *et al.* 2009*b*) with the GICE present at somewhat different levels within the Pagoda Formation at other localities. Obviously, this fact needs to be considered when making a detailed GICE-based correlation between Langkawi Islands and localities on the Yangtze Platform.

5.b. Fjäcka, Sweden

For almost 150 years, the fauna and biostratigraphy of the Fjäcka section have been subjected to a great amount of study (see, for instance, Jaanusson & Martna, 1948; Jaanusson, 1963, 1976, 1982; Laufeld, 1967; Bergström, 1971, 2007; Holmer, 1989; Nõlvak, Grahn & Sturkell, 1999) that has made the Sandbian–Katian succession at this classical locality the best known of this age in Sweden. The stratigraphic subdivision of the interval pertinent to the present study follows Jaanusson (1963, 1982), who recognized the Dalby, Skagen and Moldå formations. In terms of conodont biostratigraphy (Bergström, 2007), the topmost portion of the Dalby Formation, up to the Kinnekulle K-bentonite, belongs to the *Baltoniodus alobatus* Subzone of the *Amorphognathus tvaerensis* Zone. The non-diverse conodont fauna of the Skagen and lower part of the Moldå formations lacks zone index species but most likely represents the uppermost part of the *Amorphognathus tvaerensis* Zone. The levels of first appearance of *Amorphognathus complicatus, A. superbus* and *Hamarodus europaeus* are in the upper part of the Moldå Formation that belongs to the *Amorphognathus superbus* Zone.

As is the case in the Langkawi Islands study succession, the $\delta^{13}C$ baseline values are ~+1 ‰ in the late Sandbian part of the Fjäcka curve. However, the GICE peak values in the Malaysian curve are higher (~+3 ‰) than at Fjäcka (a little less than +2 ‰). Also, the Fjäcka GICE curve has two, rather than one peak, and the first appearance of *Hamarodus europaeus* there is a little higher stratigraphically in relation to the peaks of the GICE. As shown by, for instance, Ludvigson *et al.* (2004), Young, Saltzman & Bergström (2005) and Kaljo, Martma & Saadre (2007), one-peak GICE

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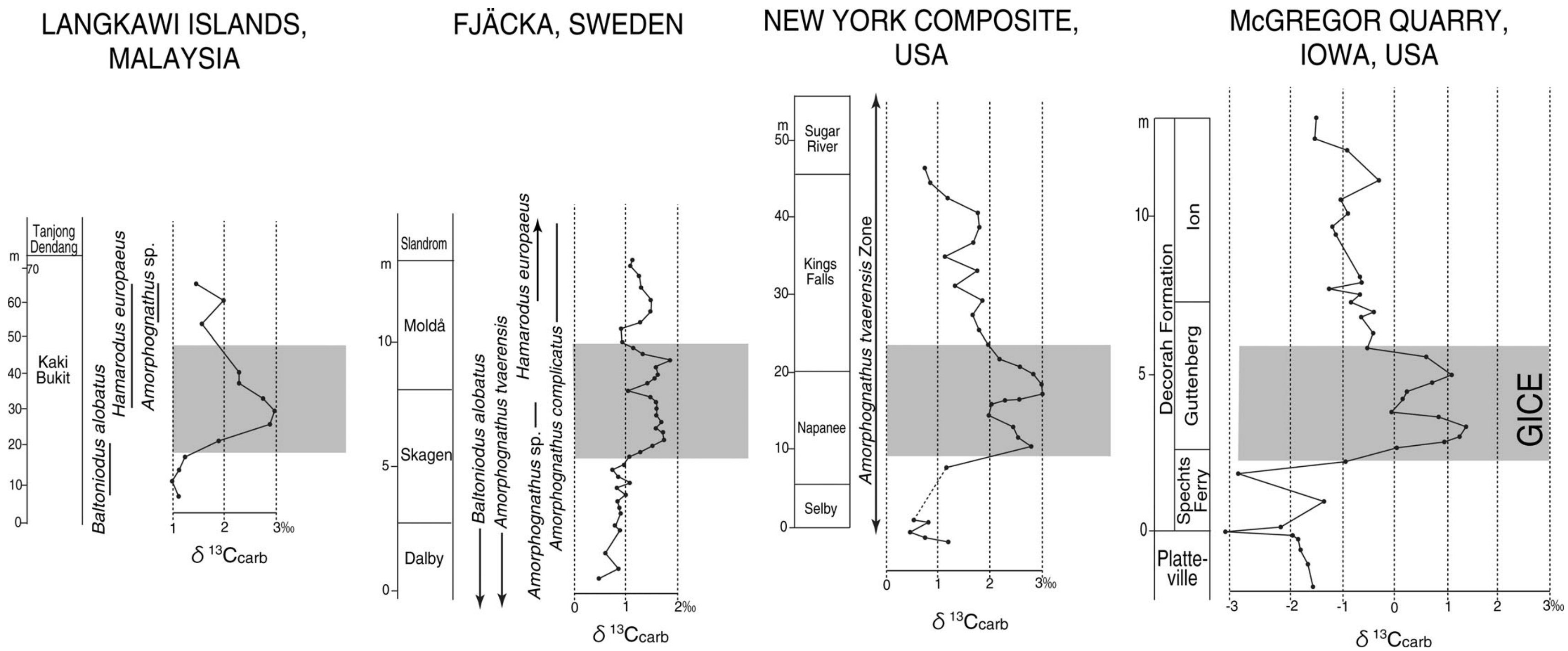

Figure 5. Comparison of the $\delta^{13}C_{carb}$ curves with the GICE from Langkawi Islands, central Sweden (Fjäcka; after Bergström *et al*. 2004), New York State, USA (after Barta *et al*. 2007), and the Upper Mississippi Valley, USA (McGregor Quarry, Iowa; after Ludvigson *et al.* 2002). The diagram illustrates the usefulness of GICE for very detailed long-distance correlations.

curves are in some cases present at localities that are relatively close to sites with 2-peak curves, and we do not attach any particular significance to this feature, and do not consider it to be a unique characteristic of the GICE. We regard the chemostratigraphic differences between the Malaysian study section and that at Fjäcka as minor, and based on both biostratigraphy and $\delta^{13}C$ chemostratigraphy, the correlation of their GICE intervals appears well established.

5.c. New York State

The Black River and Trenton groups in New York State and adjacent parts of Ontario have traditionally served as a reference standard for the regional Mohawkian (Middle Ordovician) Series in North America (see, for instance, Ross *et al.* 1982). Recent lithostratigraphic and biostratigraphic studies (see Goldman *et al.* 1994; Brett & Baird, 2002; Brett *et al.* 2004; Richardson & Bergström, 2003) have resulted in significant revisions of the complex stratigraphic classification and separation of biostratigraphic and lithostratigraphic units. The Selby, Napanee, Kings Falls and Sugar River formations listed in Figure 5 are lithostratigraphic units. The conodont biostratigraphy of the Trenton Group is now well known (Schopf, 1966; Richardson & Bergström, 2003; Barta *et al.* 2007) and adequately tied into the $\delta^{13}C$ chemostratigraphy. Importantly, in this region it is possible to directly demonstrate in a continuous succession that the *Amorphognathus tvaerensis/Amorphognathus superbus* Zone boundary is located significantly above the GICE interval (~ 60 m above the GICE in the Roaring Brook, Martinsburg succession). The conodont faunas of the Trenton Group are of Midcontinent type (Schopf, 1966; Barta *et al.* 2007) and have as a whole little in common with those of the Langkawi Islands succession.

As is the case in the Langkawi Islands succession, the $\delta^{13}C$ baseline value is ~+1 ‰ and the GICE peak values ~+3 ‰ in the New York State composite $\delta^{13}C$ curve of Barta *et al.* (2007). The GICE has two peaks similar to those in the Fjäcka curve. There is a rapid rise from the baseline value to the peak $\delta^{13}C$ values that are followed by a gradual decline toward background values. The GICE interval is approximately 15 m thick in the New York State composite curve compared with about 30 m in the Langkawi Islands succession. Although the key conodonts *Baltoniodus alobatus* and *Hamarodus europaeus* have not been found in New York State or Ontario, there is little doubt about how the GICE interval of this region correlates with that of the Langkawi Islands.

5.d. McGregor Quarry, Iowa

Since the 1980s a very considerable amount of $\delta^{13}C$ work has been carried out in the large Ordovician outcrop area in the Upper Mississippi Valley, especially in Iowa, Missouri and Minnesota (Ludvigson *et al.* 2004). The GICE was first recognized in Iowa (Hatch *et al.* 1987) and this excursion is currently recorded from more than a dozen sections in the Upper Mississippi Valley. In these sections, it is located in the Guttenberg Member of the Decorah Formation. The early Katian strata of this region are richly fossiliferous (see, for instance, Sloan, 2005) and the conodont fauna of the Decorah Formation and associated strata is well known (Webers, 1966; Sweet, 1987). However, this conodont fauna is of typical Midcontinent type and quite unlike that of apparently coeval strata on Langkawi Islands and at Fjäcka but resembles that of the Trenton Group. The Millbrig K-bentonite, which occurs in the Spechts Ferry Member (Kolata, Huff & Bergström, 1996), is a useful marker horizon for correlation with the same volcanic ash bed in the Selby Formation of New York State (Mitchell *et al.* 2004). This bed may also correspond to the widespread Kinnekulle K-bentonite in Baltoscandia (Bergström *et al*. 2004).

Among the several sections in the Upper Mississippi Valley that have been investigated for $\delta^{13}C$ chemostratigraphy, we selected for long-range comparison that at the McGregor Quarry, Clayton County, Iowa (Ludvigson *et al*. 2002), because of its typical GICE curve and stratigraphically continuous surface exposure of the GICE interval. Although one sample from the Turinian Platteville Formation and one from the overlying Spechts Ferry Member of the Decorah Formation show unusually low $\delta^{13}C$ values of ~−3 ‰ (Fig. 5), the baseline values in the uppermost Platteville Formation and the Spechts Ferry Member are between −2 ‰ and −1 ‰. Near the base of the Guttenberg Member there is a conspicuous and sudden increase in $\delta^{13}C$ values to ~+1.4 ‰, which is followed by a decrease to 0 ‰. Above this in the $\delta^{13}C$ curve is another curve segment with values of >+1 ‰. This produces a 2-peak curve similar to the composite one from New York State and that of Lexington, Kentucky (Bergström *et al.* 2004; Young, Saltzman & Bergström, 2005). The second peak in $\delta^{13}C$ values is followed by a decrease to ~−0.5 ‰ in the upper part of the Guttenberg Member. In the overlying Ion Member, the $\delta^{13}C$ values fluctuate around −1 ‰.

As just noted, there are no stratigraphically diagnostic fossils that can be used for a direct biostratigraphic comparison between the successions in the McGregor Quarry and on the Langkawi Islands. Because the biostratigraphic relations between the Sandbian–early Katian successions in Iowa and New York State are well established and non-controversial (see, for instance, Sweet, 1984, fig. 3) and consistent with the $\delta^{13}C$ chemostratigraphy, we are confident that the excursion interval in the upper Kaki Bukit Formation corresponds to that of the typical GICE in the Upper Mississippi Valley (Fig. 5). Interestingly, the magnitude of the GICE is slightly larger in Iowa (~2.5–3 ‰) than in the Langkawi Islands succession (~2 ‰). It should also be noted that the baseline values in Iowa (~−2.5 ‰) are significantly lighter than in the Malaysian section (~+1 ‰). The reasons for these differences require further study.

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6. Graptolite zone correlation of the GICE

A recent pioneer $\delta^{13}C_{org}$ investigation (Goldman *et al.* 2007) resulted in the documentation of an excursion identified as the GICE in the lowermost *Diplacanthograptus caudatus* Zone in a lowermost Katian deep-water clastic succession in Oklahoma. This suggests that the GICE interval in the Kaki Bukit Formation is coeval with this part of this standard graptolite zone. However, further studies are needed to confirm this correlation, because as shown by Young *et al*. (2008), the $\delta^{13}C_{carb}$ and $\delta^{13}C_{org}$ GICE curves are not always of a closely similar shape, even when using the same set of samples.

7. Conclusions

The principal results of the present investigation may be summarized as follows.

(1) There is an obvious similarity in the conodont faunas, and to some extent also in the lithology, between an interval of early Katian age of the Kaki Bukit Formation of Langkawi Islands, peninsular Malaysia and the Pagoda Formation of the Yangtze Platform of southern China. This supports the idea expressed in some recent palaeogeographic reconstructions that these regions were located relatively close to each other during Late Ordovician time.

(2) For the first time, the Guttenberg Isotopic Carbon Excursion (GICE) is documented from southern Asia, namely in an interval within the upper 60 m of the Kaki Bukit Formation. The only previous Asian records of this excursion are from a few localities in China.

(3) Based on $\delta^{13}C$ chemostratigraphy, and to some extent biostratigraphy, we suggest that the studied part of the Kaki Bukit Formation corresponds to the uppermost Miaopo Formation and part of the Pagoda Formation in China, the upper Dalby, Skagen and lower Moldå formations in Sweden, the Selby, Napanee and lower part of the Kings Falls formations in New York State, and the Decorah Formation in the Upper Mississippi Valley. In terms of regional stages, its equivalents would be in the upper Haljala, Keila and Oandu stages in Baltoscandia, and in the uppermost Turinian and Chatfieldian stages in North America. It would also correspond to the upper part of Stage Slice Sa2 and lower part of Stage Slice Ka1 of Bergström *et al.* (2009*a*).

(4) The discovery of the GICE in peninsular Malaysia extends the known geographic range of this carbon excursion thousands of kilometres in terms of today's geography and confirms that in all probability, it has a worldwide distribution and is comparable to the latest Ordovician HICE in terms of its utility for the establishment of both local and very long-range stratigraphic relationships. Having a magnitude of only 1–3 ‰ at most localities, the GICE is a smaller excursion than the HICE, which may have values of > 8 ‰; nevertheless, the GICE is readily distinguishable in the $\delta^{13}C$ curves, especially in the cratonic carbonate successions.

(5) It is expected that future work in the Ordovician of other Asian regions, such as the vast Siberian craton, will result in the recognition of the GICE elsewhere and further prove its usefulness for the identification of a relatively brief time interval in the early Katian.

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