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Upper Ordovician (Sandbian–Katian) graptolite and conodont zonation in the Yangtze region, China

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ABSTRACT: The graptolite and conodont biostratigraphy of the latest Darriwilian, Sandbian and early and middle Katian succession on the Yangtze Platform is reassessed based on numerous new fossil collections and previously published data. At least at some localities, the lowermost Miaopo Formation is of pre-*Nemagraptus gracilis* Zone age (uppermost *Pygodus serra* and lowermost *P. anserinus* conodont zones). The rest of this formation (except for the uppermost part, which lacks diagnostic graptolites) has a diverse graptolite fauna of the *N. gracilis* Zone. The uppermost part of the Miaopo Formation contains few biostratigraphically diagnostic graptolites but the occurrence of conodonts of the *Baltoniodus alobatus* Subzone of the *Amorphognathus tvaerensis* Zone suggests equivalence with part of the *Climacograptus bicornis* graptolite Zone. The conodont succession of the Datianba Formation is virtually identical with that of the Miaopo Formation, confirming that these units are coeval. The lowermost part of the overlying non-graptolitic Pagoda Formation represents the upper *A. tvaerensis* Zone, and its upper part represents the *A. superbus* Zone. The occurrence of *Dicellograptus elegans* in the overlying Chientsaokou Formation (equivalent to the Linhsiang Formation in Yangtze Gorges region) suggests equivalence with the *Pleurograptus linearis* Zone in Scotland, which is consistent with the relatively non-diagnostic conodont fauna in these Chinese units. The biostratigraphic data are in good agreement with the $\delta^{13}C$ chemostratigraphy and permit the establishment of precise correlations with the Baltoscandic and North American successions.

KEY WORDS: biostratigraphy, conodonts, graptolites, Yangtze Platform

Uppermost Darriwilian, Sandbian and Katian (latest Middle and Upper Ordovician) rocks cover the entire Yangtze platform in southern China (Fig. 1). The part of the succession dealt with herein includes the Miaopo, Pagoda and Linhsiang formations (Fig. 2). Stratigraphically, the Miaopo and Pagoda formations may be separated by a minor disconformity, whereas the Pagoda and Linhsiang formations form a continuous succession. The Miaopo Formation, as well as the Wufeng Formation that overlies the Linhsiang Formation, consists mainly of black graptolite-rich shales (Chen *et al.* 1995) that are lithologically very different from the carbonate strata of the Pagoda and Linhsiang formations. The entire succession is highly condensed and reaches a maximum total thickness of only a few tens of metres. Lithological and faunal data suggest that these strata were deposited in relatively deep water in a continental platform environment. Compared to the widespread Pagoda and Linhsiang formations, the Miaopo Formation has a more restricted distribution, being present in only two significant areas on the Yangtze Platform (Chen *et al.* 1995): (1) the Chengkou–Yichang–Jingshan region of western and central-southern Hubei that extends westwards into minor portions of adjacent provinces; and (2) the Hexian area of eastern Anhui (Fig. 1). These regions represented relatively small, intracratonic basins on the otherwise flat Yangtze Platform (Chen & Qiu 1986), in which stagnant environments with anoxic bottom conditions prevailed, as evidenced by the lack of bioturbation in the sediments. Interestingly, muddy limestone lenses intercalated within the upper Miaopo black shales are rich in bitumen, and this formation is one of the hydrocarbon source rocks with potential economic value in the Yangtze region. Coeval rocks outside the Miaopo Formation distribution areas consist of nautiloid-bearing limestones that are classified as the Datianba Formation.

Although the Miaopo and Pagoda formations have been the subject of numerous investigations for more than half a century, and have become classical units in the Chinese Ordovician succession, there has been little agreement about the biostratigraphic subdivision and correlation of these units. The purpose of the present study is (a) to present a modern appraisal of the graptolite and conodont biostratigraphy of the Miaopo Formation that is largely based on new collections; (b) to describe the previously incompletely known conodont biostratigraphy of the Pagoda and Linhsiang formations; and (c) to assess the stratigraphic relations between these formations

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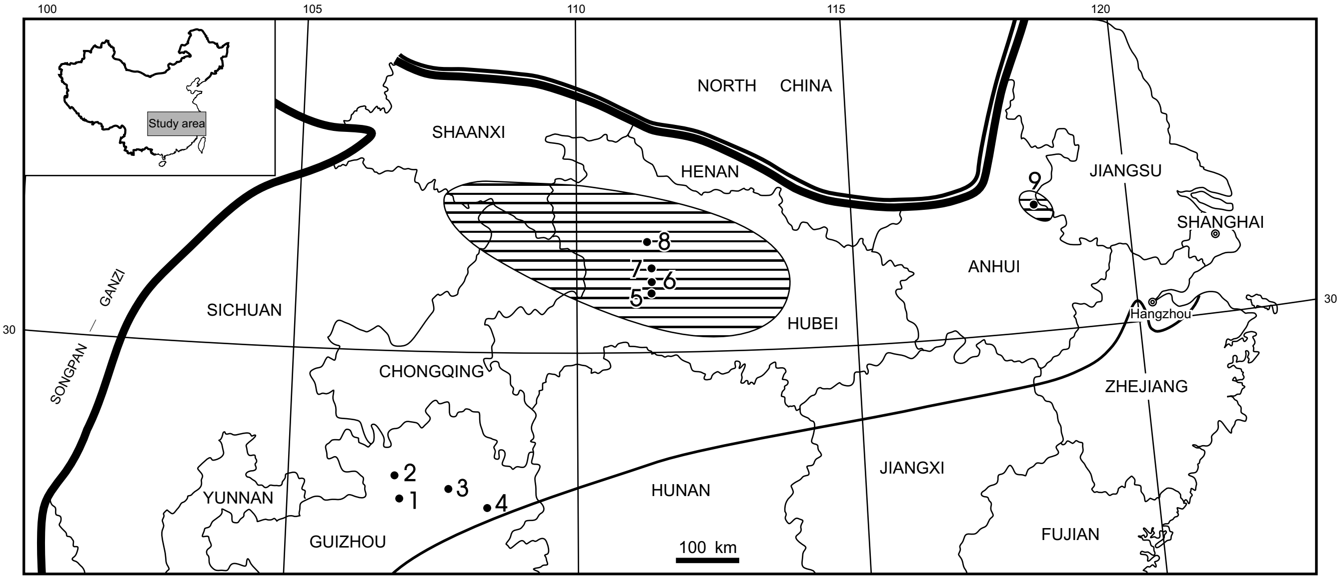

Figure 1 Map showing the location of Upper Ordovician graptolite and conodont sections on the Yangtze Platform. The two striped areas indicate the distribution of the Miaopo Formation. Localities: (1) Donggongsi (Shihtzupu), Zunyi; (2) Yanmen, Zunyi; (3) Wulipo, Meitan; (4) Wengshao, Shibin; (5) Huanghuachang, Yichang; (6) Chenjiahe (Daping), Yichang; (7) Jieling, Yuan'an; (8) Zhenjin, Yuan'an; (9) Xiaotan, Hexian, Anhui.

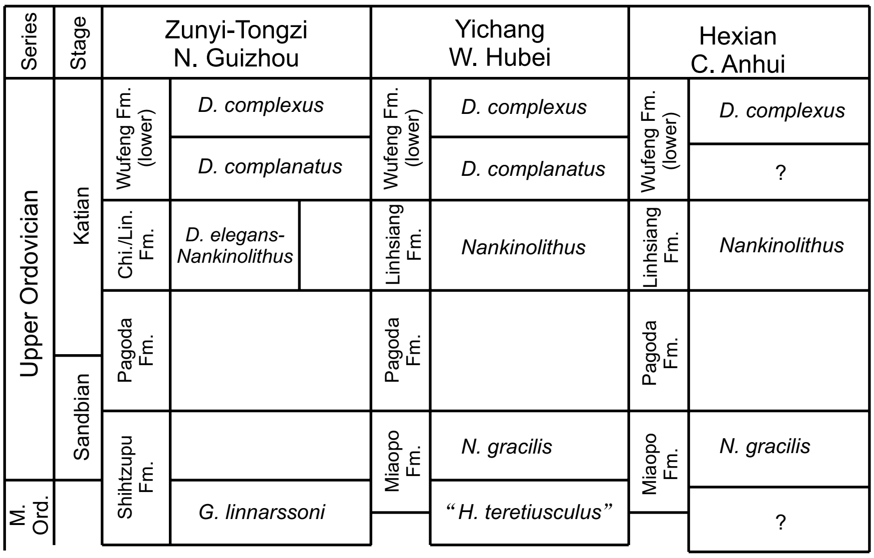

Figure 2 Diagram showing the standard classification of the Upper Ordovician formations and graptolite and trilobite zones in the key sections in the Yangtze region. Sandbian and Katian are recently ratified global stages (cf. Bergström *et al.* 2009b). Note that as discussed in the text, conodont biostratigraphy suggests that the uppermost part of the Miaopo Formation, which has not yielded stratigraphically diagnostic graptolites, may correspond to the *C. bicornis* Zone. Abbreviations of the index fossils and formations: *D.* = *Dicellograptus*; *G.* = *Gymnograptus*; *H.* = *Hustedograptus*; *N.* = *Nemagraptus*; Chi. = Chientsaokou; Lin. = Linhsiang.

and corresponding units in the Baltoscandian and North American successions. The graptolite and trilobite zonations of the uppermost Darriwilian to the upper Katian succession in the Yangtze region are summarised in Figure 2. Recently, Bergström *et al.* (2009a) described the $\delta^{13}C$ chemostratigraphy of the Pagoda and Linhsiang formations and the present paper may be considered a companion article to that study.

1. Graptolite zonation of the Miaopo Formation

The Miaopo Formation, which attains a thickness of 2–4 m, mainly consists of graptolitic black shale that is locally intercalated with muddy, commonly very fossiliferous, layers and lenses of limestone, particularly in the upper part of the unit. The shelly fauna of the Miaopo Formation recorded by Zhang (1962) and later described by Lu (1975) includes representatives of the trilobite genera *Birmanites*, *Nileus*, *Lonchodomas*, *Miaopopsis*, *Reedocalymene* and *Telephina* (Zhan & Jin 2007). Two graptolite zones were recognized by Ge (1963a, b), the *Hustedograptus teretiusculus* Zone and the overlying *Nemagraptus gracilis* Zone. Ge (1963a, b) recorded *Dicellograptus sextans sextans* (Hall), *D. sextans exilis* Elles & Wood, *Climacograptus parvus* (Hall), *Orthograptus propinquus* (Hadding) and *Hustedograptus* cf. *H. teretiusculus* (Hisinger) from his *H. teretiusculus* Zone. The ranges of all these species are now known to extend into higher beds and they are considered to be common taxa in the overlying *N. gracilis* Zone. Ge (1963a, b) further subdivided his *N. gracilis* Zone into three subzones, which are, in ascending order, the *Dicranograptus brevicaulis yangtzensis*, *Leptograptus yangtzensis* and *Corynoides*

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calicularis subzones. These subzones are local subdivisions based on uncommon and generally endemic taxa and are not useful for inter-regional correlations.

One of the present authors (ZYD) and his colleagues recently collected closely spaced samples through the Miaopo Formation in four sections in the Yichang-Yuan'an areas (Figs 1, 5–8). Based on previously collected samples and the new collections, representatives of 20 genera and 38 species and subspecies are recognised the Miaopo graptolite fauna. The species identified from these new collections are listed with their section and collection horizon occurrences in Table 1. Many of the graptolite species are illustrated in Figures 7 and 8.

Most of the genera and species listed in Table 1 are common taxa that occur in the *N. gracilis* Zone elsewhere, and comprise a well documented fauna that can be easily correlated across low and mid-palaeolatitude localities. However, the basal part of the Miaopo Formation, which lacks *Nemagraptus gracilis*, is more difficult to correlate based on its graptolite fauna alone. Two age assignments are possible for these beds – they may be correlative with the lower *N. gracilis* Zone and lack the eponymous species due to environmental control or collection failure; or the interval may contain rocks that are older than the *N. gracilis* Zone elsewhere. The basal Miaopo Formation has been collected in great detail, making collection failure unlikely and, although it contains a graptolite fauna very similar to the *N. gracilis*-bearing beds above, certain taxa (e.g., *Proclimacograptus angustatus* and *Archiclimacograptus angulatus*) are known only from pre-*N. gracilis* Zone age rocks elsewhere (Maletz 1997). Based on the absence of *N. gracilis* and the presence of the previously mentioned taxa, the present authors follow previous usage and tentatively assign this interval to the *Hustedograptus teretiusculus* Zone. This assignment is also corroborated by the conodont occurrences, which will be discussed in detail later in the paper.

However, it is appropriate to note that the name-bearing species, *H. teretiusculus*, is thought to be a poor choice for an index fossil. Although the first appearance datum (FAD) of *H. teretiusculus* is in the *H. teretiusculus* Zone in Wales (Hughes 1989; Zalasiewicz *et al.* 2009), it is also in the *Pterograptus elegans* Zone in the Oslo region (Maletz 1997; Maletz *et al.* 2007), in southern Sweden (Hede 1951), and in Kalpin, western Tarim (Zhou *et al.* 1992). Based on several sections in the Oslo region, Maletz *et al.* (2007) suggested the use of a *Dicellograptus vagus* Zone as a replacement for the *H. teretiusculus* Zone in the uppermost Darriwilian Stage, and this recommendation is supported by the present authors. According to Maletz *et al.* (2007), the *Dicellograptus vagus* Zone is based on the FAD of *D. vagus*, which in Scandinavia occurs a short distance above the last appearances of pendent didymograptids of the *D. murchisoni* type. Other species new to this zone include *Dicellograptus geniculatus* Bulman, *D. intortus* Lapworth, *D. salopiensis* Elles and Wood, *Dicranograptus irregularis* Hadding and *Nemagraptus subtilis* Hadding. Species carrying over from the underlying *Pseudamplexograptus distichus* Zone include *Proclimacograptus angustatus* and *Archiclimacograptus angulatus.*

At the Dawangou section in western Tarim, the graptolite succession in the Saergan Formation is remarkably similar to that of Baltoscandia, and contains a distinct, correlatable *D. vagus* Zone. Unfortunately, in our Miaopo collections, *D. vagus* and other characteristic taxa are either absent from the beds below the *N. gracilis* Zone (Huanghuachang and Chenjiahe sections) or have the same FAD as *N. gracilis* (Jieling and Zhenjin sections). Hence, in order to avoid confusion we continue to use the *H. teretiusculus* Zone for the basal part of the Miaopo Formation.

As noted by Ge (1963a, b), the main portion of the Miaopo Formation contains a diverse graptolite fauna that is referable to the *Nemagraptus gracilis* Zone. Common and biostratigraphically important taxa include *N. gracilis*, *N. exilis*, *Archiclimacograptus meridionalis*, *Glossograptus sinicus*, *Reteograptus geinitzianus*, *Pseudazygograptus incurvus* and *Prolasiograptus hubeiensis.* Other common taxa from the *N. gracilis* Zone in the Yichang-Yuan'an areas, which range into younger strata elsewhere, include *Dicellograptus divaricatus*, *D. sextans sextans*, *D. sextans exilis*, *Pseudoclimacograptus scharenbergi*, *P. stenostoma*, *Hallograptus mucronatus*, *Normalograptus brevis*, *N. euglyphus* and *Archiclimacograptus modestus.* One notable difference between the faunal composition of the *N. gracilis* Zone in the Miaopo Formation and correlative strata elsewhere is the presence of an abundant assemblage of *Orthograptus* species and subspecies. Specimens of the *Orthograptus calcaratus* group are mainly known from rocks younger than the *N. gracilis* Zone in Scotland, North America and Australia, but members of this species group are reported from the latter zone by Ge (1963a, b), and are also well represented in the present collections from the same zone in western Hubei.

The top portion of the Miaopo Formation is not well defined in terms of graptolite biostratigraphy. Diagnostic taxa of the *Climacograptus bicornis* Zone have not been found and the relatively few graptolites collected are not diagnostic of a particular graptolite zone. As described in section 3 below, the top part of the Miaopo Formation in the Yichang area locally has beds and lenses of muddy limestone that have yielded the conodont *Baltoniodus alobatus* (previously known in China as *Prioniodus lingulatus*: see An 1987; Ni Shizhao in Wang *et al.* 1987; Bergström *et al.* 2009a), which is the index of the *B. alobatus* Subzone. This unit is the youngest named subzone of the *Amorphognathus tvaerensis* Zone in the Atlantic conodont zone classification scheme (Bergström 1971, 2007a). Because this subzone corresponds to the middle-upper part of the *C. bicornis* Zone in the Pacific graptolite zonation (Goldman *et al.* 2007), the presence of *B. alobatus* on the Yangtze Platform suggests that the uppermost Miaopo Formation may be coeval with part of this graptolite zone.

Interestingly, the important graptolite *Climacograptus bicornis* (Hall), the index of the Pacific Province *Climacograptus bicornis* Zone, which is broadly equivalent to the Atlantic Province *D. foliaceus* Zone (Goldman *et al.* 2007), has been recorded in the Shuangjiakou Formation of the Shuangjiakou section near Qidong, Hunan, about 470 km south of Yichang, Hubei (Wang *et al.* 1992). In this stratigraphically very condensed succession, this species appears 2·59 m above the top of the range of *Nemagraptus gracilis*, which at that site occurs through an approximately 2·3 m-thick interval that is locally taken to represent the *Nemagraptus gracilis* Zone. At this locality, *C. bicornis* is associated with *Orthograptus* ex gr. *O. calcaratus*, *O. whitfieldi*, *Dicranograptus nanus* and several species of *Corynoides* and *Dicellograptus*, amongst others. This *C. bicornis* Zone fauna differs in several respects from *N. gracilis* Zone fauna in the Miaopo Formation, and is likely to represent a stratigraphically slightly younger species association than that known from the Miaopo Formation. No conodonts are known from this part of the Shuangjiakou succession, which may be coeval with the *B. gerdae* Zone. Hence, the *C. bicornis* Zone is present in Hunan but it is still unknown whether the apparent absence of its species association in the Miaopo Formation is due to a small stratigraphical gap, or to some palaeoecological or other factors.

In summary, it is concluded that, based on the closely spaced graptolite collections from the Miaopo Formation recently made by Zhang Yuandong and his colleagues at

Table 1 Stratigraphic occurrences of graptolites in the four collected sections of Miaopo Formation in Yichang area.

SPECIES	CHENJIAHE					HUANGHUACHANG				JIELING									ZHENJIN						
Sample no (AFI-)→	5011	5012	5013	5014	5015	5016	5017	5018	5019	5031	5032	5033	5035	5037	5040	5041	5042	5043	5051	5053	5054	5056	5058	5059	5061
Amplexograptus gansuensis Mu & Zhang																					X				
Amplexograptus? *perexcavatus* (Lapworth, 1876)															X										
Archiclimacograptus angulatus (Bulman)	X																								
Archiclimacograptus? *arctus* (Elles & Wood)		X																X							X
Archiclimacograptus meridionalis (Ruedemann)				X	X					X		X		X				X							
Archiclimacograptus modestus Lapworth, 1876				X	X		X							X											
Climacograptus uniformis Hsü				X	X																				
Dicellograptus divaricatus (Hall, 1859)									X												X				
Dicellograptus sextans sextans (Hall, 1847)	X	X							X											X	X				
Dicellograptus sextans exilis Elles & Wood											X									X			X		
Dicellograptus vagus Hadding											X									X					
Dicranograptus brevicaulis yangtzensis (Ge)		X		X	X						X	X								X	X				
Glossograptus sinicus Mu and Zhan												X													
Hallograptus mucronatus (Hall, 1843)		X		X	X	X	X				X	X		X	X	X	X	X					X		X
Hustedograptus teretiusculus (Hisinger)	X	X									X								X	X					
Hustedograptus uplandicus (Wiman, 1895)									X							X	X								
Hustedograptus sp.									X																
Leptograptus sp.																					X				
Nemagraptus exilis (Lapworth, 1880)		X		X	X																				
Nemagraptus gracilis (Hall)		X		X	X			X			X	X					X			X	X				
Neurograptus sp.				X	X																				
Normalograptus brevis (Elles & Wood)				X	X																				X
Normalograptus cf. *brevis* (Elles & Wood)																X									X
Normalograptus euglyphus (Lapworth, 1877)																			X						
Normalograptus haddingi (Glimberg)			X																						
Oepikograptus bekkeri (Öpik)																					X				
Orthograptus apiculatus Elles & Wood														X						X	X				
Orthograptus calcaratus basilicus Elles & Wood							X																		
Orthograptus calcaratus calcaratus Lapworth, 1876		X	X				X	X	X		X	X	X	X		X	X	X		X	X			X	X
Orthograptus calcaratus vulgatus Elles & Wood, 1907		X									X									X	X				
Proclimacograptus angustatus (Ekström)							X	X	X	X									X	X	X				
Prolasiograptus hubeiensis (Ge)							X	X																	
Prolasiograptus sp.				X	X		X		X								X	X							X
Pseudazygograptus incurvus (Ekström)										X															
Pseudoclimacograptus scharenbergi (Lapworth, 1876)				X	X	X	X	X	X	X	X	X			X	X	X	X		X	X				X
Pseudoclimacograptus stenostoma (Bulman)									X												X				
Pseudoclimacograptus tangyensis (Ge)																				X					
Retiograptus geinitzianus (Hall, 1859)		X										X									X	X			

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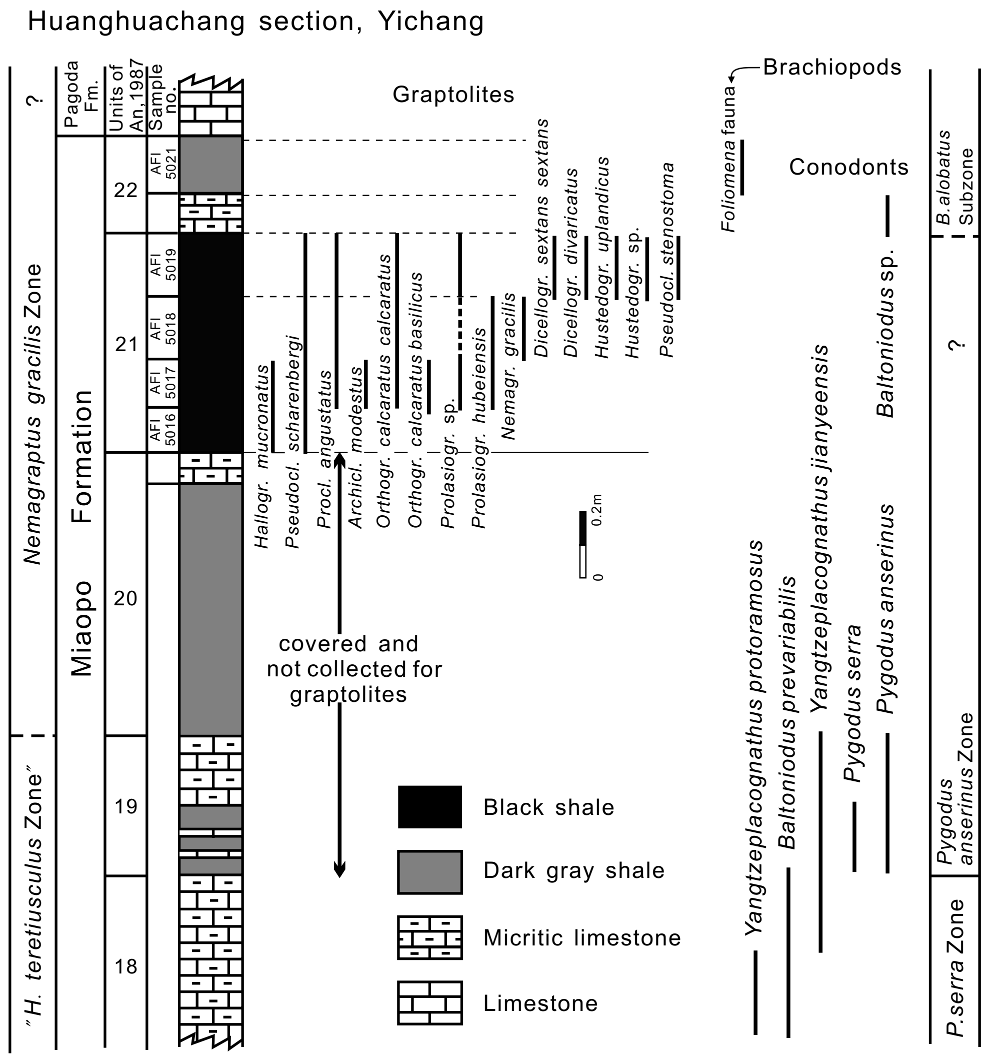

Figure 3 Ranges of graptolites, some significant shelly fossils and stratigraphically important conodonts through the Miaopo Formation at the Huanghuachang section, Yichang, Hubei. Conodont ranges are after An (1987), who placed the base of the Miaopo Formation at basal Bed 18 (at present this boundary is more commonly placed at the first appearance of shale, i.e. Bed 19). The lower part of the Miaopo Formation in Huanghuachang section is no longer exposed, and graptolites cannot be collected.

several localities, the main part of the formation is referable to the *N. gracilis* Zone. The basal and top parts of the formation have not yielded stratigraphically diagnostic graptolites, but these intervals are referred to the *H. teretiusculus* and *C. bicornis* zones, respectively, based primarily on conodont evidence. For further discussion of the stratigraphic relations between the Miaopo Formation and the overlying Pagoda Formation, see section 3 below.

2. Graptolite zonation of the Shihtzupu Formation

An up to 52 m-thick succession of greenish to grey or yellowish shales and mudstones with subordinate argillaceous limestones in the northern Guizhou, southern Sichuan and northeastern Yunnan Provinces has been referred to as the Shihtzupu Formation. For a summary of lithological and faunal details, see Chen *et al.* (1995) and Zhan & Jin (2007). Although it contains a very diverse shelly fauna, the middle and upper parts of the formation also yield late Darriwilian graptolites. Chen & Lin (in Zhang *et al.* 1964) published a list of graptolites from the Shihtzupu Formation at its original type locality at Donggongsi (Shihtzupu), and suggested that the Shihtzupu graptolite fauna was referable to a *Dicellograptus sextans exilis*–*Gymnograptus linnarssoni* Zone. At Wulipo, Meitan (Fig. 1, Loc. 3), a similar Shihtzupu graptolite fauna was recorded by Chen & Lin (in Zhang *et al.* 1964) and recently, the present authors collected a comparable Shihtzupu graptolite fauna from Yanmen, near Zunyi, northern Guizhou. From a section at Wengshao, Shibin, eastern Guizhou (Fig. 1, Loc. 4), Li (1963) described a Shihtzupu graptolite fauna, including the diagnostic taxa *Dicellograptus sextans exilis* Elles & Wood, *Hustedograptus teretiusculus* (Hisinger) (=*Glyptograptus siccatus lata* Lee, 1963 and *Glyptograptus guizhouensis* Lee, 1963) (Fig. 7K), *Normalograptus euglyphus* (Lapworth, 1877), *Glossograptus fimbriatus* (Hopkinson, 1872), *Prolasiograptus retusus* (Lapworth, 1880), *P. sinicus* Li, and *Gymnograptus linnarssoni* (Moberg, 1896). The graptolites occur in the top part of the Shihtzupu Formation at this locality.

The past use of a *Gymnograptus linnarssoni* Zone for this and other Shihtzupu successions is obviously based on the presence of *G. linnarssoni* (see Zhang & Chen 2003), one of the most characteristic and widespread graptolites in the upper Darriwilian shale and carbonate facies of Baltoscandia, where several authors (e.g., Hede 1951; Jaanusson 1960; Nõlvak *et al.* 2006) have used it as the index for a separate zone corresponding to the lower part of the *H. teretiusculus* Zone. In the classical Fågelsång succession in Scania, S. Sweden, *G. linnarssoni* occurs stratigraphically below the first appearance of

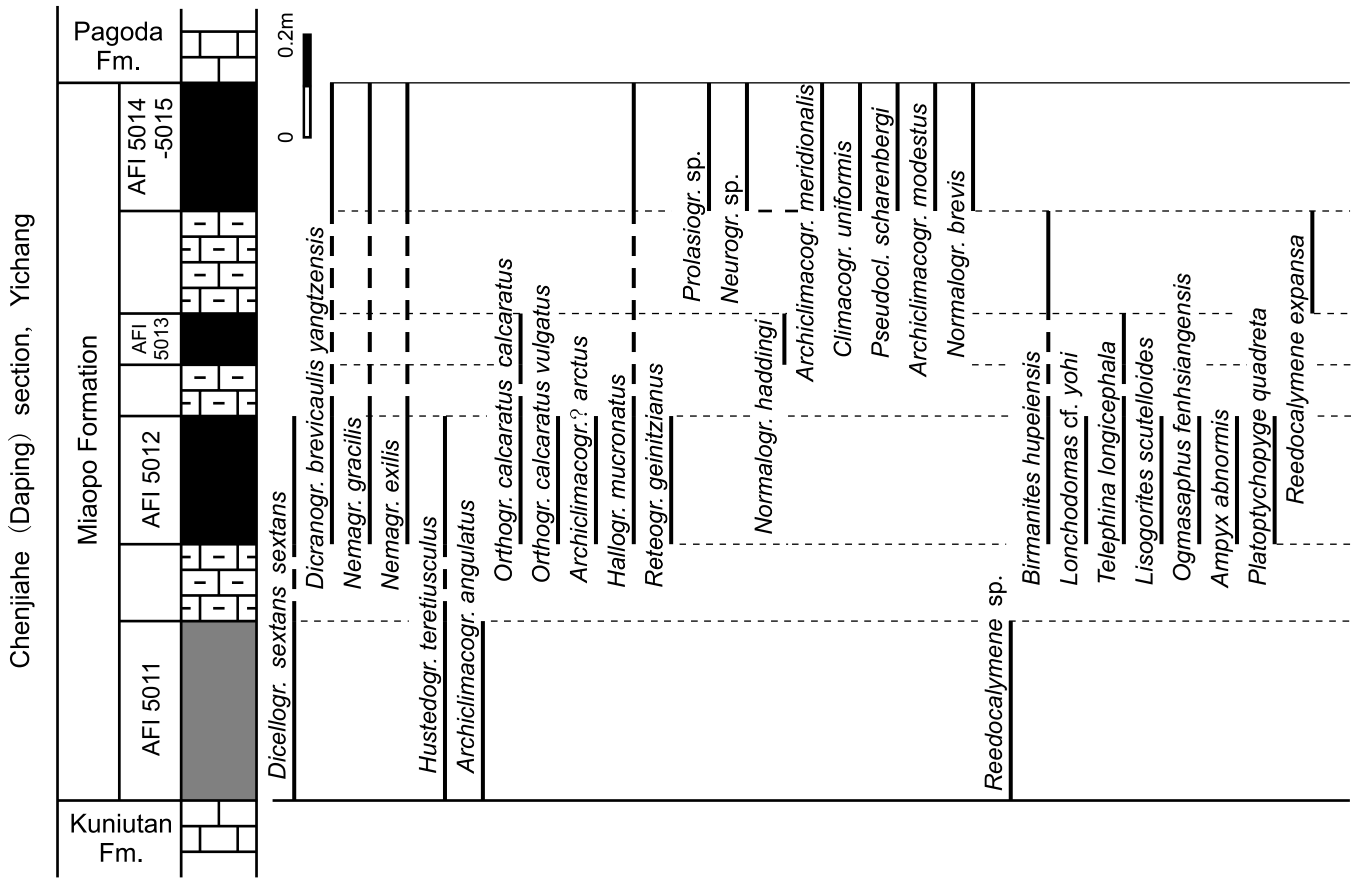

Figure 4 Ranges of graptolites and trilobites through the Miaopo Formation at the Chenjiahe (Daping) section, Yichang. For legend see Figure 3.

N. gracilis and has approximately the same range as *D. vagus* (see Hede 1951) and in the same interval as *Prolasiograptus haplus* and *Dicellograptus sextans exilis* in Sweden (Jaanusson 1960). This suggests that the Shihtzupu Formation may be at least partly coeval with the *H. teretiusculus* Zone in the lowermost Miaopo Formation in the Yichang region. As a whole, the Shihtzupu graptolite species association is reminiscent of that of the uppermost Darriwilian in Baltoscandia. Lithologic logs of the Shihtzupu Formation with graptolite identifications from collections at several sections in the Shihtzupu locality are described in descending order in Table 2.

3. Conodont zonation of the Miaopo Formation

Conodonts have been recorded from the Miaopo Formation by several authors (see, for instance, Wang *et al.* 1980; Zeng *et al.* 1983; An & Ding 1982; An *et al.* 1985; An 1987; Ni & Li 1987; Wang 1995; Zhang 1998b) but there has been disagreement regarding the biostratigraphic interpretation of the faunas. An (1987) and Ni & Li (1987) referred the Miaopo Formation conodont succession to the *Pygodus serra*, *P. anserinus* and *Prioniodus linguatus* (now *Baltoniodus alobatus*) zones, whereas Zhang (1998b, table 1) employed the *Yangtzeplacognathus foliaceus*, *Y. protoramosus* and *Y. jianyeensis–Pygodus anserinus* zones. Zhang (1998b) correlated the two former zones with part of the *Pygodus serra* Zone of the Atlantic conodont zone scheme (Bergström 1971). It should be noted that the recognition of the *Y. foliaceus* Zone (Subzone in Bergström 1971) was based on a single sample from the basalmost part of the Miaopo Formation at Fenxiang, Hubei, which contained more than 100 platform elements of the subzone index species. Because this zone or subzone is correlated with the *Pterograptus elegans* Graptolite Zone (see, for instance, Chen *et al.* 2006), this means that the base of the formation at this locality is significantly older than that reported elsewhere if the conodont-bearing limestone bed is taken to represent the basalmost Miaopo Formation. In view of this, it could perhaps be argued that what has been classified as the basalmost limestone bed of the Miaopo Formation at this locality should rather be referred to as the topmost bed of the underlying Kuniutan Formation, based on both lithology and conodont fauna. At Huanghuachang (Fig. 3), ca. 12 km south of Fenxiang, the basalmost graptolite-bearing bed of the Miaopo Formation is obviously younger than *P. elegans* Zone.

Following Bergström (1971), the base of the *Pygodus anserinus* Zone is taken to be the level of the appearance of the zone index species. At the well-known Huanghuachang section (Fig. 3), this level is approximately 0·6 m above the base of the Miaopo Formation, at Fenxiang, 0·35–0·45 m above the base of the unit, and at the now submerged Longmaxi section at Quyuan (formerly Xintan) town, 0·75–1·6 m above the base of the unit. These data suggest that at most sites this zone boundary is located in the lower part of the Miaopo Formation, within an interval that has not yielded graptolites diagnostic of a particular graptolite zone, but which is below the first appearance of *Nemagraptus gracilis*, the index of the *N. gracilis* Zone. This important conodont zonal boundary, which is based on a speciation event in the *Pygodus* lineage (Bergström 1983), is positioned within an interval formerly classified as the *Hustedograptus teretiusculus* Zone in Baltoscandia and eastern North America (Finney & Bergström 1986). Based on this conodont evidence, we conclude that the lower part of the Miaopo Formation at these localities is older than the base of the *Nemagraptus gracilis* Zone, as this zone is

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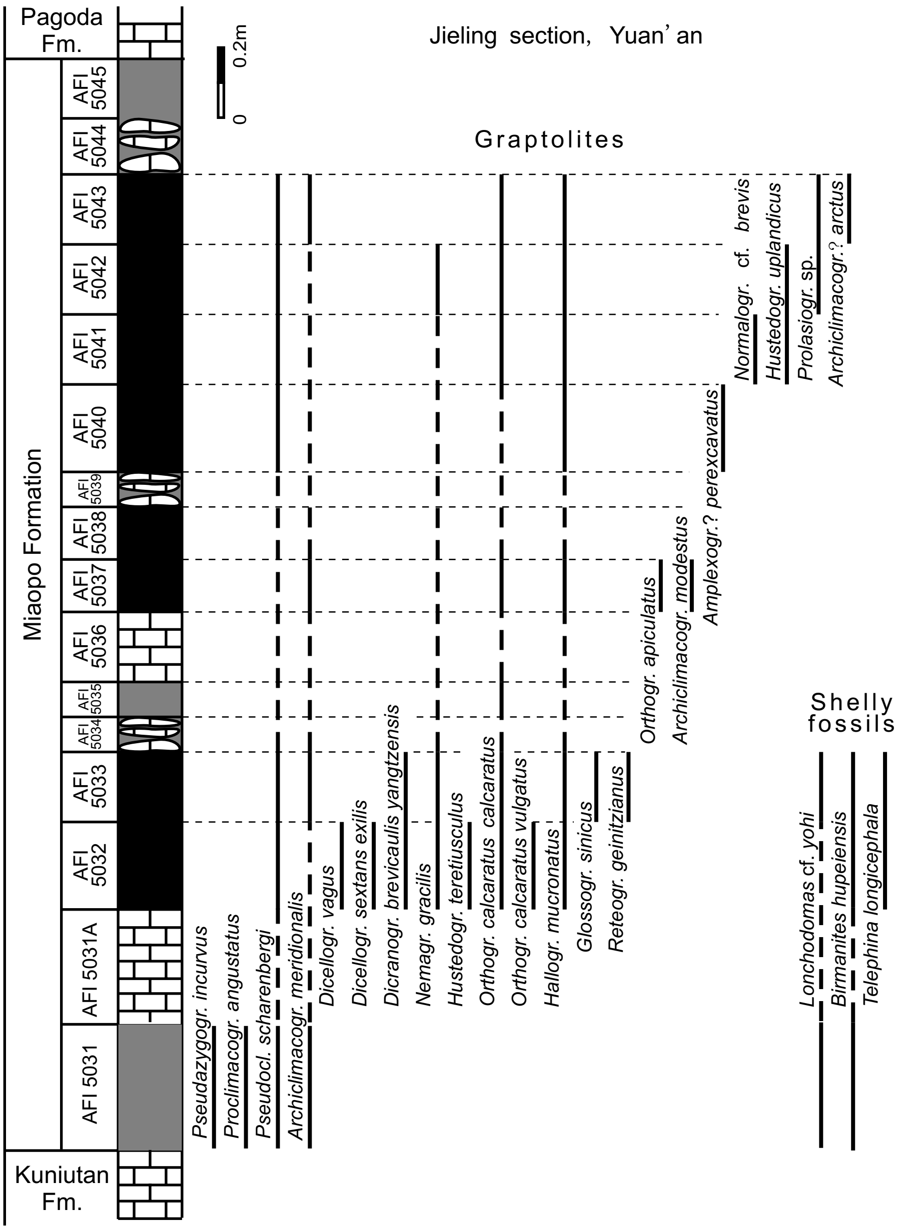

Figure 5 Ranges of graptolites and trilobites through the Miaopo Formation at the Jieling section, Yuan'an. For legend see Figure 3.

recognised elsewhere. This conclusion is in agreement with that of Chen *et al.* (1995). It should also be noted that in the Cili, Hunan section (Zhang 1998b), the *Pygodus serra*/*P. anserinus* Zone boundary is located 0·2 m above the base of the Datianba Formation, which is a carbonate unit considered to be a lateral equivalent of the Miaopo Formation (Chen *et al.* 1995).

Published conodont records reviewed above, and our own collections at Huanghuachang, confirm that the lowermost Miaopo Formation at most localities belongs to the *Pygodus serra* Zone. One exception to this is the section at Maocaopu in Hunan (Zhang 1998b), in which the basal bed of the formation rests disconformably on significantly older strata (the *Dzikodus tablepointensis* Zone) and contains *Pygodus anserinus*, the zone index of the *Pygodus anserinus* Zone, which overlies the *P. serra* Zone in stratigraphically more complete successions. Recently, the disconformity between the *P. anserinus* Zone and the *Dzikodus tablepointensis* Zone (*Microzarkodina ozarkodella* Subzone) at Maocaopu was discussed in detail by Schmitz *et al.* (2010).

Apart of the presence of the two zone indices, the conodont faunas of the *Pygodus serra* and *P. anserinus* zones in the basal part of the Miaopo Formation are closely similar (Fig. 3). Conodont faunas of this type have a pandemic distribution in coeval cold/deepwater deposits, and are recorded at many localities in, for instance, Baltoscandia (Hamar 1964; Zhang 1998a; Bergström 1990a, b, 2002, 2007a), Scotland (Armstrong 1997), eastern and southern North America (e.g., Sweet & Bergström 1962; Bergström 1973, 1978, 2007a; Bradshaw 1969; Bergström *et al.* 1974; Repetski & Ethington 1977; Fåhraeus & Hunter 1981) and China (e.g. Bergström *et al.* 1999; Finney *et al.* 1999; Wang *et al.* 2007).

However, there are some interesting differences between the Yangtze Platform conodont faunas of the *Pygodus serra* and *P. anserinus* zones and equivalent species associations in Baltoscandia and North America. One of these differences is the common occurrence of the platform conodonts *Yangtzeplacognathus protoramosus* and *Y. jianyeensis* in China. Although the former species has been recorded in both Sweden (Bergström 2007b) and Estonia, it is very rare there, and it has not been found in North America. There are no known occurrences of the latter species outside China. On the other hand, the characteristic platform genus *Cahabagnathus* is

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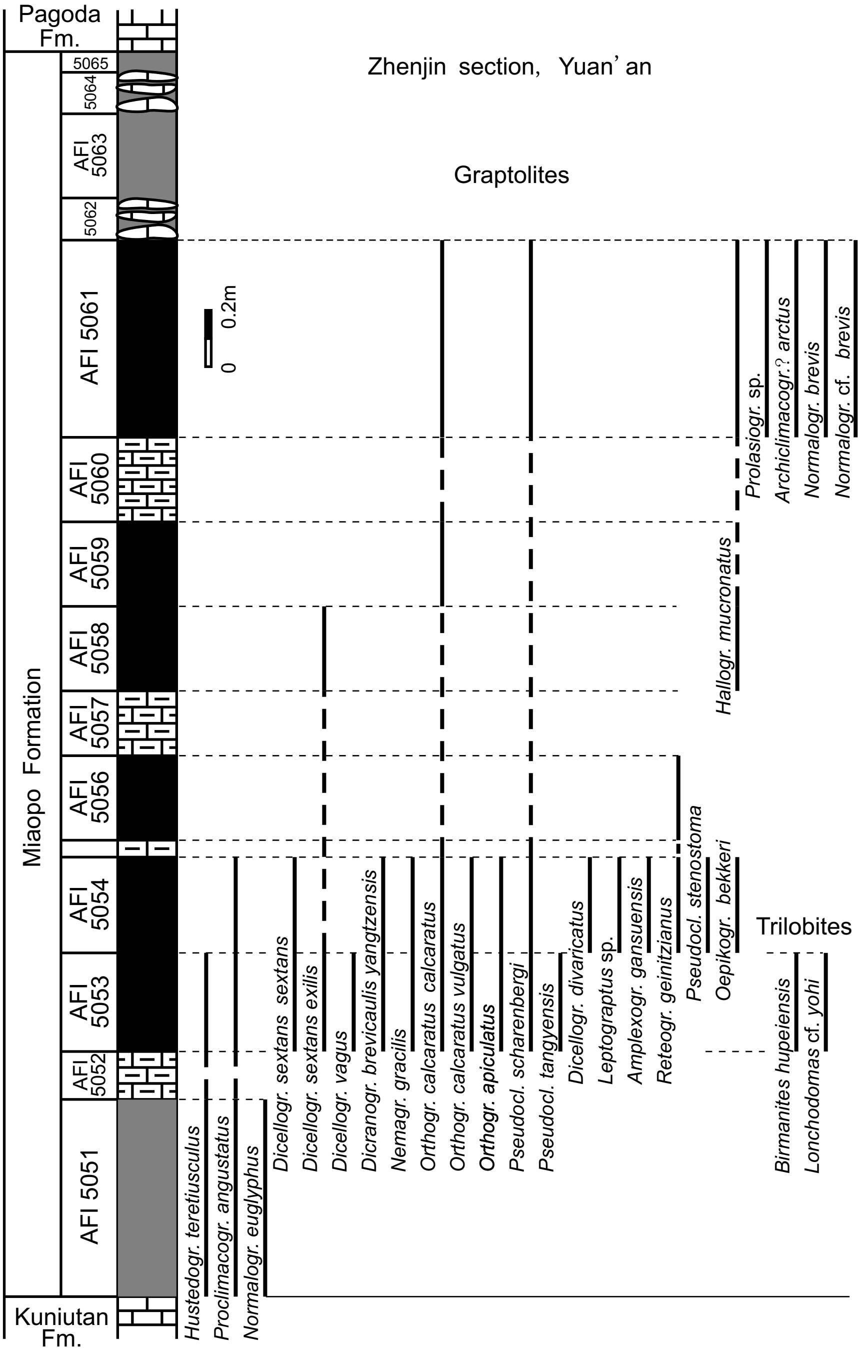

Figure 6 Ranges of graptolites and trilobites through the Miaopo Formation at the Zhenjin section, Yuan'an. For legend see Figure 3.

widely distributed in the marginal parts of North America (Bergström 1983; Leslie & Lehnert 2005) and is represented by rare occurrences of one species (*Cahabagnathus sweeti*; cf. Hamar 1964; Bergström 2007b) in Baltoscandia, but it has not been recorded from the Yangtze Platform. Another characteristic platform conodont recorded from the Miaopo Formation (An *et al.* 1985; An 1987; Zhang 1998b) is *Complexodus pugionifer*, which is also known from Baltoscandia (Bergström

Figure 7 Illustrations of selected graptolites from the Upper Ordovician in the Yangtze region. (A) *Nemagraptus gracilis* (Hall, 1847), *N. gracilis* Zone of the Miaopo Fm., Zhenjin, Yuan'an, Hubei. NIGP151568 (AFI5053). (B, E) *Dicellograptus elegans* Carruthers, 1868: (B) *D. elegans* Zone of the Daduhe Fm., Jiaodingshan, Hanyuan, W. Sichuan. NIGP56803 (K-11); (E) *D. elegans* Zone of the Chientsaokou Fm., Shizipu (Shihtzupu), Zunyi, N. Guizhou. NIGP56804 (AAE369). (C) *Dicellograptus sextans sextans* (Hall, 1843), *N. gracilis* Zone of the Miaopo Fm., Huanghuachang, Yichang, W. Hubei. NIGP151572 (AFI5019). (D) *Dicellograptus vagus* Hadding, 1913, *N. gracilis* Zone of the Miaopo Fm., Zhenjin, Yuan'an, Hubei. NIGP151569 (AFI5053). (F) *Pseudazygograptus incurvus* (Ekström, 1937), *N. gracilis* Zone of the Miaopo Fm., Jieling, Yichang, W. Hubei. NIGP151579 (AFI5031). (G) *Acrograptus nicholsoni* (Lapworth, 1875), *Gymnograptus linnarssoni* Zone of the Kuniutan Fm., Yangmen, Zunyi, N. Guizhou. NIGP151578 (AFA308). (H) *Oepikograptus bekkeri* (Öpik, 1927), *N. gracilis* Zone of the Miaopo Fm., Zhenjin, Yuan'an, W. Hubei. NIGP151582 (AFI5054). (I) *Dicranograptus brevicaulis yangtzensis* Ge, 1963a, *N. gracilis* Zone of the Miaopo Fm., Chenjiahe, Yichang, W. Hubei. NIGP151577 (AFI5012). (J) *Reteograptus geinitzianus* (Hall, 1859), *N. gracilis* Zone of the Miaopo Fm., Jieling, Yichang, W. Hubei. NIGP151599 (AFI5033). (K, P, Q) *Hustedograptus teretiusculus* (Hisinger, 1840) (=*Glyptograptus siccatus*

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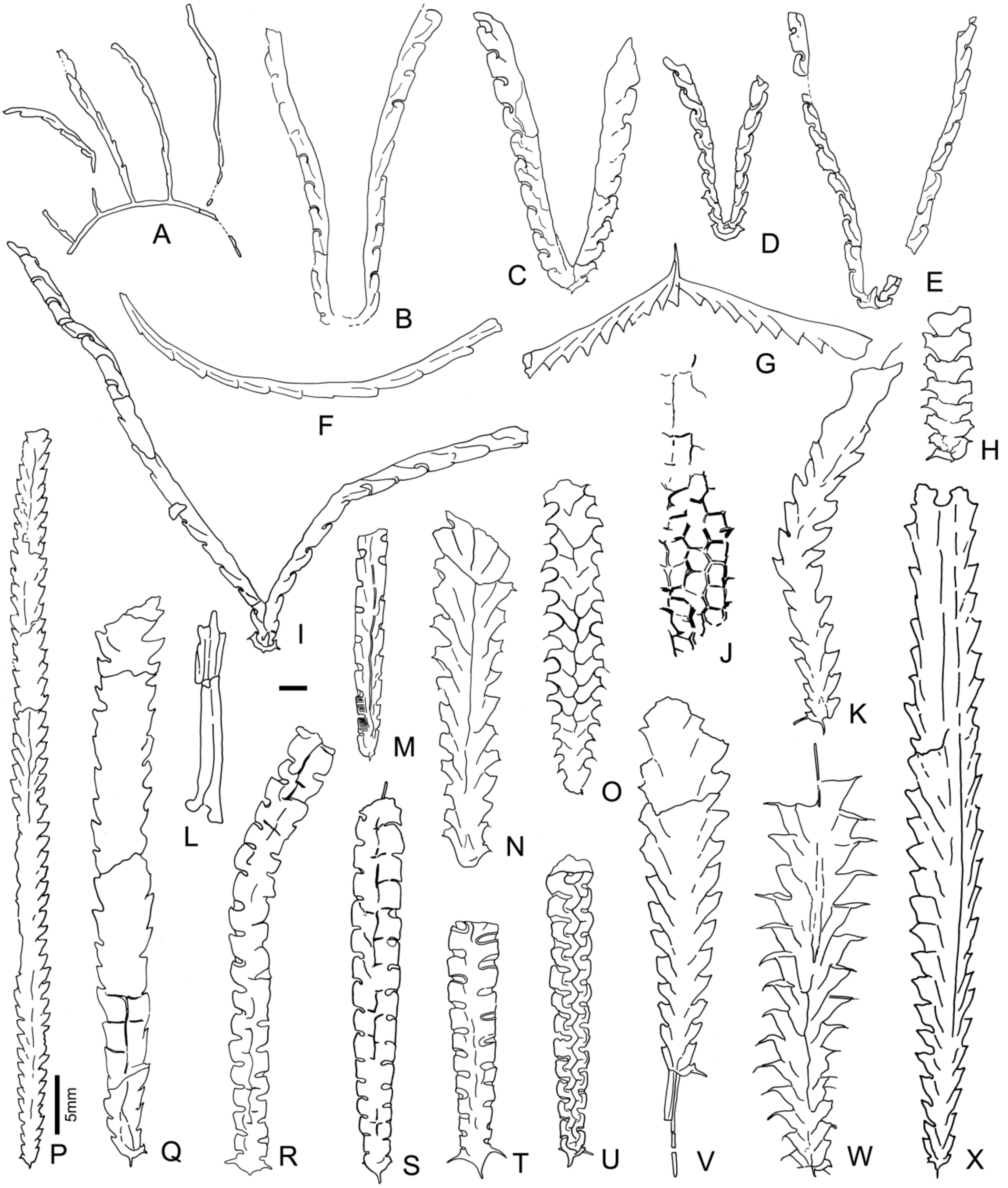

var. *lata* Lee, 1963, and *G. guizhouensis* Lee, 1963): (K) *G. linnarssoni* Zone of the Shihtzupu Fm., Shibin, NE. Guizhou. NIGP13838 (6–126). (P) *N. gracilis* Zone of the Miaopo Fm., Chenjiahe, Yichang, W. Hubei. NIGP151587 (AFI 5011); (Q) *G. linnarssoni* Zone of the Shihtzupu Fm., Yanmen, Zunyi, N. Guizhou. NIGP151588 (AFA330); (L) *Corynoides calicularis* Nicholson, 1867 [=*Corynoides pritinus* (Ruedemann) in Ge, 1963a, p. 74, Pl. 2, fig. 15, text-fig. 1d], *N. gracilis* Zone of the Miaopo Fm., Tangya, Yichang, W. Hubei. NIGP13002 (WM180). (M) *Normalograptus brevis* (Elles & Wood, 1906), *N. gracilis* Zone of the Miaopo Fm., Zhenjin, Yuan, W. Hubei. NIGP151583 (AFI5061). (N) *Prolasiograptus* sp., *N. gracilis* Zone of the Miaopo Fm., Jieling, Yichang, W. Hubei. NIGP151596 (AF5042). (O) *Prolasiograptus haplus* (Jaanusson, 1960), *G. linnarssoni* Zone of the Shihtzupu Fm., Yanmen, Zunyi, N. Guizhou. NIGP151597 (AFA329). (R) *Archiclimacograptus angulatus* (Bulman, 1953), *N. gracilis* Zone of the Miaopo Fm., Chenjiahe, Yichang, W. Hubei. NIGP151598 (AFI5011). (S) *Archiclimacograptus meridionalis* (Ruedemann, 1947), *N. gracilis* Zone of the Miaopo Fm., Jieling, Yichang, W. Hubei. NIGP151589 (AFI5043). (T) *Archiclimacograptus*? *arctus* (Elles & Wood, 1907), *N. gracilis* Zone of the Miaopo Fm., Jieling, Yichang, W. Hubei. NIGP151592 (AFI5043). (U) *Pseudoclimacograptus scharenbergi* (Lapworth, 1876), *N. gracilis* Zone of the Miaopo Fm., Chenjiahe, Yichang, W. Hubei. NIGP151593 (AFI5015). (V) *Orthograptus calcaratus calcaratus* (Lapworth, 1876), *N. gracilis* Zone of the Miaopo Fm., Chenjiahe, Yichang, W. Hubei. NIGP151594 (AFI5012). (W) *Hallograptus mucronatus* (Hall, 1843), *N. gracilis* Zone of the Miaopo Fm., Chenjiahe, Yichang, W. Hubei. NIGP151601 (AFI5015). (X) *Orthograptus apiculatus* Elles and Wood, 1906, *N. gracilis* Zone of the Miaopo Fm., Zhenjin, Yuan'an, W. Hubei. NIGP151595 (AFI5053). Scale bars = 1 mm. All figured specimens are housed in the Nanjing Institute of Geologyand Palaeontology (NIGP), Nanjing.

2007b), Poland (Dzik 1976, 1994) and Wales (Bergström & Orchard 1985). Below, the biostratigraphic significance of this species' occurrence in the Miaopo Formation is discussed further.

Apart from some data in An *et al.* (1985; see particularly their fig. 4), virtually no detailed information has been published on conodonts from the middle portion of the Miaopo Formation, which mainly consists of black to grey shale containing a *Nemagraptus gracilis* Zone graptolite fauna (Figs 3–6). The biostratigraphically most important conodont taxa recorded from this interval by An *et al.* (1985) include *Baltoniodus variabilis*, *Complexodus pugionifer* and *Yangtzeplacognathus jianyeensis*, which is a species association characteristic of the *Baltoniodus variabilis* Subzone of the *Amorphognathus tvaerensis* Zone. The presence of this conodont subzone is in good agreement with the conodont/graptolite zone relations known elsewhere (Bergström 1986) and suggests that these strata correspond to the upper *N. gracilis* Zone in southern Sweden.

At some localities, samples from limestone interbeds in the uppermost Miaopo Formation (An 1987) have yielded *Baltoniodus alobatus* (referred to as *Prioniodus* or *Baltoniodus linguatus* in some older Chinese papers; see e.g. An 1987). This distinctive species is the index of, and in Baltoscandia restricted to, the *Baltoniodus alobatus* Subzone of the *Amorphognathus tvaerensis* Zone (Bergström 1971, 2007a), which occupies an interval corresponding to the middle-upper part of the *Diplograptus foliaceus* (or *Climacograptus bicornis*) Graptolite Zone in that region (Bergström 2007a). This suggests that at least locally, the very uppermost, calcareous, part of the Miaopo Formation, which has not yielded diagnostic graptolites, is coeval with this graptolite zone. This conclusion is consistent with recently published chemostratigraphic evidence (Bergström *et al.* 2009a). It should be noted that there is no record from the Yangtze Platform successions of the *Baltoniodus gerdae* Subzone, which is present between the *B. variabilis* and *B. alobatus* Subzones in Baltoscandia (Bergström 1971, 2007a). This subzone corresponds to the lower part of the *D. foliaceus* Zone (Finney & Bergström 1986).

In summary, three conodont zones in the Miaopo Formation are recognised, namely the *Pygodus serra*, *Pygodus anserinus* and *Amorphognathus tvaerensis* zones, in those sections with the most complete biostratigraphy. The precise level of the boundary between the last two zones remains undetermined, but is likely to be somewhere above the middle part of the formation.

In this connection, it is of interest to make a comparison between the conodont succession in the Miaopo Formation and that of the Datianba Formation that has been considered an equivalent of the former unit, but developed in carbonate lithofacies (Chen *et al.* 1995). As recorded by Hao (1981), the conodont fauna of the lowest portion of the Datianba Formation in the Nanjing, Zhigui and Yidu areas includes, amongst others, *Pygodus serra*, *Baltoniodus prevariabilis*, *Periodon aculeatus*, *Yangtzeplacognathus protoramosus* (=*Eoplacognathus miaopoensis* in Hao 1981) and *Ansella fenxiangensis*, hence a *Pygodus serra* Zone species association that appears identical to that recorded above from the lowermost Miaopo Formation. A stratigraphically slightly higher interval in the Datianba Formation is characterised by a typical *Pygodus anserinus* Zone fauna that consists of, among others, *Pygodus anserinus*, *Yangtzeplacognathus jianyeensis*, *Complexodus pugionifer* and *Baltoniodus variabilis*. This species association agrees with that recorded from the Datianba Formation in the Cili and Maocaopu sections by Zhang (1998b). According to Hao (1981), the upper one-third of the Datianba Formation is characterised by, amongst others, *Baltoniodus alobatus*, *Dapsilodus mutatus* and *Walliserodus* (now *Costiconus*) *ethingtoni*, a species association that is closely similar to that in the uppermost Miaopo Formation. Hence, the biostratigraphic evidence provided by the conodonts is consistent with the idea that the Miaopo and Datianba formations are coeval units developed in quite different lithofacies.

4. Conodont zonation of the Pagoda Formation

The Pagoda (Baota) Formation is the most widespread Ordovician formation on the Yangtze Platform, where it covers thousands of square kilometres and has a thickness varying from a few metres to more than 50 metres. It consists of light-grey to reddish, medium to thick-bedded, mostly fine-grained, limestone with very thin shale partings. A highly characteristic lithological feature is the presence of locally abundant polygonal reticulate mud-filled shrinkage cracks. The formation of these structures has been much discussed, but remains controversial; for a recent summary of different opinions, see Zhan & Jin (2007). Interpretations of the depositional environment of the Pagoda Formation have differed greatly amongst authors, with proposed water depth ranging from the intertidal zone to a depth of as much as several hundred metres. The currently prevailing opinion that these rocks were deposited in relatively deep water is consistent with the character of the conodont fauna.

Information about the conodont fauna of the Pagoda Formation has been published by, amongst others, Wang *et al.* (1980), An (1981), An & Ding (1982), An *et al.* (1981, 1985), Ni & Li (1987), Sheng & Ji (1987), Wang (1993), Chen *et al.* (1995) and Bergström *et al.* (2009a). During the course of the present study, conodont samples were collected from the Pagoda formation at three localities, namely the Puxihe Quarry near Yichang, Hubei Province; the disused quarry at Baiguowan, Donggongsi north of Zunyi, Guizhou Province; and at Xiaotan, Hexian, Anhui Province. For the geographic location of these sections, see Figure 1. Acid digestion of 2-kg samples resulted in the recovery of a conodont collection of many hundred specimens. Species ranges through each section are illustrated in Figures 9–11. Because most of the specimens found represent well-known taxa that have been illustrated previously from the Pagoda Formation, they are not re-illustrated herein.

As now known, the conodont fauna of the Pagoda Formation is not particularly diverse or unusual in taxonomic composition. Approximately 12 multi-element species are present in our collections and to this number should be added at least one species not recovered by the present authors, namely *Icriodella baotaensis* An, Du, Gao & Lee, 1981. The specimens recorded and illustrated as *Amorphognathus complicatus* and *A.* aff. *complicatus* by Zeng *et al.* (1983), Sheng & Ji (1987) and Ni & Li (1987, pl. 59, figs 18, 37) are too fragmentary to be safely identified to species. One specimen illustrated by An (1987, pl. 30, fig. 12) and identified as *A. superbus* has a very short posterior lobe on the postero-lateral process and appears to be transitional between *A. superbus* and *A. complicatus.* The reduction of this lobe is even more conspicuous in specimens identified by Sheng & Ji (1987) as *A.* aff. *complicatus* (their pl. 3, fig. 4) and *A. complicatus* (their pl. 3, figs 5, 6), in which this lobe is missing but its position is indicated by a minor lateral expansion of the central denticle row in the proximal portion of the postero-lateral process. The morphology of these forms approaches that of *A. complicatus*, and it would not be surprising if typical specimens of *A. complicatus* will be found in the Pagoda Formation because the range of this species elsewhere (see, e.g. Bergström 2007a)

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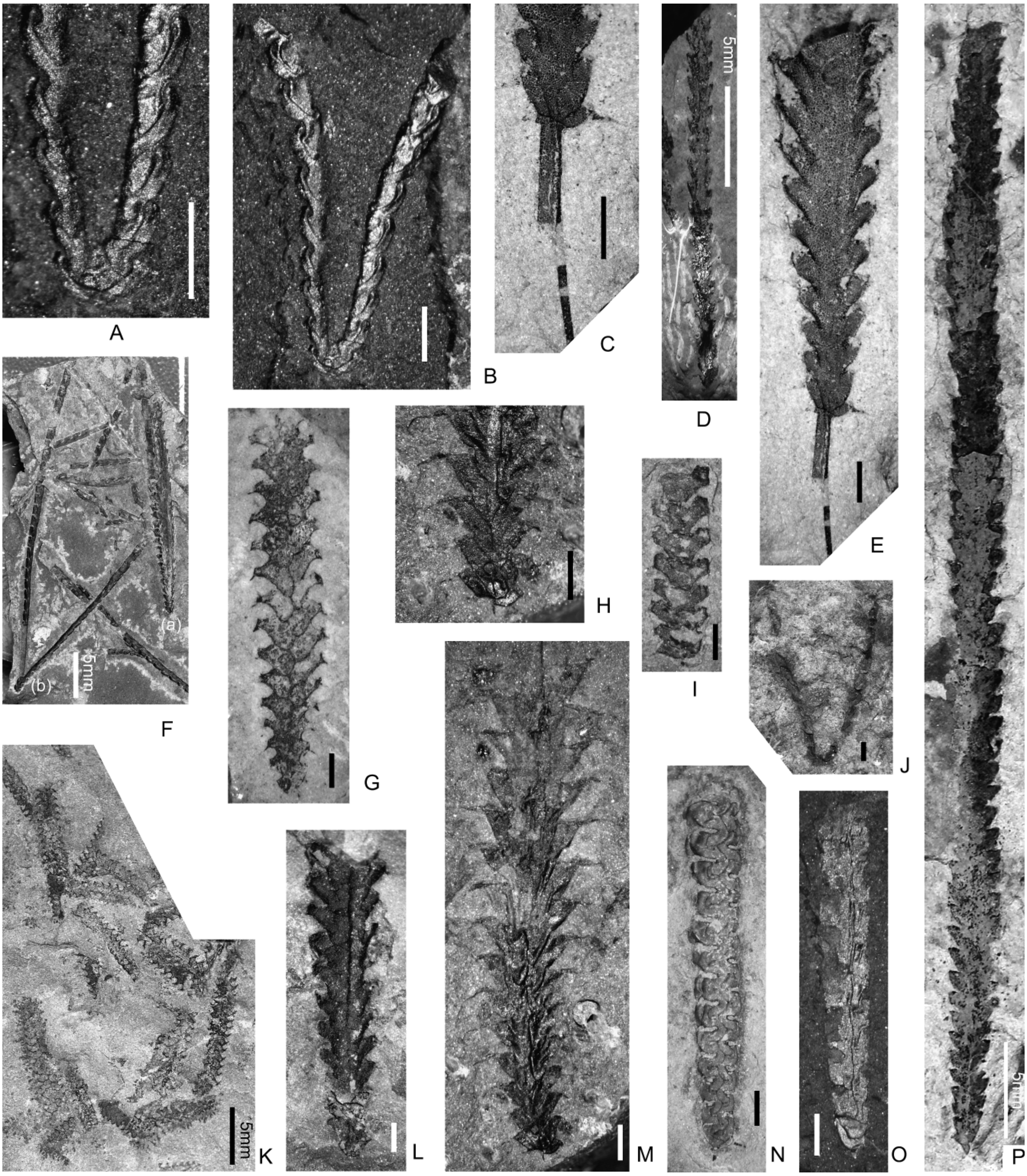

Figure 8 Photographs of some graptolites from the Upper Ordovician in the Yangtze Platform region. (A, B) *Dicellograptus vagus* Hadding, 1913: (A) is close-up of the proximal part of specimen in (B), Miaopo Fm. at Zhenjin section, Yuan'an, Hubei, NIGP151569 (AFI5053). (C, E) *Orthograptus calcaratus calcaratus* (Lapworth, 1876): (C) is close-up of the proximal part of specimen in (E), Miaopo Fm. at Chenjiahe section, Yichang, Hubei, NIGP151594 (AFI5012). (D, P.) *Hustedograptus teretiusculus* (Hisinger, 1840): (D) Shihtzupu Fm. at Yanmen section, Zunyi, Guizhou, NIGP151588 (AFA330); (P) Miaopo Fm. at Chenjiahe section, Yichang, Hubei, NIGP151587 (AFI5011). (F) *Orthograptus apiculatus* Elles & Wood, 1906 (a) and *Dicranograptus brevicaulis yangtzensis* Ge, 1963a (b), Miaopo Fm. at Zhenjin section, Yuan'an, Hubei: (a) NIGP151603 (AFI5053), (b) NIGP151595 (AFI5053). (G) *Prolasiograptus haplus* (Jaanusson, 1960), Shihtsupu Fm. at Yanmen section, Zunyi, Guizhou, NIGP151597 (AFA329). (H, M) *Hallograptus mucronatus* (Hall, 1843). (H) is close-up of the proximal part of specimen (M), Miaopo Fm. at Chenjiahe section, Yichang, Hubei, NIGP151601 (AFI5015). (I) *Oepikograptus bekkeri* (Öpik, 1927), Miaopo Fm. at Zhenjin section, Yuan'an, Hubei, NIGP151582 (AFI5054). (J) *Dicellograptus elegans* Carruthers, 1868, *D. elegans* Zone of the Chientsaokou Fm. at Shizipu (Shihtzupu) section, Zunyi, Guizhou, NIGP56804 (AAE369). (K) *Gymnograptus linnarssoni* (Moberg, 1896), Shihtzupu Fm. at Yanmen section, Zunyi, Guizhou, NIGP151604 (AFA331). (L) *Prolasiograptus* sp., Miaopo Fm. at Jieling section, Yuan'an, Hubei, NIGP151596 (AFI5042). (N) *Pseudoclimacograptus scharenbergi* (Lapworth, 1876), Miaopo Fm. at Chenjiahe section, Yichang, Hubei, NIGP151593 (AFI5015). (O) *Normalograptus brevis* (Elles & Wood, 1906), Miaopo Fm. at Zhenjin section, Yuan'an, Hubei, NIGP151583 (AFI5061). Scale bars = 1 mm unless specified. All figured specimens are housed in the Nanjing Institute of Geology and Palaeontology (NIGP), Nanjing.

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Table 2 Lithologic logs of the Shihtzupu Formation with fossil identifications from the Donggongsi, Yanmen, and Wulipo sections.

Collection number	Lithology and Fauna	Interval thickness
	Donggongsi (Shihtzupu) section, Zunyi (Fig. 1, Loc. 1)	
AAE 371	Grey-green calcareous shale with *Gymnograptus* sp., *Hustedograptus* cf. *H. teretiusculus* (Hisinger) and brachipods.	1·2 m
AAE 372	Dark grey calcareous shale with *Gymnograptus* sp., *Prolasiograptus haplus* (Jaanusson), *P. asiaticus* Lee, *Normalograptus euglyphus* (Lapworth), *Hustedograptus* cf. *teretiusculus* (Hisinger), and *Dicellograptus sextans exilis* Elles & Wood. Trilobites include *Pharostoma parapulchra* Kobayashi, *Calymenesun tingi* (Sun), *Remopleurides* sp., *Lonchodomas* sp., *Telephina* sp., *Amphilichas browni* (Sun).	8·9 m
AAE 373	Blue-grey calcareous shale with the graptolites *Gymnograptus* sp. and the trilobite *Calymenesun tingi* (Sun).	0·5 m
AAE 374	Grey and blue-grey calcareous shale with *Pseudoclimacograptus scharenbergi* (Lapworth), *Gymnograptus* sp., *Prolasiograptus* sp., *Normalograptus euglyphus* (Lapworth), the trilobites *Pharostoma parapulchra* Kobayashi, *Birmanites* sp., *Telephina* sp., and brachiopods.	9·0 m
AAE 374	Grey and blue-grey calcareous shale with the graptolites *Pseudoclimacograptus scharenbergi* (Lapworth), *Gymnograptus* sp., *Prolasiograptus* sp., *Normalograptus euglyphus* (Lapworth), the trilobites *Pharostoma parapulchra* Kobayashi, *Birmanites* sp., *Telephina* sp. and brachiopods.	9·0 m
AAE 374a	Dark grey oolitic limestone.	3·0 m
	Yanmen section, Zunyi (Fig. 1, Loc. 2)	
AFA 331	Yellow-grey mudstone with the graptolites *Gymnograptus linnarssoni* (Moberg) (Fig. 8K) and *Normalograptus euglyphus* (Lapworth).	38·0 m
AFA 330	Green-yellow mudstone with the graptolite *Hustedograptus teretiusculus* (Hisinger) (Fig. 7Q).	3·0 m
AFA 329	Yellow-grey shale with the graptolite *Prolasiograptus haplus* (Jaanusson) (Figs 7O, 8G).	3·0 m
	Wulipo section, Meitan (Fig. 1, Loc. 3)	
AAE 504, 503	Grey and grey-yellow calcareous shale with brachiopods.	10·0 m
AAE 502	Yellow-grey calcareous shale with the trilobites *Remopleurides* sp. and *Birmanites* sp.	10·0 m
AAE 500, 499 & 498	Grey and grey-yellow shale with the graptolites *Hustedograptus* cf. *H. teretiusculus* (Hisinger), *Gymnograptus* sp., the nautiloid *Dideroceras wahlenbergi* (Foord), trilobites and brachiopods.	14·0 m
AAE 498a	Grey oolitic limestone.	1·0 m

is partly within the stratigraphical interval represented by this formation.

As noted by Bergström *et al.* (2009a), the Pagoda conodont species association represents the *Hamarodus–Dapsilodus–Scabbardella* biofacies of Sweet & Bergström (1984). This biofacies, which is best known from relatively deep/cold water deposits in Baltoscandia, the United Kingdom and the Carnic Alps of northern Italy (Sweet & Bergström 1984), is strikingly different from the coeval low-latitude biofacies of the North American Midcontinent, but it shares some taxa with faunas recorded from the marginal areas of the North American continent, such as central Nevada (Sweet 2000). The North American Midcontinent faunas are characterised by widespread and common species of, amongst others, *Aphelognathus*, *Oulodus*, *Phragmodus*, *Plectodina*, *Pseudobelodina* and *Rhipidognathus*. All these are unknown in the Pagoda Formation conodont fauna, which is dominated by stratigraphically rather long-ranging, and hence biostratigraphically not very useful, representatives of *Dapsilodus*, *Drepanoistodus*, *Hamarodus*, *Panderodus*, *Protopanderodus* and *Scabbardella.* The taxonomically somewhat enigmatic species *Ansella fenxiangensis* and *Icriodella baotaensis* have not been recorded outside China, but they may prove to be useful for local biostratigraphy.

A morphologically highly characteristic species in the Pagoda Formation fauna is *Protopanderodus insculptus* (Branson & Mehl, 1933). The stratigraphic range of this species, which was originally described from Richmondian strata in Missouri (Branson & Mehl 1933; see also Leslie & Bergström 2005), is currently not well established. This is partly due to the fact that several authors, both in North America and Europe, have identified specimens of the long-ranging *Protopanderodus liripipus* Kennedy, Barnes & Uyeno, 1979 as *P. insculptus.* For instance, although *P. insculptus* has been frequently reported, there is no confirmed record from Europe of typical specimens of *P. insculptus* with the prominent denticle on the posterior part of the base. The oldest published records of *P. insculptus* are in North America from the uppermost *A. superbus* Zone, but the species is best known from the *A. ordovicicus* Zone of Nevada (Harris *et al.* 1979; Sweet 2000), Texas (Goldman *et al.* 1995), Missouri (Leslie & Bergström 2005; Bergström & Leslie 2010), and the Canadian Arctic (McCracken 1989), as well as the Timan region, northwestern Siberia (Melnikov 1999) and northeastern Siberia (Zhang & Barnes 2007). A much older (early Katian) record is from northeastern Siberia (Zhang & Barnes 2007) but, in the absence of illustration, this occurrence needs confirmation. It should be noted that the specimens from the Yangtze Platform illustrated by Ni & Li (1987, pl. 60, fig. 54), and An (1987, pl. 11, figs 16, 23; pl. 15, fig. 21) are indeed typical *P. insculptus*, and such specimens are also present in our collections from the Pagoda and Linhsiang formations. This is a stratigraphically early record of the species.

Another stratigraphically significant, and geographically widespread, species is *Hamarodus europaeus* (Serpagli, 1967). It is the most common compound species in the Pagoda Formation, and has even been used within that unit as an index of the *Hamarodus europaeus* Zone (Zeng *et al.* 1983; Ni & Li 1987; An 1987) and the *Amorphognathus superbus–Hamarodus europaeus* Zone (Wang 1995). Although best known from Baltoscandia (Hamar 1966; Viira 1974; Bergström 2007a), the United Kingdom (Rhodes 1955; Orchard 1980) and Poland (Dzik 1994), it has also been recorded from Sardinia (Ferretti & Serpagli 1999) and Germany (Ferretti & Barnes 1997). In Asia, apart from the Chinese occurrences, the species is also known from northeastern Siberia (Zhang & Barnes 2007), Thailand (Agematsu *et al.* 2007) and northwestern Malaysia

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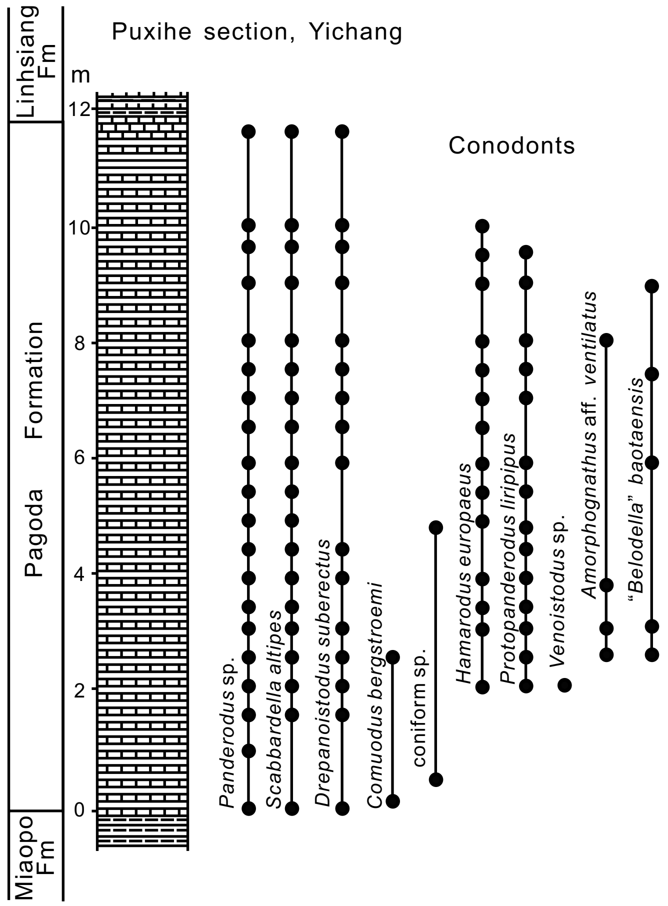

Figure 9 Ranges of conodont species through the Pagoda Formation in the Puxihe Quarry near Yichang, Hubei Province.

(Agematsu *et al.* 2008). The species is unknown in most of North America, but has been recorded from central Nevada (Sweet 2000) and questionably from southeastern Canada (Nowlan 1983). However, as noted by Nowlan (1983) and Sweet (2000), the Canadian specimens differ in several respects from typical representatives of *H. europaeus* and they may represent another species.

Because of its wide geographic distribution and relatively rapid evolution, *Amorphognathus* Branson & Mehl, 1933 is one of the biostratigraphically most important conodont genera in the Upper Ordovician. Although several of its species (*A. inaequalis*, *A. tvaerensis*, *A. superbus* and *A. ordovicicus*; cf. Bergström 2007a) have been used as zone or subzone index species, the taxonomy of the genus is currently not firmly established in all details (Bergström & Leslie 2010), and several taxa are in need of restudy. Such a taxonomic reassessment is outside the scope of the present investigation. It should be noted that such a study is hampered by the fact the diagnostic Pa elements are as a rule more or less fragmentary and the taxonomically important M elements, which tend to be uncommon in most collections, show an extraordinarily wide range of morphological variation (Fig. 12). The Pb and S elements of *Amorphognathus* exhibit a more conservative morphology through the Upper Ordovician, and hence are less useful for taxonomic discrimination.

Specimens of *Amorphognathus* occur in small numbers in some of our collections from the Pagoda Formation, but all the diagnostic Pa elements are too fragmentary for safe identification at the species level. More complete Pa elements from the Pagoda Formation at Yanjin, Yunnan and at Yidu, Hubei were identified as *A. superbus* by An (1981, pl. 4, fig. 7; 1987, pl. 30, figs. 11, 12?, 18, respectively), but their precise stratigraphic position within the formation is not clear. At any rate, they have the general morphology of the Pa elements in *A. superbus* and the illustrated specimens lack the postero-lateral lobe that is a characteristic feature of the dextral Pa elements of *A. tvaerensis*, the evolutionary ancestor of *A. superbus* and the index of the *A. tvaerensis* Zone. Specimens identifiable as *A. tvaerensis* have not been found in the present samples and, as far as the authors are aware, this species has never been recorded from the Pagoda Formation. This suggests that the interval of the Pagoda Formation bearing these *A. superbus* Pa elements is referable to the *A. superbus* Zone that, however, has a relatively long range through much of the Katian Stage.

The M elements of *Amorphognathus* have the potential to offer a more refined biostratigraphic dating of the Pagoda Formation. As shown in Figure 12, this type of element exhibits some general evolutionary trends in the morphology that are useful biostratigraphically (Bergström 1983; Dzik 1994, 1999). Although there is a great deal of shape variation in every large population of M elements, there are at least three such trends, namely (1) a reduction of number of apical denticles from several in *A. inaequalis* and *A. tvaerensis* to one in typical representatives of *A. ordovicicus*; (2) a reduction of the denticulation of the three lateral processes; and (3) a reduction of the length of the processes, which particularly applies to the posterior process that may be minute or absent in *A. ordovicicus.* As shown in Figure 12, which is based on actual specimens with no reconstruction of broken parts, it is commonly possible to separate *A. tvaerensis*, *A. superbus* and *A. ordovicicus* based on the appearance of the M elements, provided the collections are large enough to show the range of morphological variation. However, we have found it difficult

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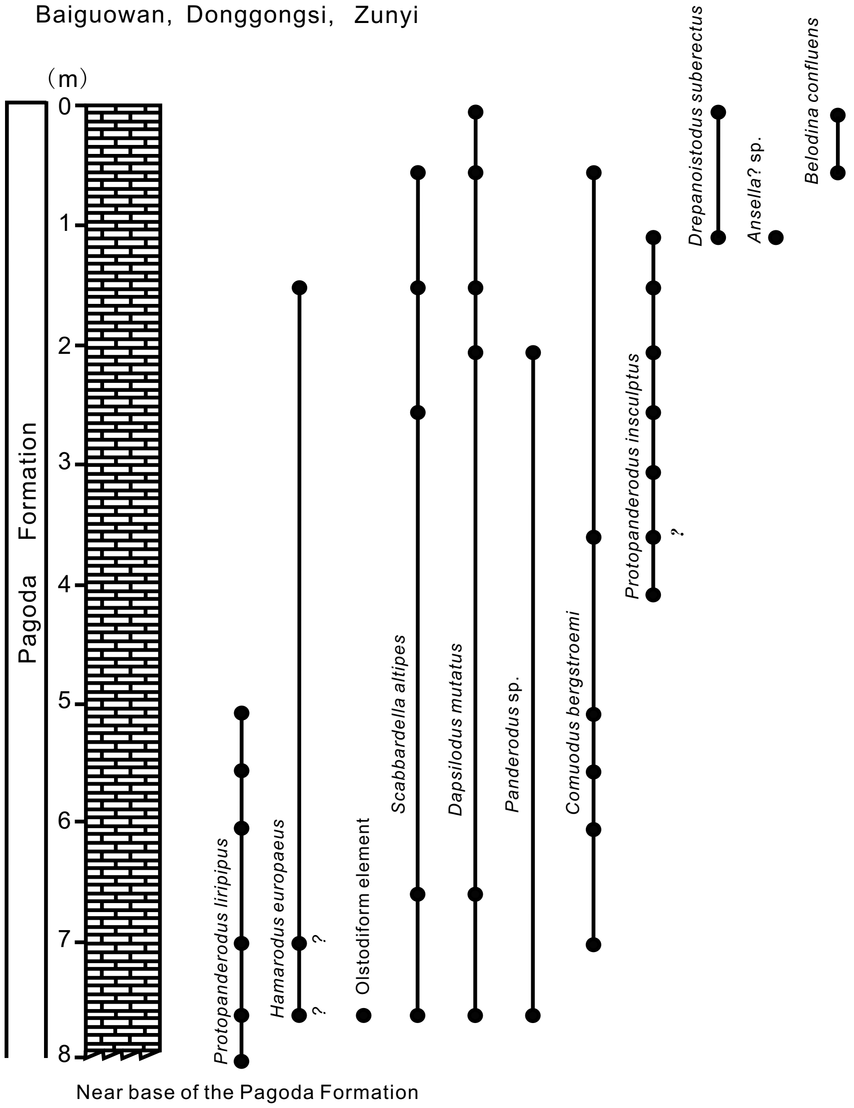

Figure 10 Ranges of conodont species through the Pagoda Formation in the section at Baiguowan, Donggongsi, Zunyi, Guizhou Province.

to find any consistent morphological feature useful for a taxonomical differentiation of M elements from the upper *A. tvaerensis* Zone from those present in the lower *A. superbus* Zone. The M elements figured by An (1987, pl. 26, fig. 24; pl. 30, fig. 8) appear to be closely similar to those in our Pagoda Formation collections, as well as to elements from the transition interval between the *A. tvaerensis* and *A. superbus* zones in the middle-upper part of the Lexington Limestone of Kentucky (Bergström & Sweet 1966) and from the Gelligrin Limestone of Wales (Fig. 12: 22–26), which is the type stratum of *A. superbus.*

Pending further studies, the specimens from the Pagoda Formation were tentatively referred to as *A.* aff. *A. ventilatus* by Bergström *et al.* (2009a) and this, admittedly somewhat unsatisfactory, practice is followed herein. Based on previously figured Pa elements (An 1987), at least the specimens from the upper Pagoda Formation are likely to represent *A. superbus.* This is also consistent with the fact that *A. superbus* first appears well above the Guttenberg $\delta^{13}C$ excursion (GICE) in Baltoscandia (Männik & Viira 2005), Kentucky (Richardson & Bergström 2003; Young *et al.* 2005) and New York State (Barta *et al.* 2007). However, in the absence of well preserved specimens of the diagnostic Pa element, the correct species identity of the *Amorphognathus* specimens in the lower Pagoda Formation remains elusive; although, based on chemostratigraphy, it is likely that they represent a stratigraphically late morphotype of *A. tvaerensis.* If so, the important *A. tvaerensis*/*A. superbus* Zone boundary corresponds to a level in the middle to upper part of the Pagoda Formation.

Two regions, namely the Holy Cross Mountains, Poland (Dzik 1994, 1999) and Estonia (Viira 1974; Männik & Viira 2005), are of particular interest for the interpretation of the biostratigraphic significance of the *Amorphognathus* morphotypes, as well as other taxa, in the Pagoda Formation. As shown in Figure 13, the Sandbian–early Katian conodont biostratigraphy of the classical and stratigraphically very condensed Mójcza Limestone succession in the Holy Cross Mountains is closely similar to that of Baltoscandia and also reminiscent of that of the Yangtze Platform. In very detailed studies, Dzik (1994, 1999) subdivided the succession into a series of zones, but his classification needs some revision based on the vast amount of new information published in recent years, particularly from Baltoscandia. Revisions of the biostratigraphic classification, which are illustrated in Figure 13, includes, amongst others, an upward extension of the *A. tvaerensis* Zone to a level slightly above the last occurrences of *Baltoniodus alobatus* and *A. tvaerensis* recorded by Dzik (1999). This level is just above Dzik's (1999) projected position of a K-bentonite, which he questionably, but probably correctly, identified as the Kinnekulle K-bentonite (K). This level

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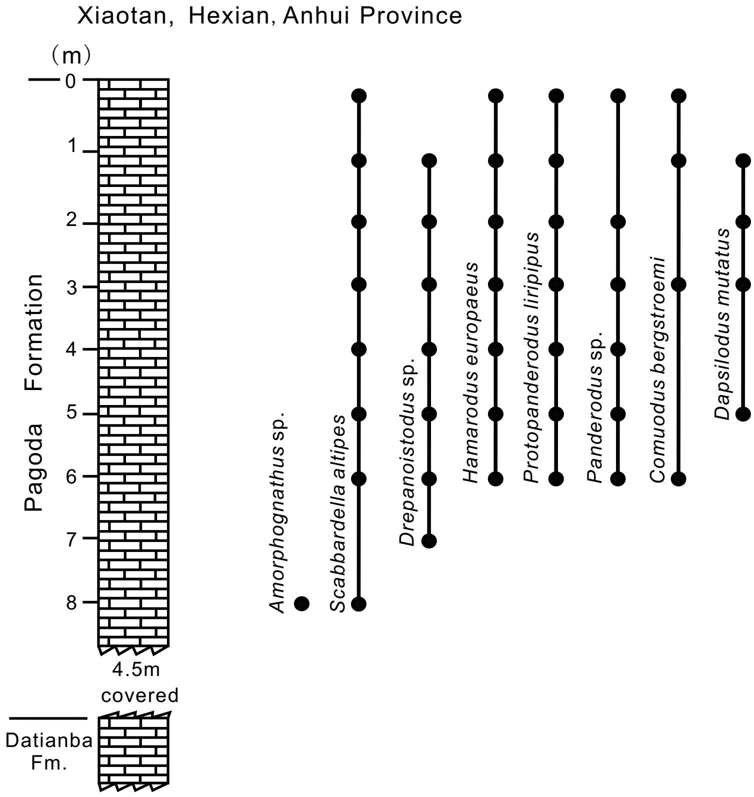

Figure 11 Ranges of conodont species through the Pagoda Formation in the section at Xiaotan, Hexian, Anhui Province.

(at his sample 153) coincides with what appears to be a disconformity that has the stratigraphic position of the base of the Keila Stage in Baltoscandia, the M4/M5 sequence boundary in the United States Midcontinent and, as noted above, the base of the Pagoda Formation in the Yangtze Platform region.

Dzik (1999) separated his *A. tvaerensis* and *A. superbus* zones by an *A. ventilatus* Zone (Fig. 13). There are at least two problems with the introduction of this zone. First, Dzik (1994, fig. 22) illustrated dextral Pa elements of *Amorphognathus* having the posterior-lateral lobe characteristic of the same type of element in *A. tvaerensis* from his sample 96, which was collected from the middle part of his *A. ventilatus* Zone, which is only ~0·2 m thick. Hence, following the well-established scope of the *A. tvaerensis* Zone as corresponding to the range of its index species, the *A. ventilatus* Zone would correspond to an upper part of the *A. tvaerensis* Zone. This interpretation is supported by the fact that *Baltoniodus alobatus*, which is not known to range above the top of the Haljala Stage in Baltoscandia (Bergström 2007a), is recorded throughout the *A. ventilatus* Zone by Dzik (1994, 1999). Secondly, the poorly known species *A. ventilatus* was first described, based only on M elements, from significantly younger strata (*A. ordovicicus* Zone; cf. Ferretti & Barnes 1997) in southeastern Germany. Dzik (1999) noted morphological differences between the Polish and German specimens and, as indicated by Bergström *et al.* (2009a), it appears quite unlikely that the German species is conspecific with Dzik's Mójcza specimens. The M elements of *Amorphognathus* from the Pagoda Formation (Fig. 12: 16–20) appear slightly more advanced in terms of process development and denticulation than those from the *A. tvaerensis* Zone at Mójcza (Fig. 12: 33–41), which are similar to specimens present in the upper *A. tvaerensis* Zone in Ohio and Kentucky (Fig. 12: 29–31). At least some of the Pagoda specimens are more similar to those in the Polish *A. superbus* Zone of our new classification, which is in agreement with the local ranges of *Hamarodus europaeus* in the Mójcza and Chinese successions. It should be noted that Dzik & Pisera (1994, fig. 10) referred to the *A. superbus* Zone the stratigraphic interval that Dzik (1999) later classified as the *A. ventilatus* Zone. In the present interpretation, the Pagoda Formation corresponds approximately to an interval from Dzik's (1999) sample 153 to at least the level of his sample 156, but it is quite possible that it may range even higher but not as high as the level of his sample 165.

Evidently influenced by the Polish investigations, recent workers in Estonia (see Männik 2003, 2004; Männik & Viira 2005) have distinguished an *A. ventilatus* Zone between the *A. tvaerensis* and the *A. superbus* zones in the East Baltic successions (Fig. 13). The principal basis for this has been the identification of *Amorphognathus* M elements present in an interval above the local range of *A. tvaerensis* as *A. ventilatus.* Investigation of two such M elements from the middle Oandu Stage of the Mehikoorma (421) drill-core kindly supplied by Dr P. Männik (Fig. 12: 27–28) suggests that they are not conspecific with the German species *A. ventilatus*, but are closely similar to M elements from the interval round the *A. tvaerensis*/*A. superbus* Zone boundary in the Cincinnati region of Kentucky and Ohio. They are also similar to the M elements present in the Pagoda Formation (Fig. 12: 16–20). Männik & Viira (2005) recorded the lowest occurrence of typical *A. superbus* from the uppermost Oandu Stage at a level just above the Guttenberg $\delta^{13}C$ excursion (GICE). This is a stratigraphic position that, in its relationship to the GICE, is closely similar to the base of the *A. superbus* Zone in North America (Richardson & Bergström 2003; Young *et al.* 2005), where the GICE occurs within the *A. tvaerensis* Zone (Barta *et al.* 2007). Accordingly, the present authors suggest that the GICE interval in the Pagoda Formation is within the *A. tvaerensis* Zone, and that the *A. tvaerensis*/*A. superbus* Zone boundary corresponds to an as yet undetermined level in the upper part of the formation.

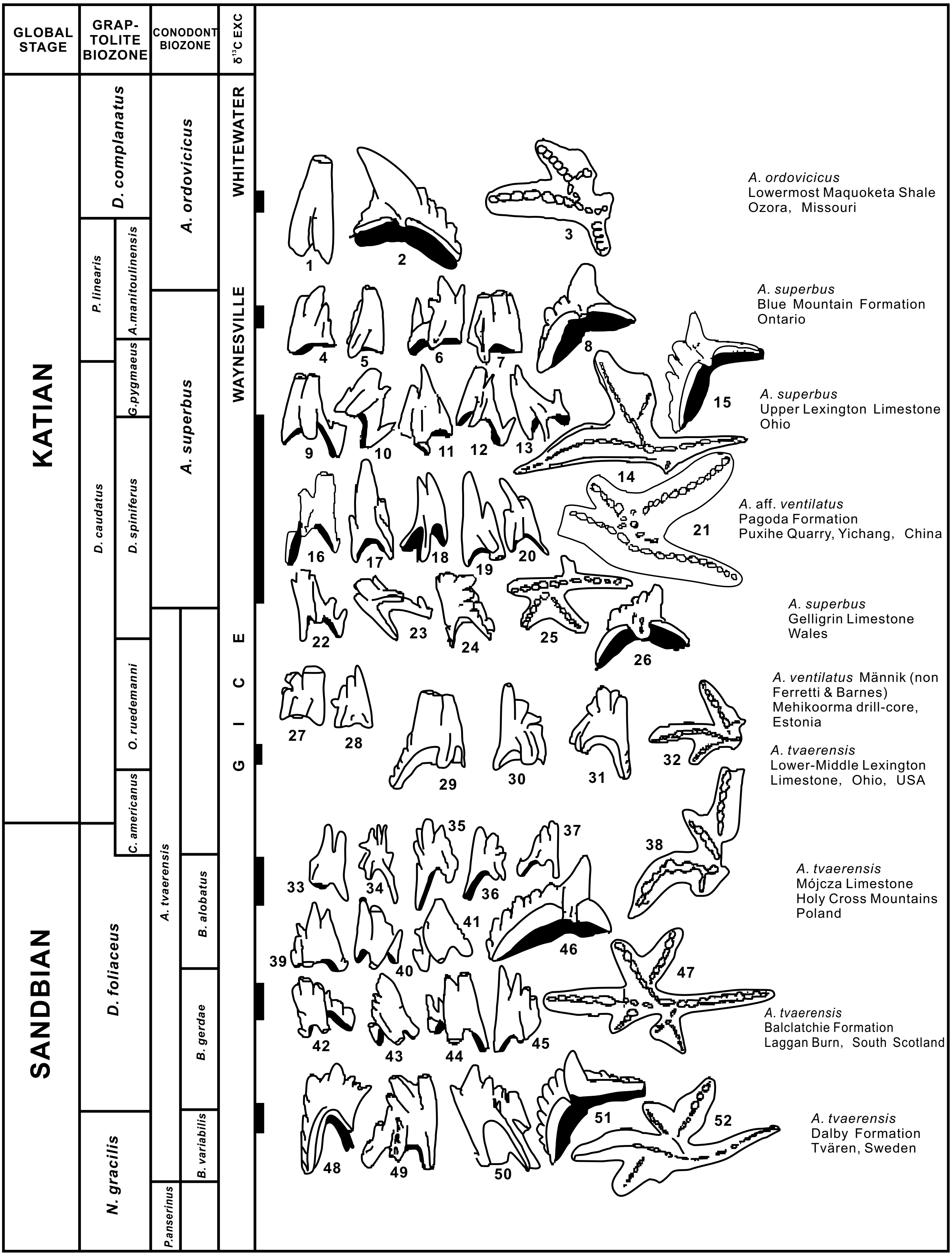

Figure 12 Schematic illustrations of conodont M and P elements of Sandbian and Katian species of *Amorphognathus*. No reconstructions of incomplete specimens have been made. Note the extraordinary morphological variation in the M elements. (1–3) *A. ordovicicus* Branson & Mehl, 1933. All specimens are from the type stratum (basalmost Maquoketa Shale) at Ozora, Missouri (Leslie & Bergström 2005): (1) M element; (2) Pb element; (3) Dextral Pa element (after Branson & Mehl 1933, pl. 10, fig. 38). (4–26) *A. superbus* Rhodes, 1953: (4–8) from the Blue Mountain Formation, lower *Amplexograptus manitoulinensis* Zone, approx. 10 m above base of creek section near highway (Goldman & Bergström 1997, fig. 3) about 5 km S of Little Current, Manitoulin

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The precise biostratigraphic age of the top of the Pagoda Formation remains undetermined, but it is likely to correspond to a level within the *A. superbus* Zone. This is consistent with the presence of *Belodina confluens* in the uppermost Pagoda Limestone in the Baiguowan section (Fig. 10). In North America, this species, which evolved from *B. compressa*, appears just below the base of the *A. superbus* Zone (e.g. Richardson & Bergström 2003). It should also be noted that, as suggested by the $\delta^{13}C$ chemostratigraphy (Bergström *et al.* 2009a), the top of the Pagoda Formation may be of slightly different age at different localities.

5. Graptolite zonation of the Linhsiang and Chientsaokou formations

In the study area, the Pagoda Formation is conformably overlain by either the Linhsiang or the Chientsaokou formations (Chen *et al.* 1995). The former unit, which has a thickness of up to 20 m, consists of grey-green nodular limestone with a shelly fauna. The latter unit, which is only 1–3 m thick, includes yellow-grey calcareous shales and mudstones. Only one graptolite species occurs in the Linhsiang Formation at Jiaodingshan, Hanyuan, western Sichuan and in the Chientsaokou Formation at Donggongsi (Shihtzupu), northern Zunyi, Guizhou (Fig. 1). This species was identified as *Dicellograptus* cf. *D. johnstrupi* (Hadding) by Chen (in Zhang *et al.* 1964), listed under that designation by Mu *et al.* (1974), and later described by Mu *et al.* (1993).

After recent restudy of the specimens from both Donggongsi and Jiaodingshan, the identification of this form is revised to *Dicellograptus elegans* Carruthers (Fig. 7E). *D. elegans* occurs in the *Pleurograptus linearis* Zone in S. Scotland and Ireland (Elles & Wood 1904; Williams 1982), and in the *Dicranograptus kirki* (Ea3) and *Dicellograptus gravis* (Ea4) zones of Victoria, Australia (VandenBerg & Cooper 1992). Carter & Churkin (1977) described *D.* cf. *D. elegans* from the Passage beds of the Trail Creek, Idaho succession. However, their specimen is poorly preserved and the species was not recorded in a recent reassessment of the Trail Creek graptolites by Mitchell *et al.* (2003). The occurrence of *D. elegans* in the Chientsaokou Formation at Donggongsi may be taken as support for the idea that this formation corresponds to the Linhsiang Formation at Honghuayuan, a locality situated only 80 km north of Donggongsi. The shaley Chientsaokou Formation and limey Linhsiang Formation appear to represent two coeval, but lithologically different, units in the Upper Yangtze region.

6. Conodont zonation of the Linhsiang Formation

A succession of 10 samples collected through the 4·19 m-thick Linhsiang Formation from an outcrop at Honghuayuan, Tongzi in Guizhou Province (Fig. 1) yielded moderately common conodonts that are referred to 13 species (Fig. 14). The species association is quite similar to that in the Pagoda Formation and includes long-ranging taxa of little biostratigraphic significance. Because no representatives of the biostratigraphically useful platform conodonts have been found, the precise age of the Linhsiang Formation in terms of conodont biostratigraphy is not readily established. Both *Hamarodus europaeus* and *Protopanderodus insculptus* range through most of the formation and these taxa suggest that it represents parts of, or the whole, interval from the middle *A. superbus* Zone to possibly the lowermost *A. ordovicicus* Zone. Closely similar conodont species associations that contain also platform conodonts are known from middle Katian strata in Sweden (Bergström 2007a) and England (Orchard 1980).

7. Comparison with the Baltoscandic and North American successions

Although there are some obvious regional faunal differences, both the graptolite and the conodont biostratigraphy herein established in the study successions on the Yangtze Platform are in most respects similar to those in coeval successions in Baltoscandia and North America. This makes it possible to carry out inter-continental biostratigraphic correlations between these regions in more detail than previously has been the case. We will briefly discuss some of these correlations that are schematically illustrated in Figure 15.

In Baltoscandia, equivalents to the Miaopo Formation are to be found in, for instance, the upper Almelund Shale and the Sularp Formation in Scania, southern Sweden. These units contain a graptolite succession spanning the same stratigraphic interval as the Miaopo Formation (Bergström *et al.* 2000a) and several of its key conodonts are shared with the Miaopo Formation. Interestingly, the top of the Sularp Formation appears to be approximately coeval with the top of the Miaopo

Island, Ontario (Bergström coll. 90B12–1): (4–7), M elements; (8) Pb element; (9–15) all from the Lexington Limestone, Middletown drill-core, Ohio (Bergström & Sweet 1966; Richardson & Bergström 2003), lower *Amorphognathus superbus* Zone, (sample 61Z-385 of Bergström & Sweet 1966): (9–13), M elements; (14) dextral Pa element; (15) Pb element; (16–20) all from sample AFF 446, 2·5 m above the base of the Pagoda Formation, Puxihe Quarry, 29 km N of Yichang. Hubei Province, China, M elements; (21) from the Pagoda Formation at Yidu, Hubei Province, dextral Pa element (after An 1987, pl. 30, fig. 18); (22–26) from the Gelli-grin Limestone at the type locality (Rhodes 1953); (22–24), M elements; (25) dextral Pa element (after Rhodes 1953, pl. 20, fig. 48); (26) Pb element (after Rhodes 1953, pl. 20, fig. 31). (27–28) M elements identified as *A. ventilatus* by P. Männik, from the Mehikoorma (421) drill-core, 292·2–292·3 m depth (middle Oandu Stage, cf. Männik & Viira 2005, fig. 5). (29–52) *A. tvaerensis* Bergström, 1962: (29–30) M elements from the Middletown drill-core, Ohio (Bergström & Sweet 1966; Richardson & Bergström 2003, upper *A. tvaerensis* Zone (sample 61X-578 of Bergström & Sweet 1966); (31–32) from the lower Lexington Limestone, upper *A. tvaerensis* Zone, Logan drill-core (Bergström & Mitchell 1992), M element and dextral Pa elements (after Bergström & Mitchell 1992, pl. 1, figs 28 & 30, respectively); (33–38) all from the Mójcza Limestone, Holy Cross, Mountains, Poland: (33–37) M elements (after Dzik 1999, pl. 1, figs 15, 10, 20, 19, 8, respectively; (38) dextral Pa element (after Dzik 1994, fig. 22 (from Dzik's (1994) sample 96); (39–47) all from the *B. gerdae* Subzone of the *A. tvaerensis* Zone at Laggan Burn, Givan area, southern Scotland (Bergström 1990b, sample Sd65–18); (39–45), M elements; (46) Pb element; (47) dextral Pa element (after Bergström & Orchard 1985, pl. 2.3, fig. 11); (48–52) from the Dalby Limestone at Tvären, Sweden (Bergström 1962), top part of the *Baltoniodus variabilis* Subzone of the *A. tvaerensis* Zone: (48–50) M elements (after Bergström 1962, pl. 1, figs1, 3); (51) Pb element (after Bergström, 1962, pl. 3, fig. 11); (52) Pa element (after Bergström, 1962, pl. 4, fig. 7).

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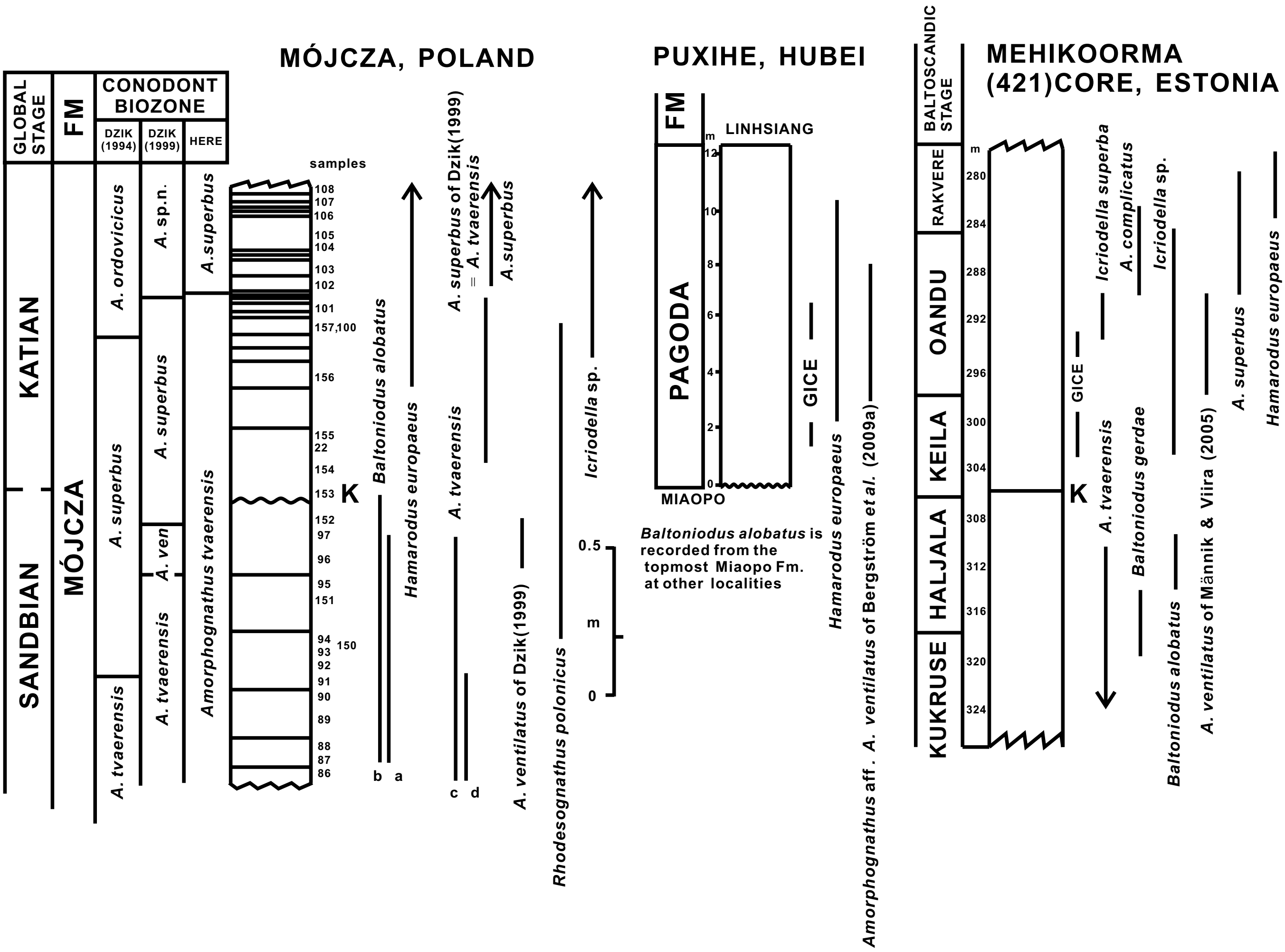

Figure 13 Comparison between vertical ranges of selected conodont taxa in the Mójcza Quarry, Poland (Dzik 1994, 1999), the Puxihe Quarry, Hubei and the Mehikoorma (421) drill-core, Estonia (Männik & Viira 2005).

Formation, which suggests eustatic sea-level control. In terms of the standard Baltoscandic regional stage succession (Nõlvak *et al.* 2006), the Miaopo Formation ranges from the lower part of the Uhaku Stage to the base of the Keila Stage. This correlation is largely based on conodonts, but it is consistent with the graptolite evidence. The Pagoda Formation appears to be equivalent to the Skagen and Moldå formations in Sweden, based on conodont and $\delta^{13}C$ chemostratigraphy (Bergström *et al.* 2009a). This interval approximates the scope of the upper *Diplograptus foliaceus* and the *Dicranograptus clingani* graptolite zones. In terms of Baltoscandic standard stages, this interval includes the Keila, Oandu, and Rakvere stages.

In North America, graptolite-bearing strata equivalent to the Miaopo Formation are present in, for instance, the Athens Shale of the Southern Appalachians (Finney 1984), especially as this formation is developed in Alabama and Tennessee, and in the Womble Shale of the Ouachita Mountains of Oklahoma and Arkansas (Finney 1986). Based on conodonts and chemostratigraphy, equivalents to the Pagoda Formation are to be found in units of the Chatfieldian Stage of the North American Midcontinent, such as the Lexington Limestone of Kentucky and adjacent states (Richardson & Bergström 2003), the lower part of the Viola Springs Formation of Oklahoma (Young *et al.* 2005), and parts of the Trenton Group of New York State and Ontario (Barta *et al.* 2007; also cf. Brett *et al.* 2004). These proposed correlations of the Pagoda Formation are summarised in Figure 15.

Precise equivalents of the Linhsiang Formation are more difficult to recognise in the Baltoscandic and North American successions, although they should be present within *Pleurograptus linearis* Zone in Baltoscandia that includes the Nabala and Vormsi stages (Nõlvak *et al.* 2006). In North America, the European *P. linearis* Zone corresponds at least broadly to the upper *Geniculograptus pygmaeus* and *Amplexograptus manitoulinensis* zones that are equivalent to parts of the Maysvillian and lower Richmondian stages (Goldman & Bergström 1997). However, the scant faunal evidence presently available is insufficient for a close correlation of the Linhsiang Formation with North American units. It may be significant to note that, based on the presence of *Dicellograptus complanatus* Zone graptolites in the overlying Wufeng Formation, it is clear that the Linhsiang Formation is not younger than the middle Richmondian Stage that has yielded *Dicellograptus complanatus* (Goldman & Bergström 1997).

8. Concluding remarks

In summary, the main results of the present study are as follows:

1. Whereas the graptolite fauna of the Miaopo Formation is a mixture of more or less pandemic taxa and a significant number of species that are endemic to China, the conodont species associations in the Miaopo, Pagoda, and Linhsiang formations, apart from a couple of possibly endemic forms,

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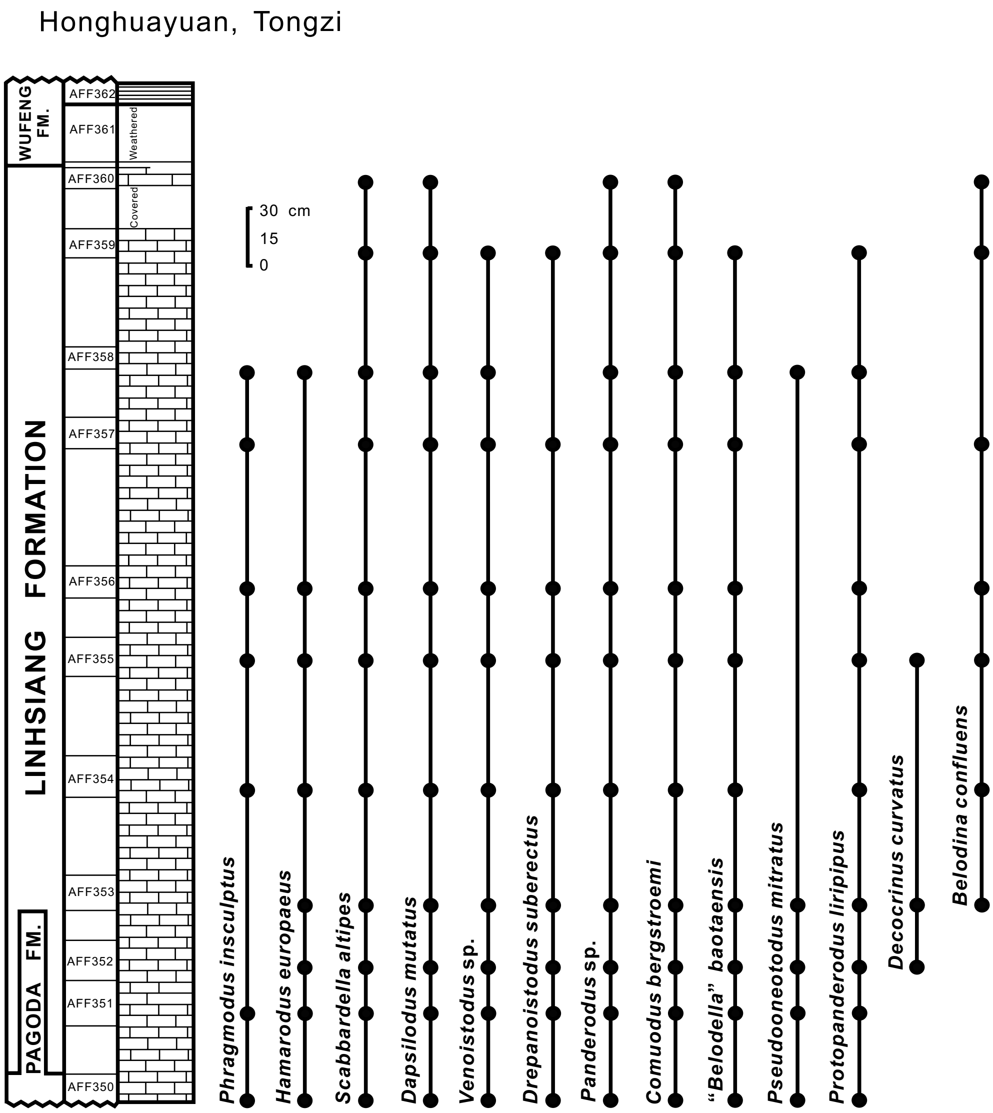

Figure 14 Conodont species ranges through the Linhsiang Formation in the Honghuayuan section, Tongzi, Guizhou Province. Note the similarity of the conodont fauna to that of the underlying Pagoda Formation (Figs 3, 10–12).

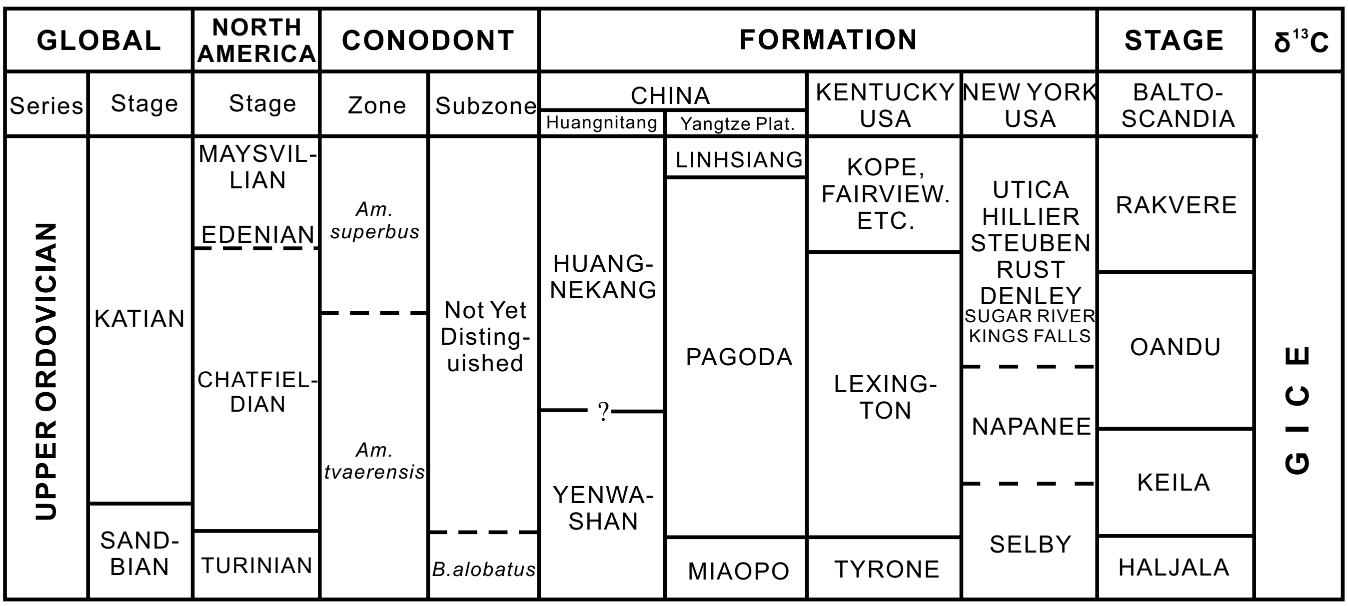

Figure 15 Conodont-based correlation table showing the inferred relations between the uppermost Miaopo, Pagoda, and lowermost Linhsiang formations and some stratigraphical units in North America and Estonia.

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consist of taxa known from deep/cool water environments at many localities round the world. As a whole, the studied conodont faunas are strikingly different from the coeval tropical shallow-water faunas in, for instance, the North American Midcontinent.

2. Our detailed graptolite vertical distribution data indicate that in the most stratigraphically complete successions, two graptolite zones can be recognised in the Miaopo Formation, namely the *Hustedograptus teretiusculus* and *Nemagraptus gracilis* zones. Conodont data suggest that the uppermost part of the Miaopo Formation, which lacks index graptolites, is younger than the *Nemagraptus gracilis* Zone and corresponds to a portion of the *Climacograptus bicornis* (or *Diplograptus foliaceus*) Zone. There is no firm graptolite evidence of the presence of this graptolite zone in the Miaopo Formation, but it is known to be present at Shuangjiakou, Hunan about 470 km south of Yichang.
3. Three conodont zones are present in the Miaopo Formation, namely the *Pygodus serra*, *Pygodus anserinus* and *Amorphognathus tvaerensis* zones. The *Baltoniodus variabilis* and *Baltoniodus alobatus* subzones of the *Amorphognathus tvaerensis* Zone are also recognisable, but the *Baltoniodus gerdae* Subzone, which is present between these subzones in Baltoscandia and North America, has not been documented in the Miaopo Formation. It is currently unknown whether the absence of this subzone is due to the presence of a stratigraphic gap below the *B. alobatus* Subzone in the Miaopo succession, or to some other factors. Also, the conodont biostratigraphy shows that in some sections, the stratigraphic interval just below the Miaopo Formation, and its equivalent the Datianba Formation, is extremely condensed, or there is an obvious stratigraphic gap. For instance, in the Maocaopu and Cili sections, this gap corresponds to two or three conodont subzones.
4. No graptolites are known from the Pagoda Formation, but one species, here identified as *Dicellograptus elegans*, is present in the overlying equivalents of the Linhsiang Formation on the Yangtze Platform (i.e. the Daduhe and Chientsaokou formations). The occurrence of this taxon suggests that this formation is equivalent to part of the *Pleurograptus linearis* Zone in northern Europe.
5. Conodonts occur in moderate numbers throughout the Pagoda Formation, but only a few species, such as *Hamarodus europaeus*, *Protopanderodus insculptus* and morphotypes of *Amorphognathus* provisionally referred to as *A.* aff. *A. ventilatus*, have biostratigraphic significance. The evidence from conodont biostratigraphy, combined with that from the recently published $\delta^{13}C$ chemostratigraphy, suggest that the lower part of the Pagoda Formation (including the GICE interval) corresponds to the *Amorphognathus tvaerensis* Zone and that the upper part of the formation is coeval with the lower portion of the *Amorphognathus superbus* Zone. The conodont species association of the Linhsiang Formation is similar to that of the Pagoda Formation; but in the absence of platform conodonts, it is not highly diagnostic biostratigraphically, although it shows a general similarity to that of the Nabala and Vormsi stages (*Pleurograptus linearis* Zone) in Baltoscandia.
6. Whereas the contact between the Pagoda and Linhsiang formations appears gradual and conformable, that between the Miaopo and Pagoda formations may be disconformable and represent a minor stratigraphic gap.
7. Viewed in a regional perspective, the biostratigraphy and the recently established $\delta^{13}C$ chemostratigraphy of the Pagoda Formation are in good agreement. However, the biostratigraphic data at hand are insufficient to prove or disprove the indication from the chemostratigraphy that the chronostratigraphic scope of the Pagoda Formation is not precisely the same across its wide distribution area across the Yangtze Platform.

9. Acknowledgements

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10. Appendix 1. Taxonomic and biostratigraphic notes

1. Ge (1963a, b) recorded three species, *Corynoides calicularis* Nicholson (Fig. 7L), *C. pristinus* Ruedemann, and *C.* cf. *C. comma* Ruedemann from his *Corynoides calicularis* Subzone. The present restudy of his reference specimens indicates that all of them are referable to *C. calicularis* Nicholson.
2. *Orthograptus propinquus* (Hadding) was originally described as a species of *Diplograptus.* However, the type specimen (LO 2403T) has a Pattern A primordial astogeny of Mitchell (1987) and belongs to the genus *Hustedograptus.*
3. *Glossograptus sinicus* Mu & Zhan was first described from the *N. gracilis* Zone in the Saergan Formation at Kalpin, western Tarim (Mu & Zhan 1966) and its occurrence in the Miaopo Formation strengthens the correlation of the *N. gracilis* Zone between the Tarim and Yangtze regions.
4. *Hustedograptus teretiusculus* first appears in the *P. elegans* Zone elsewhere in the world but the stratigraphic level of its last occurrence is still uncertain, although Nilsson (1977) recorded it as high as the lowermost *Diplograptus foliaceus* Zone in Scania, and one of the present authors (DG) has identified *H.* cf. *teretiusculus* in the *Climacograptus bicornis* Zone in the Normanskill Shale of New York State.
5. The figured specimens of *Orthograptus calcaratus priscus* Elles & Wood (Elles & Wood 1907, pl. XXX, fig. 6a–c) come from the *D. murchisoni* Zone at Abereiddy Bay, south Wales. Although the present authors have not personally examined these specimens, the figured specimens exhibit the characteristic proximal (amplexograptid) to distal (orthograptid) thecal gradient, and the very broad proximal end with no anti-virgellar spines of *Pseudamplexograptus distichus.* Topotype material from Abereiddy Bay examined by J. Maletz (pers. comm. 2010) is also referable to *P. distichus*, and Maletz (1997) considered *O. c. priscus* to be a junior synonym of *P. distichus.* All true members of the *O. calcaratus* species group exhibit a Pattern G primordial astogeny (Mitchell 1987) and have anti-virgellar spines on the sicula. The morphology and stratigraphic distribution of the specimens collected from the Miaopo Formation, which superficially resemble *O. c. priscus* sensu Elles and Wood, 1907, indicate that they are referable to *Hustedograptus.*
6. *Archiclimacograptus* species: *Archiclimacograptus*? *arctus* is common in the *N. gracilis* Zone of the United Kingdom (Elles & Wood 1907). *A. angulatus* is well known from the upper Darriwilian in northern Europe (Bulman 1953; Jaanusson l960; Maletz 1997), and has recently also been found by the present authors in strata of that age in western Tarim. Although the total biostratigraphic range

of this species has not yet been documented, the present record indicates that it ranges as high as in the *N. gracilis* Zone. *A. meridionalis* and *A. modestus* are known from the Normanskill Shale of New York and the Athens Shale of Alabama, and their ranges extend into the *C. bicornis* Zone in North America (Ruedemann 1947; Finney 1984).

7. *Climacograptus parvus* was placed into synonymy with *Pseudoclimacograptus scharenbergi* by Riva (1974).
8. *Amplexograptus gansuensis* is an endemic form from the Tianzhu Formation, which occurs at a slightly higher stratigraphic interval than the *N. gracilis* Zone at the type locality at Tianzhu in the Gansu Province (Mu & Zhang 1964). However, the first appearance of this species is still uncertain, because the type specimen is from a section that has not been collected in detail. The presence of the species in the Miaopo Formation in western Hubei may be its stratigraphically oldest recorded appearance.
9. *Normalograptus haddingi* was first named by Glimberg (1952) based on specimens from the late Darriwilian Almelund Shale (formerly Lower *Dicellograptus* Shale) in southern Sweden. In that region, it was previously identified as *Climacograptus putillus* Hall by Hadding (1913), Hede (1951), and others. It ranges into the lowermost *N. gracilis* Zone in southern Sweden (Bergström *et al.* 2000a, b).
10. Elles & Wood (1906) report an unusually long range of Llandeilo to Ashgill for *Normalograptus brevis* in Scotland, but the middle and late Katian occurrences are almost certainly misidentifications. Its occurrence in the *N. gracilis* Zone in Hubei is within its true stratigraphic range in Scotland.
11. *Climacograptus uniformis* Hsü has previously been recorded from the *Nicholsonograptus fasciculatus* Zone of the Ningkuo Formation in S. Anhui (Hsü 1934) and it is not unexpected that the range of this species extends into the *N. gracilis* Zone. This species has not yet been reported from localities outside South China.
12. *Pseudoclimacograptus scharenbergi* and *P. stenostoma* are common forms of the *N. gracilis* and *C. bicornis* zones elsewhere. The endemic species *Pseudoclimacograptus tangyensis* Ge was recently collected from the same part of the *N. gracilis* Zone in the same area (Yichang region) as the original specimens.
13. *Prolasiograptus hubeiensis* was originally described as *Orthograptus hubeiensis* by Ge (1963a, b), based on specimens from the *N. gracilis* Zone at Tangya, Yichang.
14. *Hallograptus mucronatus* and *Reteograptus geinitzianus* are common forms in the *N. gracilis* Zone that also range into the *C. bicornis* Zone elsewhere.
15. *Proclimacograptus angustatus* was reported by Maletz (1997) to range from the *Nicholsonograptus fasciculatus* Zone to *Pseudamplexograptus distichus* Zone in the Oslo region.

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