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The base of the Middle Ordovician in China with special reference to the succession at Hengtang near Jiangshan, Zhejiang Province, southern China

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Extensive work during the last decade has led to the recent decision by the International Subcommission on Ordovician Stratigraphy that the base of the Middle Ordovician Series should be placed at the base of the *Baltoniodus triangularis* Conodont Biozone in the Huanghuachang GSSP (Global Stratotype Section and Point) section near Yichang, Hubei Province, China. A review of the biostratigraphy of successions in many parts of China shows that for various reasons, it is currently difficult to recognize the precise boundary level in many regions, and additional studies are clearly needed. A newly exposed, previously poorly known, condensed section in deeperwater facies at Hengtang near Jiangshan in the Chiangnan (Jiangnan) belt has yielded a substantial number of important graptolites and conodonts through the boundary interval. It provides a more informative illustration of the relations between the ranges of several key taxa of these groups than any other section in China, and the level of the base of the Middle Ordovician appears to be within an about 1.8 m thick interval of Ningkuo Formation, and lies in the lower *Isograptus caduceus imitatus* Biozone. □ *Biostratigraphy*, *China*, *conodonts*, *graptolites*, *Middle Ordovician*.

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During the last decade, much international work has been carried out with the goal of establishing globally recognizable series and stages in the Ordovician System. The marked provincial differentiation of Ordovician faunas (Jaanusson 1979) has caused this work to be more difficult than was envisioned when several working groups were established in the mid-1990s (Webby 1994). The International Subcommission on Ordovician Stratigraphy (ISOS) decided in 1995 that the Ordovician should be subdivided into three series, the Lower, Middle and Upper Ordovician series. It was also proposed (Webby 1994) that the base of the Middle Ordovician Series should be defined as the level of first occurrence of the conodont *Tripodus laevis*. In terms of graptolite biozones, this level was considered to be somewhere within the *Isograptus victoriae lunatus* Biozone (Finney & Ethington 1995). This horizon was regarded as close to, if not coeval with, the base of the Volkhovian Stage in Baltoscandia and was characterized as an 'extraordinary reference level for global correlation' by Bergström (1995). Unfortunately, further studies suggested that there are serious problems with both the appearance level of *T. laevis* and the graptolite biostratigraphy in the Whiterock Canyon section in Nevada that had been proposed as the candidate section for the Middle Ordovician Series GSSP (Global Stratotype Section and Point) (Mitchell 2001). These problems made the Whiterock Canyon section unsuitable as a GSSP, and subsequently, two other sections, the Huanghuachang section on the Yangtze platform (Wang *et al.* 2005) and the Niquivil section in the Argentine Precordillera (Albanesi *et al.* 2003, 2006), were proposed as GSSP candidate sections for this series boundary. After considerable discussion of the merits of each of these sections, the Huanghuachang section was selected as the GSSP in 2006 based on its approval by a large majority of the votes by the Subcommission members in a formal vote by the ISOS.

In the Huanghuachang section, the GSSP level is the first appearance datum (FAD) of the conodont *Baltoniodus triangularis* as was proposed by Wang *et al.* (2005). This level coincides with the FAD of *Periodon* sp. A and is just below the FAD of *Microzarkodina flabellum*. It is also well above the local base of the *Azygograptus suecicus* Graptolite Biozone of Wang *et al.* (2005). Hence, it is near the level advocated by Li *et al.* (2002), Zhang & Chen

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(2003) and Chen *et al.* (2003a), namely that the base of the Middle Ordovician should be near the base of the '*A. suecicus* Biozone' in the Yangtze region or within that biozone. When referring to this biozone in the Yangtze region, we use quotation marks ('*A. suecicus* Biozone') because as shown in succeeding discussions, the range of this biozone is markedly different between the Yangtze region and its typical development in the Chiangnan (Jiangnan) region. The precise level of the base of the *B. triangularis* Biozone in terms of the international graptolite zonal classification is not yet firmly established. However, the conodont-graptolite biozone relations in Scandinavia (cf. Maletz 2005) suggest that this horizon is very close to, if not the same as, the base of the *I. victoriae victoriae* Biozone.

In China, the subdivision and correlation of the Lower and Middle Ordovician have been one of the research foci of Chinese Ordovician stratigraphers. A review of the biostratigraphy of the interval around the base of the global Middle Ordovician Series in the vast territory of China is particularly relevant at this time in view of the recent formal selection of a GSSP for this level in China. Moreover, much of the pertinent information about this stratigraphic interval is in Chinese and/or in publications not readily available outside China. The interval across the proposed GSSP level is developed in apparently stratigraphically continuous carbonate facies successions on three major palaeoplates, the Tarim, North China, and Tibet palaeoplates (Chen & Rong 1992). The relevant stratigraphy in each of these regions, along with that in some other areas, is briefly reviewed in the first part of this paper. The last part of the paper focuses on South China, especially a new and particularly important section at Hengtang, Jiangshan, in Zhejiang Province.

Regional review

Tarim

In western Tarim, the succession from the Lower Ordovician to the lower part of the Middle Ordovician is mainly developed in shallow-water, in many cases dolomitic, limestones that are assigned to the Qiulitag Group. Previously, the base of the Middle Ordovician has been taken to be the base of the *Aurilobus leptosomas-Loxodus dissectus* Biozone (Zhao *et al.* 2000) at Bachu (Fig. 1, loc. 3) on the western edge of the Tarim platform. This level is below their *Paroistodus originalis* Biozone and well above the characteristic *Serratognathus diversus* Biozone that is generally correlated with the *Paroistodus proteus* Biozone in Baltoscandia. However, recent work (Wang & Zhou 1998; Wang & Qi 2001; Wang *et al.* 2007) shows that the interval containing *S. diversus* is overlain by strata containing the *Scolopodus*? *tarimensis* fauna that is currently difficult to place precisely in the detailed conodont biozone scheme in South China (An 1987), Baltoscandia (Lindström 1971), and North America (Ethington & Clark 1982). The base of the global Middle Ordovician Series is likely to be within the upper part of the Upper Qiulitag Group, but further studies are needed to pinpoint its precise position. Unfortunately, conodonts are sparse in that shallow-water carbonate interval, and those available are not very useful for long-distance correlations. Furthermore, based on the available biostratigraphic evidence, it cannot be excluded that a significant stratigraphic gap separates the Upper Qiulitag Group from the overlying Yijianfang Formation, which is at least partly of Darriwilian age (Wang *et al.* 2007).

At Dawangou, Kalpin (Fig. 1, loc. 2), on the western slope of the Tarim Platform, the boundary is within the interval between the *Paroistodus proteus* Conodont Biozone and *Baltoniodus* aff. *navis* Conodont Biozone (Wang Zhi-hao in Zhou *et al.* 1990). No graptolites have been recovered from the Qiulitag carbonate successions. In the Wuligezitag area in eastern Tarim (Fig. 1, loc. 4), the boundary between the Lower and Middle Ordovician appears to correspond to the base of the *Periodon flabellum – Baltoniodus*? *triangularis* Conodont Biozone in the Xiangguletag Formation (Zhao *et al.* 2000) that consists of shallow-water limestone. In the deeper-water facies belt, as represented by the Heituao Formation in the Queerqueke area (Fig. 1, loc. 5), this boundary may be within the *Expansograptus abnormis* Graptolite Biozone (Zhong & Hao 1990). Establishing the precise level of the base of the Middle Ordovician clearly requires further study, but this biozonal index graptolite, although being an endemic species for China, is common in the *A. suecicus* Graptolite Biozone in the southern part of this country including the Chiangnan transitional belt. However, the detailed stratigraphic distribution of the key conodonts and graptolites now used for the definition of the base of the Middle Ordovician have not yet been completely described in either the shallow or deep-water facies of Tarim. We hope that further studies will fill this gap in our knowledge about the geology of one of the most important Ordovician areas in China.

North China

The areas so far investigated on the North China palaeoplate include mainly the North China platform and its western mobile belt. The Tremadocian to Sandbian strata are mainly carbonate deposits with

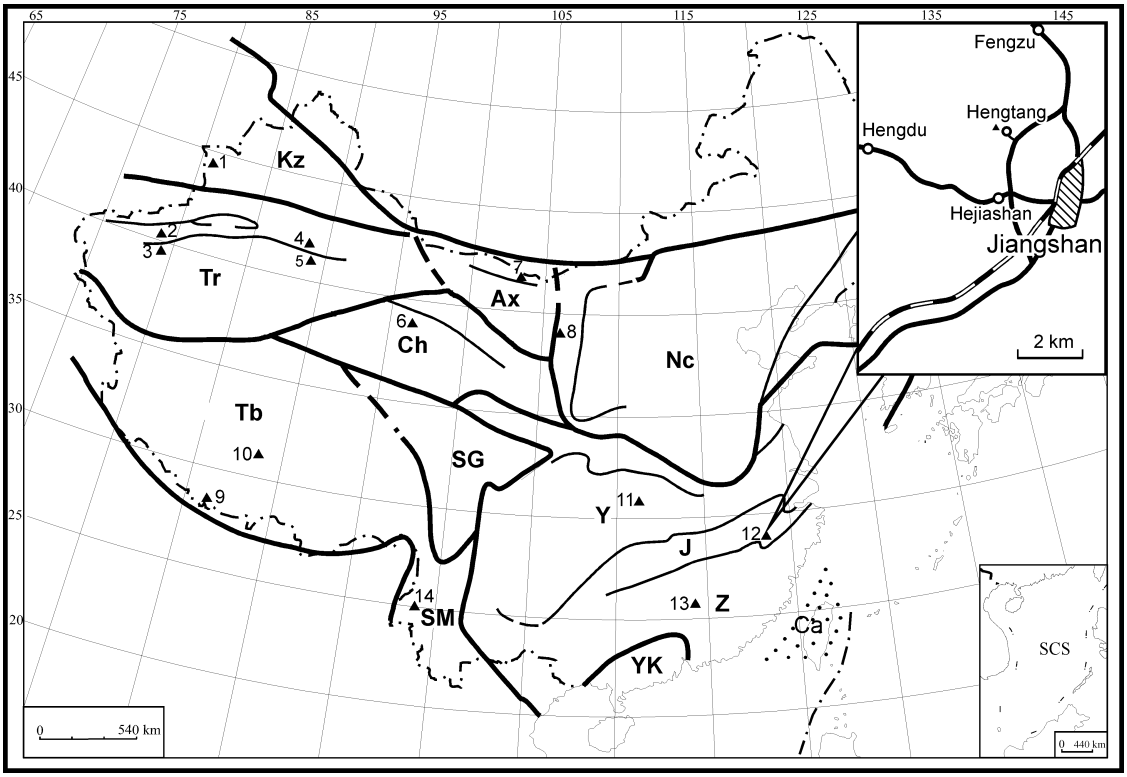

Fig. 1. Index map of important Ordovician localities and tectonic units of China. Numbers refer to localities discussed in the text. Abbreviations of tectonic units: Ax, Alxa; Ca, Cathaysian Land; Ch, Qaidam; J, Jiangnan (South China); Kz, Kazakhstan; Nc, North China; SCS, South China Sea; SG, Songpan-Ganzi; SM, Sibumasu; Tb, Tibet; Tr, Tarim; Y, Yangtze (South China); YK, Yunkai; Z, Zhujiang (South China).

many endemic conodonts and shelly faunas that are uniformly distributed across the North China platform. Graptolites are very rare and include mainly Tremadocian dendrograptid and anisograptid taxa. The base of the Middle Ordovician in this vast region may be within the interval of the conodont *Aurilobodus leptosomatus-L. dissectus* Biozone and *Tangshanodus tangshanensis* Biozone in the Lower Machiakou (= Beianzhuang) Formation (An *et al.* 1983). It should be noted that the key conodont *B. triangularis* has not yet been recorded from the North China platform.

In the western mobile belt of the North China Palaeoplate (Fig. 1, loc. 8), the *A. leptosomatus-L. dissectus* Conodont Biozone has been recognized in the Sandaokan and lower part of the Zhuozishan formations at Zhouzishan, and in the Zhongliangsi Formation in Helanshan (An & Zheng 1990). Yet, the precise position of the base of the global Middle Ordovician is currently not yet established in this region.

Tibet

Lower–Middle Ordovician carbonate deposits (lower Chaitsun Formation) have been identified in Nyalam (Fig. 1, loc. 9) in Southern Tibet (Mu *et al.* 1973). Conodonts and graptolites have not yet been recorded from that area, and the shelly fossils reported, which are mainly nautiloids, brachiopods, trilobites and gastropods, are not useful for determining the level of the base of the Middle Ordovician. In the Xainza area of north-central Tibet (Fig. 1, loc. 10), Lower to Middle Ordovician strata have not yet been recognized (Chen *et al.* 1986).

Western China

In western China, graptolites through the Lower–Middle Ordovician interval have been recorded from the eastern Kazakhstan, Chaidam and Alxa palaeoplates or palaeoblocks. At Guozigou, Huocheng (Fig. 1, loc. 1), in western Xinjiang on the eastern Kazakhstan palaeoplate, *Isograptus victoriae maximus* Harris has been identified in the Xinertai Formation (Chen *et al.* 1998) but unfortunately, there is no known continuous graptolite sequence between the *I. victoriae maximus* Biozone and the underlying *Pendeograptus fruticosus* Biozone. From the top of the Duoquanshan Formation to the base of the Shihuigou Formation at Oulongbuluke on the Chaidam palaeoplate (Fig. 1, loc. 6), Mu *et al.* (1960) described *Isograptus victoriae maximodivergens*

Harris and *I. victoriae divergens* in strata referred to the upper *Expansograptus hirundo* Biozone. Early subspecies of the *I. victoriae* group are apparently absent, probably because of unfavourable lithologies in the pre-*I. victoriae divergens* interval.

From the Woboer Formation at Hangwula on the northern margin of the Alxa block (Fig. 1, loc. 7), Ge *et al.* (l990) recorded taxa of the *I. victoriae* species group, including *I. victoriae divergens* Harris, *I. victoriae maximus* Harris, *I. victoriae maximodivergens* Harris, and *I. imitatus* Harris but, unfortunately, the collections are only from a single locality and are not in stratigraphical order. However, the northern margin of the Alxa block is a promising area for solving problems in Lower–Middle Ordovician boundary correlations in graptolite facies. In the Baoshan area of western Yunnan (Fig. 1, loc. 14), on the Sibumasu palaeoplate (Chen *et al.* 1995a), Zhang (1962) recorded *Undulograptus austrodentatus* (Harris & Keble), but taxa of the *I. victoriae* group have not yet been reported from the subjacent strata in that region.

South China

Compared with the regions just discussed, the sections on the South China palaeoplate have greater potential for establishing the position of the global Lower–Middle Ordovician boundary because both graptolites and conodonts have been described from many successions in this region. The South China palaeoplate includes three parts: the Yangtze platform, the Zhujiang basin and the Chiangnan transitional belt in between (Chen & Rong 1992).

Yangtze platform. – A Lower and Middle Ordovician graptolite zonal succession for South China was defined by Chen (in Zhang *et al.* 1964) and later by Mu *et al.* (1979). Extensive graptolite and conodont investigations have been carried out in recent years on the Lower and Middle Ordovician carbonate succession in the Yangtze region (Wang *et al.* 1987, 2003a,b, 2005; Wang 1993; Zhang 1998, etc.). Of particular importance for the definition of the base of the global Middle Ordovician Series are recent studies on conodonts (Wang *et al.* 2003a,b, 2005) and graptolites (Zhang & Chen 2003). Based on very detailed sampling in the lower Dawan Formation in the classic section at Huanghuachang, Wang *et al.* (2003a,b, 2005) recorded the key index conodont *B. triangularis* along with a diverse association of other condonts. Stouge (*in* Tongiorgi *et al.* 2003) suggested that the base of the Baltoscandian *B. triangularis* Biozone correlated with the base of the *B. triangularis* Biozone at Yichang on the Yangtze platform. Based on the Huanghuachang section and other exposures, Wang *et al.* (2005) subdivided the *Oepikodus evae* Biozone into two parts: a lower part containing *Oepikodus evae* and an upper part characterized by *Oe. intermedius* and new species of *Baltoniodus* and *Tripodus*. They placed the base of the *B. triangularis* Biozone at the FAD of typical *B. triangularis*, and this level is now formally ratified as the base of the global Middle Ordovician Series in the Huanghuachang GSSP section.

This level, which is less than 0.2 m below the FAD of *M. flabellum*, can readily be recognized in the Baltoscandian, Argentinian and Laurentian successions. It is about 5 m above the top of the local range of the graptolite *Didymograptellus bifidus* in the stratigraphically rather condensed Huanghuachang succession. The associated graptolite assemblage, which is referred to the '*A. suecicus* Biozone', includes, among others, *Azygograptus suecicus*, *A. eivionicus*, *A. ellesi*, *Expansograptus* cf. *suecicus*, *Phyllograptus anna*, *Tetragraptus reclinatus reclinatus* and *Xiphograptus svalbardensis*. *Azygograptus eivionicus* is previously recorded from the *Pseudophyllograptus angustifolius elongatus* Biozone and the *E. hirundo* Biozone in Norway (Cooper & Lindholm 1990; Beckly & Maletz 1991) and *X. svalbardensis* was first described from the V3 part of the Olenidsletta Member of Valhallfonna Formation in Spitsbergen (Cooper & Fortey 1982), which corresponds to the *I. victoriae victoriae* Biozone (Ca2) in Australia.

The base of the *B. triangularis* Biozone, which marks the base of the Baltoscandian Volkhovian Stage, is in Sweden correlated with the base of the *E. hirundo* Biozone, the lower part of which contains *I. victoriae victoriae* (Cooper & Lindholm 1990). The Swedish *P. angustifolius elongatus* Biozone, which underlies the *E. hirundo* Biozone, has yielded *I. victoriae lunatus* (Cooper & Lindholm 1990). In a recent paper, Maletz (2005, text-fig. 8) correlated the top of the *P. angustifolius elongatus* Biozone in Scandinavia with the top of the *I. victoriae lunatus* Biozone. The relations between conodont and graptolite biozones in Sweden are consistent with the interpretation that the base of the *B. triangularis* Biozone at Huanghuachang, as well as in Sweden, is approximately equivalent to the top of the *I. victoriae lunatus* Biozone. It should be noted that Chen & Bergström (1995) proposed that the Australian *I. v. lunatus* Biozone and *I. v. victoriae* Biozone may correspond to the *A. suecicus* Biozone as developed in the Chiangnan belt in South China.

A slightly different interpretation was recently presented by Zhang & Chen (2003) and Chen *et al.* (2003a) in a review of the Lower and Middle Ordovician graptolite biostratigraphy in the Upper Yangtze region. They suggested that the base of the Middle Ordovician corresponds to a level within the *A. suecicus* Biozone that they correlated with the base of the *I. victoriae lunatus* Biozone. Because the deeper-water isograptid biofacies is not present in the relatively shallow-water succession in the Yangtze region, this correlation was necessarily indirect. A somewhat different graptolitic biozone interpretation was presented by Wang *et al.* (2005), who placed the base of the '*A. suecicus* Biozone' at Huanghuachang at the FAD of the zonal index, a level that is just above the top of the range of *Oepikodus evae* in the *Oe. evae* Biozone and well below the FAD of *Baltoniodus triangularis*. Because graptolites are scarce in the critical interval in the carbonate-dominated Yangtze succession, and the graptolite species diversity is low, it is difficult to precisely locate the graptolite biozone boundaries.

Zhujiang Basin. – A particularly important graptolite succession is present in the Zhujiang Basin southeast of the Jiangnan belt in South China, where the Ordovician sequence consists of graptolitic flysch or turbiditic deposits (Xiao & Huang 1974; Xiao *et al.* 1975). In this region, representatives of the *I. victoriae* species group were first reported from Guobu in southern Jiangxi (Fig. 1, loc. 13), where the graptolite fauna was recently described by Li *et al.* (2000). Unfortunately, the Guobu section has not yet been continuously and densely collected for graptolites. Li *et al.* (2000) reported, in ascending order, *Isograptus v. lunatus* and *I. divergens* from Bed 8 (25.8 m in thickness), *I. v. lunatus*, *I. divergens* and *I. caduceus imitatus* from Bed 9 (48.8 m in thickness), *I. v. lunatus* and other *Isograptus* species from Bed 10 (38.1 m in thickness) and *I. divergens*, *I. v. maximodivergens* and *I. caduceus imitatus* from Bed 11 (5.3 m in thickness). These species records indicate that *I. v. maximodivergens* occurs higher stratigraphically than the other taxa of the *I. victoriae* species group in the Guobu section, but the Australian biozone succession based on *I. victoriae* subspecies cannot be recognized. It appears that a new study based on closely spaced samples through the Guobu sequence has the potential to solve problems related to the graptolite biostratigraphy around the Lower/Middle Ordovician Series boundary. Unfortunately, conodonts and shelly fossils have not been found, as is also the case in the other sections of this age in the Zhujiang basin.

Chiangnan belt. – Because it has sections containing graptolites, shelly fossils and conodonts, the Chiangnan transitional belt between the Yangtze platform and Zhujiang basin has particular potential for solving biostratigraphic problems related to the global Lower/Middle Ordovician boundary. Sections in the Jiangshan-Changshan-Yushan (JCY) area in this belt near the border between the Zhejiang and Jiangxi provinces (Fig. 1, loc. 12) are especially important (Chen *et al.* 1983, 1995b). Their graptolites and graptolite biostratigraphy have been dealt with by many authors since the 1950s (see Chen & Bergström [eds] 1995). Xiao & Chen (1990) described the graptolites in the Chenjiawu section, Yushan and used endemic species, such as *Oncograptus magnus* and *Cardiograptus amplus*, as biozone index fossils between the *A. suecicus* Biozone and the *Undulograptus austrodentus* Biozone. Chen & Bergström (1995) suggested that these two biozones should be replaced by the *Isograptus caduceus imitatus* Biozone and the *Exigraptus clavus* Biozone, respectively.

Figure 2 summarizes the graptolite and conodont zonations in the different regions discussed herein.

The Hengtang Quarry succession

In the best section in the JCY area, namely the Huangnitang section near Changshan County town, the *I. caduceus imitatus* Biozone is covered but this interval is now well exposed in the Hengtang section and has recently been restudied. The results of this restudy are presented in succeeding discussions.

Hengtang Village is located about 4 km northwest of Jiangshan County town in the JCY area (Fig. 1). As noted by Chen & Bergström (1995), the Hengtang section originally consisted of two parts, the main section on the western side of the Hengtang pond and a shorter section with seven layers of limestone intercalated within the shale about 50 m west of the pond. The former section is now completely covered by a new road and soil infilling.

Recently, a new quarry, here referred to as the Hengtang Quarry (Figs 3, 4), was opened by the Hengtang villagers. This quarry provides a continuous section from the top of the Yinchufu Formation into the *E. clavus* Biozone of the upper Ningkuo Formation. Because the sequence consists of graptolitic black shales intercalated with limestone beds, it has good potential for clarifying the relations between the graptolite and conodont biostratigraphy in this interval. In the spring of 2000, three of us (CX, ZYD and FJX) collected the Hengtang Quarry section layer by layer. Graptolites were identified by the senior author, and the rock samples were subsequently processed and the conodonts identified by SMB, who investigated the locality and made additional collections in March 2006.

Lithostratigraphy

The lower part of the Ningkuo Formation consists of bedded limestone (5.9 m thick), which corresponds to the Huangnitang Member at Huangnitang, Changshan

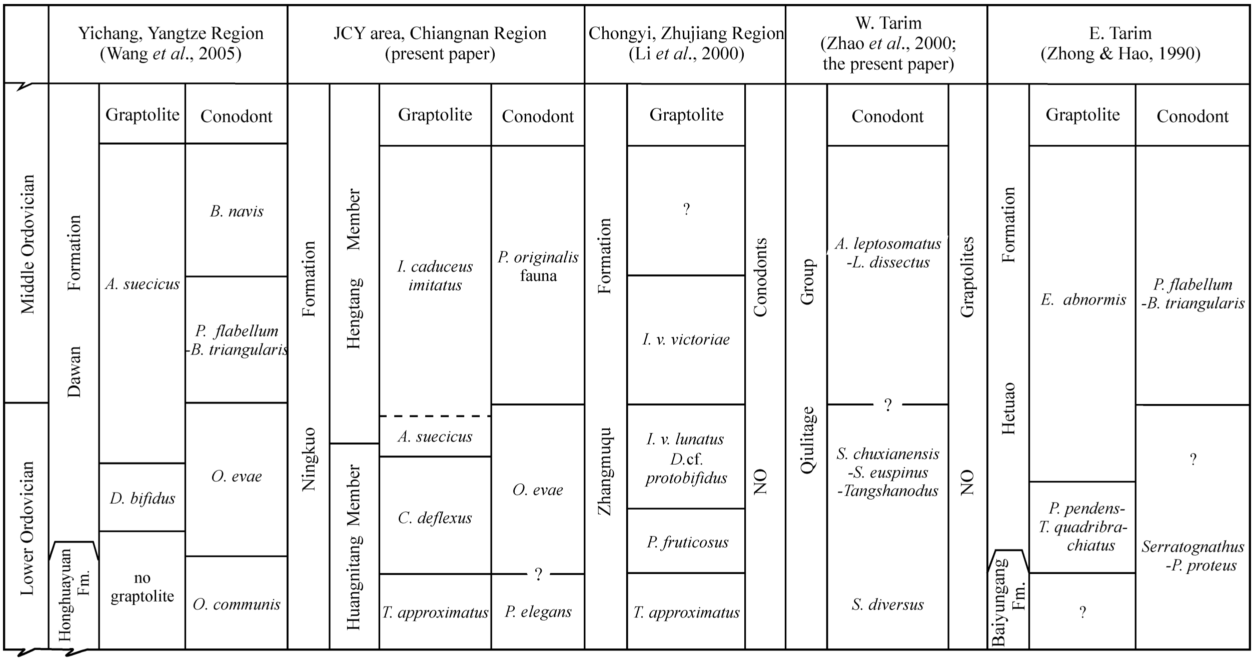

Fig. 2. Correlation of Lower–Middle Ordovician graptolite and conodont biozones in the Chinese regions.

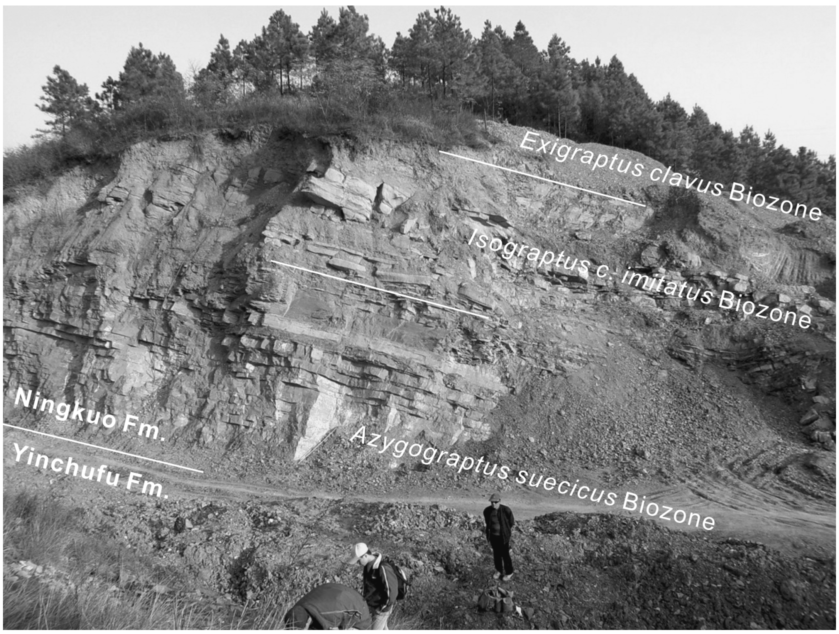

Fig. 3. View of the face of the Hengtang Quarry showing the vertical range of graptolite biozones.

(Chen *et al.* 2003b). The top of the Huangnitang Member corresponds broadly to that at the type locality of the Huangnitang Member, and is near the local base of the *A. suecicus* Biozone.

Lenticular limestone beds are common in the shales below the *E. clavus* Biozone and above the Huangnitang Member of the Ningkuo Formation at Hengtang as well as elsewhere in the JCY area. We suggest that this calcareous and shaly middle part of the Ningkuo Formation is recognized as a new member, the Hengtang Member, with its type locality at the Hengtang Quarry. This member, which differs from the still unnamed upper member of the Ningkuo Formation, mainly consists of graptolite shales with many thin limestone beds. The Hengtang Member is 10.96 m thick in the Hengtang Quarry. Although

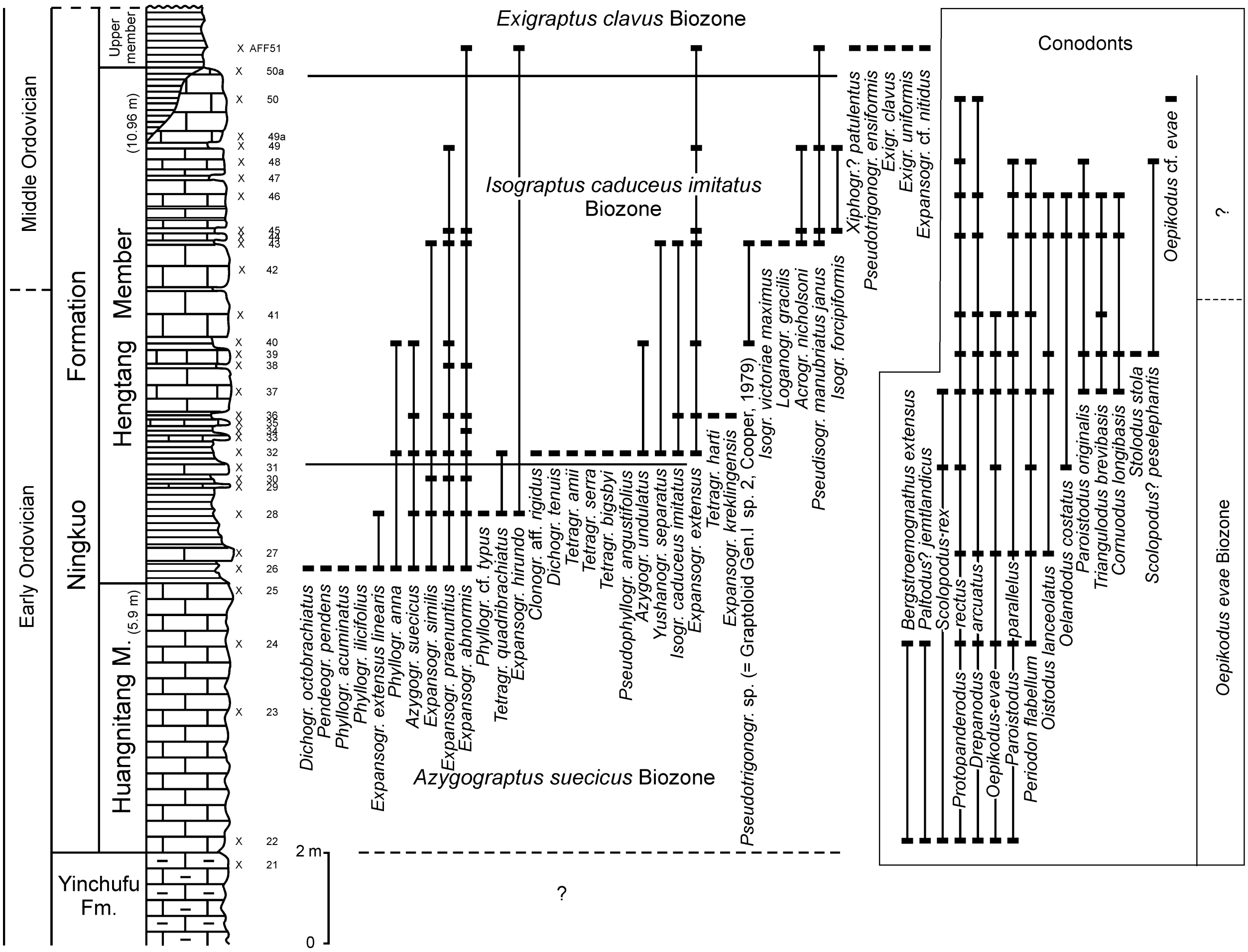

Fig. 4. Range chart of graptolite and conodont species in the Hengtang Quarry section.

the base and the top of this member are possibly diachronous in the JCY area, it has about the same lithological development in the Huangnitang section at Changshan. At Fengzu in Jiangshan, the succession is different in that the member has only one limestone interval, about 5 m thick, and at Chenjiawu, Yushan, there is only one limestone lens in the *I. caduceus imitatus* Biozone.

Graptolite biostratigraphy

In the Hengtang Quarry, the Hengtang Member includes, in ascending order, the *A. suecicus* Biozone and the *I. caduceus imitatus* Biozone. The latter is overlain by the *E. clavus* Biozone, the lowest biozone of the Upper Member of the Ningkuo Formation (Figs 3 and 4).

A total of 36 graptolite species belonging to 16 genera have been identified in the interval from the *A. suecicus* Biozone to the lower part of the *E. clavus* Biozone at the Hengtang Quarry. The ranges of these graptolites, as well as of conodonts, through the Hengtang Member are shown in Fig. 4, and most of the graptolite taxa are illustrated in Figures 5 and 6. Each of the graptolite biozones is discussed separately in succeeding discussions.

The A. suecicus *Biozone.* – Cooper & Lindholm (1990) provided a worldwide correlation of the Lower Ordovician based on a composite graptolite standard sequence assembled from key sections in six major regions with graptolite-bearing rocks. They correlated the '*A. suecicus* Biozone' of the Yangtze region with the middle and upper Castlemainian (Ca2–3) of the Australian standard sequence and assumed the presence of a faunal break corresponding to this biozone in the Zhujiang region. However, their interpretation is likely to have been somewhat different if the data from the JCY area had been published at that time. Chen (1994) recorded the biozonal index *A. suecicus* not only from the Yangtze region but also from the Chiangnan belt. In the new Hengtang collections, there are 13 graptolite species present in the *A. suecicus* Biozone. Seven of these species have

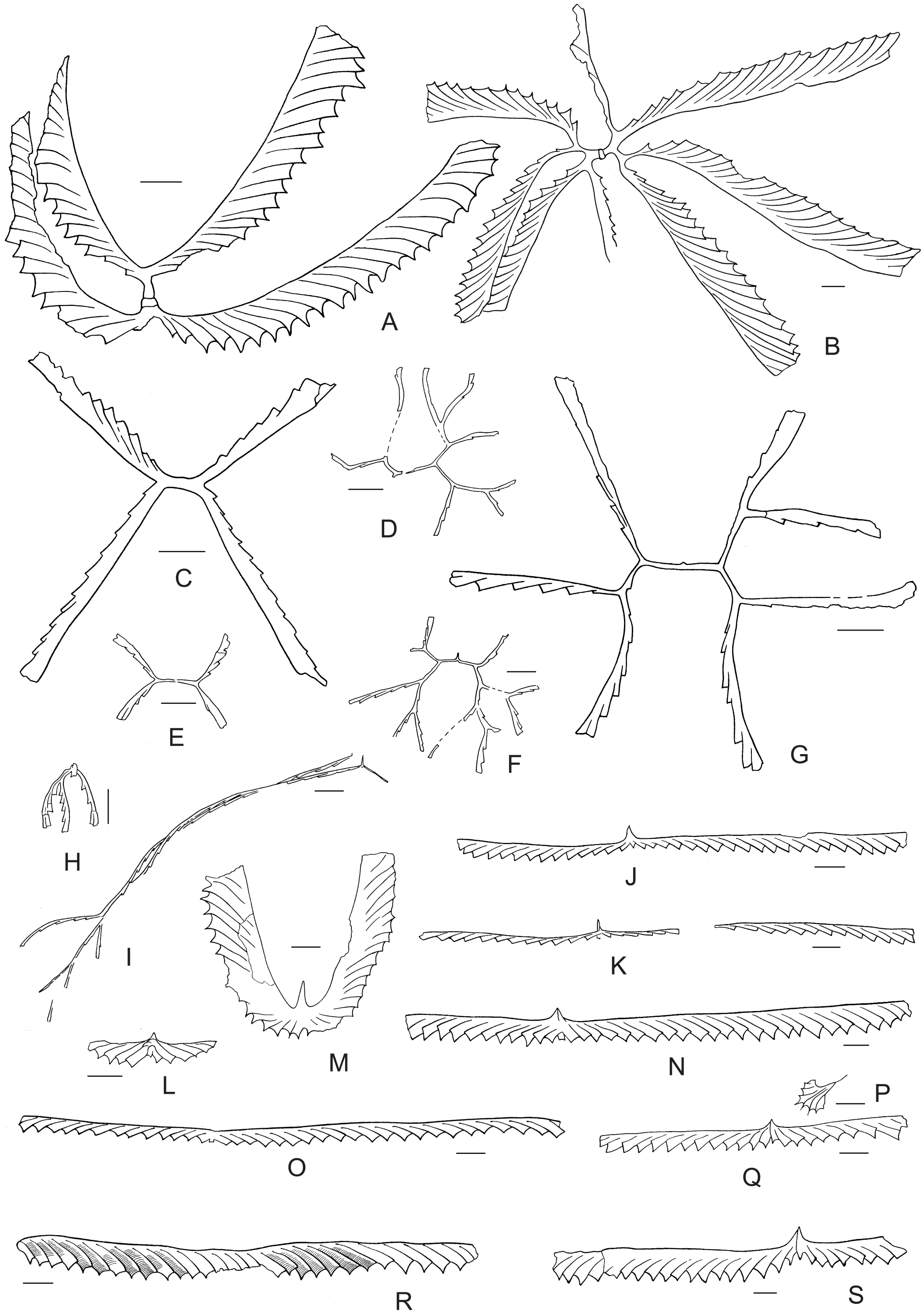

Fig. 5. Some important graptolites from the Hengtang Quarry section. Scale bar corresponds to 1 mm. A. *Tetragraptus amii* Lapworth, 1902. AFF32, NIGP140809, *I. caduceus imitatus* Biozone. B. *Dichograptus octobrachiatus* (Hall 1858). AFF26, NIGP140810, *A. suecicus* Biozone. C. *Tetragraptus quadribrachiatus* (Hall 1858). AFF28, NIGP140811, *A. suecicus* Biozone. D. *L. gracilis* Mu, 1957. AFF43, NIGP140812, *I. caduceus imitatus* Biozone. E. *Tetragraptus harti*, T.S. Hall, 1914. AFF36, NIGP140813, *I. caduceus imitatus* Biozone. F. *Clonograptus* sp. aff. *C. rigidus* (Hall 1858). AFF32, NIGP140814, *I. caduceus imitatus* Biozone. G. *Dichograptus tenuis* Monsen, 1937. AFF32, NIGP140815, *I. caduceus imitatus* Biozone. H. *Pendeograptus pendens* (Elles 1898). AFF26, NIGP140816, *A. suecicus* Biozone. I. *Yushanograptus separatus* Chen, Han and Sun, 1964. AFF32, NIGP140817, *I. caduceus imitatus* Biozone. J. *Expansograptus* cf. *nitidus* (Hall 1858). AFF51, NIGP140818, base of the *E. clavus* Biozone. K. *Expansograptus* sp. AFF36, NIGP140819, *I. caduceus imitatus* Biozone. L. *E. abnormis* (Hsu 1934). AFF26, NIGP140820, *A. suecicus* Biozone. M. *I. victoriae maximus* Harris, 1933. AFF43, NIGP140821, *I. caduceus imitatus* Biozone. N. *Expansograptus praenuntius* (Törnquist 1901). AFF26, NIGP140822, *A. suecicus* Biozone. O. *Expansograptus extensus linearis* (Monsen 1937). AFF26, NIGP140823, *A. suecicus* Biozone. P. *P. manubriatus janus* Cooper and Ni. AFF43, NIGP140824, *I. caduceus imitatus* Biozone. Q. *Expansograptus extensus similis* (Hall 1865). AFF43, NIGP140825, *I. caduceus imitatus* Biozone. R. *Expansograptus* sp. cf. *E. hirundo* (Salter 1863). AFF28, *A. suecicus* Biozone. S. *Expansograptus patulentus* Chen. AFF51, NIGP140827, base of the *E. clavus* Biozone.

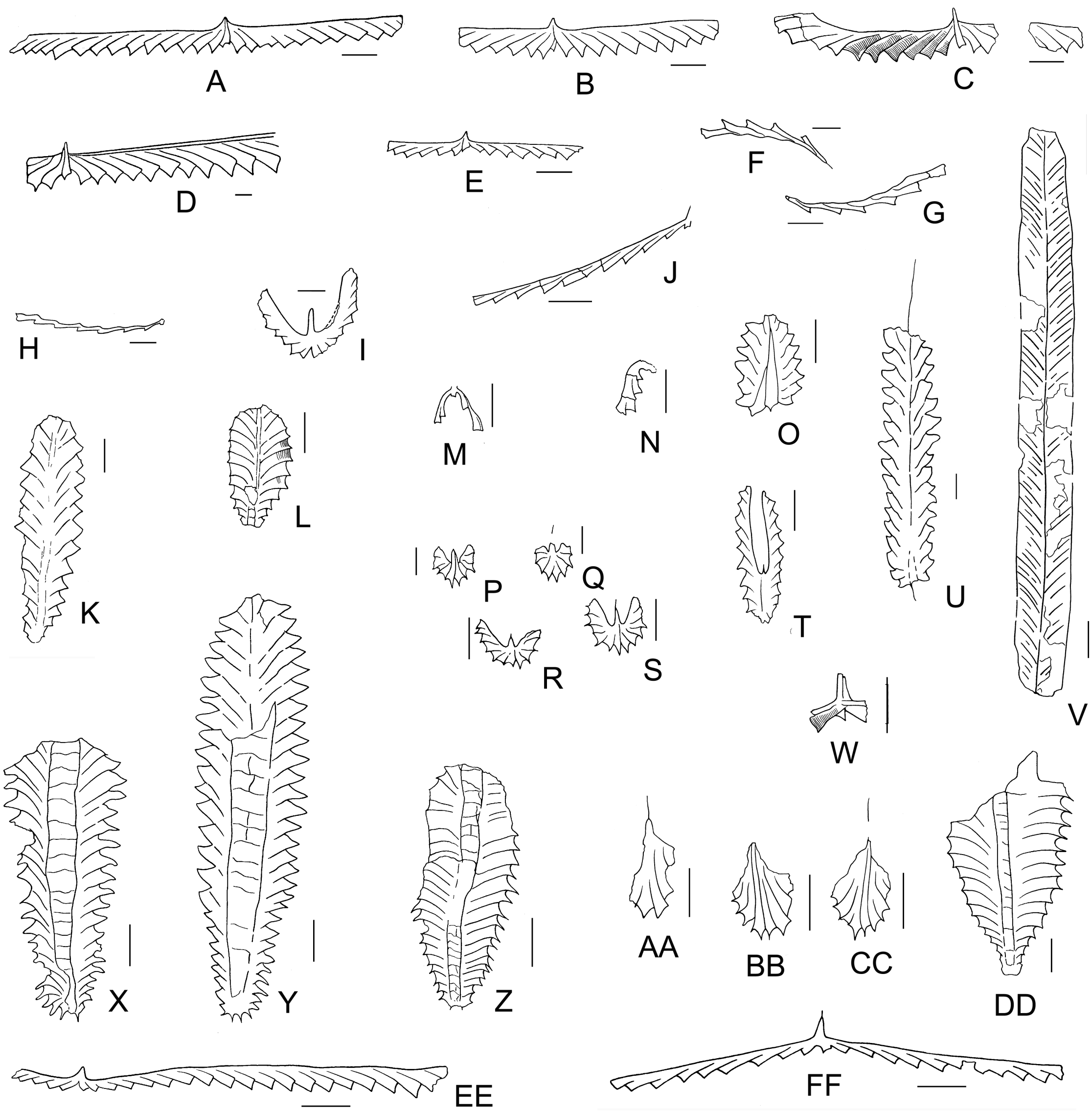

Fig. 6. Some important graptolites from the Hengtang Quarry section. Scale bar corresponds to 1 mm. A. *Expansograptus extensus similis* (Hall, 1865). AFF26, NIGP140828, *Azygograptus suecicus* Biozone. B. *E. abnormis* (Hsu 1934). AFF28, NIGP140829, *A. suecicus* Biozone. C, D. *Expansograptus praenuntius* (Törnquist, 1901). AFF36, 32, NIGP140830, 140831, *I. caduceus imitatus* Biozone. E. *Expansograptus extensus* (Hall, 1858). AFF43, NIGP140832, *I. caduceus imitatus* Biozone. F, G, H. *Azygograptus undulatus* (Chen and Xia 1979). AFF40, 32, NIGP140833, 140834, 140835, *I. caduceus imitatus* Biozone. I. *I. caduceus imitatus* Harris, 1933. AFF36, NIGP140836, *I. caduceus imitatus* Biozone. J. *Azygograptus suecicus* (Moberg 1892). AFF26, NIGP140837, *A. suecicus* Biozone. K. *Pseudotrigonograptus* sp. (= Graptoloid gen. 1, sp. 2, Cooper 1979). AFF43, NIGP140838, *I. caduceus imitatus* Biozone. L. *Phyllograptus anna* Hall 1865. AFF32, NIGP140839, *I. caduceus imitatus* Biozone. M. *Didymograptellus* sp. AFF30, NIGP140840, *A. suecicus* Biozone. N. Corymbograptid. AFF28, NIGP140841, *A. suecicus Biozone.* O. *E. clavus* Mu, 1979. AFF51, NIGP140842, base of the *E. clavus* Biozone. P–S. *I. caduceus imitatus* Harris 1933. AFF36, 43, NIGP140843, 140844, 140845, 140846, *I. caduceus imitatus* Biozone. T. *I. forcipiformis* (Ruedemann 1904). AFF49, NIGP140847, *I. caduceus imitatus* Biozone. U. *E. uniformis* Mu 1979. AFF51, NIGP140848, base of the *E. clavus* Biozone. V. *P. ensiformis* (Hall 1858). AFF51, NIGP140849, base of the *E. clavus* Biozone. W. Isograptid development type in *extensus* species group of expansograptid. AFF28, NIGP140850, *A. suecicus* Biozone. X, Y. *P. angustifolius* (Hall 1858). AFF32, NIGP140851, 140852, *I. caduceus imitatus* Biozone. Z. *P. acuminatus* Chen and Xia. AFF26, NIGP140853, *A. suecicus* Biozone. AA, BB, CC. *P. manubriatus janus* Cooper and Ni. AFF43, NIGP140854, 140855, 140856, *I. caduceus imitatus* Biozone. DD. *Phyllograptus* sp. cf. *P. typus* Hall, 1858. AFF28, NIGP140857, *A. suecicus* Biozone. EE. *Expansograptus kreklingensis* (Monsen 1936). AFF36, NIGP140858, *I. caduceus imitatus* Biozone. FF. *A. nicholsoni* (Lapworth 1875). AFF43, NIGP140859, *I. caduceus imitatus* Biozone.

been recorded in Australia, including *Dichograptus octobrachiatus*, *Expansograptus similis*, *Pendeograptus pendens*, *Phyllograptus anna*, *P. ilicifolius*, *P.* cf. *typus* and *Tetragraptus quadribrachiatus*. All these forms have a FAD that is lower than the Castlemainian and the last appearance of *E. similis*, *P. ilicifolius*, *P. pendens* and *P. typus* is in the upper Chewtonian (Ch2). Four other Hengtang species, *A. suecicus*, *Expansograptus* *extensus linearis*, *E. hirundo* and *E. prenuntius*, were recorded from the *P. densus* Biozone to the *P. angustifolius elongatus* Biozone interval in the Tøyen Formation (formerly Lower *Didymograptus* Shale) in the Oslo region, Norway (Monsen 1937). Cooper & Lindholm (1990) correlated the latter two biozones with the uppermost Bendigonian (Be4) to lower Castlemainian (Ca1) interval in Australia. Although the ranges of the species listed previously do not allow a precise correlation of the Hengtang *A. suecicus* Biozone with a narrow interval in the Australian graptolite succession, they do suggest that the base of the *A. suecicus* Biozone is stratigraphically lower than suggested by Cooper & Lindholm (1990). It seems now more reasonable to consider the base of this biozone to be coeval with a level below the base of the *I. victoriae lunatus* Biozone (Ca1). This is in good agreement with the age provided by the conodonts. The *Corymbograptus deflexus* Biozone and the *Tetragraptus approximatus* Biozone below the *A. suecicus* Biozone are well developed in the JCY area (Chen *et al.* 1983, 2003b).

Among the remaining taxa in the *A. suecicus* Biozone, two species are endemic for South China, namely *E. abnormis* Hsu, 1934 and *Phyllograptus acuminatus* Chen and Xia (*in* Mu *et al.* 1979). The former is present in the *E. abnormis* Biozone in the Chiangnan belt, which is a biozone equivalent to the *A. suecicus* Biozone, whereas the latter occurs in the Yangtze region in an interval from the *C. deflexus* Biozone to the '*A. suecicus* Biozone' (Mu *et al.* 1979). Finally, a corymbograptid and *Didymograptellus* sp., which occur near the top of the *A. suecicus* Biozone at Hengtang, might be the youngest representatives of corymbograptids and *Didymograptellus* in the JCY region.

The I. caduceus imitatus *Biozone.* – Twenty-five graptolite species belonging to 13 genera are present in this biozone at Hengtang. The base of the biozone is marked by the appearance of the biozonal index. Present from the base of the biozone are also *Clonograptus* sp. aff. *C. rigidus*, *Dichograptus tenuis*, *Expansograptus extensus*, *Azygograptus undulatus*, *P. angustifolius*, *Tetragraptus amii*, *T. bigsbyi*, *T. serra*, and *Yushanograptus separatus*. Except *I. caduceus imitatus*, *Azygograptus undulatus*, and *Yushanograptus separatus*, these species have been recorded from older stratigraphical intervals in Australia and Norway, and the marked faunal change between sample levels 31 and 32 shown in Figure 4 may reflect biofacies control rather than a case of global faunal turnover. Two other graptolites, *Expansograptus kreklingensis* and *Tetragraptus harti*, which occur in the lower part of the biozone, are known from older beds at other localities. Five species that occur in the middle-upper part of this biozone include *I. victoriae maximus*, *Acrograptus nicholsoni*, *Isograptus forcipiformis*, *Loganograptus gracilis* and *Pseudisograptus manubriatus janus*. *I. forcipiformis* and *P. m. janus* have been recorded from younger strata in the Darriwilian and Yapeenian, respectively in Australia (VandenBerg & Cooper 1992). However, the co-occurrence of *I. caduceus imitatus* and *I. victoriae maximus* in the present biozone indicates a late Castlemainian (Ca3) age. In our interpretation, most of the *I. caduceus imitatus* Biozone corresponds to Ca3 and Ca4 in the Australian sequence.

The E. clavus *Biozone.* – Only the basal part of the *E. clavus* Biozone is currently exposed in the topmost part of the Hengtang Quarry section. Nine species, apart from the biozonal index, have been collected from this biozone, namely *Expansograptus nitidus*, *Exigraptus uniformis*, *Pseudotrigonograptus ensiformis*, and *Xiphograptus*? *patulentus*. Mitchell & Chen (1995) concluded that the *E. clavus* Biozone may be correlated with the Australian Yapeenian.

Conodont biostratigraphy

Previous work and new collections. – Conodonts have previously been recorded from an approximately 11 m thick stratigraphic interval in the Ningkuo Formation in the ditch section about 50 m east of the Hengtang Quarry (Wang & Bergström 1995). The precise relations between this sequence and that now exposed in the quarry is difficult to determine but the ditch section, which is now destroyed by infilling, appears to have corresponded to the lower–middle portion of the Hengtang Member and the uppermost *A. suecicus* Biozone and lower *I. caduceus imitatus* Biozone. The seven collections studied by Wang & Bergström (1995) included a total of 12 species that were interpreted to represent the uppermost *Oepikodus evae* Biozone and the lowermost *P. originalis* Biozone. Although the fauna was of low diversity, the stratigraphically lowest three samples contained the biozonal index *Oepikodus evae*. The top of the *Oe. evae* Biozone was placed just above the level of the highest occurrence of this species and of *Bergstroemognathus extensus* (Wang & Bergström 1995, fig. 10).

During the detailed graptolite investigation of the new exposure in the Hengtang Quarry 11 conodont samples were collected from selected limestone interbeds through the Ningkuo Formation (Fig. 4). After standard acetic acid laboratory treatment, these samples produced many conodont elements. Their state of preservation ranges from mediocre to good but most specimens are broken. They show a CAI (Conodont Coloration Alteration Index) of 4–5 indicating a heating of 200–300 °C (Rejebian *et al.* 1987).

Conodont biozones. – The lower 10 m of the Ningkou Formation (including the Huangnitang Member and the lower Hengtang Member) in the quarry section) is characterized by a species association (Fig. 4) that includes, among others, *B. extensus*, *Oe. evae*, and *Pe. flabellum* that is diagnostic of the *Oe. evae* Biozone. This species association most probably represents the lower part of this biozone as suggested by the fact that similar species associations are present in that interval in, for instance, the lower to middle part of the *Oe. evae* Biozone in the lower Dawan Formation at the Huanghuachang GSSP section on the Yangtze Platform (Wang *et al.* 2005), the San Juan Limestone of the Argentine Precordillera (Albanesi 1988) and the Cow Head Group of western Newfoundland (Stouge & Bagnoli 1988). That *B. extensus* does not range into the very uppermost *Oe. evae* Biozone in most described sections, including the Huanghuachang GSSP section (Wang *et al.* 2005), and is already absent below the disappearance of *Oe. evae* in the Hengtang succession may be taken as an indication that this interval does not represent the highest part of the *Oe. evae* Biozone. *Oepikodus evae* is well represented in sample AFF 41, which represents a level at about 5.2 m above the base of the Hengtang Member. The conodont fauna in the next higher interval up to the level of sample AFF 46 is virtually the same as in sample AFF 41 although *Oe. evae* has not been found. A single, poorly preserved, conodont element of *Oepikodus* found in the sample AFF 50 appears to be closely similar to a Pa element of *Oe. evae* but its mediocre preservation precludes firm identification, and it may well have been redeposited. It is here referred to as *Oepikodus* cf. *evae*. In the Precordillera of Argentina and in Baltoscandia (Löfgren 1994), *Oe. evae* is missing in the very uppermost *Oe. evae* Biozone at most localities, and in this interval in the Precordillera and on the Yangtze Platform, it is replaced by its likely descendant, the closely similar *Oepikodus intermedius* (Serpagli 1974; Albanesi 1988). In the Precordillera, the latter species serves as an index of a separate biozone, the *Oe. intermedius* Biozone. This species has not yet been found in the Hengtang succession or elsewhere in the Chiangnan belt.

Apart from the single specimens here identified as *Oe.* cf. *evae*, none of the few conodonts recovered from the uppermost part of the Hengtang Member is diagnostic of a particular conodont biozone. Based on the common occurrence of *Oe. evae*, the level of sample AFF 41 is most likely to be within the *Oe. evae* Biozone, and it may well be that the top of this biozone, as it is recognized elsewhere, is just below the level of sample AFF 44. Similar biostratigraphically undiagnostic species associations were referred to the *P. originalis* Biozone by Wang & Bergström (1995). Presumably, the middle part of the Hengtang Member represents either the upper part of the *Oe. evae* Biozone or, more likely, it is coeval with the *M. flabellum-B. triangularis* Biozone, or even a younger interval, on the Yangtze Platform (Wang *et al.* 2005).

Conodont/graptolite zonal relations elsewhere, for instance on western Newfoundland (Bagnoli & Stouge 1997), indicate that the *Oe. evae* Biozone does not extend above the *I. victoriae lunatus* Biozone (Ca1). The graptolites present above the level of sample AFF 44, especially *I. caduceus imitatus*, *I. victoriae maximus* and *I. forcipiformis*, indicate an age not older than the *I. victoriae maximus* Biozone (Ca3) in the Australian succession. Although no index fossils of the *I. v. victoriae* Biozone have been recovered, both conodonts and graptolites suggest that the base of the Middle Ordovician, as taken as the base of the *I. victoriae victoriae* Biozone and the base of the *B. triangularis* Biozone, is likely to be within the approximately 1.8 m thick interval between the last occurrence of firmly identified *Oe. evae* in sample AFF 41 and the first occurrence of *I. victoriae maximus* in sample AFF 44. In view of the fact, this interval would include equivalents of at least the *I. v. victoriae* Biozone and possibly also a part of the *I. v. lunatus* Biozone, as well as the *Oe. intermedius* Biozone and the *B. triangularis* Biozone, as these biozones are developed in the Yangtze platform, it cannot be excluded that there is a stratigraphic gap between the levels of samples AFF 41 and AFF 44. A search for lithological evidence of such a gap in the quarry succession was unsuccessful in 2006. An alternative interpretation would be that *Oe. evae* extends slightly higher stratigraphically in the Hengtang Quarry section than it has been recorded elsewhere; if so, the base of the Middle Ordovician would be slightly lower stratigraphically.

A comparison between the graptolite and conodont biozone successions shows that the top of the *Oe. evae* Biozone is in the lower to middle part of the *I. caduceus imitatus* Biozone at Hengtang whereas it is near the middle of the '*A. suecicus* Biozone' as this biozone is currently recognized at Huanghuachang (Wang *et al.* 2005). This suggests that the stratigraphic range of the '*A. suecicus* Biozone' on the Yangtze Platform is not the same as the *A. suecicus* Biozone in the Chiangnan belt.

Concluding remarks

A current and important area of Ordovician biostratigraphic research is the correlation of the base of the global Middle Ordovician Series that is now defined at the base of the *B. triangularis* Conodont

Biozone. This level is close to, if not the same as, the base of the Pacific Realm *I. victoriae victoriae* Graptolite Biozone, and the base of the North European *E. hirundo* Graptolite Biozone. As shown by this brief review of the biostratigraphy of sections through the Lower–Middle Ordovician boundary interval in various parts of China, this boundary level currently cannot be recognized with a great deal of precision in many regions. In most cases, this is probably because of the current lack of detailed studies in these areas but it is likely that the key conodonts and graptolites are not present in the successions in some regions, and hence, the boundary level must be recognized using other taxa. The boundary level can be best defined on the Yangtze platform, especially in the proposed GSSP section at Huanghuachang near Yichang, where, however, graptolites are scarce. The best Chinese graptolite-bearing sections are those in the deeper-water successions in southern China but because well-documented sequences with both conodonts and the key index species of the *I. v. lunatus* Biozone and the *I. v. victoriae* Biozones (C1–C2) are virtually unknown, the precise level of the base of the Middle Ordovician is currently also difficult to recognize in that region. A recent exposure of a stratigraphically condensed succession through the Ningkuo Formation at Hengtang near Jiangshan in the Zhejiang Province has an excellent graptolite and a relatively good sequence of conodont species within the series boundary interval. The Floian–Dapingian Stage boundary, which marks the base of the Middle Ordovician, appears to be within an about 1.8 m thick interval within which biostratigraphically diagnostic taxa have not been found. Nevertheless, the Hengtang succession provides an unusual illustration of the direct relations between the ranges of several biostratigraphically useful conodonts and graptolites and it is therefore of considerable interest for global correlation of the base of the Middle Ordovician Series.

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