Sinian-Cambrian stratigraphic framework for shallow- to deep-water environments of the Yangtze Platform: an integrated approach*

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Abstract The Sinian (Terminal Proterozoic) and Early Cambrian shallow- to deep-water sequences of the Yangtze Platform were investigated. Based on integrated lithostratigraphic, biostratigraphic, and other approaches, the shallow-water sequence from the base of the Sinian (base of the Doushantuo Formation) to the top of the Qiongzhusian (top of the Yu'anshan Formation) was subdivided into 12 stratigraphic intervals. These 12 intervals were applied in turn to the subdivision and correlation of the sequences present in various facies of the Yangtze Platform. The high-resolution stratigraphic framework here developed can serve as a time frame for ongoing multidisciplinary analyses of the "Cambrian explosion".

Keywords: Neoproterozoic, Sinian, Cambrian, stratigraphy, Cambrian Explosion, Yangtze Platform.

Recent paleontological investigations of the Chengjiang fauna, small shelly fossils (SSF's), and the Weng'an biota have together demonstrated that the Sinian (Terminal Proterozoic)-Cambrian transition interval of the Yangtze Platform (South China) is extremely important for understanding the "Cambrian explosion," a major event in the evolution of life. Sinian-Cambrian sequences ranging in origin from shallow to deep marine are well developed and exposed throughout this region. For this reason, an increasing number of global research programs employing multidisciplinary analyses of this critical geological interval have focused on the Yangtze Platform. However, as on other continents, Sinian-Cambrian fossil material from the Yangtze Platform occurs in sequences developed in a variety of paleoenvironments. Because correlation of these facies has not previously been conducted at fine scales[1,2], the temporal and spatial relationships of these sequences generally are uncertain. Therefore, a high-resolution stratigraphy for the Terminal Proterozoic-Cambrian transitional interval is needed urgently. Despite global stratigraphic studies conducted during the past several decades, subdivision and correlation of the Terminal Proterozoic and Early Cambrian remain unclear[3,4]. Although various biostratigraphic zonations have been proposed (e.g. Acritarch zonations for the Neoproterozoic of Australia[5], SSF zonations for the Early Cambrian of South China[6], and Early Cambrian biozonations of Siberia[7], interbasinal and global correlations of these biozones are few in number and uncertain. Due mainly to low species diversity, taxonomic uncertainty, and sporadic and endemic paleogeographic distributions, the usefulness of biostratigraphic approaches (standard for the Phanerozoic) in developing a global time scale for the Terminal Proterozoic and Early Cambrian is limited. Therefore, other stratigraphic tools must be applied. Based on bio-, litho-, chemo-, sequence, and event stratigraphic principles, the present investigation attempts to establish a high-resolution stratigraphic framework for this interval on the Yangtze Platform.

1 Sinian stratigraphy

Since the designation of the Yangtze Gorges as the type locality for the Sinian System[8], the Sinian sections of that area have been investigated intensively[9~11]. Traditionally, the Sinian has been interpreted as consisting of the interval between the top of the Huangling Granite and the base of the Cambrian System. In addition, the type section for the Sinian has consisted of exposures along the Yangtze River from Liantuo to Wangjiaping, in the eastern part of the

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Yangtze Gorges. In 2001, the National Stratigraphic Commission of China presented a new definition of the Sinian System, restricting this unit to the interval between the top of the Nantuo Tillite and the base of the Meishucunian Stage (the base of the Tianzhushan Member of the Dengying Formation)[12]. Because of the construction of the great dam of the Yangtze Gorges, many new sections have been exposed and studied[13~18]. These studies indicate that the type section from Liantuo to Wangjiaping has two serious shortcomings: the Doushantuo Formation is not well exposed, and the upper contact with the Cambrian System is an obvious unconformity.

The results of our stratigraphic investigations show that the sections in the southwestern part of the Huangling Anticline are better developed and exposed than the type section. Based on examination of the sections at Hengdunyan (along the new road from Maoping to Zigui), Wuhe-Yangjiahe, and Hezi' ao (Changyan), we have adopted Wang et al.'s[2] suggestion that the Sinian rocks of the Yangtze Gorges can be subdivided into 7 intervals. Listed in ascending order, these are: (1) Member 1 of the Doushantuo Formation (the cap dolomite above the Nantuo Tillite); (2) Member 2 of the Doushantuo Formation (dark argillaceous shales with intercalations of argillaceous dolomite); (3) Member 3 of the Doushantuo Formation (laminated dolomites); (4) Member 4 of the Doushantuo Formation (black shales containing the Miaohe Biota[19~21]; (5) The Hamajing Member of the Dengying Formation (thick bedded dolomite with oolites and oncolites); (6) The Shibantan Member of the Dengying Formation (dark, laminated argillaceous limestone rich in *Vendotaenia* and simple horizontal trace fossils (the Xilingxia Biota, see Ref. 22); (7) The Baimatuo Member of the Dengying Formation (thick-bedded dolomite).

The foregoing subdivisions of the Sinian are used here as a stratigraphic standard for subdividing and correlating Sinian sequences throughout the Yangtze Platform. Together these sequences represent a variety of facies ranging from shallow to deep marine. More than 20 Sinian sections were investigated along two transects from the inner-platform (shallow-water environment) to the platform slope (deep-water environment) (Fig. 1). The Sinian sections from the Yangtze Gorges area through northwest Hunan to west and central Hunan (Fig. 2), and the sections extending from west of the platform (eastern Yunnan and southern Shaanxi) through southwest Guizhou to southeast Guizhou (Fig. 3), were subdivided and roughly correlated. Because of the limitation of the space, our descriptions of these sections will be given in separate publications. Here we present two preliminary correlation charts (Figs. 2 and 3). In these two charts, the following remarks should be noted:

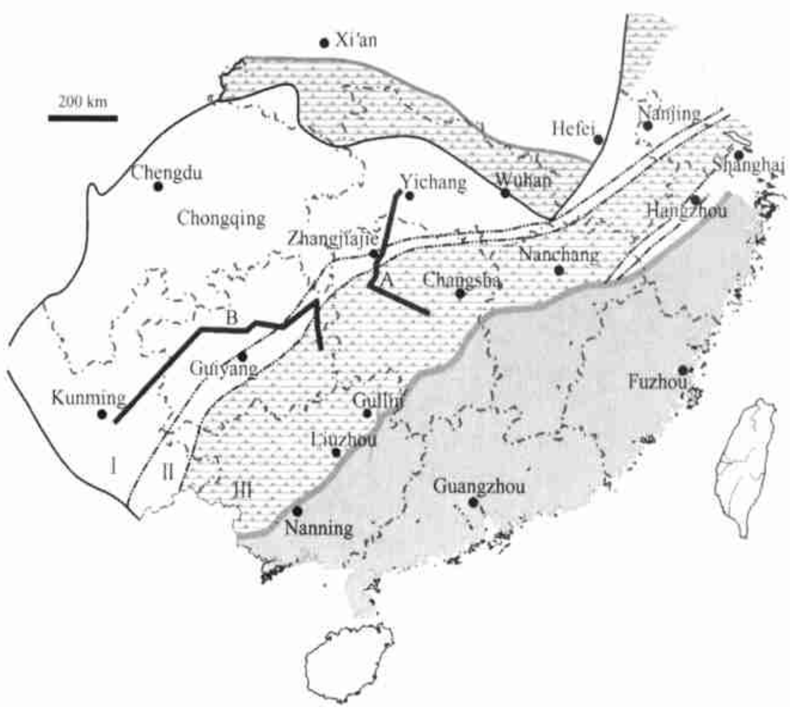

Fig. 1. Simplified palaeogeographic map of the Yangtze Platform during Sinian-Cambrian boundary interval, showing two transections A and B of investigated sections in Figs. 3 and 4. I= platform interior; II= transitional zone; III= slope and deep basin.

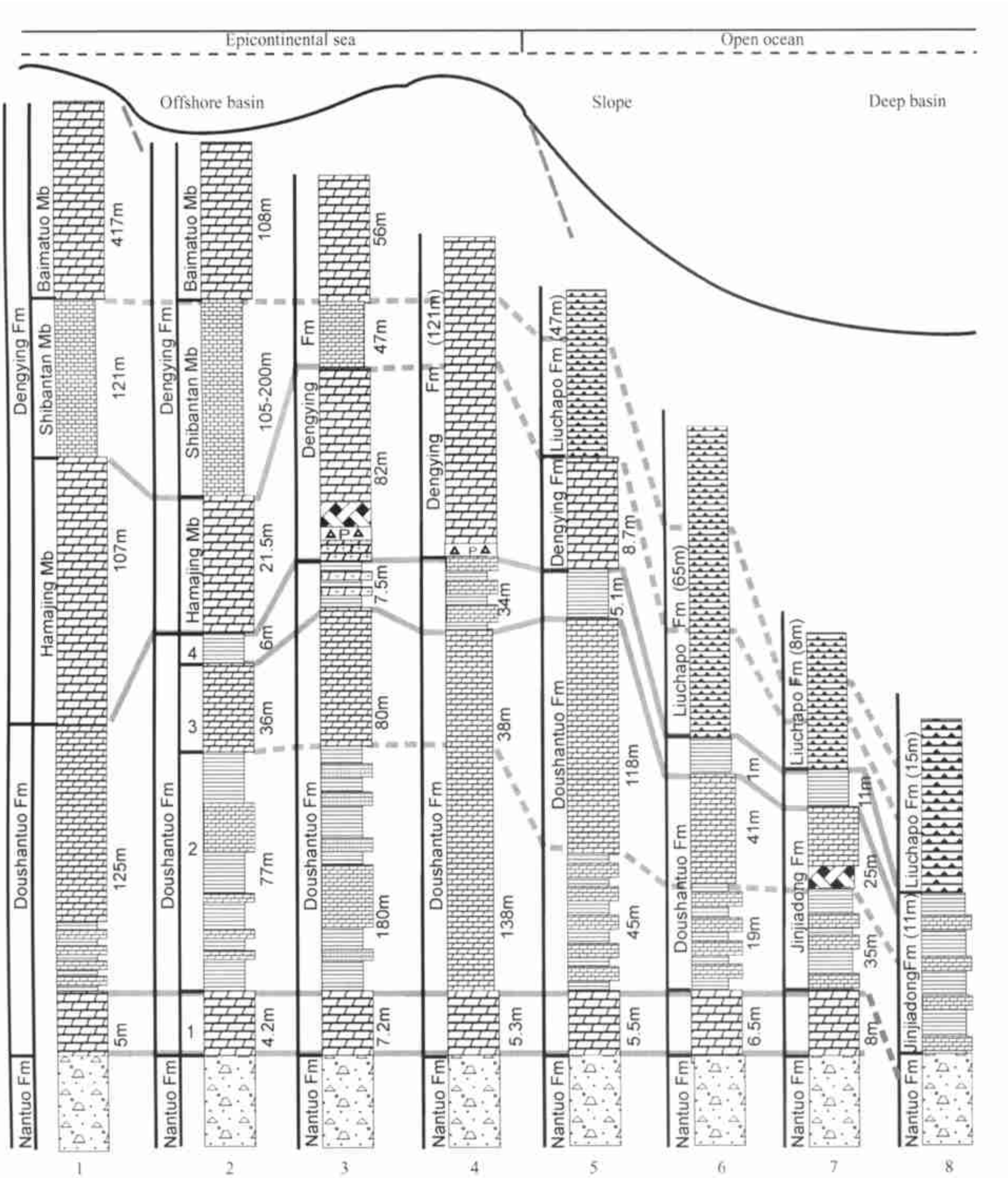

Fig. 2. Sketch chart showing correlations of the Sinian sections from the Yangtze Gorges to Central Hunan (transection A in Fig. 1). 1, Liantuo-Wangjiaping section, Yichang, Hubei; 2, Wuhe section, Sandouping, Yichang, Hubei; 3, Zhongling section (Doushantuo Fm) and Yangjiaping section (Dengying Fm), Shimen County, NW Hunan; 4, Tianping section, Zhangjiajie, Hunan; 5, Sidouping section, Zhangjiajie, Hunan; 6, Yanwutan section, Yuanling County, Hunan; 7, Xixi section, Louxi County, Hunan; 8, Bajiaotan section, Shuangfeng County, Hunan. The legends are same as in Fig. 3.

(1) During the Sinian, the Sancha-Tainping-Sidouping area (near Zhangjiajie in Hunan) and the Yuqing-Taijiang area (Guizhou) were located in the transition zone between the epeiric platform and slope environments. The sequences in environments of the inner platform, transitional zone, and the slope area differ from each other considerably. In general, the Sinian sequences in the slope area are much more condensed than that in the basins on the platform, and the sequence boundaries in the Yangtze Gorges area are difficult to recognize in the slope area. In particular, during the interval equivalent to the Dengying

Formation, sediments composed of cherts and black shales were deposited in the slope area, while carbonate sediments were deposited in the shallow-water environments. Because of the absence of preferred stratigraphic markers in the slope area, correlation is problematic. Other stratigraphic methods are required in the future.

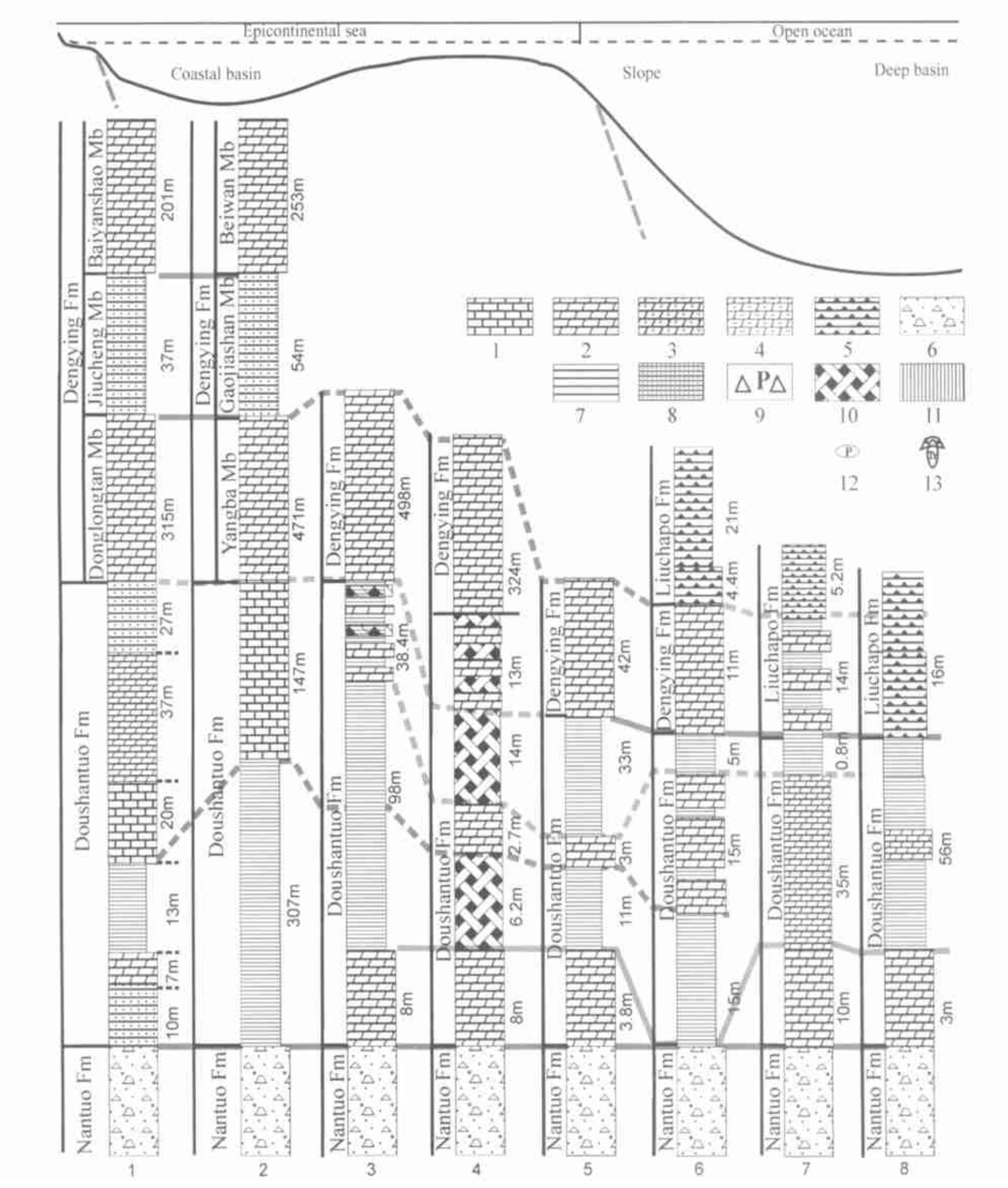

Fig. 3. Sketch chart showing correlations of the Sinian sections from the west of the Yangtze Platform to the east of Guizhou (transection B in Fig. 1). 1, Piantoushan section, Wangjiawan, Jinning County, Yunnan; 2, Hujiaba section, Ninqiang County, S. Shaanxi; 3, Songlin section, Zuiyi, Guizhou; 4, Baidoushan section, Weng' an County, Guizhou; 5, Yuqing, Guizhou; 6, Wuhe section, Taijiang County, Guizhou; 7, Huanglian section, Songtao County, Guizhou; 8, Xikou section (Doushantuo Fm), Jiangkou County, and Bahuang section (Liuchapo Fm) Tongren City, Guizhou. Legends: 1, limestone; 2, dolomite; 3, oolitic dolomite; 4, muddy dolomite; 5, chert; 6, tillite; 7, shale; 8, siltstone; 9, phosphatic conglomerate; 10, phosphorite; 11, hiatus; 12, phosphatic nodule; 13, trilobite.

(2) The so-called cap-dolomite at the base of the Sinian is widely recognized at the base of the Doushantuo Formation, except in a few basins in the west (eastern Yunnan and Ningqiang, S. Shaanxi) and in the deeper slope area. The reason for the absence of the cap-carbonate in the basin of the Yangtze Platform may be the shallow-water environment with inputs of clastic sediments from the nearby landmass. The absence of the cap-carbonate in the deep slope environment may be due to deposition below the carbonate compensation boundary. However, further investigation is required to recognize the equivalent unit of the cap-carbonate in these sequences.

(3) A black shale horizon is well developed at the top of the Doushantuo Formation in almost all paleoenvironments of the Yangtze Platform, as shown in Fig. 2. This horizon marks the base of a new sequence and marine transgression, and therefore can be used as a stratigraphic marker. However, corresponding horizon in the sections from the western Yangtze Platform and central Guizhou requires further detailed work on these sections (Fig. 3).

(4) During the interval of the Doushantuo Formation, phosphorite horizons were deposited in certain limited areas. The best-known occurrences are located in the area of the Kaiyang and Wen' an phosphorite mines in central Guizhou. In northwest Hunan, the Dongshanfeng phosphorite mine occurs at the top of the Doushantuo Formation in the Yangjiaping area. In central Hunan, phosphorite horizons are distributed over a large area in the middle of the Doushantuo Formation (for instance in the Xixi phosphorite mine). Other occurrences include sections at the Caoyang Phosphorite Mine (Shangrao, Jiangxi), the Baichu Phosphorite Mine (Baokang, Hubei), and Chadian (Mianxian, South Shaanxi)[23]. The phosphorite facies is a very significant indicator of paleoceanographic and paleoenvironmental changes; however, detailed correlations of these phosphorite horizons are questionable. Because of problematic correlation, the exact age of the well preserved algae and embryo fossils in the Weng' an biota[24~26] and other phophorites of the Doushantuo Formation remain uncertain. Therefore, whether the age of the Weng' an biota is equivalent to that of the Miaohe biota is unclear.

(5) The Dengying dolomite is divided into three parts by a middle unit that consists of thin-bedded, argillaceous, laminated carbonates or variegated argillaceous siltstone (the interior of the Yangtze Platform). Oolitic textures and oncolites in the dolomite of the Hamajing Member indicate a high-energy facies which overlies above the black shale at the top of the Doushantuo Formation. The sea-level drop from the Doushantuo to Dengying Formations can be recognized in all facies on the Yangtze Platform. Based on this fact, the phospharite interval at the top of the Doushantuo Formation in the Yangjiaping area may be equivalent to the Hamajing Member in Yangtze Gorges. Similar situation may also exist in the Weng' an phospharite mine area, where the upper part of the upper phosphorate could be correlated with the Hamajing Member. However, the detailed correlations of the transitional interval of the Doushantuo and Dengying Formations require more investigations in file scales by comprehensive methods in more sections.

(6) The base of the middle member of the Dengying Formation, which generally is unconformable, represents the beginning of a new sequence. It is probable that a tectonic event or sea-level change occurred during the interval of the middle Dengying Formation. Therefore, the Shibantan (Yangtze Gorges), Gaojiashan (South Shaanxi) and Jiucheng (eastern Yunnan) members of the Dengying Formation can be considered as representing the same interval. However, the dark limestone of Shibanan Member deposited in the offshore basin, whereas the siliciclastic rocks of the Gaojiashan and Jiucheng Members deposited in the coastal basins with inputs of clastic sediments from nearby landmass (Figs. 2 and 3). Correlation suggests that the Xilingxia biota is equivalent to the Gaojiashan biota[27].

(7) Biostratigraphically, Sinian acritarch zonations have not been recognized at fine scales. Megafossil zonation is even more difficult. Up to now, only problematical tube fossils such as *Cloudina*, which occurs at the top of the Dengying Formation and below the first occurrence of SSF' s, may be considered as a stratigraphic marker. A stage-level unit of the Sinian would be defined by the fist occurrence of *Cloudina*, which can be used for global correlation of the Neoproterozoic III. However, the distribution of *Cloudina* on the Yangtze Platform is still limited to the south Shaanxi area[27, 28]. It would be a future focus to look for new occurrence of *Cloudina* in other areas of the Yangtze Platform, and to understand what controls distribution of *Cloudina*.

(8) The strong negative excursion of C isotopes is detected at the interval between the extinction of *Cloudina* and first occurrence of SSF's, which has been also globally recognized. Therefore, we suggested that the negative excursion event could be the best marker for defining an interval at the top of the Sinian, as well as at the top of the Neoproterozoic III in other continents.

(9) It is uncertain whether the middle and upper parts of the Dengying Formation are not developed in the north and central Guizhou as suggested by Cao et al.[29], e.g. Songling section in Zunyi, Baidoushan section in Weng'an County and section in Yuqing (sections 3~5 in Fig. 3). Correlation of the Dengying Formation in this region requires further study.

2 Sinian-Cambrian boundary stratigraphy

The Sinian-Cambrian boundary interval of the Yangtze Platform was investigated intensively during the 1980s (see Ref. [6]). However, previous studies focused on the biostratigraphy of SSF's and trace fossils, which occur primarily in areas containing exposures of shallow-water facies. Among these areas, eastern Yunnan is of special importance because about 200 m of the pre-trilobite Cambrian sequence is well exposed here and contains abundant SSF's and trace fossils. The Sinian-Cambrian boundary interval in eastern Yunnan has traditionally been regarded as the best candidate for the Early Cambrian stratotype not only of China, but also of the world. In addition, the Meishucun section is the type section. However, there are two major unconformities in this section, one at the base of the Zhongyicun Member and the other at the top of the Dahai Member. For this reason, it has been proposed that sections in the Dahai[30] and Yongshan[31] areas in northeastern Yunnan be chosen as a new stratotype section of the Sinian-Cambrian boundary interval.

The Sinian-Cambrian boundary stratigraphy in eastern Yunnan was reviewed in detail by Zhu et al.[32]. Five intervals, which can be used as standards for subdivision and correlation of the Sinian-Cambrian boundary interval in other areas on the Yangtze Platform, are described in ascending order as follows: (1) The Daibu Member is composed of laminated silicate with intercalations of laminated dolomite and black shale. The unit represents the interval between the thick-bedded dolomite of the Dengying Formation and the first occurrence of SSF's in the Meishucunian phosphorite; (2) The Zhongyicun Member consists of phosphorite and phosphotized dolomite with abundant SSF's. Two SSF assemblages (the *Anabarites trisulcatus-Protoherzina anabarica* Zone and the *Siphogonuchites triangularis-Paragloborilus subglobosus* Zone) have been recognized; (3) The Dahai Member consists of dolomite and limestone and contains the *Watsonella* (*Heraultipegma*) *yunnanensis* Zone, which is the third SSF assemblage; (4) The late Meishucunian interval between the base of the Shiyantou Formation and the horizon containing the first occurrence of trilobites. The base of the Shiyantou Formation is marked by a sharp contact between carbonate facies and black siliciclastic sequences. The fourth SSF assemblage (the *Sinosachites flabelliformis-Tannuolina zhangwentangi* Zone) is recognized in this interval; (5) The Qiongzhusian interval contains the two earliest trilobite zones (the *Parabadiella* Zone and the *Eoredlichia-Wutingaspis* Zone) as well as the Chengjiang biota.

In order to understand the biological and geological evolution across the Sinian-Cambrian transition interval, we investigated more than 50 sections in shallow- to deep-water environments of the Yangtze Platform. Our results demonstrate that this critical interval shows dramatic differences between the sections, and that unconformities occur in nearly all sections except those in central Hunan and southeast Guizhou, which were located in the deep-water slope environment. Fig. 4 shows preliminary correlations of some representative sections. In this correlation chart, the following important remarks should be noted:

(1) Based on trace fossils and SSF's, the base of the Cambrian in eastern Yunnan can be placed at the base of the Zhongyicun Member. The base of the Cambrian in other shallow-water sections on the platform generally is marked by the base of a phosphatic horizon with SSF's. In these sections, the base of the Cambrian is an unconformity. The exact placement of the Sinian-Cambrian boundary in the transitional sequences of the slope area is uncertain because of the lack of SSF's and other stratigraphic marker.

(2) The best Sinian-Cambrian boundary interval, one without any obvious unconformities, is located either in a few basins in the western part of the Yangtze Platform or in the slope area of the southeastern part of this platform. The representative sections are those in far northeastern Yunnan (the Dahai

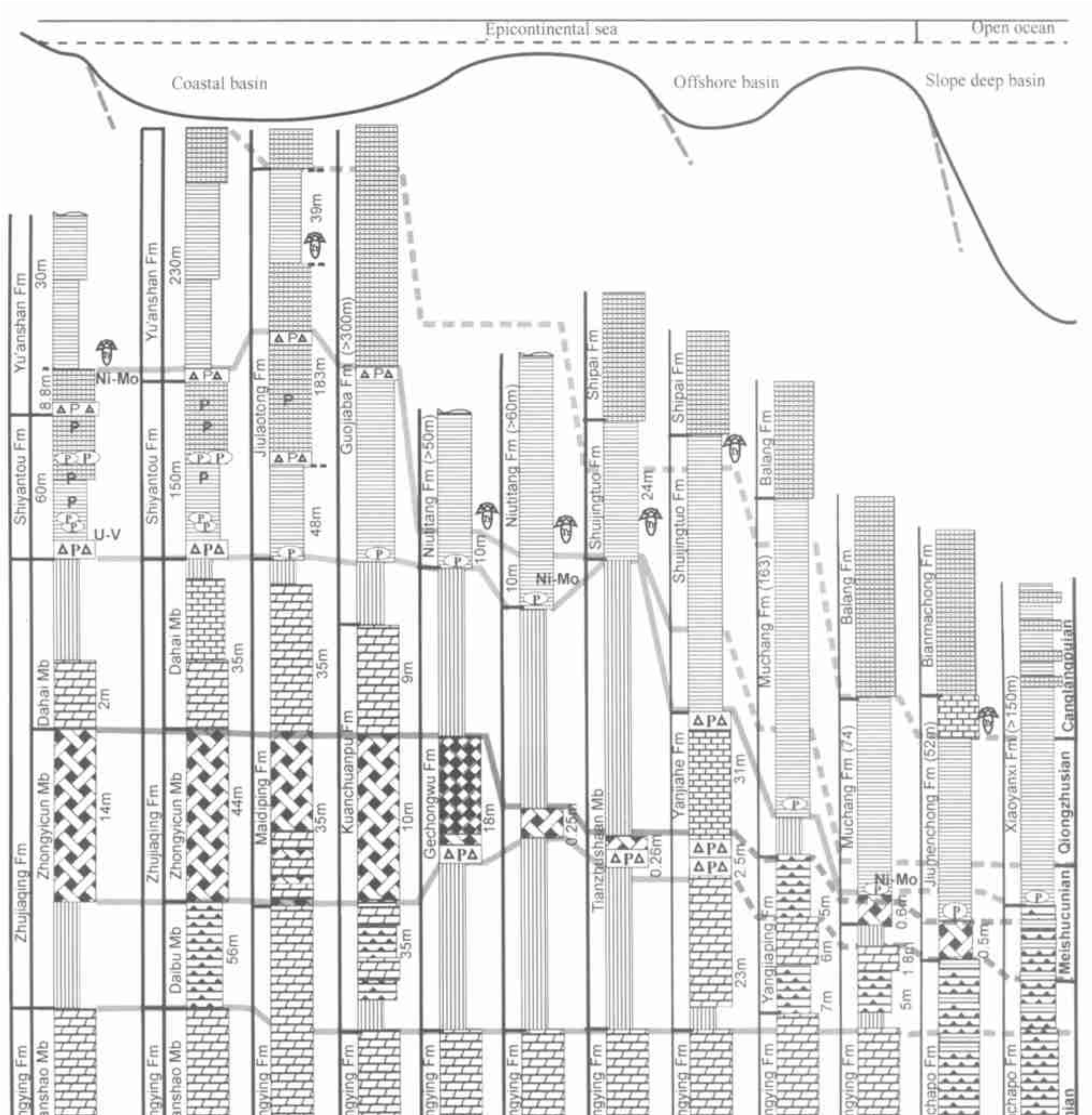

Fig. 4. Sketch chart showing correlations of the Sinian - Cambrian boundary interval on the Yangtze Platform. 1, Meishucun section, Jinning County, Yunnan; 2, Dahai section, Huize County, Yunnan; 3, Maidiping section, Emei, Sichuang; 4, Kuanchuangpu section, Ninqiang County, S Shaanxi; 5, Gezhongwu section, Zhijin County, Guizhou; 6, Heishapo section, Songlin County, Guizhou; 7, Wangjiaping section, Yichang, Hubei; 8, Yanjiahe sectrion, Yichang, Hubei; 9, Yangjiaping section, Shimen County, NW Hunan; 10, Sancha-Daping section, Zhangjiajie, Hunan; 11, Huanglian section, Songtao County, Guizhou; 12, Lijiatuo section, Yuanling County, Hunan. The legends are same as in Fig. 3.

and Xiaotan sections), the Emei area (the Meidiping section), and central Hunnan (the Lijiatuo section, near Yuanling).

(3) The base of the Shiyantou Formation in eastern Yunnan is marked by a sharp contact between carbonate and siliciclastic rocks. This contact is the most easily recognized boundary in nearly all environments of the Yangtze Platform, and represents a major tectonic event.

(4) In eastern Yunnan, the base of the

Qionzhusian is defined by the first occurrences of trilobites. At this same level, bradoriids, brachiopods, lipped hyolithes, and other distinct shelly fossils also first appear, and these fossils are readily distinguishable from the SSF's in strata immediately below the Qiongzhusian. Therefore, the base of the Qiongzhusian can be recognized in sections containing mega-fossils. However, fossils generally are absent in the basalmost Cambrian black shale of the Yangtze Platform. In this unit we use a geochemical horizon containing exceptionally high Ni-Mo concentrations as a stratigraphic marker for defining the base of the Qiongzhusian. The reason for this decision is that a geochemically corresponding layer occurs at the base of the Qiongzhusian in eastern Yunnan, and has been widely detected in the basalmost Cambrian black shale of the Yangtze Platfrom. In general, this horizon is located at the base of the "stone coal" interval and above a black shale interval containing abundant phosphatic nodules. Our investigations show that the black shale interval with phosphatic nodules generally at the basal part of the Niutitang and Jiumenchong Formations is very condensed and is equivalent to the interval between the base of the Shiyantou Formation and the base of the Qiongzhusian in eastern Yunnan (Fig. 4).

(5) Integrated correlation indicates that pre-trilobite Lower Cambrian strata are not well developed in shallow-water facies and are condensed in deep-water facies. The best, thickest sections are located in eastern and northeastern Yunnan (the Zhujiaqing and Shitantou Formations), in Emei in central Sichuan (the Maidiping Formation and the lower member of the Jiulaodong Formations), in Ningqiang in southern Shaanxi (the Kuanchuanpu Formation and the lower member of the Guojiaba Formation), and south of the Yangtze Gorges (the Yanjiahe Formation and the lower member of the Shuijintuo Formation). These sections represent sequences in the basins of platform interior (Fig. 4).

(6) The upper boundary of the Qiongzhusian is defined by (i) occurrences of Canglangpuian trilobites (the *Yiliangella* assemblage), (ii) the extinction of *Eoredlichia* and *Wutingaspis* in shallow-water facies, and (iii) the occurrence of *Hupeidiscus* in deep-water facies. Correlation shows that the Qiongzhusian interval consists of muddy and silty rocks with abundant fossils in shallow-water facies, and black shales with few fossils in deep-water facies[33,34].

3 Carbon isotope stratigraphy

Lambert et al.[35] first published a complete Sinian C isotope profile based on 33 samples from the former type section of the Yangtze Gorges, and correlated it with sections in Siberia and Morocco. Using 98 samples, Yang et al.[36] conducted a more detailed C isotope investigation of the same section. Because of the problems with the type section mentioned above (e.g. the absence of cap dolomites at the base and the presence of a major unconformity at the top), the C isotopic curve needs to be revised. Multiple investigations on the C isotopes of the Sinian in the Yangtze Gorges were published recently[17,18]. Although their samples were collected from the better-developed sections than the type section, the resolution of their data is still very poor. Sinian C isotopic studies have also been carried out in other few sections except that in the Yangtze Gorges (e.g. Doushantuo Formation at Weng'an[37]; Dengying Formation in Chengjiang[38]), but C isotopic data are only from the limited intervals sporadically located in different areas.

As part of our facies analyses of the Yangtze Platform, we selected more complete Sinian sections with stable carbonate facies for high-resolution C isotopic study. The Doushantuo Formation at Tianping near Zhangjiajie, and the Dengying Formation at Yangjiaping (northwest Hunan) and Hujiaba in Ningqiang (South Shaanxi), were sampled. Preliminary results (Fig. 5) show a similar pattern of the Terminal Proterozoic C isotope variation summarized by Jacobsen & Kaufman[39]. In general, our high-resolution curve exhibits 3 negative excursions at the base, middle and top of the Sinian, respectively, and 2 positive excursions in between the negative excursions. Surprisingly, the curve is exactly identical to that proposed by Knoll[3] and Shield[40], demonstrating that the new C isotopic data, which will be published later, can be applied to other Sinian sequences and be used for global correlations.

Carbon isotopic research on the Precambrian-Cambrian boundary interval has been conducted on the Meishucun and Maidiping sections by Brasier et al.[41], Chen et al.[42], and Shen et al.[43,44]. Because the Meishucun section has two major unconformities, one at the base of the Zhangyicun Member and the other at the top of the Dahai Member, the C isotopic curve for the Xiaotan section (Yongshan, northeastern Yunnan) represents a more complete

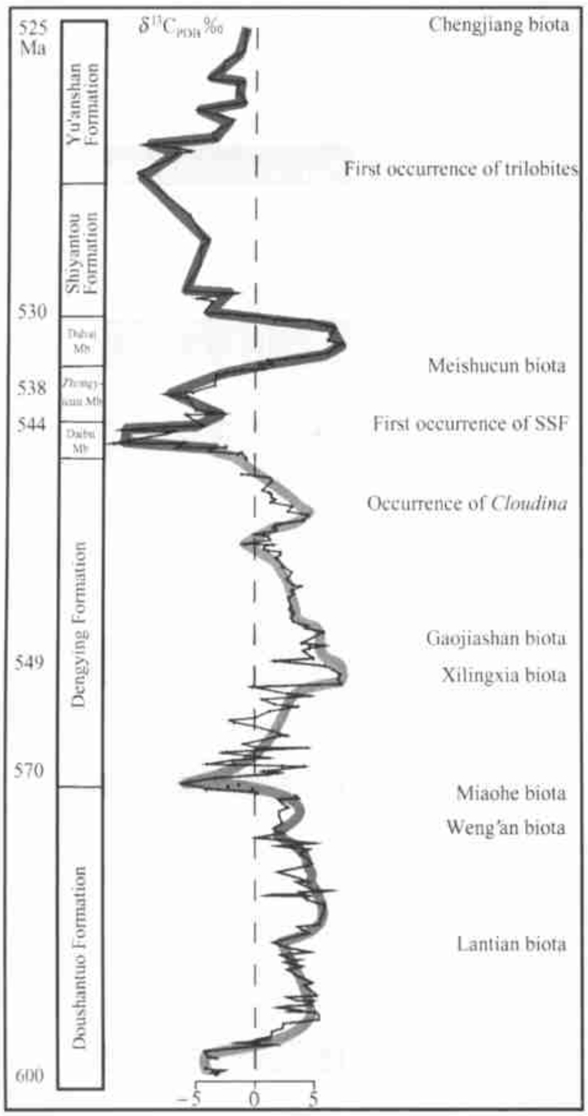

Fig. 5. Sketch drawing showing C isotopic evolution and occurrences of major biotas across the Sinian-Cambrian boundary interval on the Yangtze Platform. C isotopic data across the boundary interval are from Zhang et al.[45] C isotopic data for the Sinian interval are from unpublished data of the present authors.

curve for the Sinian-Cambrian boundary interval[45, 46]. The distinct negative excursion at the base of the Daibu Member and the positive excursion within the Dahai Member can be applied as reliable stratigraphic markers for inter- and intrabasinal and global correlations.

4 Conclusion

As shown in Figs. 2 ~ 4, correlations of the shallow-water stratigraphic standards to sequences in the deep-water facies in fine scale are still problematic, except for some major boundaries. Clearly, additional integrated investigations are required. Fig. 5 shows a general stratigraphic sequence and fossils occurrences during the Sinian-Early Cambrian interval. Age estimates of some important horizons are given in Fig. 5 based on our integrated global correlations. Although the Sinian-Early Cambrian stratigraphic framework presented here is still preliminary, it should serve as a basic time frame for investigations of biological and environmental evolution during the Neoproterozoic-Cambrian transitional interval of the Yangtze Platform.

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