Chapter 2. Paleotopographic influence on the development of the late Ediacaran Yangtze platform (Hubei, Hunan, and Guizhou provinces, China)

Abstract

A facies map compiled from 49 sections in three provinces (Hunan, Guizhou and Hubei provinces) and field data allow highlighting the changes of depositional environments on the shelf. Facies interpretation suggests three depositional environments: (a) deep-water basin, which develops slope facies on its margins (Maoping and Wuhe sections in Hubei province); (b) shallow-water environment subjected to wave energy and tides (Yangjiaping and Zhongling sections, Hunan province, and Weng'an section, Guizhou province); (c) a medium-water-depth shelf environment, subjected to currents. Therefore, during Doushantuo Formation time (~635 Ma-551 Ma), the shelf shows an irregular bathymetry, interpreted as inherited of the passive margin history of the Yangtze platform following the breakup of Rodinia (approx. 700 Ma). The tilted blocks support the platform development and influence the facies distribution. More than the entire Doushantuo Formation time (~ 84 Ma) appears to have been necessary to compensate the inherited paleobathymetry.

1. Introduction

Ediacaran and Cambrian strata of the Yangtze platform are one of the foremost locations worldwide to study the conditions and setting of the early Cambrian bioradiation. Indeed, numerous sites show exceptional well-preserved soft-bodies fauna (Chengjiang biota, Yunnan province (Chen et al., 1991; Chen et al., 1999; Babcock et al., 2001; Babcock and Zhang, 2001; Hou and Bergstrom, 2003; Hou et al., 2004; Shu et al., 2004), Miaohe biota, Hubei Province (Xiao et al., 2002); Weng'an biota, Guizhou Province (Yin et al., 2001; Chen et al., 2004; Yin et al., 2004)) and the sediments appear to have not been affected by post-Precambrian tectonics. The reconstruction of sedimentary environments and their evolution through the Precambrian-Cambrian transition is an important key for the understanding of the Cambrian bioradiation. The Yangtze platform during Doushantuo time was a carbonate-dominated shallow-water shelf in low northern latitudes subjected to medium-energy currents favouring the sedimentation mostly of laminated silty limestones. However, some regions are dominated by suspension-settling sedimentation while others are dominated by high-energy sedimentation, which collectively indicate that the bathymetry of the platform was variable.

The purpose of this paper is to draw attention to the existence of intra-shelf basins and highs, to constrain their geometry, and to understand how the passive-margin evolution of Yangtze platform following the breakup of Rodinia supercontinent may have affected the formation and subsequent growth of the platform.

2. METHODS AND GEOLOGICAL BACKGROUND

2.1. Methods

Stratigraphic measured sections were recorded in 2002 and 2003. Representative samples were cut, polished, and commonly scanned in order to highlight sedimentary structures and facilitate facies analysis. Petrographic thin sections aided in the identification of mineralogy, diagenesis, and microfacies analysis. Stratigraphic columns from regional geological survey publications (Bureau of Geology and Mineral Resources, 1987; 1988; 1990) enlarged my own database in purpose of drawing regional lithofacies and isopach maps.

2.2. Geological setting

The location of the South China craton during the late Neoproterozoic and the location of the craton in the Rodinia supercontinent, like that of many other small cratons, is poorly known. Paleomagnetic analysis indicate an equatorial paleolatitude (Macouin et al., 2004) at 600 Ma. Li et al. (1995), Fairchild et al. (2000) propose that the South China plate linked Australia with Laurentia from 1 Ga to 700 Ma. Powell and Pisarevsky (2002), in their reconstruction of Gondwana and Laurentia, also join South China with Australia. In the terminal Neoproterozoic (590-543 Ma) and the early Cambrian, the Yangtze block may have been to the northwest of northern India near the equator (Jiang et al., 2003c). According to Condie (2003) and Pisarevsky et al. (2003), the Yangtze platform and Cathaysia (south-eastern part of present-day China) collided to form the South China craton during the Meso- and early Neoproterozoic before they were separated again during Rodinia break-up. The general Neoproterozoic tectonic setting of the Yangtze platform is, due to the break-up of Rodinia, extensional. Since the late Neoproterozoic, the platform evolved as a passive margin (Jiang et al., 2003c; Wang and Li, 2003). To the north, the Gingfeng-Xiangfan-Guangji (Qin-Lin) fault, extending from Tibet to northern Anhui, and to the southeast, the Cathaysia suture constrain the present-day Yangtze platform. Its current setting is the result of its collision with the Cathaysia arc to the SE during the Silurian and with the North China craton during the early Triassic (Kenneth and Cheng, 1999) (Fig. 5). Despite of the complex tectonic history of China, the sedimentary rocks on the Yangtze Platform have not been deformed. Generally, Proterozoic-Paleozoic strata are preserved in a thickness of several kilometres and are moderately and large-scale folded. However, Cretaceous extension created large, fault-bounded basins (e.g. Jianghe Basin, Fig. 18) filled by lithologies of continental facies, which covered the Ediacaran sediments.

2.3. Location and stratigraphic succession

This study focuses on the southern margin of Yangtze platform in Hunan, Hubei and Guizhou provinces (Fig. 11). Formation names change between provinces, largely as a function of lithology and dominant depositional environment (see Erdtmann and Steiner, 2001; Wang and Li, 2003 for equivalences). We will refer to the formation names as time indicators, without lithological and geographical considerations (Fig. 12).

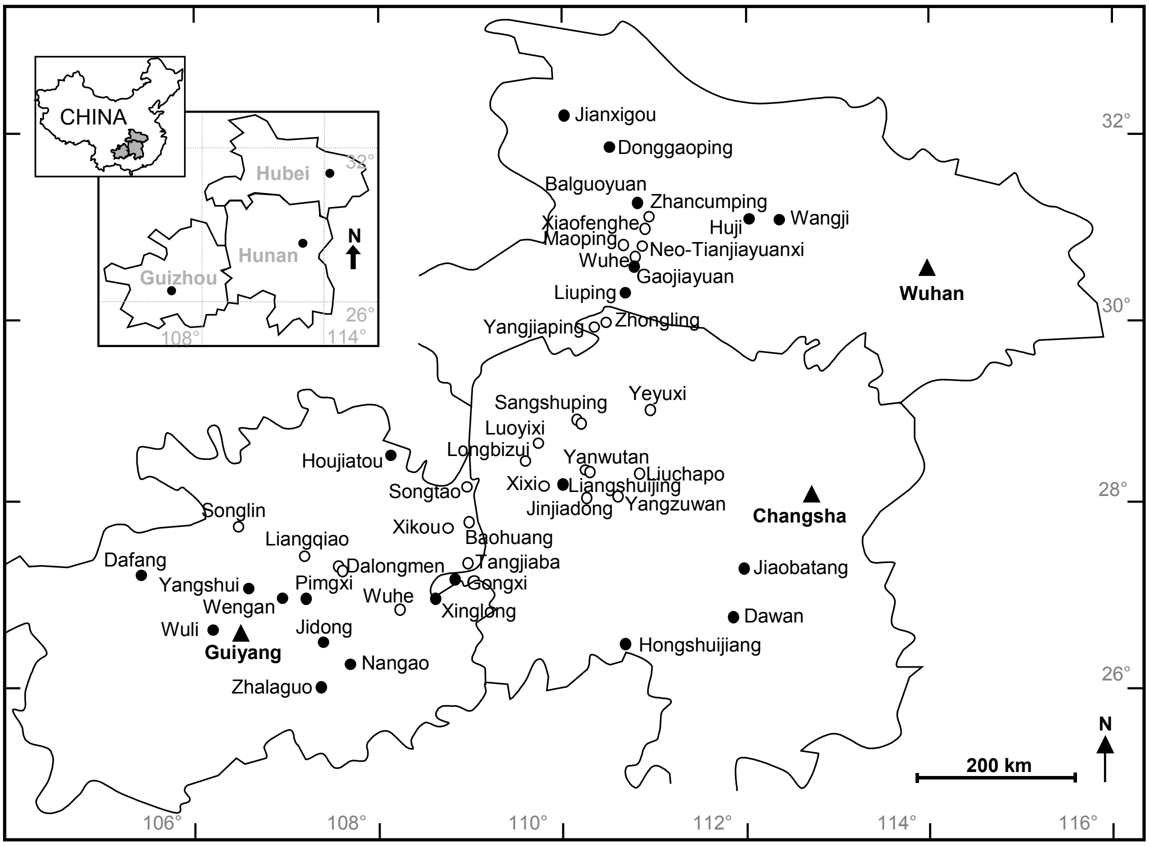

Fig. 11. Location of study area, showing Guizhou, Hubei and Hunan provinces. Black circles correspond to literature data sections (Bureau of Geology and Mineral Resources, 1987; 1988; 1990) and white circles to visited sections.

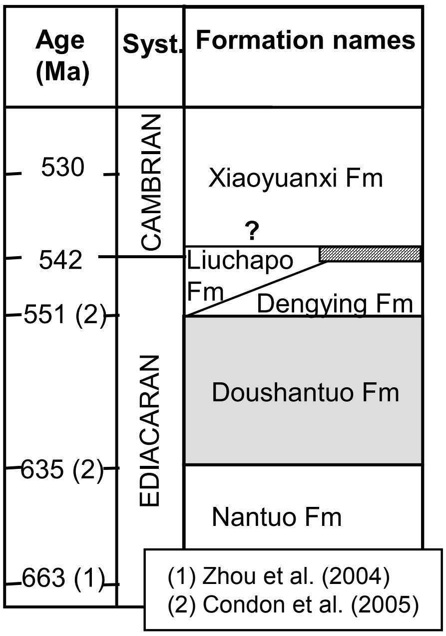

Fig. 12. Formation correlation diagram for the Neoproterozoic of south-central China. Almost each region of China has different formation names according to its sedimentary record. However, in order to simplify the discourse, this study uses the formation names as time-indicators.

The sedimentary record in the study area begins with thick diamictites of the Nantuo Formation. Locally, their glacial origin and age is debated (Bahlburg, 2004; Dobrzinski et al., 2004; Eyles and Januszczak, 2004). Evans et al., (2000), Wang and Li (2003) give a Sturtian age (approx. 750 Ma, Frimmel et al., 2002) whereas Jiang et al. (2003c), Chen et al. (2004), Dobrzinski et al. (2004), Zhou et al. (2004) propose that Nantuo tillites are time-equivalent to the Marinoan glaciation (between 663 Ma, Knoll and Xiao, 1999, and 635 Ma, Condon et al., 2005). These locally glaciogenic sediments gathered renewed interest with the "Snowball Earth" theory (Hoffman et al., 1998; Hoffman and Schrag, 2000; Hyde et al. 2000; Runnegar, 2000; Hoffman and Schrag, 2002). A "cap carbonate" overlies the diamictites and forms the base of the Doushantuo Formation. These carbonates locally show unusual sedimentary structures (Sumner, 2002; Nogueira et al., 2003) and a pronounced negative δC^{13} isotope anomaly (Knoll et al, 1993; Germs, 1995; Corsetti and Hagadorn, 2000), interpreted as chemical precipitation under "hothouse" conditions following the end of the glaciations. The Nantuo Formation diamictites and the Doushantuo Formation "cap carbonate" extend regionally throughout the central and southern Yangtze platform. The bulk of the overlying Doushantuo Formation on the Yangtze platform consists of limestones interbedded with shales, corresponding to variations in sea level and of depositional environment. However, a few sections in Hubei province and numerous sections in Hunan and Guizhou provinces consist of thick intervals of black shales with common gravity-related sedimentary structures, indicating a south-facing slope beyond the shelf break. The Doushantuo Formation is overlain by dolomitized wackestones/packstones of the Dengying Formation. The transition between both formations is sharp. In several sections (Maoping and Wuhe sections, Hubei province; Wuhe section, Guizhou province), a thin, three-to-four-centimetre thick bentonite bed (550 +/- 0,78 Ma, Condon et al., 2005) separates the two formations. Similar to the pronounced facies change in the Doushantuo Formation, the carbonates of the Dengying Formation also grade southward and downdip into black silicified shales of the Liuchapo Formation of slope and basin environment.

3. Results and analysis

3.1. Facies distribution

Translated, essentially lithologic sections from regional geological surveys (Bureau of Geology and Mineral Resources, 1987; 1988; 1990) and own field data allow to draw a lithological map of the southern Yangtze platform in Hunan, Hubei, and Guizhou provinces during Doushantuo time (Fig. 13). The 49 sections are geographically unevenly distributed; therefore, the sedimentology of a large part of the platform remains poorly known. The thickness of the Doushantuo Formation is variable (Fig. 14) and reaches a maximum near Liuping section, Hubei province, with 322 m, and Songlin section, Guizhou province, with 147 m. These thick sedimentary columns involve shale and silty shale lithofacies.

In order to show the dominant lithology on the platform during Doushantuo time, the sedimentary record has been simplified to the most typical lithology (Table 2). That done, six facies-diagnostic lithologies (or lithologies in combination with diagnostic sedimentary structures) can be distinguished:

1. (dolomitized) limestones / silty limestones

2. Packstones / grainstones
3. Silty shales / shales interbedded with siltstones
4. Silty limestones with slump folds
5. Shales with shallow-water limestone olistoliths and slump folds
6. Shales without gravity-induced sedimentary structures and without allochthonous silty sediments supplies

(Silty) limestones and packstones/grainstones are present in Hubei and central Guizhou province on the shelf of the southern Yangtze platform (Steiner, 2001). Shales occur, as expected, dominantly in the slope and deep basin environment in Hunan province (Steiner, 2001). However, they also dominate parts of the platform in central Guizhou province and in three parts of Hubei province. Their environmental and tectonic significance will be discussed below.

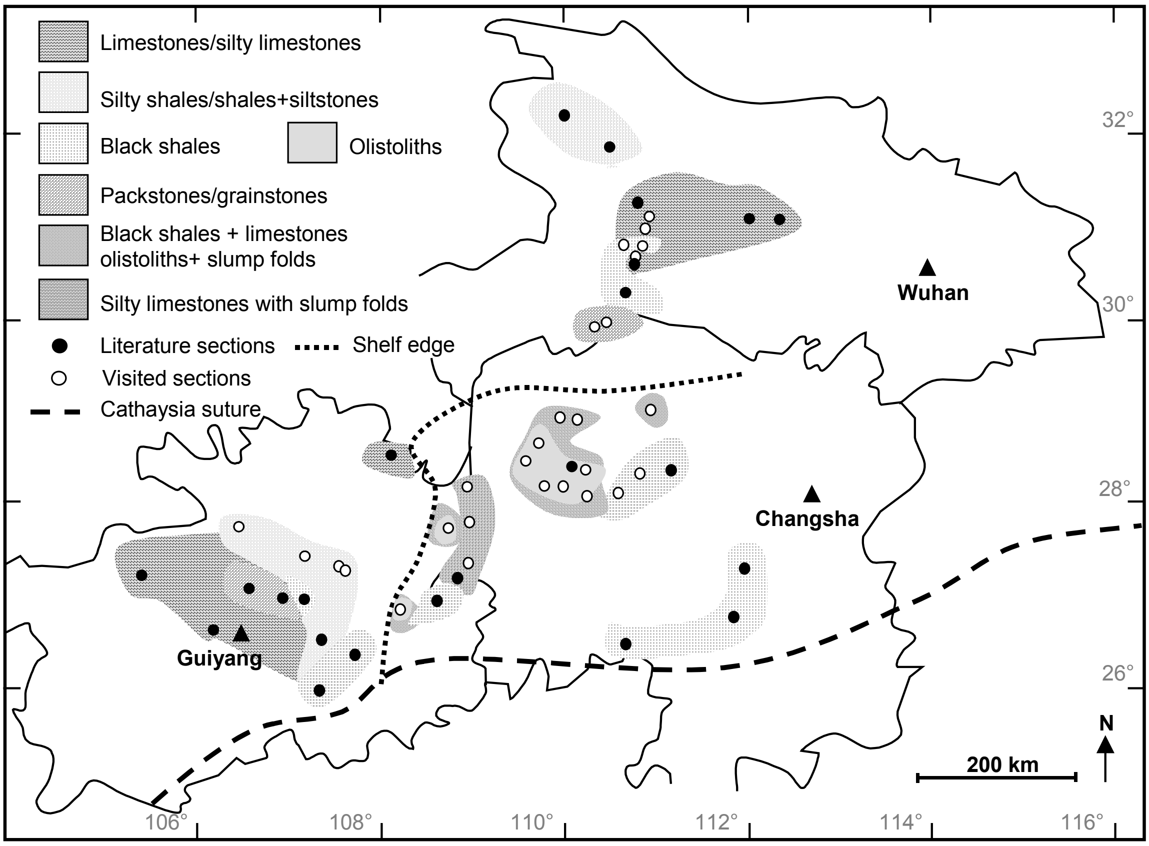

Fig. 13. Map of dominant lithologies (with indications of sedimentary structures where available) on the southern margin of the Yangtze platform during Doushantuo Formation time. Data are compiled from regional geological survey literature (Bureau of Geology and Mineral Resources, 1987; 1988; 1990) and from own field data. Note the occurrence of shale both on the shelf and on the continental slope.

Shales are deposited in low-energy environments (Potter et al., 1980; Weaver, 1989; Wetzel, 1991). They are present both in shallow-water protected environments such as lagoons (Sageman et al., 1991; Jones and Desrochers, 1992) as well as in deep environments such as ocean basins (Boer, 1991; Sageman et al., 1991) and generally make a poor water depth indicator. In absence of fossils, only facies associations can give water depth indications.

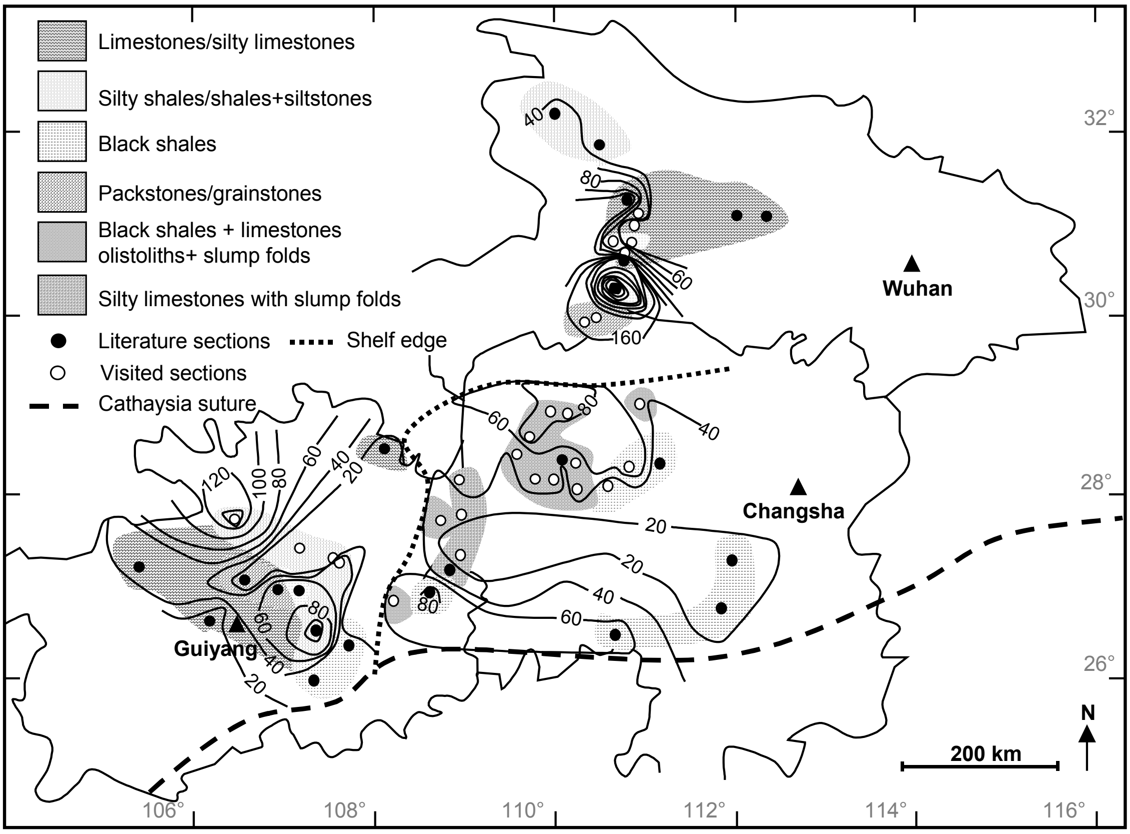

Fig. 14. Thickness isopachs map of the Doushantuo Formation. A relationship between the thickness and the facies/lithology or the paleoenvironment is not evident. Contour lines represent 20 m thickness.

Unfortunately, the absence of documented sedimentary structures in the literature sections (marked by black circles in Fig. 11) makes it difficult to distinguish between shallow- and deep-water environments. The absence of common seismites (Alfaro et al., 2001; Peng et al., 2001), debrites (except in Yangjiaping and Zhongling sections, Hunan province, upper part of the Doushantuo Formation), tectonic breccia and conglomerate deposited indicates that the thickness variation in the Doushantuo Formation expresses variations of facies, related to variation of depositional conditions (due to variations of depositional environment) rather than active tectonics.

3.2. Evidence for intra-shelf basin in central Hubei Province (Three Gorges dam region)

Three visited sections (Maoping, Neo-Tianjiayuanzi and Wuhe) in central Hubei province show a shale-dominated sedimentary record, atypical in comparison with the shallow-water-shelf-facies-dominated sections nearby.

3.2.1. Sedimentary record

The sedimentary record of Maoping and Wuhe sections begins with thick black silicified shales interbedded with thinly bedded siltstones of the lower Doushantuo Formation (Fig. 15-1A, 15-2A, 15-3B), overlying the Nantuo Formation and the basal Doushantuo Formation “cap carbonate”.

	Sections names	Province	Doushantuo thickness (in m.)	Dominant facies
1	Baohuang	Guizhou	1	Shales
2	Dafang	Guizhou	45	Limestones/silty limestones
3	Dalongmen	Guizhou	17	Shales
4	Houjiatou	Guizhou	13	Limestones/silty limestones
5	Jidong	Guizhou	103	Silty shales/shales interbedded with siltstones
6	Liangqiao	Guizhou	9	Shales
7	Nangao	Guizhou	25	Shales
8	Pimgxi	Guizhou	62	Shales
9	Songlin	Guizhou	147	Silty shales/shales interbedded with siltstones
10	Songtao	Guizhou	43	Limestones/silty limestones
11	Tangjiaba	Guizhou	10	Limestones/silty limestones
12	Weng'an	Guizhou	63	Packstones/grainstones
13	Wuhe/Taijiang	Guizhou	74	Shales with shallow-water limestones olistoliths and slump folds
14	Wuli	Guizhou	14	Limestones/silty limestones
15	Xiaosai-Suyang	Guizhou	49	Silty shales/shales interbedded with siltstones
16	Xikou	Guizhou	25	Shales with shallow-water limestones olistoliths and slump folds
17	Xinglong	Guizhou	85	Shales
18	Yangshui	Guizhou	17	Packstones/grainstones
19	Zhalaguo	Guizhou	38	Shales
20	Balguoyuan	Hubei	126	Limestones/silty limestones
21	Donggaoping	Hubei	14	Silty shales/shales interbedded with siltstones
22	Gaojiayan	Hubei	202	Limestones/silty limestones
23	Jianxigou	Hubei	47	Silty shales/shales interbedded with siltstones
24	Liujiaping	Hubei	322	Silty shales/shales interbedded with siltstones
25	Maoping	Hubei	65	Shales with shallow-water limestones olistoliths and slump folds
26	Wuhe	Hubei	90	Limestones/silty limestones
27	Tianjiayuanzi	Hubei	22	Limestones/silty limestones
28	Xiaofenghe	Hubei	45	Limestones/silty limestones
29	Zhancumping	Hubei	72	Limestones/silty limestones
30	Dawan	Hunan	10	Shales
31	Gongxi	Hunan	16	Silty shales/shales interbedded with siltstones
32	Hongshuijiang	Hunan	67	Silty shales/shales interbedded with siltstones
33	Jiaobatang	Hunan	11	Silty shales/shales interbedded with siltstones
34	Jinjiadong	Hunan	50	Shales with shallow-water limestones olistoliths and slump folds
35	Liangshuijing	Hunan	71	Shales with shallow-water limestones olistoliths and slump folds
36	Ligonggang	Hunan	41	Shales with shallow-water limestones olistoliths and slump folds
37	Lijiatou	Hunan	50	Shales with shallow-water limestones olistoliths and slump folds
38	Liuchapo	Hunan	71	Shales
39	Liujata	Hunan	56	Shales with shallow-water limestones olistoliths and slump folds
40	Longbizui	Hunan	85	Shales with shallow-water limestones olistoliths and slump folds
41	Luoyixi	Hunan	45	Shales with shallow-water limestones olistoliths and slump folds
42	Nanmudong	Hunan	19	Silty shales/shales interbedded with siltstones
43	Sangshuping	Hunan	82	Shales with shallow-water limestones olistoliths and slump folds
44	Xixi	Hunan	28	Shales with shallow-water limestones olistoliths and slump folds
45	Xiaoyuanxi	Hunan	18	Shales
46	Yangjiaping	Hunan	170	Packstones/grainstones
47	Yangzhuwan	Hunan	29	Shales
48	Yanwutan	Hunan	45	Shales with shallow-water limestones olistoliths and slump folds
49	Zhongling	Hunan	171	Packstones/grainstones

Table 2. Database to maps of Figs. 13 and 14 showing thickness of Doushantuo Formation in 49 sections of Hunan, Hubei and Guizhou provinces. Data from Bureau of Geology and Mineral Resources of Guizhou, Hubei, and Hunan provinces (1987; 1988; 1990) and own data.

These shales are locally disrupted and slump-folded on small- and medium-scale (Fig. 15-1C, 15-3A). Thinly laminated, light grey silty wackestones overlie the black shales. In Maoping section, this carbonate interval is large-scale slump-folded by disharmonic tight and isoclinal folds (Fig. 15-

1B) whereas the equivalent stratigraphic interval in nearby Wuhe section is undeformed (Fig. 15-3C). The carbonate interval is overlain by black shales and C_{org}-rich "algal coal" of the upper Doushantuo Formation in both sections (mined in Wuhe section) (Fig. 15-3D), with those at Maoping again slump-folded and overlying the top of the carbonate section with an angular contact. In the both locations, the contact to the overlying Dengying carbonates is marked by a few-cm-thick grey bentonite, dated at 550,42+-0,78 Ma (Condon et al., 2005) above which follow thick-bedded shallow-water dolomites. In Maoping section, the basal 10m of the Dengying Formation involves (tuffaceous?) centimetre- to decimetre-thick, silt- to coarse-sand-grained, normally graded packstones, locally deformed by centimetre-sized, soft-deformation folds (Fig. 15-1D, 15-3D). These packstones are interbedded with decimetre-thick, fine-sand-supported carbonate slab conglomerate (Fig. 16A, 16B). In Wuhe section, the base of the Dengying Formation shows mudstones interbedded with wackestones and rare, sand-supported, mudstone slab conglomerates. Centimetre-sized, stromatolitic domes deform locally the mudstone bedding (Fig. 16C). The nearby, stratigraphically incomplete Neo-Tianjiayuanzi section is dominated in its lower part by suspension-settling sedimentation with black mudstones, involving towards the top thinly laminated silty dolomitized limestones. They are correlatable with silty dolomitized limestones at the top of Wuhe and Maoping sections (Fig. 15-2C). The sedimentary bedding in Neo-Tianjiayuanzi section is laterally continuous, and no slump folds have been observed. However, the ten to 30m thick, horizontal, well-bedded black limestones show local wedge-shaped beds (Fig. 15-2B) due to low-angle intraformational discontinuities.

3.2.2. Orientation of folds

At Maoping and in the lower part of Wuhe section, the Doushantuo and Dengying Formation carbonates are large-scale folded in tight and isoclinal folds. However, it is not clear whether deformation in the Dengying carbonates is soft-sedimentary or tectonic. Open fissures and (sub)-recent euhedral calcite fracture fills at Maoping section suggest that at least some major-offset faults which complicate the stratigraphic sequence are due to Quaternary and major but local gravitationally-induced landslides along the slopes of the steep and old Yangtze River valley. Doushantuo Formation folds axes of Maoping section trend approx. 120° (Fig. 17), after correction for tectonic dip, and differ significantly from the slope environment of the Yangtze platform, which shows an axial fold direction of 30°-35°, with a dip towards SE.

3.2.3. Presence of gravity-related sedimentary deposits

Facies attributable to gravity instabilities in the Doushantuo Formation include normally graded wackestones interbedded with shales and mudstones, suggesting high-density currents with decreasing energy below wavebase. In addition, mud-supported conglomerates including dm-sized intraclasts, interpreted as mass-flow deposits, are common.

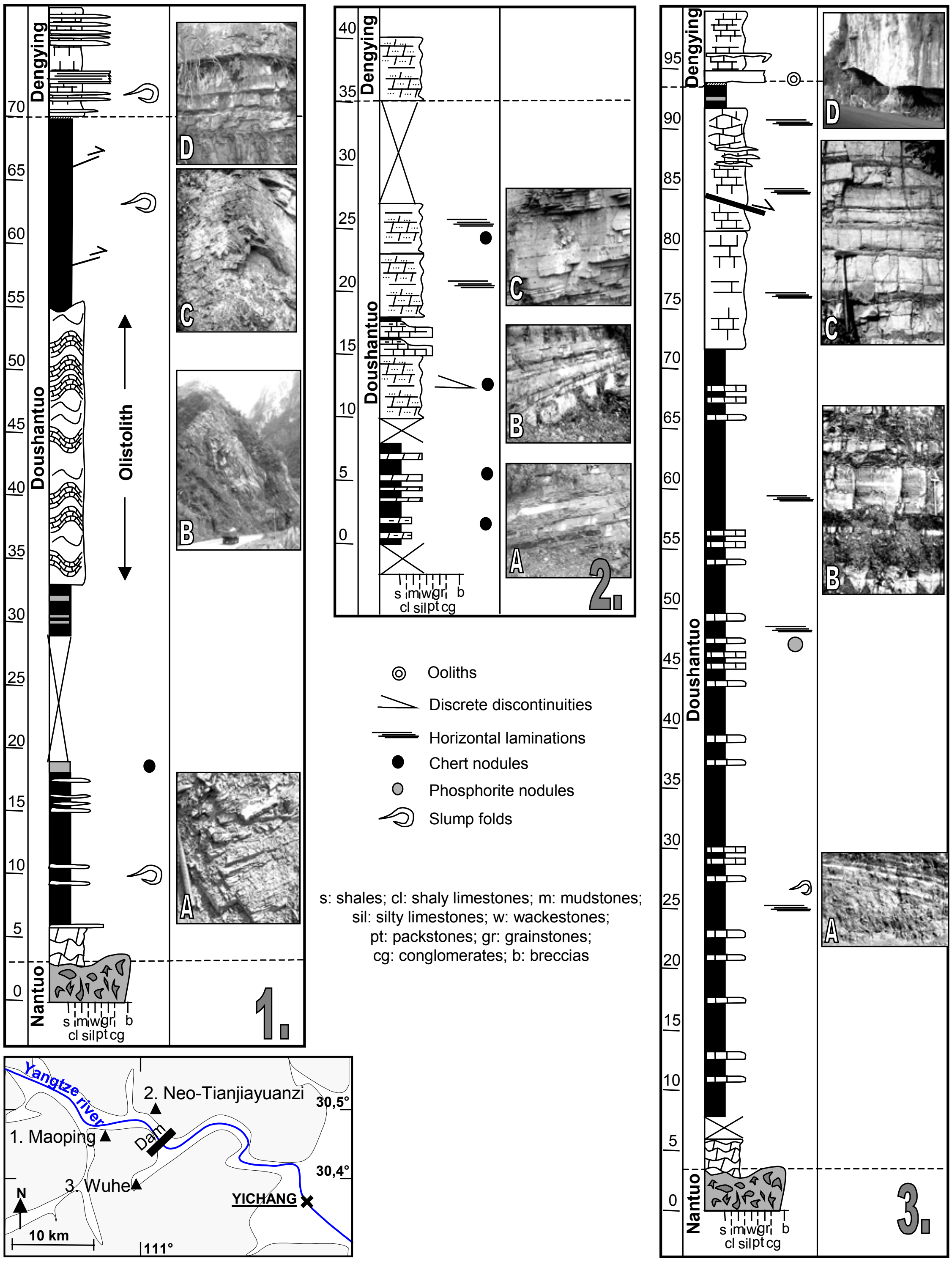

Fig. 15. Stratigraphic columns of (1) Maoping, (2) Neo-Tianjiayuanzi, and (3) Wuhe sections, Hubei province located approx. 10 km from each other. The sections are arranged from the middle slope with well-developed folds (Maoping section) to the basin edge with undeformed bedding (Wuhe section), via the upper slope with discrete discontinuities (Neo-Tianjiayuanzi section). The presence of several reverse faults (not shown) approximately doubles the thickness of black shales/silty limestones in the Wuhe section. 1.A. Type aspect of black shales; 1.B. Large-scale folds in limestones; 1.C. Slump fold in shales. 1.D. Contact between Doushantuo and Dengying Formations; 2.A. Interbedded shale and dolomite; 2.B. Silty dolomite with chert nodules; 2.C. Discrete discontinuity in dolomite; 3.A. Disturbed shale interval; 3.B. Interbedded dolo-limestone and shale; 3.C. Thinly laminated dolomite interbedded with cm-thick, kerogen-rich shale. 3.D. Doushantuo Fm coal mine overlain by Dengying Fm dolomite. (Photographs from Maoping and Wuhe: C. Heubeck; Photographs from Neo-Tianjiayuanzi: E. Vernhet).

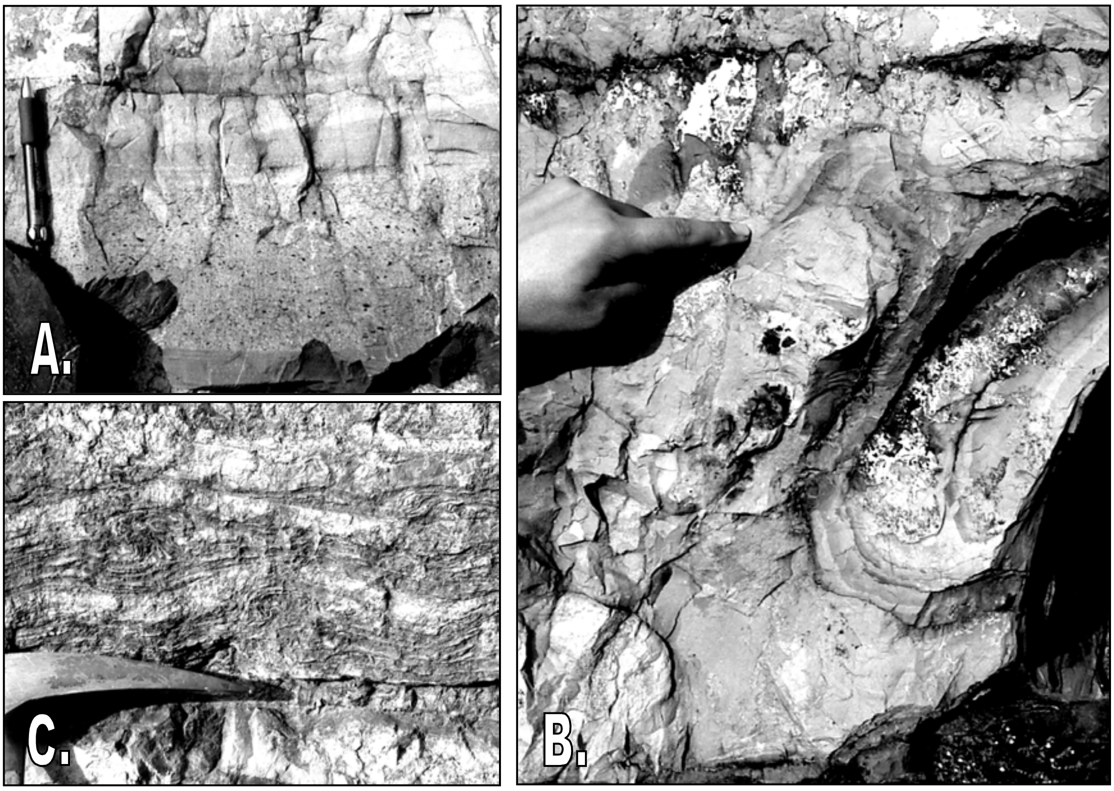

Fig. 16. Outcrop photographs. A., Mud-supported debrite (Dengying Formation, Maoping section, Hubei province); B., Decimetre-sized slump folds (Dengying Formation, Maoping section, Hubei province); C., Centimetre-sized stromatolites (Dengying Formation, Wuhe section, Hubei province).

The overlying Dengying Formation limestones in Maoping section also show sand-sized-matrix-supported conglomerates interbedded with the mudstones.

3.2.4. Structural setting

Two major fault directions, striking ENE (1, Fig. 18) and N to NNE (2, Fig. 18), respectively, affect the Proterozoic and Cambrian terrains. According to Ma et al. (1984), this fabric results from continental accretion during the end of the Mesoproterozoic and the early Neoproterozoic. Wang and Li (2003) describe Neoproterozoic rifting, in the same orientation as the Meso- and early Neoproterozoic faults documented by Ma et al. (1984) (Fig. 18).

3.2.5. Interpretation

During the Doushantuo Formation, the southern margin of Yangtze platform evolved as passive margin (Wang and Li, 2003), however, ancient faults may control the development of some facies. For example, the slope environment of the Yangtze platform follows the line of the major faults (1 and 2, Fig. 18), which stretches from Zhenyuan (Guizhou province) to Nanchang (Jiangxi province), via Zhijiang and Xupu (Hunan province).

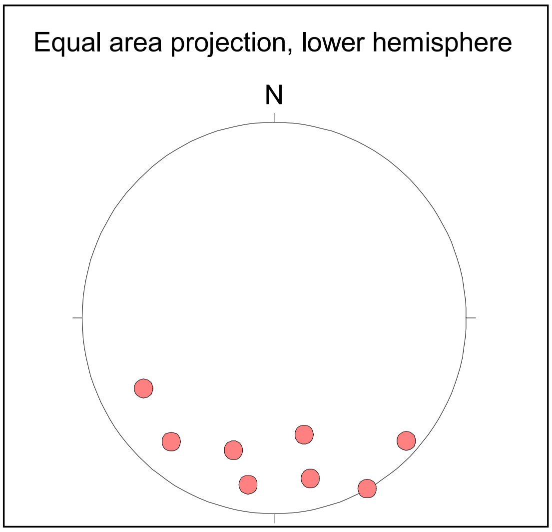

Fig. 17. The stereogram represents eight measured normals to bedding planes in folds (Maoping section) with fold axes orientated approx. 120°.

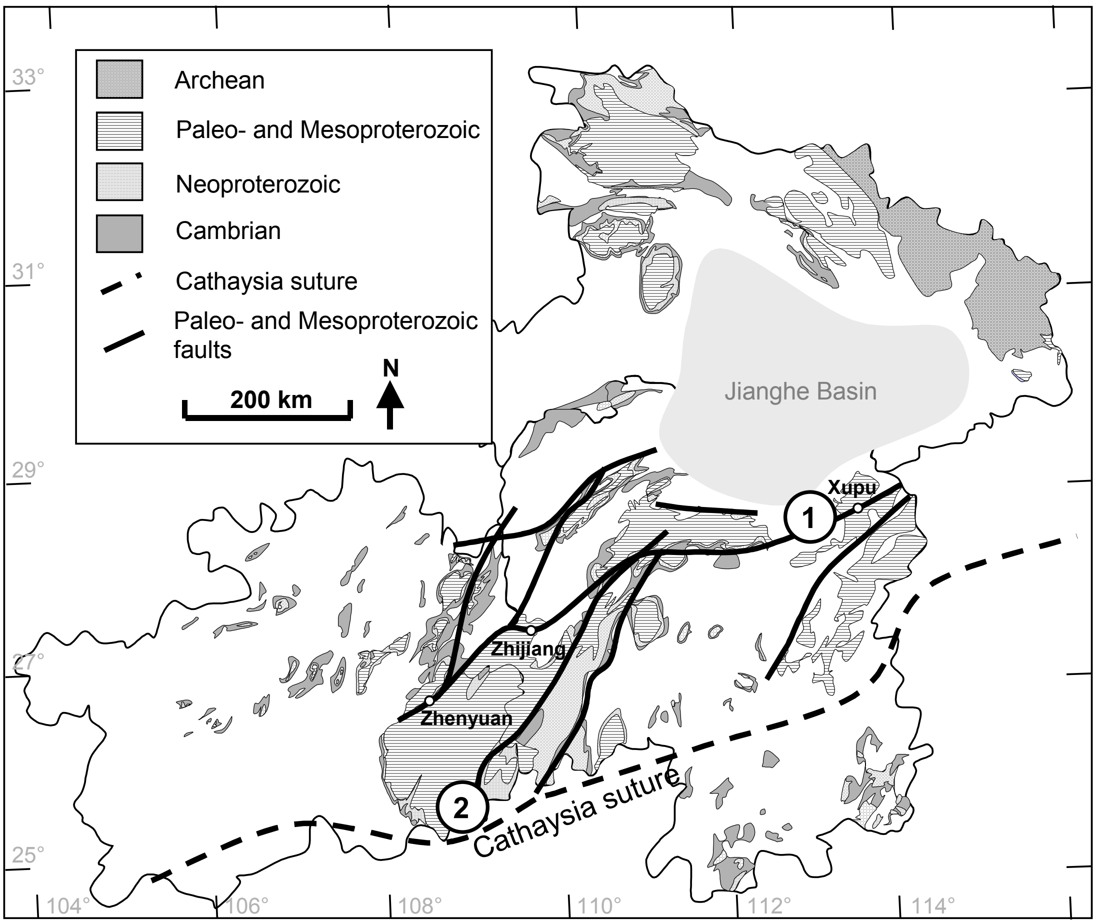

Fig. 18. Tectonic map showing the major Mesoproterozoic faults affecting the southern Yangtze platform. 1 and 2 indicate the two main directions of faults. The difference of bathymetry on the Ediacaran shelf may have been inherited from these faults. Modified from Ma et al. (1984).

Sedimentary structures suggest that the Maoping, Neo-Tianjiayuanzi and lower part of the Wuhe sections represent an unstable slope environment, where gravity movements disturb the autochthonous black shales sedimentation. Thus, I interpret the carbonate interval of the middle Doushantuo Formation at Maoping section as a large, plastically deformed olistolith or slide sheet (Coniglio and Dix, 1992; Stow et al., 1998) of semi-consolidated silty limestones, derived from an unexposed part of the shelf but corresponding stratigraphically to the “in-situ“ silty limestones interval at Wuhe and Neo-Tianjiayuanzi sections. The low-angle discontinuities in the Neo-Tianjiayuanzi section affecting mudstones may represent basal slide planes of rigid packages. Thus, the upper part of the Wuhe section and the Neo-Tianjiayuanzi section represent the shelf and the top of the slope of an intrashelf basin, respectively. According to the average fold axis orientation, the slope in Maoping section shows a different orientation than the south-facing slope of the Yangtze platform several 100 km south. Therefore, the slope in Maoping section is part of an intra-shelf basin (or lagoon) system. Unfortunately, the paucity of outcrops in western Hubei province makes difficult to constrain the exact geometry of this basin. The pronounced difference in facies between Maoping and Wuhe sections, separated by only approx. 10 km distance, indicates the presence of a steep-sloped, possibly fault-bounded intra-shelf basin. The small basins on the shelf may be also constrained by inherited Early Neoproterozoic faults. The facies contrast between the Wuhe and Maoping sections continues in the lower Dengying Formation: in Maoping section, slope turbidites and debrites dominate the sedimentary record whereas Wuhe section limestones and mudstones, small-scale stromatolites, and occasional slab conglomerates appear to have been deposited in tidal environments.

3.3. Platform highs

Plan-parallel laminated (dolomitised) wackestones to packstones make up large parts of the Doushantuo shelf (Fig. 19A). However, high-energy, coarse-grained facies associations occur in Zhancumping section, Hubei province, Yangjiaping and Zhongling sections, northern Hunan province and in Weng’an section, Guizhou province. They involve (phos-) (oolitic-) grainstones/packstones with trough or planar crossbedding (Fig. 19B, 19C) interbedded with decimetre-thick, sand-supported breccias with centimetre- to decimetre-sized, elongated phosmicrite or mudstone clasts and (phos) sand-supported conglomerates with common, 8-to-65-mm-sized micrite pebbles. The base of conglomerates can show cracks filled by sandy matrix. Two-to-ten-cm-thick mudstones separate the high-energy deposits. Above erosive bases, they are commonly incorporated into the basal sections of overlying coarse-grained, rarely graded beds as up-to decimetre-long mud clasts in grainstones, as rounded pebbles in the conglomerates, and as centimetre-sized, angular clasts in the breccias. Mudcracks occasionally segment the thin mudstone beds (Fig. 19D). In Zhancumping and Yangjiaping/Zhongling sections, the high-energy facies occurs near the middle and at the top of the Doushantuo Formation, respectively. In Weng’an, almost the entire Doushantuo Formation consists of (oolitic) grainstones and conglomerates.

The dominant shelf sediments, subjected to winnowing by waves or currents (Clifton, 2003; Coffey and Read, 2004) are deposited above the limit of the fair-weather wave base (approx. 30 m) on the shallow shelf.

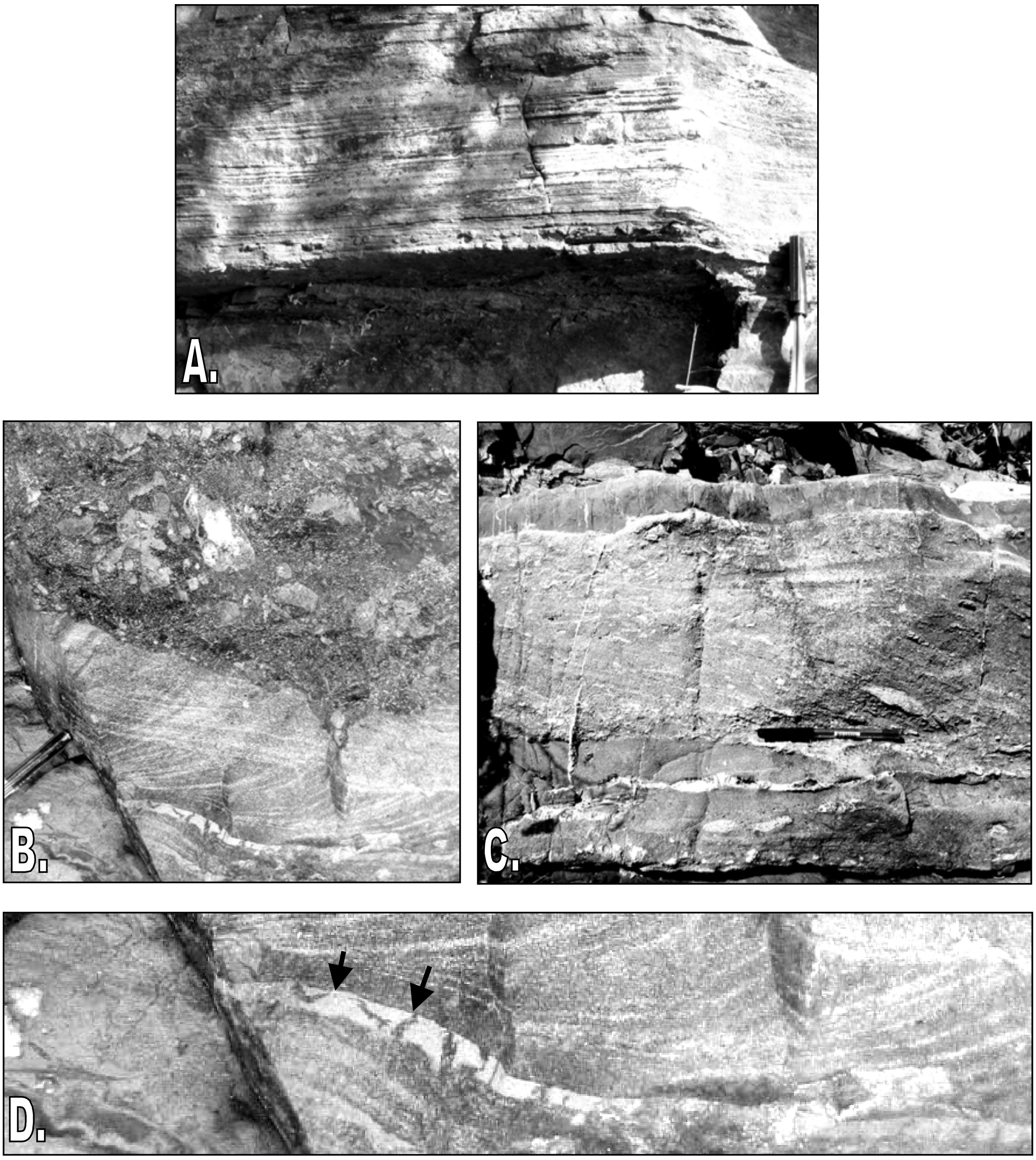

Fig. 19. Outcrop photographs. A. Plan-parallel laminated packstones are the dominant facies on the open shelf (Zhongling section, Hunan province), B. Trough-crossbedded phosgrainstones overlain by a storm-induced phos-conglomerate (Yangjiaping section, Hunan province), C. Sand-sized grainstone with planar, oblique crossbedding (Zhongling section, Hunan province). D. Very-thinly-bedded mudstones with mudcracks, interbedded with grainstones and conglomerates (Yangjiaping section, Hunan province).

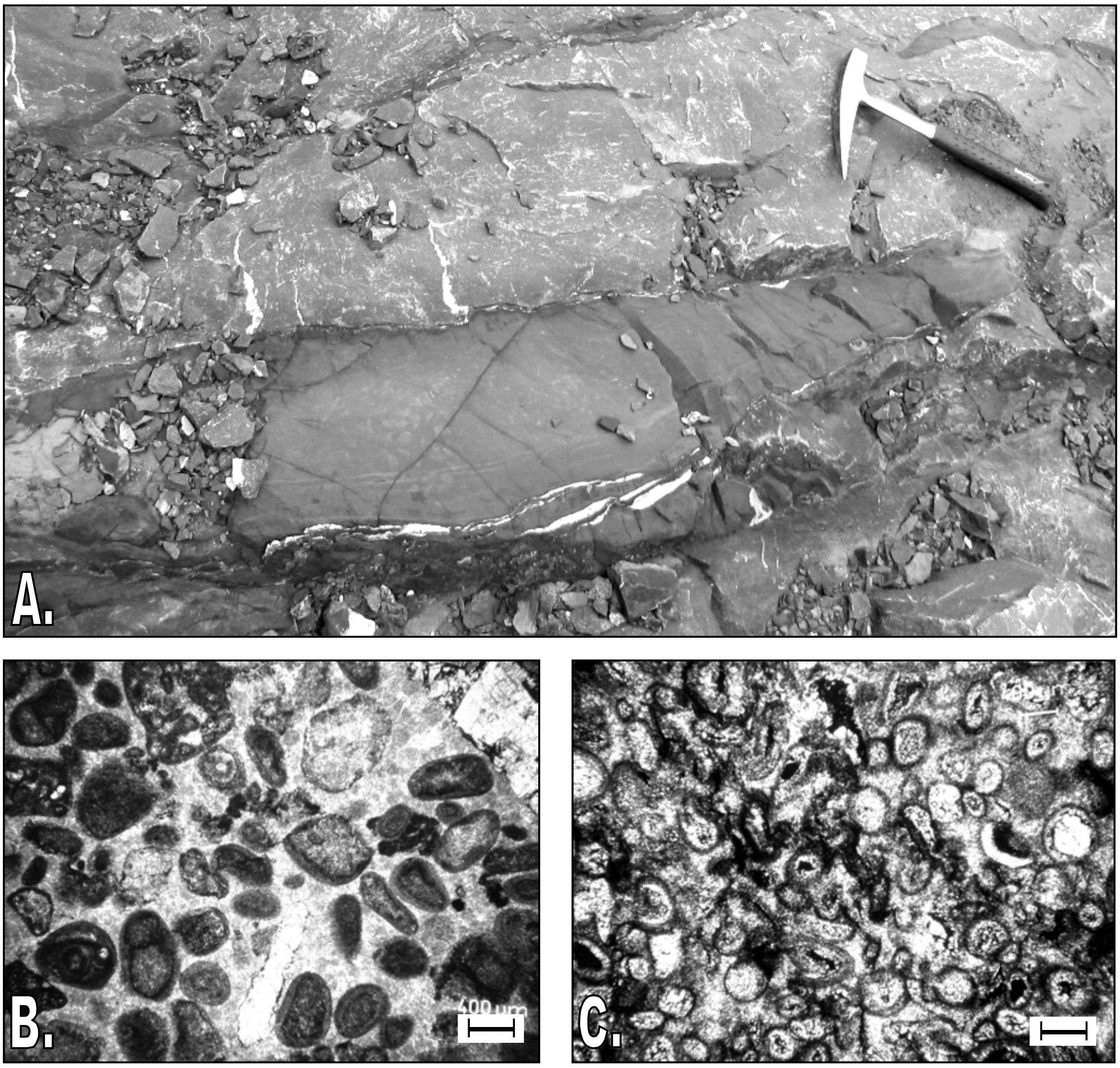

Fig. 20. A. Outcrop picture: oversized mud clast into a phosoolitic debrite. B and C. Thin section showing the oolitic grains of the debrite (Yangjiaping section, Hunan province).

The coarse-grained facies association describes an agitated environment which allows the formation of current ripples, such as near-shore or peritidal environment. Storm events produced breccias and slab conglomerates and eroded the underlying beds. The few thin micrite beds, locally segmented by mudcracks and interbedded with the coarse-grained facies implicate an environment subjected to periods without current, dominated by suspension settling and possibly periods of emergence such as in the upper part of an intertidal environment.

- Inner- and outer-shelf environments may have presented a sedimentary record rich in micrite intervals with rare deposit of storm-induced instabilities. In these environments, current-rippled sediments may have been deposited in tidal or shelf channels. Basal shear during storms on the thin beds of carbonate mudstones may have induced their segmentation. However, the dominant presence of coarse-grained facies appears to exclude these both environments.

- Shallow-water subtidal shelf is the domain of the horizontal-laminated wackestones/packstones, which dominate the sedimentation on the southern part of the Yangtze platform shelf. Cemented sediments of the coarse-grained facies association indicate a higher energy environment, shallower than the shallow subtidal shelf.
- Peritidal/shoal highs fulfill the conditions for sedimentation of the coarse-grained facies association. The relief that they create compared to the rounded shallow subtidal shelf is subjected to fair-weather and storm waves. However, the upper part of these intertidal highs may allow the deposition and desiccation of micrite.

3.4. Debrites as evidence for the presence of paleohighs

Two of the studied sections on the shallow-water platform show indications of substantial modification by mass-flows. Yangjiaping section shows thin- to very thick-bedded grainstones with cm-to-m-sized dolo- or phosmicrite mud clasts, interpreted as grain-supported debrites (Fig. 20A). The grains are phosintraclasts or phosooliths (Fig. 20B, 20C). The grainstones are interbedded with one-to-50-cm-thick dolo- or phosmicrites, which provide mud clasts for the debrites. High-energy, peritidal facies overlie these debrites. Several debrites are recorded in the stratigraphic column and represent approx. 10 m of deposition.

Sediment instabilities are common on shoreface environment. Storms or waves can cause shelf sediments to move basinward as shelf turbidites, incorporating decimeter-sized mud chips at their bases. There, the high-density and high-energy currents may incorporate oversized mud clasts from canyon walls or bases. The ooliths, formed in the most agitated shallow-water environment at not more than three to four meters water-depth (Scoffin, 1987; Greensmith, 1989; Tucker and Wright, 1990), argue for the peritidal/shoal depositional environment. Therefore, the debrites reworked sediments from a nearby oolithic shoal. The overall thickness of these debrite intervals and the change of oolith types may indicate the perennial character of the high.

3.5. Highs and intra-shelf basins at the shelf edge

In Hunan Province (Luoyixi, Xixi, Yanwutan sections), olistoliths involve shallow-water deposits including phosmicrites associated with evaporites (Vernhet et al. 2004b). A small part of the platform margin of Guizhou province, also reconstructed from olistoliths observed in Xikou and Wuhe sections, show decimetre-sized wave-ripple bedding draped by fine-grained siltstones (Fig. 21) and mudstones with mudcracks and exposure surface on the top, respectively.

The existence of a complex, segmented shallow depositional environment near the south-facing Yangtze platform shelf edge can also be inferred from the lithologies and facies in numerous shelf-edge-derived olistoliths and slide blocks in slope sections (Vernhet et al, 2004b). Indeed, the sedimentation of (phos)micrites and evaporites in Hunan province sections (Xixi, Luoyixi and Yanwutan) suggests a shallow-water environment, possibly even subjected to evaporation, such as a protected lagoon. In turn, the presence of enclosed intra-shelf basins on the shelf margin implicates the presence of highs acting as barriers (Vernhet et al., 2004a). The facies observed in the Xikou and Wuhe sections olistoliths document an intertidal environment subjected to high-energy currents and a shallow-water, low-energy lagoon with exposure periods, respectively.

Wuhe lagoon implicates the presence of highs acting as barriers. In contrast, the olistoliths of Xikou section may represent the facies deposited on one of these highs acting as barriers, on which the waves deposited high-energy, intertidal facies.

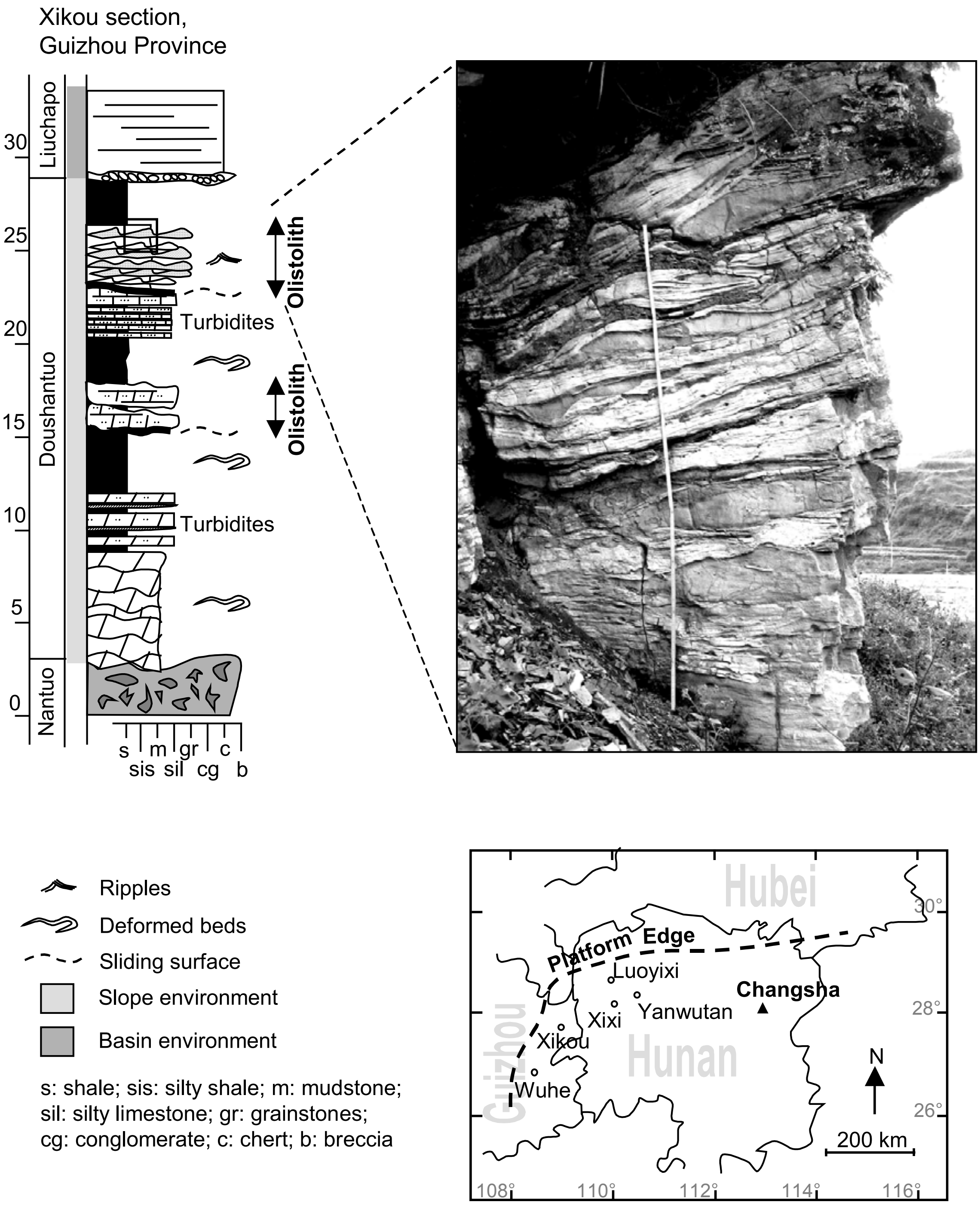

Fig. 21. The stratigraphic column of Xikou section, Guizhou province, documents the presence of olistoliths with shallow-water platform facies in the slope environment, suggesting peritidal environment at the shelf margin.

4. Discussion

4.1. What did the Doushantuo Formation Yangtze platform look like?

The facies map on the platform during Doushantuo Formation (Fig. 13) allows drawing an interpretative map of its paleoenvironments (Fig. 22). In map view, the platfom margin shows a right angle: in Hunan province, the slope is oriented east/west; whereas in Guizhou province, the slope is oriented north/south. The platform in adjacent Hubei and in Guizhou provinces shows similar features:

- Shallow-water platform where silty limestones with current-related sedimentary structures are deposited
- Intra-shelf basins filled by silty shales, shales interbedded with siltstones, and/or shales.
- Highs where peritidal facies are developed

Moreover, the olistoliths in the slope sections highlight the presence of peritidal environments (Xikou section, Guizhou province) and of shallow-water basins protected from the open ocean by a barrier (Luoyixi, Xixi and Yanwutan sections, Hunan province) near the platform margin. The rapid facies changes between the different locations argue for fault-bounded blocks limiting distinct sedimentary environment on the shelf of southern Yangtze platform the shelf (Fig. 22). The absence of transitional facies between the shelf and the slope indicates that the change between slope and shallow-water platform environments was abrupt, and thus, that the slope of the southern part of Yangtze platform may have been fault-controlled.

4.2. Origin of intra-shelf basins and highs

The Yangtze platform during Doushantuo Formation shows, at least in some parts, an irregular bathymetry with highs and intra-shelf basins. The approx. 30° and 70° trending slope in Hunan and Guizhou provinces reflects the orientation of major middle to late Precambrian faults (Fig. 18) (Ma et al., 1984; Wand and Li, 2003). Several studies have demonstrated the importance of passive-margin geometry for platform development (Santantonio, 1994; Bosence et al., 1998). A highs/basins geometry or tilted-blocks geometry allows developing shallow-water platform facies above the highs, slope facies on the fault zones, and basin facies between two highs. Therefore, the irregular bathymetry of Doushantuo Formation Yangtze platform may reflect the rifting history of the Yangtze platform. According to Wang and Li (2003), the Nantuo Formation was deposited during the final rifting stage and during the thermal subsidence of the margin. The Nantuo diamictites may have not compensated the relief due to the vertical movements. This residual relief influenced the Doushantuo Formation sedimentation. Moreover, the sedimentary record of the Dengying Formation in the literature sections (Bureau of Geology and Mineral Resources, 1987; 1988; 1990) show uniformly distributed shallow-water, dolomitized facies indicating that irregular bathymetry did not affect anymore shelf depositional conditions, except in deep intra-shelf basins such as documented at Maoping section. Therefore, compensation of the rifting-inherited paleotopography took place during Doushantuo and locally at the beginning of Dengying time. Thus, > 50 Ma have been needed to compensate the paleorelief.

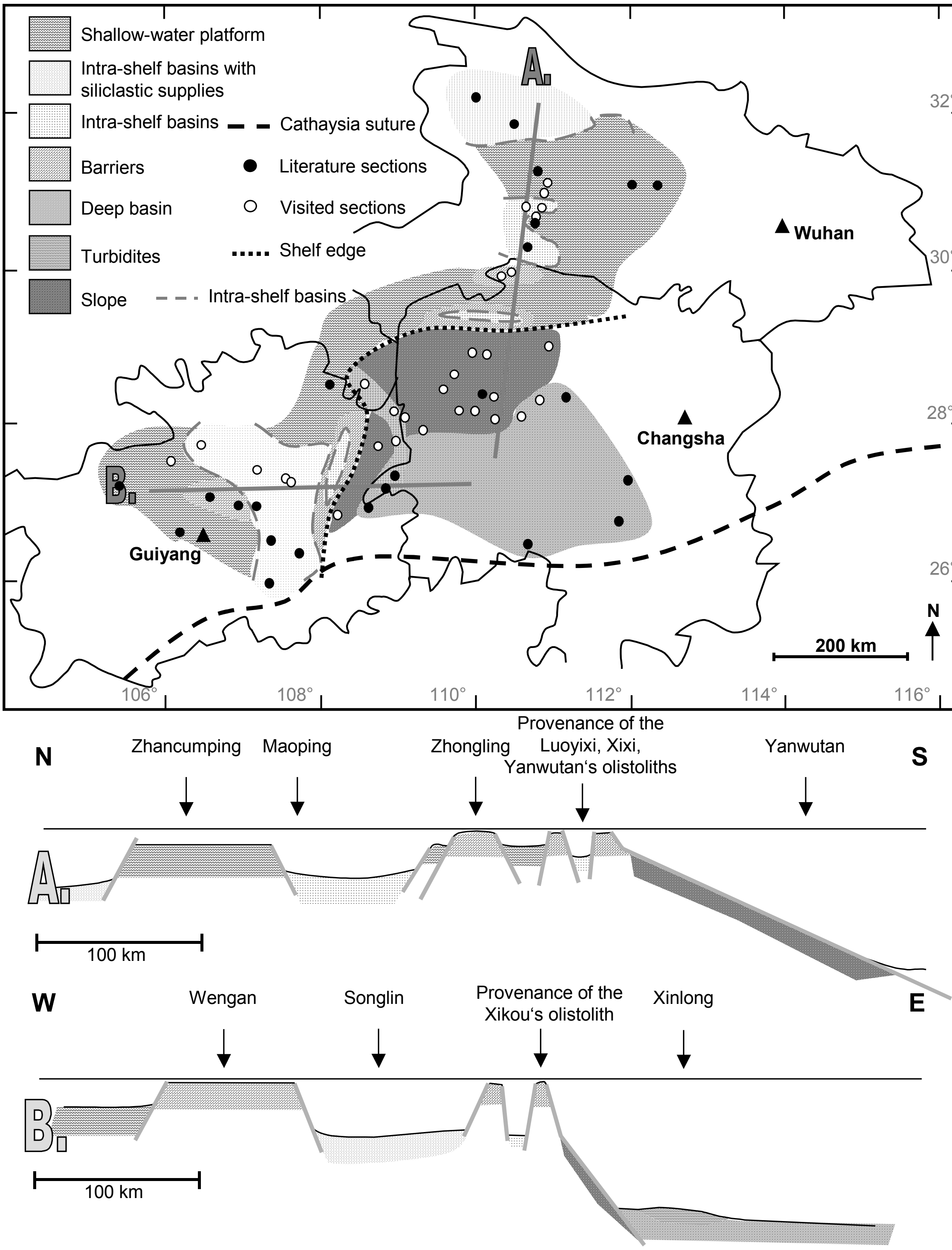

Fig. 22. Paleoenvironmental reconstruction of the southern part of Yangtze platform. A. North-south cross-section from northern Hubei province (shelf) to central Hunan province (basin). B. East-west cross-section from central Guizhou province (shelf) to central Hunan province (basin). The cross sections show the irregular bathymetry of the Yangtze platform due to different domains of sedimentation bounded by inherited faults.

However, facies analysis shows that facies variations are also related to sea level variations. Thus, only the sections where the depositional environment is quite constant during Doushantuo

Formation represent certainly a residual relief inherited of the rifting history of the Yangtze platform. In our study, Weng'an section represents a high, while Songlin and Maoping sections may represent depressions of unknown water depth. Moreover, the shallow-water, protected basins located near the shelf edge (olistoliths of Hunan sections) in the lower part of the Doushantuo Formation may have been affected by the presence of inherited highs.

5. Conclusions

The conclusions of this study are:

1. The shelf shows an important diversity of facies, which allow identifying three depositional environments: middle-depth shelf, highs, and intra-shelf basins, locally deep enough for developing slope facies.
2. Because of the sudden change in facies, the different depositional environment domains may have been fault-bounded.
3. The inferred irregular shelf bathymetry may be due to the geometry of the rifted-margin history of the Yangtze platform during the Rodinia breakup.
4. Locally, approximately 50 Ma were necessary to compensate the bathymetric differences on the southern Yangtze platform.