

Chapter 3. Sequence-stratigraphic analysis and sedimentary evolution of the Ediacaran Yangtze platform shelf (Hubei and Hunan provinces, central China)

Abstract

The Ediacaran Doushantuo Formation (ca. 635-551 Ma) overlies the Nantuo Formation diamictites, generally correlated with the worldwide Marinoan glaciation (approx. 660 Ma), and may give some keys for understanding the paleoenvironmental changes, possibly drivers of the Cambrian bioradiation.

Facies analysis focused on the evolution of a North-South transect in Hubei and Hunan provinces. Ten facies were identified and classified in five facies associations, each related to a depositional environment: (1) lagoon, (2) peritidal, (3) shoal, (4) shallow subtidal, and (5) basin/slope. The facies associations are organized into shallowing-upward sequences, which in turn are organized in second-order parasequences. The constant number of shallowing-upward sequences in the parasequence indicates an allocyclic origin of the facies variation, most probably related to eustatic movements. In contrast to previous studies, the black shales are interpreted as the regressive system tract. On the whole, it appears that the Doushantuo Formation Yangtze platform shelf has evolved alternately as a shallow-water carbonate-rimmed shelf and as an open shelf, according to sea level variations.

1. INTRODUCTION

The Ediacaran and Cambrian strata of the Yangtze platform are one of the world's foremost locations for studying the conditions and setting of Early Cambrian bioradiation. Indeed, numerous sites show exceptionally well-preserved soft-body fauna (Chengjiang biota, Yunnan province (Chen et al., 1991, Chen et al., 1999, Babcock and Zhang, 2001, Babcock et al., 2001, Hou and Bergstrom, 2003, Hou et al., 2004, Shu et al., 2004), Miaohu 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 sedimentary rocks have escaped major tectonic deformation. An understanding of the Doushantuo Formation environment may highlight the environmental conditions preceding the Ediacaran and the early Cambrian bioradiations.

This study develops a facies and sequence-stratigraphic analysis of seven measured stratigraphic sections of the southern margin of the Yangtze platform. Two depositional environmental models are proposed and a relative chronostratigraphy of the Doushantuo Formation environmental changes is presented. The aim of this study is to correlate sections on the Yangtze platform shelf with only very few absolute age dates and a poor fossil record, using sequence analysis.

1.1. Location and geologic setting

The studied sections are located in northern Hunan and central Hubei provinces (Fig. 23). They represent the shelf environment of the Yangtze platform during the Ediacaran Doushantuo Formation (Fig. 24).

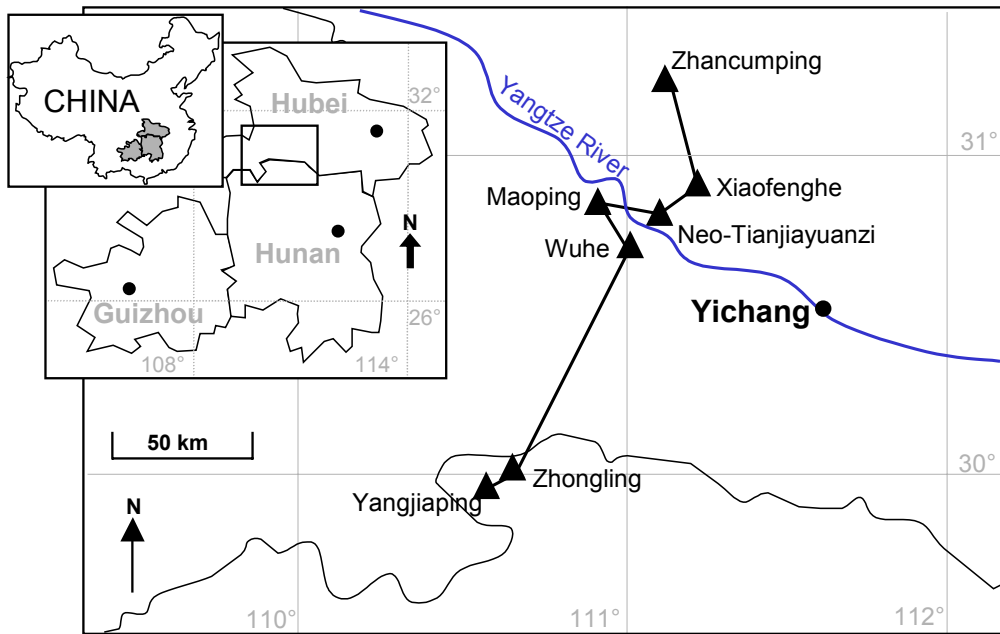


Fig. 23. Location of the study area. Triangles denote location of measured sections.

The present-day Yangtze platform spreads out between the Qin-Lin fault to the north, extending from Tibet to northern Anhui, and the Cathaysia suture to the southeast, extending from northern Guangxi to southern of Changsha in Hunan province. The North China craton to the north collided with the Yangtze craton during the early Triassic (Kenneth and Cheng, 1999), while the Cathaysia arc to the southeast collided with the Yangtze craton during the Silurian (Fig. 25). However, the Proterozoic and Paleozoic sedimentary cover of the Yangtze platform shows only moderate deformation. Cretaceous extension created large, fault-bounded basins filled with continental facies which locally cover the Proterozoic sediments. Generally, Proterozoic-Paleozoic strata are preserved in a thickness of several kilometers and show moderate and large-scale folding.

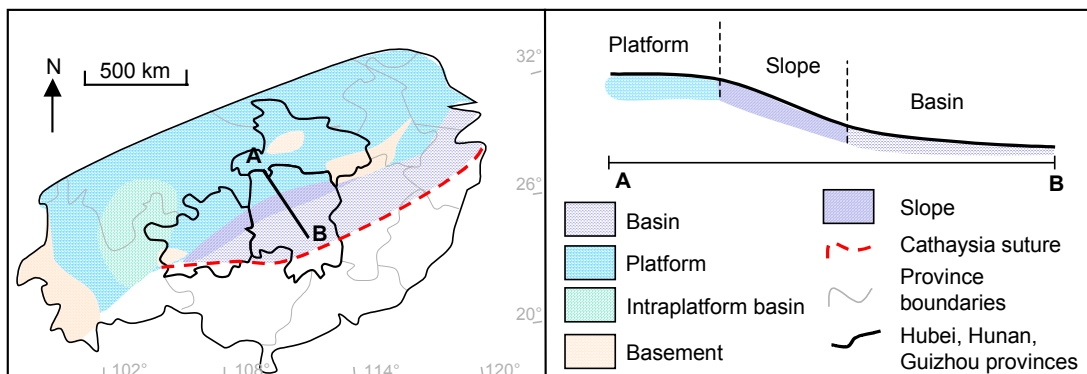


Fig. 24. Paleoenvironmental reconstruction of the study area during Doushantuo time (~ 635-551 Ma) (in part modified after Steiner, 2001).

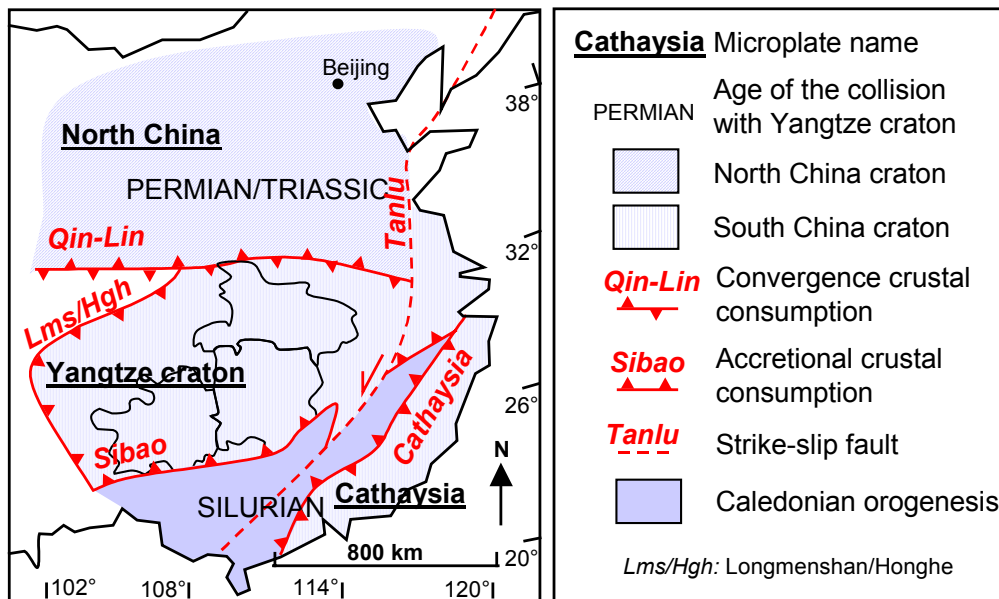


Fig. 25. Blocks forming present-day eastern China. The North China craton collided with Yangtze craton during the Permian/Triassic, while the Cathaysia arc collided with it during the Silurian. Yangtze craton plus Cathaysia arc form the South China plate (After Wang and Mo, 1995).

The location of the South China craton during the Ediacaran and its place in the Rodinia supercontinent, like that of many other small cratons, is poorly known. Li et al. (1995) 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. Because of the breakup of Rodinia, the global tectonics during the Ediacaran has been extensional, and the Yangtze platform has evolved as a passive-margin since the late Ediacaran.

1.2. Stratigraphic succession

Ediacaran Formation names in central China vary regionally, mostly owing to lithological and facies changes. Erdtmann and Steiner (2001) and Wang and Li (2003) propose a correlation table for the Yangtze platform from the Ediacaran to the Cambrian. The Ediacaran stratigraphic succession in Hunan and Hubei provinces (Fig. 26) begins with the Nantuo Formation. The glacial character of the Nantuo Formation is locally doubtful (Bahlburg, 2004; Dobrzinski et al. (2004); Eyles and Januszczak, 2004). Its age is also debated: Evans et al. (2000) and Wang and Li (2003); argue for a Sturtian glaciation (approx. 750 Ma, Frimmel et al., 2002) whereas Jiang et al. (2003c); Chen et al. (2004); Zhou et al. (2004) propose that Nantuo tillites are time-equivalent to the Marinoan glaciation (approx. 663 Ma, Knoll and Xiao, 1999). The thickness of the Nantuo Formation on the southern Yangtze platform ranges from 0 to more than 2000 meters. Its maximum is reported in northern Guangxi province (Wang and Li, 2003; Zhang, 2004). These partially glaciogenic sediments attracted 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; Donnadieu et al., 2004). A “cap carbonate” approximately six meters thick overlies the diamictites and forms the basal unit of the Doushantuo Formation.

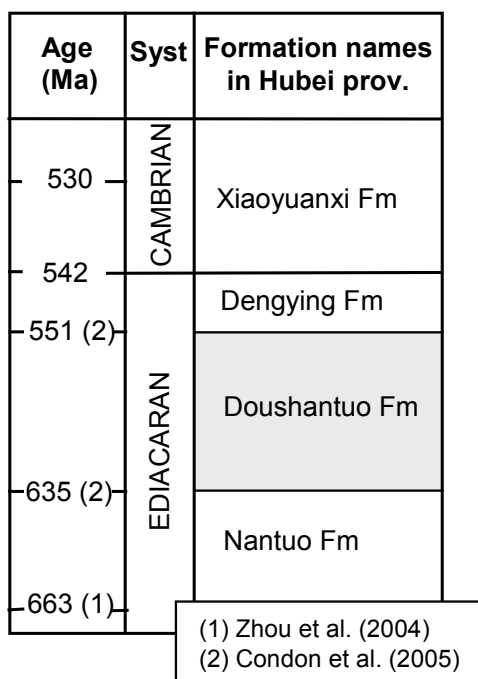


Fig. 26. Schematic stratigraphic column and correlation diagram for the Ediacaran and Cambrian system in Hubei Province.

These carbonates show unusual sedimentary structures (Sumner, 2002; Nogueira et al., 2003; Allen and Hoffman, 2005) and a negative $\delta^{13}\text{C}$ isotope anomaly (Knoll et al, 1993; Germs, 1995; Corsetti and Hagadorn, 2000), marking a sudden Ediacaran change from icehouse to greenhouse conditions. The Nantuo Formation diamictites and its “cap carbonate”, the basal unit of the Doushantuo Formation, extend regionally throughout the central and southern Yangtze Platform. The Doushantuo Formation on the Yangtze platform shelf includes black shales apparently deposited below wave base, shallow-water carbonates, and regionally traceable phosphorite horizons. The contact from the Doushantuo Formation to the overlying Dengying Formation is conventionally drawn at the first occurrence of light grey dolomitized limestones. Unfortunately, few visited sections show this contact. To the south, the dolomitized limestones of Dengying Formation grade downdip into silicified black shales of the approximately time-equivalent Liuchapo Formation, which is widespread on the Yangtze platform slope and basin environments of central Hunan and eastern Guizhou provinces.

2. FACIES ANALYSIS

2.1. Facies description

The Doushantuo Formation begins with a 4-to-6-m-thick dolomite, the so-called "cap carbonate", which overlies the Nantuo diamictites. These dolomites and diamictites have not been the object of this study and are only used as time markers to facilitate section correlation. The 10 facies are classified into five facies associations, summarized in Table 3.

Facies association	Facies	Description	Components	Grain descriptions	Bedding type	Sedimentary structures	Vertical sequence	Interpretation
Shelf environment								
Lagoonal	Facies 1	Laminated shales/mudstones wackestones interbedded with grainstones/packstones	(Calcareous) shales, medium sand-sized packstones/grainstones	mm-sized intraclasts, dolomite and opaque minerals	Thin-bedded, laterally continuous, non-cyclic	Thin parallel laminations due to biomats	5,7	Lagoon with clastic input
Peritidal	Facies 2	Biolaminated phosphorites, dolomite and/or patchy chert. Locally, interbedded with fine-sized grainstones	Silica, Phosphorite, Evaporites	mm-sized dolo- or phos- intraclasts. Stromatolitic clasts.	~10-cm thick, laterally continuous, non-cyclic. Lenticular bedding for the grainstones	Bio-laminations, desiccation structures as mudcracks and "tepees"	7	Edge of lagoon with emergence periods
	Facies 3	Phosmicrites with evaporitic dolomiticrites. Collapse and micro breccias.	Apatite cement, dolomite micrites, evaporites	cm-to-dm-sized phos-intraclasts	Laterally discontinuous, lenticular bedding	Collapse breccias, evaporite-induced convolutes	2	Peritidal, shallow-water lagoon edge, evaporitic conditions, eolian influences
	Facies 4	Phosgrainstones with lenticular dolomiticrites	Phos- intraclasts, biolaminations, dolomiticrite, apatite cement	mm-sized, very well-sorted phosintraclasts	Laterally discontinuous, cm-thick lenticular bedding	Common convolute bedding in the dolomiticrites	1,3	Peritidal lagoon edge. Evaporitic conditions
Shoal	Facies 5	Breccias, debris and conglomerates	Dolomite micrite, (phos-) intraclasts, phosooliths, calclitic cement	cm-sized, phos- or dolo- intraclasts. mm-sized phosooliths and oncoliths coated by phosphorite around relic crystals, intraclasts or ooliths.	5cm-to-3m thick, limited lateral extent	Mass deposit, sometimes erosive base	6	Storm-induced instabilities
	Facies 6	Grainstones with trough or planar crossbedding	Dolo- and phos- intraclasts, calclitic cement	mm- to cm-sized phos- and dolo- intraclasts and/or phosooliths	5-to-20cm thick, limited lateral extent	dm-scale trough and planar crossbedding	5	Wave-influenced environment and tidal channel
Shallow subtidal	Facies 7	Medium sand-sized wackestones / packstones with horizontal laminations or trough crossbedding. Locally, thin-bedded breccia	Intraclasts, carbonate micrite matrix, evaporite (?)	Medium sand-sized dolo- intraclasts. Cm-sized phos- intraclasts in breccia	cm-to-dm-thick bedding, laterally continuous	Winnowing-induced horizontal laminations, cm-scale trough crossbedding	1, 4, 8	Above fairweather wave base (~30 m water depth)
	Facies 8	Cross-stratified grainstones/medium-sand- sized grainstones/packstones	Intraclasts, recrystallized dolomites, micrite	Medium sand-sized dolo- intraclasts	dm-thick bedding, cross- stratified, laterally discontinuous	Trough crossbedding	7	Sand banks (5 to 60 m water depth)
Basin/slope environment								
Basin or slope	Facies 9	Shales, shales interbedded with phosphorites and/or siltstones.	(Calcareous) shales, apatite cement, (calcareous) siltstones		Thin-bedded, laterally continuous, non-cyclic	Thin parallel laminations due to discrete changes in grain size	1, 4, 7	Basin and slope with turbidite deposits
	Facies 10	Shales, mudstones, wackestones/packstones, slump folds, olistoliths	(Calcareous) shales, fine- grained sand wackestones/ packstones. Varying in olistoliths		Thin-bedded, laterally discontinuous, non- cyclic	Thin, plan-parallel laminations, slump folds, varying in olistoliths	9	Slope with turbidite deposits and olistostromes

Table 3. Summary table of the Doushantuo Formation shelf facies. Numbers in the column "Vertical sequence" refer to facies in column 2.

2.1.1. Lagoonal facies association

The lagoonal facies association is represented by micrites interbedded with wackestones and rare packstones. At outcrop scale, facies (1) shows five-to-thirty-cm-thick, thinly laminated shales/phosphoritic or dolomitic wackestones interbedded with five-to-ten-cm-thick, fine sand-sized intraclast packstones/grainstones. The bedding is plan without an erosive base and laterally continuous. This facies interval varies between two and several tens of meters thick. In thin section, the wackestones show abundant, poorly sorted, and reworked dolomite or opaque crystals in a micritic matrix. Few well-shaped euhedral crystals are observable. The thin, kerogen-rich laminations are biomats, which locally drape dolomite crystals.

Facies (1) occurs in Zhancumping and Xiaofenghe (Hubei province) and in Zhongling and Yangjiaping sections (Hunan province). This facies evolves upward into high-energy, coarse-grained facies such as facies (5) and facies (7).

The principal characteristic of this facies is its organic-rich environment and the shale-dominated sedimentation. The few sand-sized packstones/ grainstones indicate instabilities in the lagoon, maybe due to storm events or nearby tidal channels (Sami and James, 1994). Because of the absence of clear emergence structures such as mudcracks or erosional surfaces, facies (1) argues for a permanently subaqueous environment. The development of biomats suggests sedimentation in the photic zone (approx. 100m water depth). However, the absence of gravity-related folds in the studied sections may indicate that the basin was not deep enough to develop a slope on these edges. The euhedral crystals indicate diagenetic dolomite.

Thus, this facies was deposited in protected environments of lagoon or mud banks. Few instabilities deposited packstones /grainstones in this lagoon. Because of its similarity with the deep basin environment (facies 9), the vertical facies succession must be studied.

2.1.2. Peritidal facies association

Three facies are included in this association. Facies (2) consists of 10 to-15-cm-thick beds of biolaminated phosphoritic wackestones with trapped, mm-to-cm-sized phosmicrite or dolomicrite intraclasts (Fig. 27A). This interval is 40 cm thick and its top shows an erosive surface with mud cracks. In thin section, laminations appear as kerogen-rich bands, which trap mm-sized, reworked, essentially phosphorite grains and few cm-sized stromatolite clasts. The matrix is phosmicrite.

Facies (3) consists of 2-to-40-cm-thick phosmicrite interbedded with dolomicrite and occasional, very thin-bedded, very fine sand-sized, well-sorted phosgrainstones (Fig. 27B). Locally, dolomicrite breccias with dm-sized phosphorite intraclasts are present. In hand sample, the dolomicrite represents more than 60% of the total rock volume. Locally, it shows cm-sized convolute deformation. Phosmicrite and phosgrainstones occupy the remaining 40%. In thin section, the matrix is phosmicrite. In the grainstones, the grains are phosmicrite clasts or phosoliths. The dolomicrite consists of equant, well-shaped, well-sorted, mm-sized dolomite crystals.

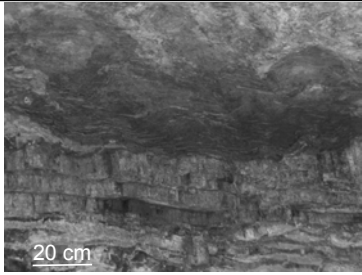
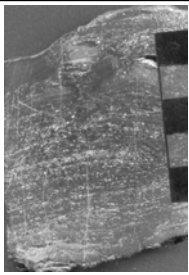
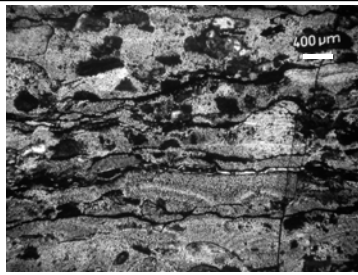
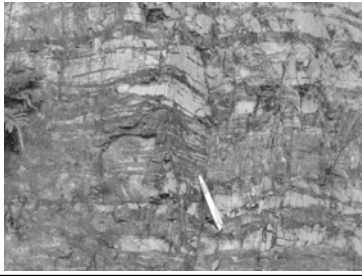
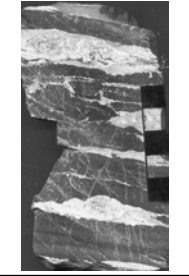
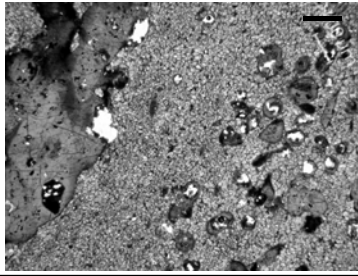
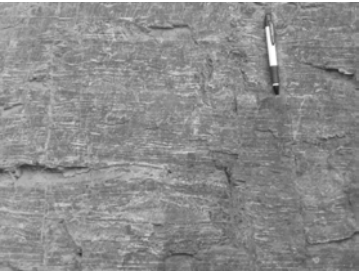
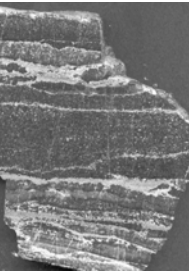
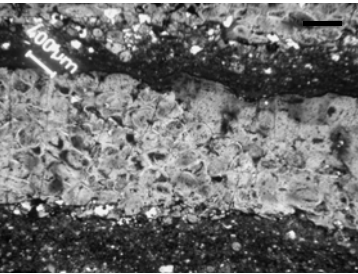


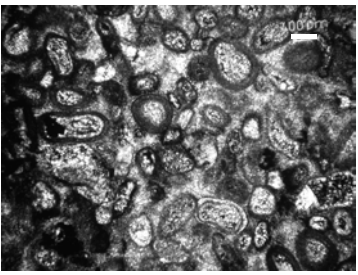
F.A.	Ref.	Outcrop pictures	Hand samples	Thin sections
PERITIDAL	A			
	B			
	C			
SHOAL	D			

Fig. 27. Outcrop, hand sample, and thin section of the facies 2 (A), 3 (B), 4 (C), and 5 (D). F.A. stands for Facies Association. A, B, and C: Zhancumping section, Hubei province; D: Zhongling section, Hunan province.

Facies (4) shows interbedded 2- to 5-mm-thick, thinly laminated, lenticular-bedded dolomicrite with 1- to 3-cm-thick phosgrainstone beds (Fig. 27C). The grains are black, rounded, mm-sized phosmicrite. They are well sorted. No sedimentary structures are observed in grainstone beds. The phosgrainstone represents, at least, 90% of the total rock volume. In thin section, the thinly laminated dolomite appears to consist of irregular kerogen-rich beds, attributed to biomats, which draped or trapped grains of underlying grainstone beds. Grains are mm-sized phosmicrite surrounded by apatite cement. Locally, only the apatite cement is visible. The thin fringe of calcite cement surrounding the grains is locally absent and the grains are in contact with each other. Facies (2), (3), and (4) are represented in Zhancumping section in Hubei province.

The biomats argue for low sedimentation rate, which may have facilitated the development of biomats. The biomats trap some rare phosphorite grains transported by water and/or wind. An erosional surface with desiccation cracks, marking the end of sequence I, may represent a period of emergence. Thus, the depositional environment of facies (2) represents a shallow-water peritidal facies on the lagoon edge.

The presence of evaporites, inferred from the presence of convolute structures (Fig. 28A) and from thin section analysis, induces the formation collapse breccias by precipitation and dissolution of salts (Blatt, 1992). The small and identical size of grains in the few thin beds of grainstones may indicate temporary eolian influence (Fig. 28A). The dominance of dolomicrite or phosmicrite suggests a low-energy environment, protected from wave and tide currents. The presence of breccia with phosmicrite chips may indicate that the environment was subject to sudden inundation due to storm action. The absence of biomats in facies (3) - although they are present in the underlying facies (4) and the overlying facies (2) - may be due to the rapid precipitation of evaporite, which may block the development of biomats. Facies (3) is indicative of a very shallow-water environment, subjected to evaporation and to oversaturation of the water. In facies (4), the relationships between apatite cement and apatite grains in thin section indicate that the grains are formed in situ by segmentation and erosion selective of the apatite cement or by direct precipitation of apatite as round grains. Therefore, these grainstones are not necessarily indicative of an agitated depositional environment. The absence of sedimentary structures in the grainstones supports this idea. Between periods of phosphogenesis, biomats in dolomite cover the phosgrainstones. Compaction has dissolved the calcite cement fringe between the grains without deforming the grain shapes.

All these facies have been deposited in a shallow-water lagoon. The depositional environment shallowed upward from facies (4) to facies (2). Facies (2) represents the most proximal part of the lagoon edge, which underwent emergence periods.

2.1.3. Shoal facies association

Facies (5) includes coarse-grained facies as such breccias and debrites interbedded with facies (6) and thin-bedded mudstones, segmented by mudcracks. Breccias are ten- to 30-cm-thick and dolomicrite-supported, with mm-to-cm-sized, elongated, flat, phosphorite or dolomite intraclasts. Debrites (Fig. 27D) represents sand-sized (coated) grain-supported conglomerates with three- to ten-cm-thick rounded phos- or dolomicrite pebbles. Locally, m-scale mud boulders are present. Stylolites are abundant. In thin sections, it appears that dolomite crystals, micrite fragments, or older ooliths may form the core of ooids. Oncoids are also common. One to several rings of phosmicrite may coat the grains; however, each debrite shows well-sorted, coated grain types. Calcite cement separates the grains.

Facies (6) consists of 10- to 30-cm-thick, sand-sized (oolithic) grainstones with dm-sized trough or planar crossbeds (Fig. 28B). The grains can be phos- or dolomicrite intraclasts or coated. Single coated grains are common. Oncoliths are rare. The grains are generally well sorted, mm-sized in the grainstones with trough crossbedding, in contrast to the planar-crossbedded grainstones. The contact between the grainstones and the underlying deposits is generally sharp and tabular.

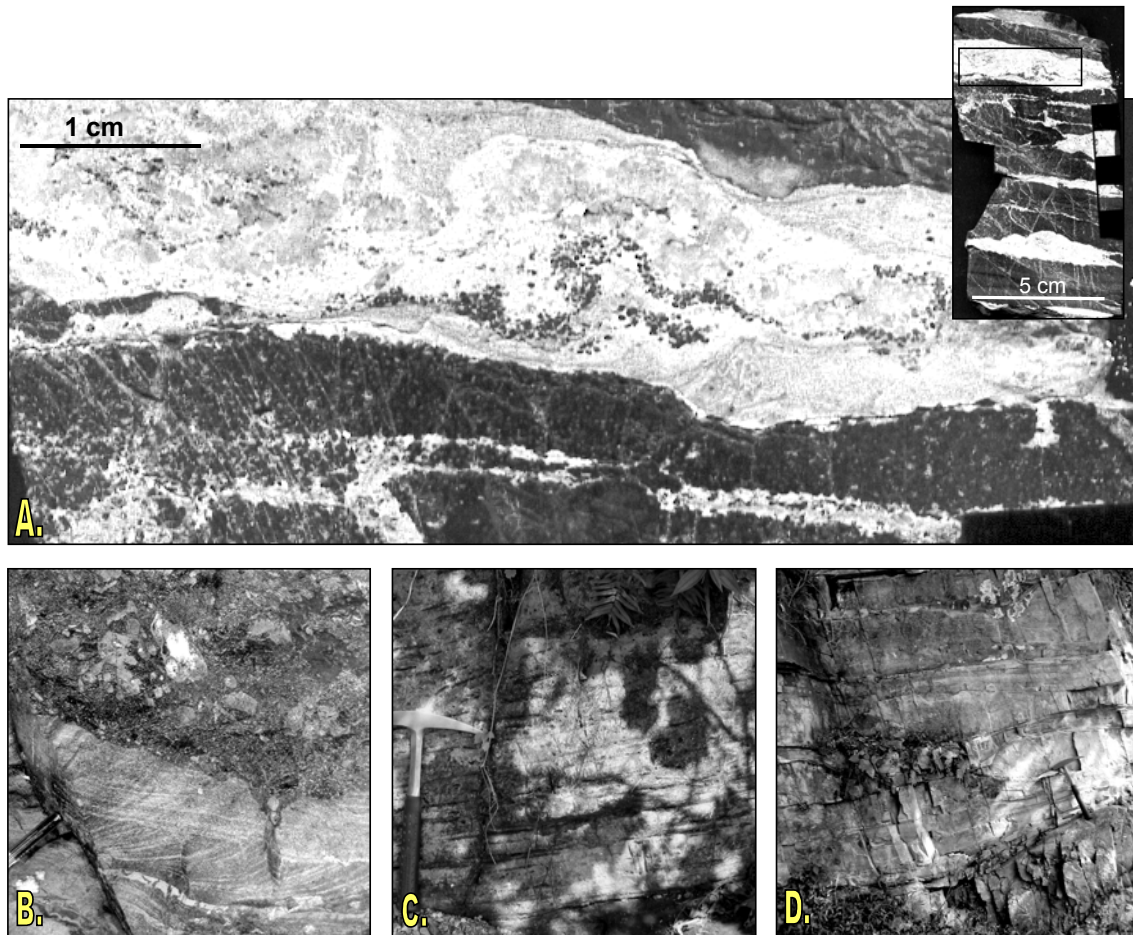


Fig. 28. A. Detail of facies (3) showing convolute bedding due to the former presence of evaporite. Note also the very small grain size in the grainstone, which may be interpreted as eolian deposits (hand samples, Zhancumping section; Hubei province). B. Trough-crossbedded grainstone of facies (6) with an overlying grain-supported conglomerate with cm-sized mud clasts corresponding to facies (5) (Yangjiaping section; Hunan province). C. Example of plan-laminated packstones facies (7) illustrating the dominant facies on the Yangtze platform edge (Zhongling section, Hunan province). D. Trough cross-bedded packstones/grainstones interpreted as sand bank deposits (Zhancumping section, Hubei province).

Facies (5) and (6) are interbedded with 1- to 15-cm-thick, massive, grey, dolomite mudstones. Vertical mud cracks may segment the mudstone beds.

These facies are represented in Zhongling and Yangjiaping sections in Hunan province.

The facies association may indicate sedimentation in a shallow-water, high-energy environment as shown by trough crossbedding, suggesting migration of ripples. Planar crossbedding corresponds to a higher-energy regime and is common in tidal channels (Mueller et al., 2002). This environment was subjected to frequent storm events, which induced mass wasting and the deposition of breccias and debrites of facies (5). The nearby presence of an oolite sand bank is inferred from the presence of oolite grains in the debrite. Therefore, the depositional environment of this facies association may have been deeper than 4m, the maximum water depth for oolite formation (Scoffin, 1987; Greensmith, 1989; Tucker and Wright, 1990). However, the average coarse grain size in grainstones argues for a relatively shallower water environment than that of facies (7).

2.1.4. Shallow subtidal facies association

The shallow subtidal association includes two calcareous facies with current-related sedimentary structures. Facies (7) is sand-sized wackestone/packstone with tabular laminations or cm-scale trough crossbedding (Fig. 28C). The thickness of facies (7) varies from one to a few tens of meters. Facies (8) shows 30- to 100-cm-thick, large-scale cross-stratified, medium sand-sized, dolomitized grainstones (Fig. 28D). Diagenetic dolomites locally mask the initial lithology of the facies (8). At outcrop scale, these facies represent intervals of two- to three-meters and are not laterally extensive. Cm- to dm-sized trough crossbedding occurs.

Facies (7) dominates the shelf and is present in almost every visited sections of Yangtze platform shelf. Facies (8) is located in Zhancumping and Xiaofenghe sections in Hubei province.

Facies (7) and (8) were deposited in an agitated environment allowing the winnowing of sediment and their planar reorganisation. Coastal currents induced the formation and the migration of sand ripples and banks, formed under increasing current energy.

The continuous presence of current-related sedimentary structures in facies (7) indicates that sedimentation occurred above the fair-weather wave base, which may mean up to 30 m water-depth. Facies (8) corresponds to the deposition of sand banks formed by coastal currents, which reworked the sediments of the shelf. Such sand banks can form between 5 and 70 m water-depth (Reynaud et al., 1999; Trentesaux et al., 1999). They have a limited lateral extent and move quickly on the shelf, which makes it impossible to correlate these deposits from section to section.

2.1.5. Basin/slope association

The basin/slope facies association includes two facies. Facies (9) comprises 5- to 20-cm-thick, thinly laminated black (silicified) shales, locally interbedded with thin-bedded phosphorites and/or very fine-grained sandstones organized in rhythmite. These facies may be tens of meters thick and are laterally persistent. Facies (10) shows thinly laminated (silicified) black shales, locally interbedded with very fine-grained sandstones, dm-thick debrites, and shallow-water (dolomitized), gently folded limestones. These sediments are disturbed to different degrees by slump folds and/or by discrete unconformities.

These facies are laterally continuous but geographically limited to Maoping section. Facies (9) covers the “cap carbonate” in all visited sections. On outcrop, these deposits can reach several tens of meters in thickness.

These facies are interpreted as representing basin and slope environments. Facies (9), which directly overlies the “cap carbonate”, is inferred to result from the high sea-level stand following the Marinoan deglaciation (Allen and Hoffman, 2005).

Gravity-related sedimentary structures such as slump folds and discrete discontinuities indicate the development of slope in the intra-shelf basins (Coniglio and Dix, 1992). Then, the softly folded limestones are interpreted to be a shallow-water, platform-derived slide block corresponding to facies (7). This olistostrome may come from the edge of the intra-shelf basin represented *in situ* by the carbonate interval present in Wuhe section (Hubei province). Therefore, facies (10) indicates the presence of an intra-shelf basin deep enough to develop a slope.

2.2. Shallowing-upward sequences

In order to determine the factors responsible of the depositional environment, the facies have been organised in shallowing-upward sequences (Fig. 29, 30, 31, and 32) for extracting the eustatic variations from the sedimentary record. Locally, these sequences can be modified by erosion and/or lack of sedimentation. Comparison of shallowing-upward sequences with the sedimentary column of sections allows us to demonstrate the systematic evolution of the sedimentary record and to draw correlation lines.

Shallowing-upward sequences A, B, and C have an identical base: a thick (approx. 20m) interval of black shales (facies 9) overlying the “cap carbonate”. The sequences differ by the sediments above the black shales.

2.2.1. Shallowing-upward sequence type A

Facies are organised from base to top:

1. Phosgrainstones interbedded with dolomites and wavy-bedded laminations (facies 4),
2. Phosmicrites interbedded with dolomite containing evaporite (facies 3),
3. Interbedded phospackstones with biomat laminations. The top of this phosphorite interval is marked by an emergence surface showing mud cracks (facies 2).

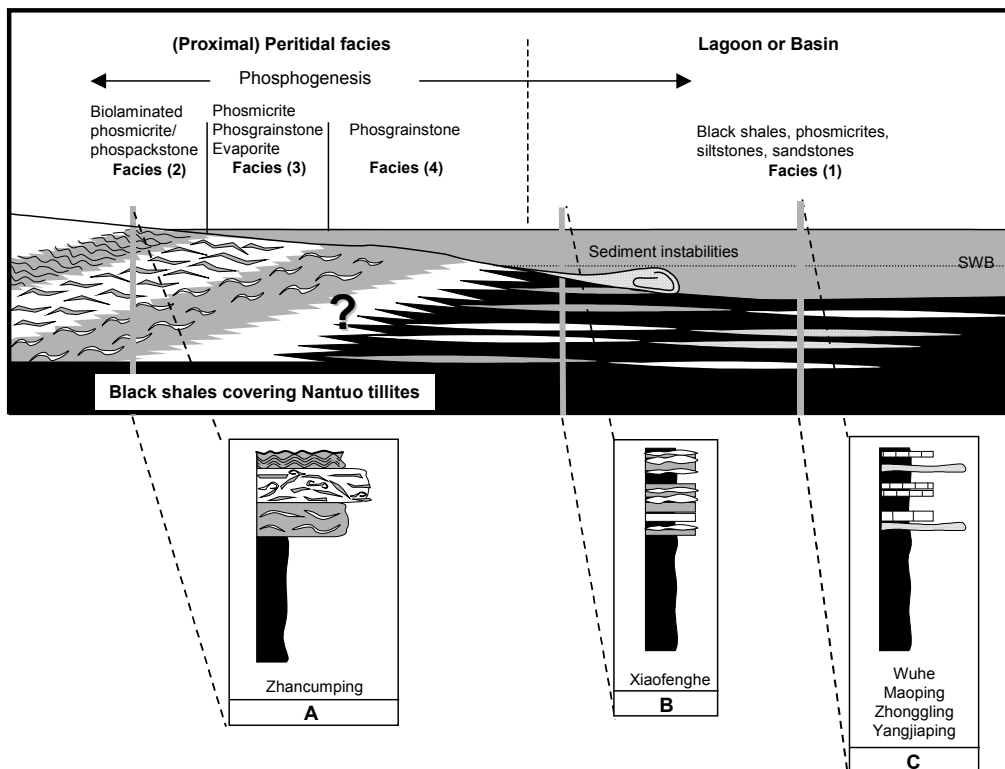


Fig. 29. Location of shallowing-upward sequences in a progradational depositional environment during parasequence I. SWB: Storm wave base. Sections and depositional environment are not to scale.

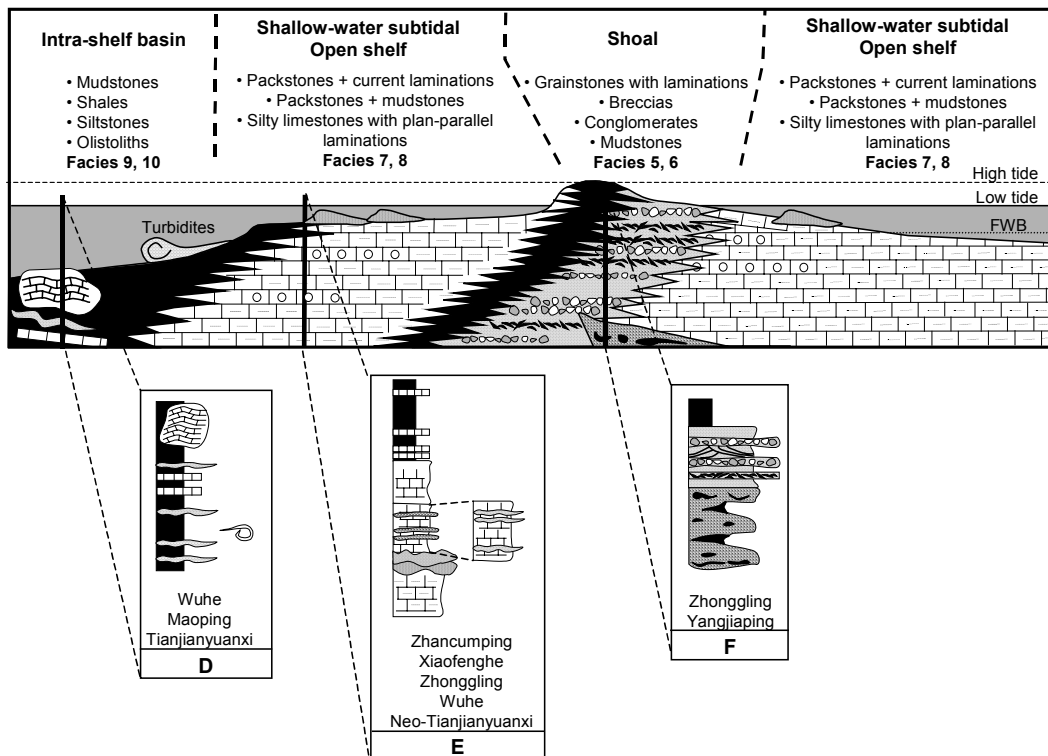


Fig. 30. Location of shallowing-upward sequences in a progradational depositional environment during parasequences II and III. FWB: Fair weather waves action base. Succession of facies is respected. Sections and depositional environment are not to scale.

Facies evolve from deep basin to peritidal depositional environments. This shallowing-upward sequence is observable in Zhancumping section, Hubei province.

2.2.2. Shallowing-upward sequence type B

The uppermost part of the sequence comprises interbedded shales, mudstones, wackestones/packstones, and phosphorites (facies 1). The presence of limestones indicates a shallower environment than that of the basal black shales (facies 9). This sequence is represented by Xiaofenghe section in Hubei province. The presence of phosphorites distinguishes this shallowing-upward sequence from the shallowing-upward sequence type C.

2.2.3. Shallowing-upward sequence type C

The uppermost part of the sequence shows interbedded shales, mudstones, wackestones/packstones, and patchy biolaminated cherts (facies 1).

2.2.4. Shallowing-upward sequence type D

Black shales dominate this sequence (facies 9), which is principally represented in Maoping section, Hubei province. They are interbedded with thin-bedded packstones/grainstones (facies 10). Slump folds are common. A thick interval of deformed limestones with large slump folds marks the top of this sequence (facies 10).

2.2.5. Shallowing-upward sequence type E

At the base of the sequence there occur high- to medium-energy deposits (facies 7, 8) deposited into a shallow-water subtidal depositional environment. They evolve upward in mudstones or interbedded black shales and mudstones (facies 1) characteristic of the lagoon environment.

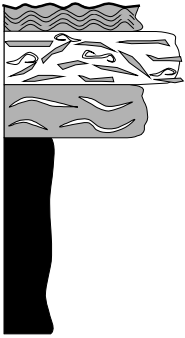
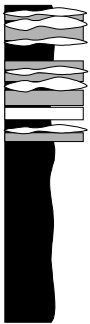
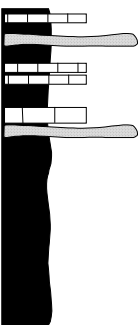
Ref.	Sequences	Facies description	Facies	Environment
A		d. Phosboundstones interbedded with reworked stromatolitic clasts and phosphorite grains layers	2	Peritidal
		c. Brecciated phosmicrite: phosmicrite clasts into dolomite matrix with convolute-like structures	3	
		b. Phosgrainstone with wavy-bedding: phosintraclasts grainstones interbedded with thin-bedded lenticular dolomites	4	
		a. Black shales	9	Lagoon or Basin
B		b. Thin-bedded phosmicrites interbedded with thin-bedded nodular cherts and black shales	1	Lagoon or Basin
		a. Black shales	9	
C		b. thin-bedded limestones interbedded with thin-bedded siltstones and black shales	1	Lagoon or Basin
		a. Black shales	9	

Fig. 31. Description of shallowing-upward sequences of-parasequence I. These sequences were deposited on the top of the Nantuo Fm. tillites. The black shales may represent the highstand sea level due to deglaciation; however, the presence of peritidal facies on top of parasequence I argues for a shallow-water depositional environment for at least the upper part of these black shales.

Ref.	Sequences	Facies description	Facies	Environment
D		c. Limestone olistoliths	10	Intra-shelf basin and slope
		b. Black shales interbedded with thin-bedded siltstones and limestones	9	
		a. Shales and siltstones with slump folds	10	
E		e. Interbedded black shales with black mudstones	1	Lagoon
		d. Black mudstones		
		c. Interbedded limestones with packstones or siltstones	7	Shallow subtidal upper shelf
		b. Crossbedded fine grainstones	8	
		a. Packstones with conglomerates	7	
F		c. Black shales	1	Lagoon
		b. Phosgrainstones with current-related laminations associated with thin-bedded dolomite matrix-supported breccias with phosphorite clasts and conglomerates	5, 6	Shoal
		a. Phosdebrites: phosoolites or phosintraclasts grainstones with mud pebbles	5	

Fig. 32. Description of shallowing-upward sequences of parasequences II and III. These series show the evolution of an open shelf during a drop of sea level. The lagoon facies on top of the sequences E and F indicate a change into the platform geometry, from the open shelf model to a rimmed shelf model due to the drop of sea level.

2.2.6. Shallowing-upward sequence type F

High-energy, shoal environment debrites, crossbedded grainstones and/or breccias (facies 5, 6) form the base of the shallowing-upward sequence type F. Mudstones/wackestones (of Dengying Formation) of a lagoon environment (facies 1) overlie the shoal deposits. The evolution of the depositional environment expresses a progradation of the system owing to a drop of the sea level.

3. INTERPRETATION

3.1. Shelf geometry

The facies analysis suggests that the southern Yangtze platform shelf evolved during Ediacaran Doushantuo Formation according to two geometries (Fig. 33):

1. A rimmed platform, which allows the development of back rim sedimentation characterized essentially by low-energy deposits dominated by suspension settling. A rim separates the lagoon and peritidal environments from the open ocean (Tucker and Wright, 1990). Rim facies

as domal, columnar microbialites or sand shoal have not been observed in outcrop, and the rim is inferred from the presence of low-energy facies (facies 1 to 4) and from the presence of shallow-water intrashelf basin (Vernhet et al., 2004a). The large dimensions of the Yangtze platform classify it as an epeiric platform, but without developing the classical facies distribution defined by Irwin (1965) or Eriksson et al. (2002). Instead, the Yangtze platform shelf is closer to the *mosaic* model proposed by Pratt and James (1986), with a large diversity of local depositional environments.

2. An open-shelf platform, where medium- to high-energy facies (facies 5 to 8) can be deposited by coastal currents and wave action (Jones and Desrochers, 1992).

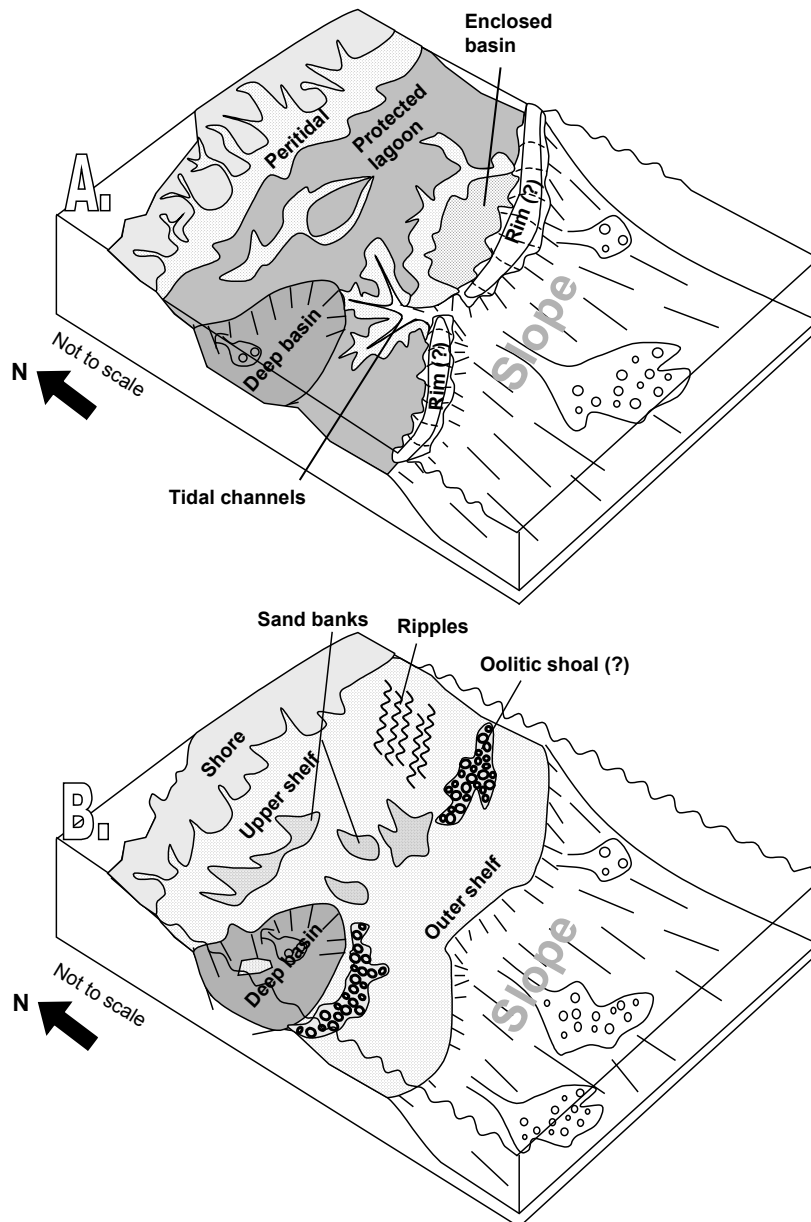


Fig. 33. Depositional environment models. A. Rimmed epeiric shelf model. The large dimension of the shelf allows the evolution of independent systems such as the intra-shelf basin (“Deep basin” in the block diagram) in Maoping section, Hubei province. B. Open shelf model. In the absence of a rim, the water entered the shelf with substantial energy and deposited grainstones/packstones.

3.1.1. Rimmed epeiric platform

The Yangtze platform rimmed shelf is characterized by a low-energy facies in the lagoon (facies 1), and temporary, local evaporative and emergent conditions in the peritidal zones (facies 2, 3, 4). Peritidal sand banks can create relief and isolate small shallow-water, intra-shelf basins. The sea floor of the rimmed shelf is irregular, and deep-water basins are differentiated locally (facies 9, 10). Vernhet et al. (2004a) showed that enclosed basins, protected by a barrier, occur at the platform edge, strengthening the existence of a rim (Chapter 5).

3.1.2. Open shelf platform

The facies 5 to 8 argue for a wave-dominated platform. The entire visited platform shelf was subjected to medium-energy currents allowing the deposition of packstones with sedimentary structures (facies 7). Locally, high-energy currents reworked sediment from the shelf and formed sand banks (facies 8) wandering on the shelf (Meng et al., 1997; Reynaud et al., 1999; Trentesaux et al., 1999) and oolite shoals (inferred from the facies (5) and few deposits of facies (6)). The oolite shoals may have been deposited at the edge of the platform and formed by wave energy (Chen et al., 2002).

3.2. Sequence analysis

The division of the sedimentary record of the sections in shallowing-upward sequences leads to recognition that Doushantuo Formation includes two and a half parasequences. Each complete parasequence is characterized by a full cycle of eustatic changes: each parasequence records a rise, then a drop of the sea level. The determination of parasequences allows the correlation of sections.

Shallow subtidal shelf (facies 7, 8) or shoal (facies 5, 6) facies associations ordinarily represent the transgressive system tract (the lower part of a parasequence), whereas lagoon (facies 1) or peritidal (facies 2, 3, 4) facies associations define the regressive interval at the upper part of a parasequence. In Zhancumping section; Hubei province, an emergence surface (SB-1) on the top of parasequence I marks the surface of maximum regression. Everywhere else, the surfaces of maximum flooding or regression are uncertain, and major shifts of facies marking the sudden rise of sea level indicate the boundary between two parasequences (SB-2) (Fig. 34). For Maoping and a part of Wuhe sections, Hubei province, the monotony of facies makes it difficult to determine parasequence boundaries. Here, an approximation will be proposed. The parasequences represent geographic lateral changes of time-equivalent, shallowing-upward sequences (Fig. 35).

3.2.1. Parasequence I

Three shallowing-upward sequences (A, B, and C) are recorded in parasequence I. Parasequence I follows the Marinoan deglaciation. The sudden sea-level rise, due to melting of the ice, induces the transgressive event of parasequence I, yet none of the visited sections shows a clear transgressive system tract. Indeed, black shales more probably represent the highstand interval and include the maximum flooding surface. However, the emergence surface (SB-1) representing

the parasequence I upper boundary, indicates that the upper part of the shales may have been deposited into a shallow-water lagoon, at least, in Zhancumping and Xiaofenghe sections.

The absence of facies change between the transgressive and the regressive shales argues in favour of a slow sea level fall into an enclosed lagoon protected from the open ocean currents.

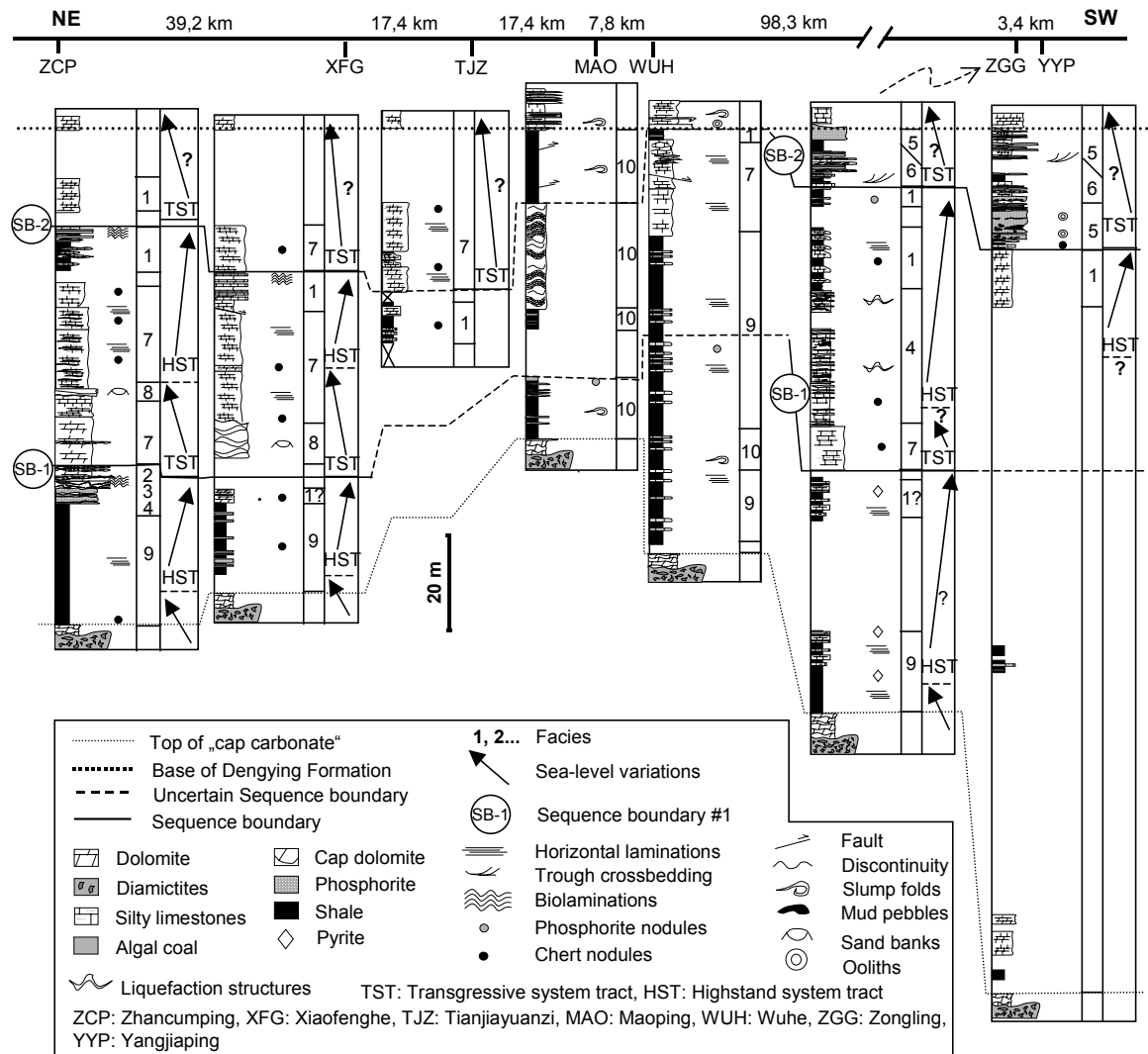


Fig. 34. Correlation of seven stratigraphic sections on the shelf. The correlation uses the sequence-stratigraphic analysis and two reference markers: the top of the “cap carbonate” and the generally accepted lower Dengying Formation boundary.

3.2.2. Parasequences II and III

Three shallowing-upward sequences (D, E, and F) define parasequence II. The shallowing-upward sequence type D with the slump folds indicates a slope environment implying the existence of an intra-shelf basin. The sliding block of limestones (facies 7) may be deposited during a regressive interval. The shallowing-upward sequence type E shows the classical facies evolution of shelf during a drop of the sea level. The transgression induces the inundation of the platform by a shallow open ocean. Thus, the wave energy allows the sedimentation of coarse-grained sediments as representative of transgressive system tract (TST). The transition between

parasequences II and I is clearly marked, in Zhancumping section, by an emergence surface corresponding to the maximum regression of parasequence I (SB-1) and the overlying transgressive packstones (facies 7) of parasequence II (TST). In Maoping and Wuhe section, the exclusive presence of facies 9 and 10 does not allow the identification of the parasequence II base. For the other sections, the occurrence of first carbonates (facies 8 and 7) marks the base of parasequence II. The low-energy facies of the lagoon (facies 1) or the limestone sliding block in Maoping section marks the upper limit (SB-2) of parasequence II. The lagoonal facies (facies 1) of parasequence II shifts into shallow subtidal open shelf (facies 7, 8) and shoal (facies 5, 6) facies of the parasequence III transgressive system tract (TST). Owing to the absence of a well-exposed transition between the Doushantuo Formation and Dengying Formation, the top of parasequence III is difficult or impossible to locate, but it appears to continue during the Early Dengying Formation.

The lateral facies change during the transgressive period of parasequence III ranges from shoal environment in distal Zhongling and Yangjiaping sections, Hunan province, to protected lagoon environment in the proximal Zhancumping section, Hubei province. In contrast, the transgressive period of parasequence II deposited only facies of the shallow subtidal, open shelf environment. Thus, the transgression of parasequence III is lower amplitude than the transgression during parasequence II. Therefore, it appears that in spite of three transgressive events, the Doushantuo Formation records a global regressive period or a progradation of the platform.

4. DISCUSSION

4.1. Origin and organization of sequences

The decametres-thick sequences described above are regionally correlatable (Fig. 34, 35). Therefore, they are controlled by global phenomena affecting the relative level of the sea. Miall (1997) describes second-order sequences as related to global tectonic movements such as the formation and the breakup of supercontinents. The Ediacaran marks the end of the Rodinia breakup and crustal extension. Therefore, the parasequences may have been second-order sequences with a period of 10 to 100 Ma (Miall, 1997; Einsele, 2000), which is consistent with the two and half sequences observed during the 84 Ma of Doushantuo Formation. However, the eustatism can be locally influenced by regional depositional conditions and higher-frequency sea level variations, which increase or diminish the global effect on the sedimentary record (Miall, 1997; Einsele, 2000; Rey and Hidalgo, 2004). Thus, the thermal subsidence following the end of rifting during the Marinoan glaciation and the beginning of passive-margin evolution during the Doushantuo Formation (Wang and Li, 2003) may have exacerbated the response of sediments to relative sea level rise and diminished the effect of a sea level fall. In absence of a finely spaced age dating network, an estimate of the sedimentation rate is impossible.

Thus, it is actually impossible to differentiate the part played by eustatic variations and the part played by thermal subsidence in the creation of space available for sediments (Calvet et al., 1990). Moreover, Vernhet and Heubeck (2004) document a segmentation of the platform presumably due to rift-history-inherited morphology. The local presence of depressions and highs

may have influenced the sedimentation and perturbed the eustatic-induced signal recorded by the deposits.

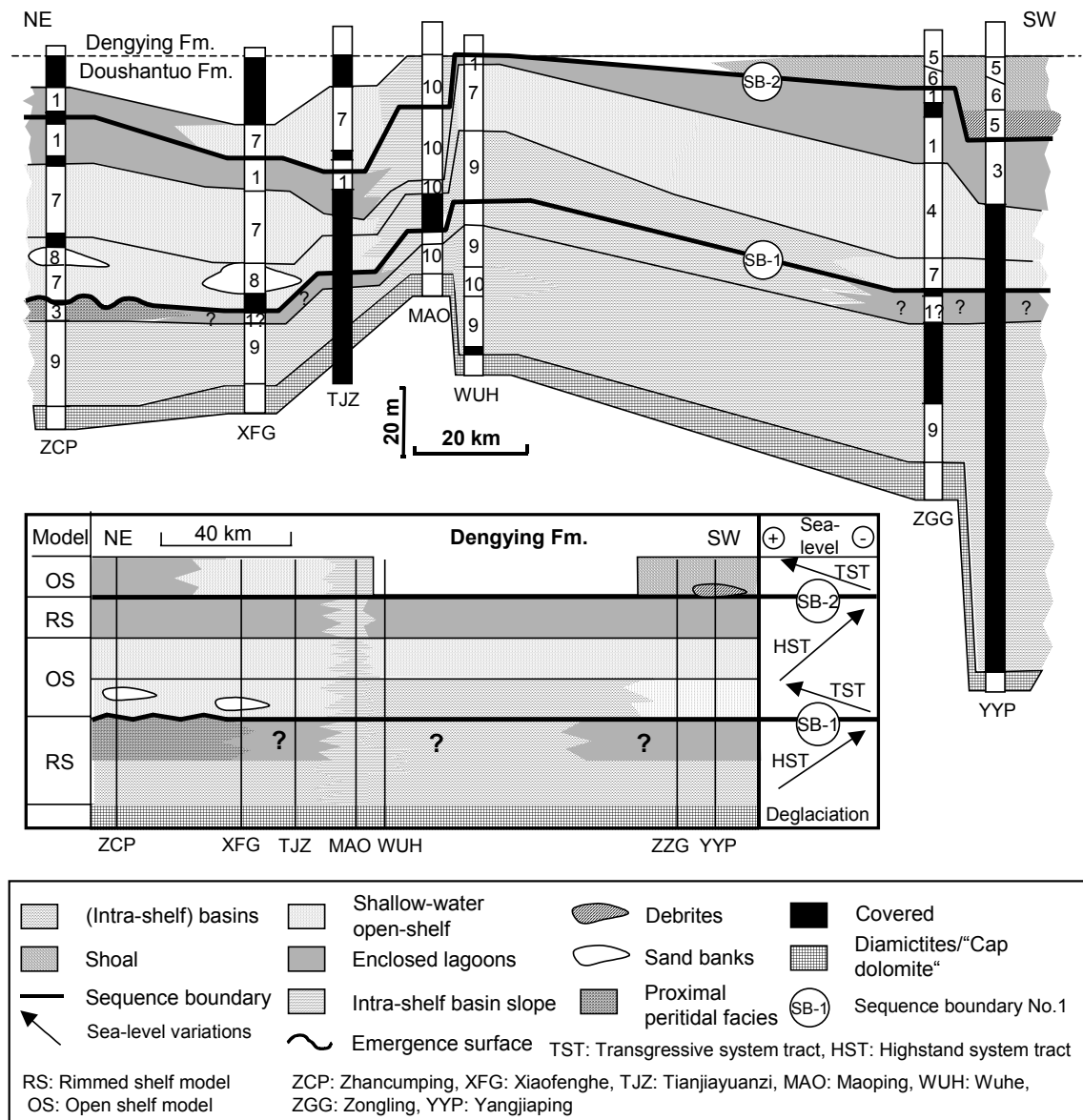


Fig. 35. Correlation of stratigraphic sections highlighting the lateral evolution of facies and their arrangement. The chronostratigraphic is a synthesised interpretation of the correlation diagram above.

4.2. Why do black shales represent regression?

Shales are present in low-energy environments where suspension-settling sedimentation dominates. In marine environments, they characterise deep ocean basins or shallow-water, protected lagoonal environments. In fossil-free sequences, only the association of facies allows the depositional environment of shales to be determined.

Ideally, the shallowing-upward sequence from deep ocean basin to inner platform of a carbonate shelf should include the following steps:

1. Basin deposits: shales, shales/mudstones interbedded with turbidite deposits.

2. Slope deposits with mudstone and/or shales with gravity-related sedimentary structures and turbidite deposits.
3. Outer shelf with mudstones with proximal turbidite deposits
4. Middle shelf with packstone/grainstones and current-related sedimentary structures
5. Upper shelf with high-energy, coarse grainstones and breccias
6. Inner shelf with black shales interbedded with siltstones/sandstones beds

Thus, the above facies evolution (1 to 6) shows that several intermediate facies may have been present between the black shales from a deep environment (1, corresponding to facies 9) and the silty (dolomitized) limestones/packstones/grainstones with current-related laminations (4, corresponding to facies 8), which dominate the shelf sedimentation and overlie the black shales (Sequence Boundary, SB-2). The interpretation of black shales as maximum flooding deposits implicates that two major shifts in the sediment succession occur: (1) below the shales, which is consistent with a transgressive period, (2) above the shales, because shallow subtidal facies overlie the deep-environment shales without transitional facies. By contrast, the shales interpreted as lagoon facies implicate only one shift of facies occurring during the rise of sea level and depositing the shallow subtidal facies of open shelf.

Then, the regional distribution of shales seems to have resulted from the peculiar geometry (rimmed epeiric platform) of the Yangtze platform rather than from a major transgression, and black shale deposits are the consequence of a drop in sea level, which produces a general decrease in the energy of the platform. Figure 36 shows the evolution of the shelf on the Yangtze platform during Doushantuo Formation time in relation to the sea level variations.

4.3. The Yangtze platform shelf geometry of the post-Marinoan deglaciation

In previous sections, it appears that the uppermost part of the black shales overlying the “cap carbonate” may have been deposited in a shallow-water environment. The same conclusion can be drawn from the presence of shallow-water intra-shelf basins at the shelf edge (Vernhet et al., 2004a). The very presence of a rim, inferred from the presence of shallow-water intrashelf basins at the edge, isolates shelf from well-developed slope environments, excluding the possibility of ramp geometry (Jiang et al., 2003a) in Hunan and Hubei provinces.

Do black shales represent a deep environment and a high sea level? Yamazaki et al. (2004) show that the “cap carbonate” of Wuhe section, Hubei Province was deposited in a deep environment by microbial precipitation. Our paleoenvironment reconstruction has shown that, at the beginning of the Doushantuo Formation, Wuhe section developed slope facies and represented the edge of a deep intra-shelf basin. Thus, the deep-water character of the Wuhe’s “cap carbonate” cannot be generalized to the entire shelf. Field observations did not allow the identification of clear criteria of bathymetry in the black shales. If the shallow-water character of these shales is certain on the top of parasequence I in the most proximal section of the shelf (Zhancumping section; Hubei province), it appears also certain that the Marinoan deglaciation induced a global rise of sea level. Thus, we suppose that the rim allowing the isolation of the intrashelf basin has at the same time cut the communication between the proximal shelf and the open ocean and induced the formation

of isolated, stagnant systems. The emergence of the most proximal Zhancumping section is due to progressive evaporation of the water in this enclosed environment.

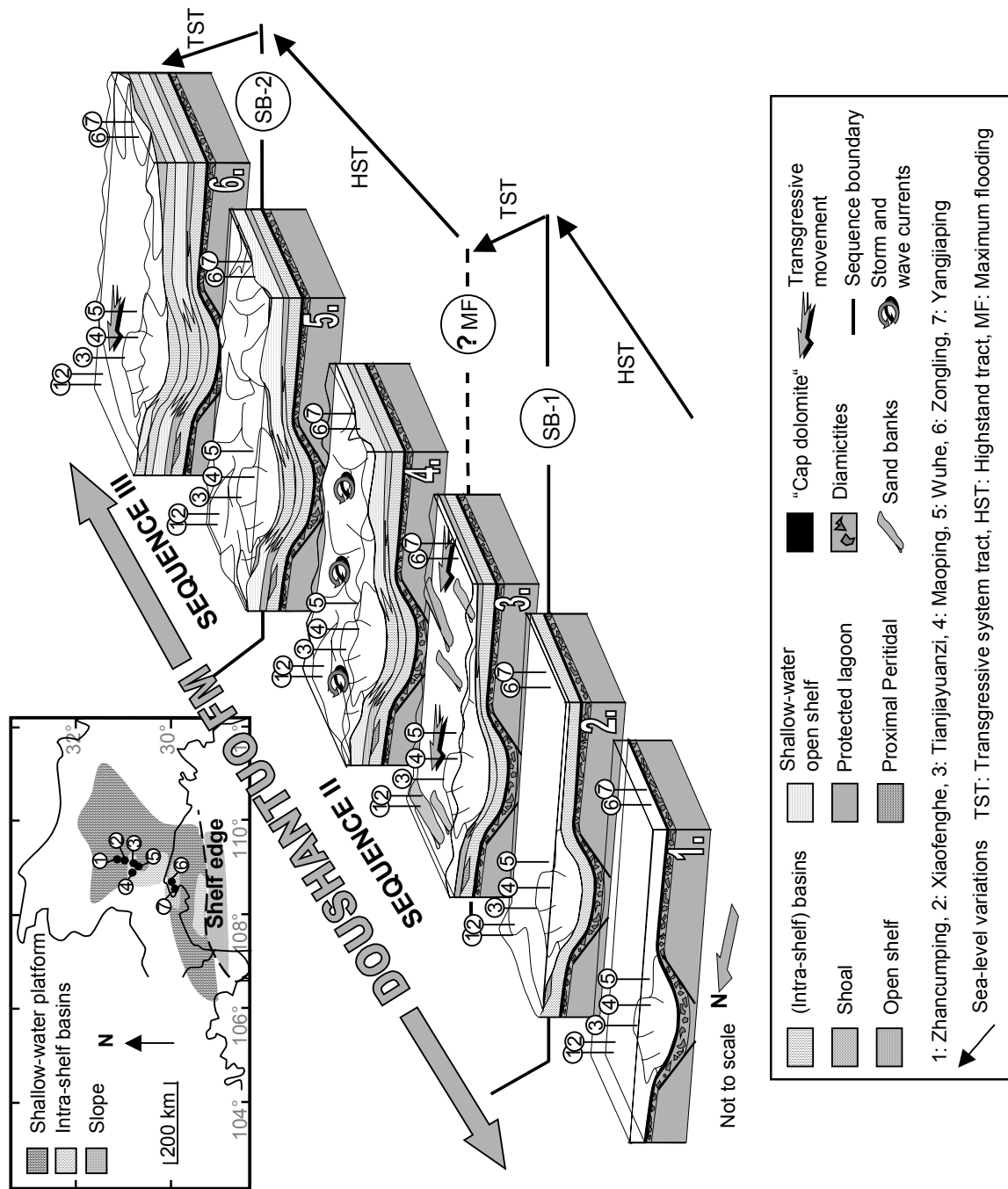


Fig. 36. Three-dimensional scheme showing the evolution of the Yangtze platform shelf environment during the entire Doushantuo Formation.

5. CONCLUSIONS

Detailed facies analysis highlights the evolution of the Yangtze platform shelf during the Doushantuo Formation along a north/south transect from Hubei Province to the extreme northern

boundary of Hunan Province and gives a new sequence-stratigraphic analysis interpretation in which black shales represent the latest term of the regressive interval. The Yangtze platform shelf during Doushantuo Formation records two second-order sequences and the beginning of a third and evolves from a carbonate shallow-water (epeiric) rimmed platform to a carbonate open shelf subjected to wave energy, to become a rimmed platform again at the end of Doushantuo Formation time. The scale of the shallowing-upward sequences and their regional correlation implicate an allocyclic influence such as eustatic fluctuations.