Chapter 4. Large-scale slope instability at the southern margin of the Ediacaran Yangtze platform (Hunan province, central China)

Abstract

Thirteen detailed stratigraphic sections of the Doushantuo Formation in Hunan province, central China, revealed large-scale mass wasting on the Yangtze platform margin in the time interval between the late Neoproterozoic glaciation and the earliest Cambrian. Numerous sedimentary discontinuities due to regional slides, olistostromes, and slumps, modified the transitional stratal pattern between the shallow-water carbonate platform margin and the siliciclastic slope. Slide blocks are generally gently deformed and are largely composed of shallow-water dolomitized limestone; they may reach a regional extent of up to ~ 5400km² and are embedded in anoxic shales of unknown water depth.

1. INTRODUCTION

The Neoproterozoic and Cambrian strata of the Yangtze platform are one of the foremost locations worldwide to study the conditions and setting of the Cambrian bioradiation. A detailed understanding of the temporal succession and ecologic factors involved of this radiation event, however, has been hindered both by a lack of detailed correlation between the numerous fossil-bearing locations and by a poor understanding of the depositional processes. The transition zone between the fossiliferous, stratigraphically incomplete, shallow-water carbonate environment, and the stratigraphically complete but fossil-free, deepwater siliciclastic environment may help to correlate between platform and basin. Such a correlation will help to reconstruct a detailed stratigraphic account of the tectonic and climatic drivers in the evolution of the Yangtze platform

The Yangtze platform represents the central part of southern China and covers an area of approximately 800,000 km^2. This study focuses on the southeastern margin of the Yangtze platform in Hunan province where the Neoproterozoic slope facies is well exposed. Large-scale, regionally distributed slide sheets have been identified based on data derived from measured stratigraphic sections.

1.1. Methods

Thirteen stratigraphic sections were measured during two field seasons in 2002 and 2003. Representative samples were cut, polished, and commonly scanned in order to highlight sedimentary structures and sedimentary facies. Thin-section petrography aided in the identification of mineralogy, diagenesis and microfacies.

1.2. Geological setting

All sections are located in Hunan province, south China (Fig. 37). Geologically, they are located on the southeastward-dipping slope of the Yangtze carbonate platform during the Late Neoproterozoic (ca. 635-550 Ma; Condon et al., 2005). During this time, carbonates interbedded with phosphorites of the Doushantuo Formation were deposited.

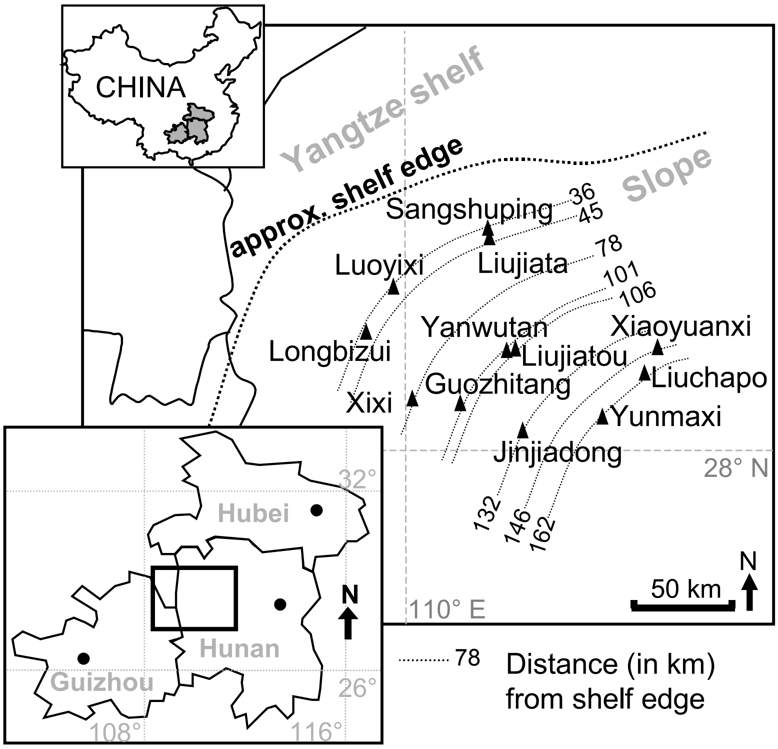


Fig. 37. Geographic and tectonic location of the study area, largely in northern Hunan Province, South-central China, representing the Ediacaran southeastward-dipping slope of the Yangtze platform.

During the Late Neoproterozoic, the palaeogeographic location of the South China block and its position in the Rodinia supercontinent, like many other small cratons, is still poorly known.

Palaeomagnetic analysis suggest an equatorial position (Macouin et al. 2004) at 600 Ma. Li et al. (1995) proposed that the South China plate linked Australia with Laurentia between 1 Ga and 700 Ma. In their reconstruction of Gondwana and Laurentia, Powell and Pisarevsky (2002) also joined South China with Australia. According to Condie (2003), and Pisarevsky et al. (2003), the Yangtze platform and Cathaysia (the southeastern part of present-day China) collided, forming the South China craton, from the Mesoproterozoic to the early Neoproterozoic.

During the Neoproterozoic, the Yangtze platform was localized within an extensional regime (rift basin) as a result of break-up of Rodinia. Since the Late Neoproterozoic, the platform evolved into a passive continental margin (Wang and Li, 2003). At present, the Yangtze platform is limited between the Gingfeng-Xiangfan-Guangji (Qin-Lin) fault zone to the north, extending from Tibet to northern Anhui, and the Cathaysia suture to the southeast. This scenario is a result of its collision with the Cathaysia arc to the southeast during the Silurian and with the North China craton during the early Triassic (Hsü and Chen, 1999) (Fig. 38). These collisions resulted in a moderate deformation of the Palaeozoic sedimentary cover of the Yangtze platform. Cretaceous extensional tectonics created large, fault-bounded basins filled by continental depositional facies. Generally, Proterozoic-Palaeozoic strata are preserved in a thickness of several kilometres, which were generally moderately deformed by large-scale folds.

1.3. Stratigraphy

In the studied stratigraphic interval (Fig. 39), the sedimentary record begins with the diamictite of the Nantuo Formation, which is probably a product of the Marinoan glaciation (Zhou et al, 2004). These putatively glaciogenic sediments have received renewed interest with the “Snowball Earth” theory (Hoffman et al., 1998). A “cap carbonate” unit that overlies the tillites forms the base of the Doushantuo Formation. Unusual sedimentary structures (Nogueira et al., 2003) and a negative $\delta^{13}C$ isotope anomaly (Knoll et al, 1993; Germs, 1995; Corsetti and Hagadorn, 2000) occur in these “cap carbonates”, marking a sudden change from an icehouse to greenhouse condition during the Late Neoproterozoic. The diamictites of Nantuo Formation and the overlying “cap carbonates” of Doushantuo Formation widely occur throughout the central and southern Yangtze platform. The Doushantuo Formation in Hunan province is dominated by black, thinly laminated, variably silicified shales interbedded with thin dark-grey siltstone that resulted from turbidity currents, rarely with thinly laminated chert. Within this formation, two phosphorite units are regionally traceable and commonly taken as correlation markers. Tuffaceous sediments are common to abundant but largely dispersed in the shales. The boundary of the Doushantuo Formation with the overlying Liuchapo Formation is conventionally placed at the first occurrence of thick-bedded black chert. However, this boundary is commonly erosive in origin; in several visited sections, it represents the base of a major slide involving olistostromes and contorted bedding. The black silicified shales of the Liuchapo Formation grade updip into dolomitized shallow-water limestones of the Dengying Formation, which is widespread in the platform facies of northern Hunan and Hubei provinces.

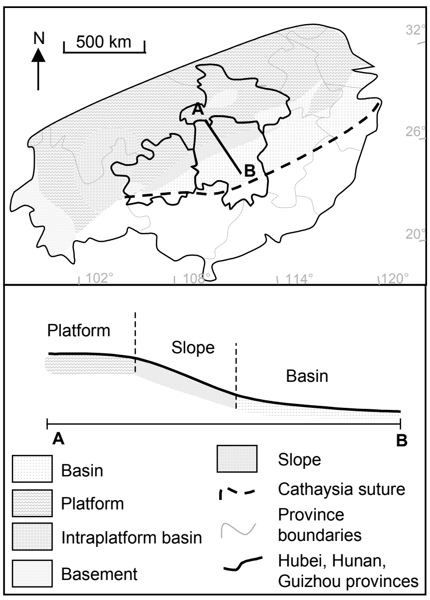


Fig. 38. Paleoenvironmental reconstruction of the southern Yangtze platform during the late Ediacaran (Doushantuo Fm; ~ 635-550 Ma (Condon et al., 2005)) (partly modified after Steiner, 2001).

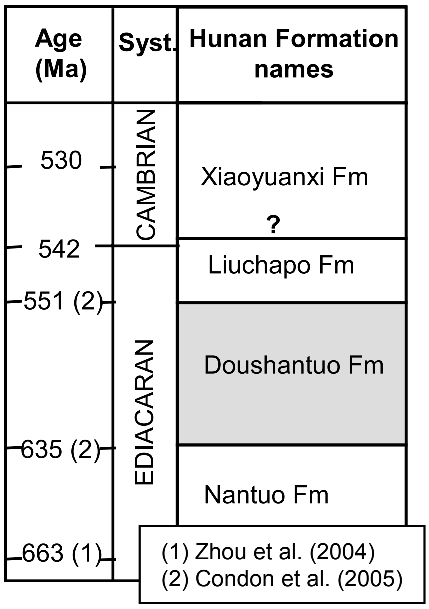


Fig. 39. Schematic stratigraphic column for the Ediacaran and basal Cambrian of south-central China.

2. Facies description

When the measured sections are arranged according to their distance from the (inferred) edge of the shallow-water, carbonate-dominated Yangtze platform (Fig. 37, Fig. 40), they show an overall progradational sequence of numerous laterally related, correlatable gravity deposits, including slump folds, slides, olistostromes, debris flows, and turbidites.

In four sections closest to the inferred platform margin (between Luoyixi and Liujiata sections), slump-folded shales are interbedded with gently deformed shallow-water carbonates, which range in thickness from 3 m (Luoyixi section, slide No. 4) to 25 m (Liujiata section, slide No. 2). Evaporites and phosphorites overlain by laminated silty limestone in the No. 3 slide are known only from Luoyixi section. In six sections of the centrally located midslope region (between Xixi and Jinjiadong sections), slide No. 3 attains its greatest thickness of approx. 45 m. There, adjacent parautochthonous deformed black shales and siltstones also include, at least, a dozen olistoliths of several- to tens-of-m diameter. At Xixi section, like at Luoyixi section, the slide sheet shows basal evaporitic/phosphoritic lithologies, overlain by laminated silty limestone (dark grey interval at the base of slide No. 3, Fig. 40). The slide sheet No. 3 in Yanwutan section contains a poorly developed basal phosphorite interval overlain by approx. 40 m of intraclast grainstone/packstone and silty limestone. The distal equivalent of slide sheet No. 3 in Jinjiadong section (54 km from Xixi section) is an olistostrome with meter-sized carbonate blocks. Finally, in the three most basinward sections (Yunmaxi to Xiaoyuanxi sections), small-scale folded and faulted, variably silicified black shale dominates the stratigraphic succession. Slide sheets and olistostromes identified by the presence of shallow-water limestones facies may be correlated because of their equivalent stratigraphic position, their similarity in clast lithology and transport processes from Luoyixi to Xixi sections for slide sheet No. 2 and from Luoyixi to Jinjiadong sections for slide sheet No. 3. The thickness of these units first increases and then decreases basinward (Fig. 40). At Luoyixi section, slide sheet No. 3 reaches 20 m thick whereas the same interval reaches 60 m thick at Yanwutan section, 126 km downdip from Luoyixi section. The allochthonous carbonate beds are, however, not exposed in the Longbizui section and do not appear in the basinal Liuchapo and Xiaoyuanxi sections, either. The contact between allochthonous carbonate slide blocks and underlying shales is always sharp and marked in well-exposed sections, such as at Xixi section, by an approximately five-to-ten-cm thick unit of highly deformed scaly and fissile shale (Fig. 42E).

2.1. Description of slides

The slide sheets sediments (e.g. slide No.3 at Xixi, Yanwutan sections, cf. Fig. 40) are internally folded into large-scale open folds tens-of-meter wide and several meters in amplitude. Unambiguous tight and isoclinal soft-sedimentary slump folds, lacking foliation and showing plastic behaviour also deform the adjacent autochthonous or parautochthonous slope sediments. The base of the slide sheets mostly forms a low-angle contact with underlying autochthonous shales indicating a low erosive potential of the slide sheet. Orientation of slump folds in Luoyixi, Xixi, and Jinjiadong sections suggest a general NE-to-SW direction of transport (Fig. 41). The decimetre- to metre-scale carbonate olistoliths and discontinuity-bounded carbonate sections in the stratigraphic profiles are composed largely of shallow-water carbonate platform lithologies (Chapter 5).

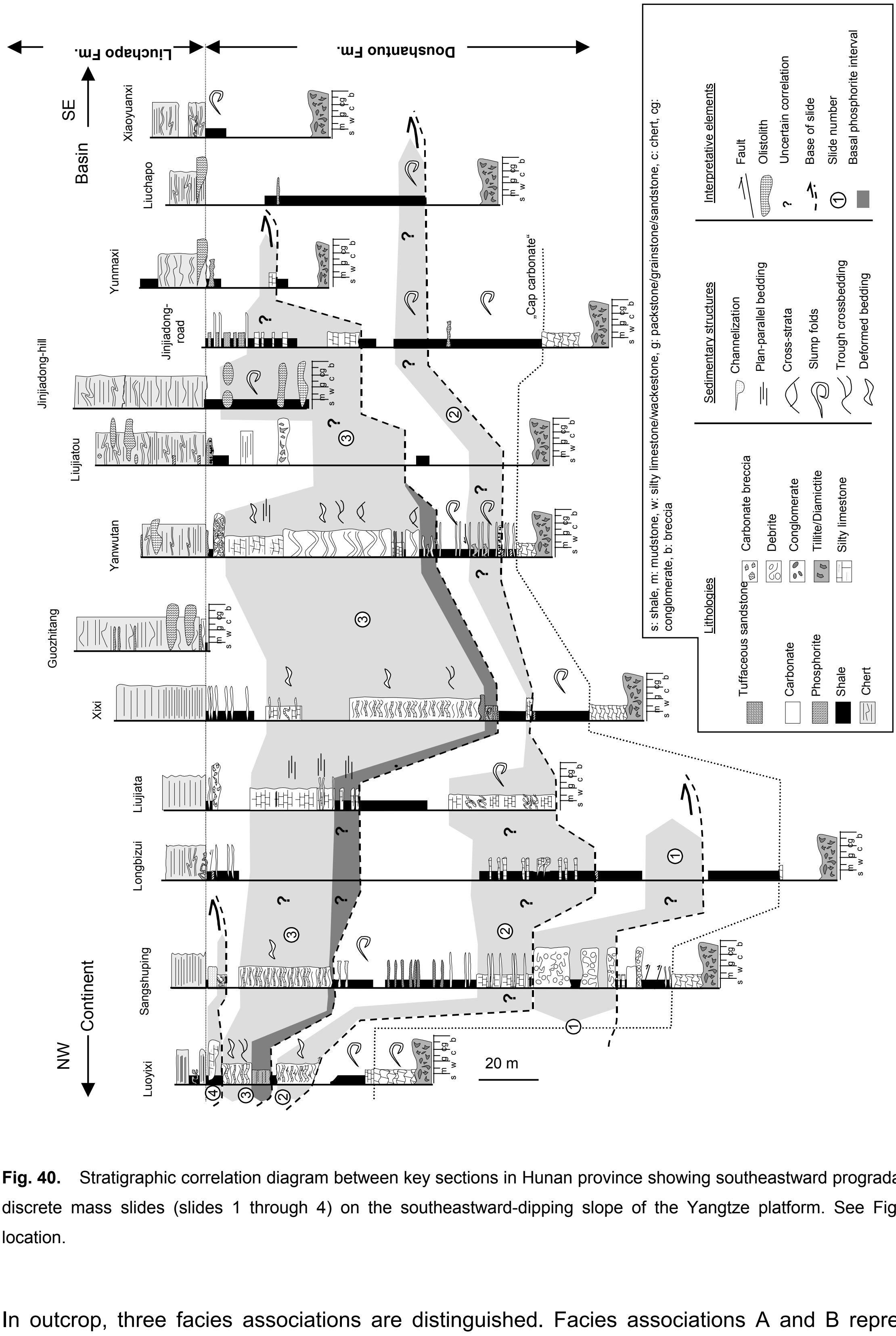


Fig. 40. Stratigraphic correlation diagram between key sections in Hunan province showing southeastward progradation of discrete mass slides (slides 1 through 4) on the southeastward-dipping slope of the Yangtze platform. See Fig. 1 for location.

In outcrop, three facies associations are distinguished. Facies associations A and B represent allochthonous sediments, whereas facies association C corresponds to the autochthonous slope sediments (Table 4). Each facies is affected to variable degrees by gravity movements. In addition, volcanic activity may modify the composition of all sediments types (Chapter 5).

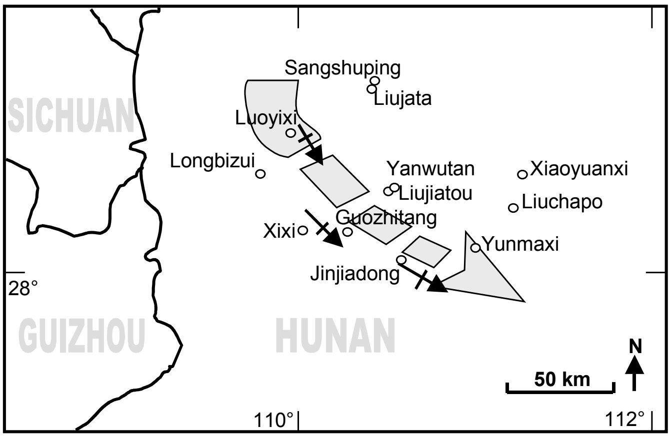


Fig. 41. Sediment transport direction, as inferred from orientation of slump fold axes in three locations (Luoyixi, Xixi and Jinjiadong sections). Thin arrows indicate the downslope direction, perpendicular to the axial plane of synsedimentary folds, and the large grey arrow indicates overall direction of mass wasting.

2.1.1. Facies association A: Phosphorite/Chert/Dolomite/Evaporite

Facies association A consists of two facies. Facies 1 is a thinly bedded, dolomitic phosmicrite interbedded with biolaminated patchy chert and (evaporitic) dolomicrite. Facies 2 consists of interbedded micrite and chert with very-thinly-bedded phosphorite-clast microbreccia or cm-sized phosphorite clasts breccia. “Tepee” structures and convolute structures are common in the biolaminated patchy chert and micrite.

The former presence of evaporite is inferred from convolute structures and petrographic analysis of thin sections. Dissolution likely induced collapse of the phosmicrite and formed breccia with cm-sized clasts. The micro-breccia resulted from the high-energy currents. The evaporites and micrites may either indicate a restricted evaporitic environment that was apparently located close enough to the platform margin to be incorporated into the slides, or, alternatively, may have formed under early diagenetic conditions due to oxidation of biogenic H_2S resulting from decaying organic matter (Hill, 1995). Microbreccias suggest an environment subjected to storms.

2.1.2. Facies association B: silty dolomitized limestones and grainstones/packstones

Facies association B is composed of only one facies, Facies 3, represented by medium-to-high-energy deposits. Sub-facies 3A includes packstones with mm-sized intraclasts organized in normally graded, plan-parallel stratified beds and of silty dolomitized limestones with cm-sized trough crossbedding. Sub-facies 3B shows dm-sized, trough cross-stratified massive dolomitized limestones. Sub-facies 3C consists of dm-thick, trough cross-stratified and crossbedded dolomitized limestones.

Facies 3 was deposited on a shallow-water, wave-dominated subtidal shelf, forming cm-sized ripples or horizontal bedding (Sub-facies 3A). Sub-facies 3B and sub-facies 3C correspond to higher-energy traction currents and may correspond to the formation of sand banks and megaripples, respectively. The secondary dolomitization renders primary textures difficult to identify. However, the sedimentary structures of facies 3B and 3C suggest that the dolomitized limestones were previously intraclast grainstones.

2.1.3. Facies association C: shales/silty shales/packstones/wackestones /debrites

This facies association is represented by thin-bedded shales interbedded with thin-bedded silty shales, (normal-graded) packstones/wackestones (interpreted as turbidites), and debrites. Slump folds may locally disturb the bedding.

Facies association C corresponds to autochthonous and para-autochthonous sediments deposited on the slope by suspension settling or by turbiditic currents induced by gravity-related mass movements.

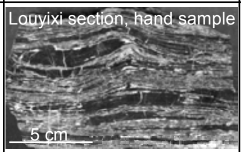
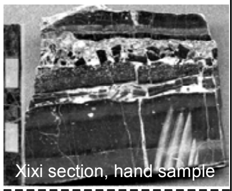
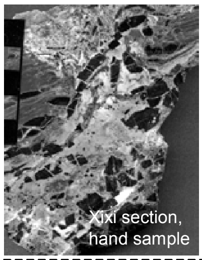
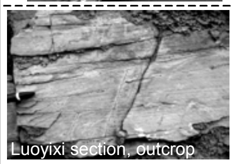
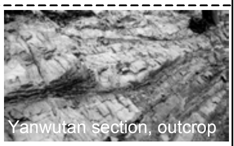
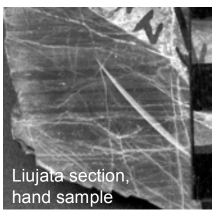
	Facies	Lithology	Hand samples and outcrop facies	Process	Energy, Water depth	Depositional environment
ALLOCHTHONOUS	**1**	Thin-bedded micrite (carbonate and phosphorite). Biolaminated, evaporitic dolomite interbedded with patchy chert.		Suspension settling	Low energy, shallow water. Some high-energy events	**Intra-platform basin**
	2	Thin-bedded micro-breccia with structureless phosphorite rip-up mm-sized clasts interbedded with thin-bedded (< 5cm thick) phosmicrite		Traction current Suspension settling		
		Phosbreccia with several cm-sized phosphorite clasts interbedded with evaporite-rich dolomite		Evaporites-mediated brecciation		
	3	A. Silty dolomitized limestone with cm-sized cross-bedding (ripple) and plan-parallel laminations		Current	High energy, shallow-water	**Shallow subtidal platform**
		B and C. Dolo-grainstone with m-sized cross-strata and dm-sized crossbedding				
AUTOCHTHONOUS	**4**	Black shale (+ slump folds) Black shale interbedded with silty limestone (+ slump folds) Black chert (+ slump folds)		Suspension settling Distal turbidite	Low energy, deep water	**Basin, Slope**

Table 4. Summary table of slope facies

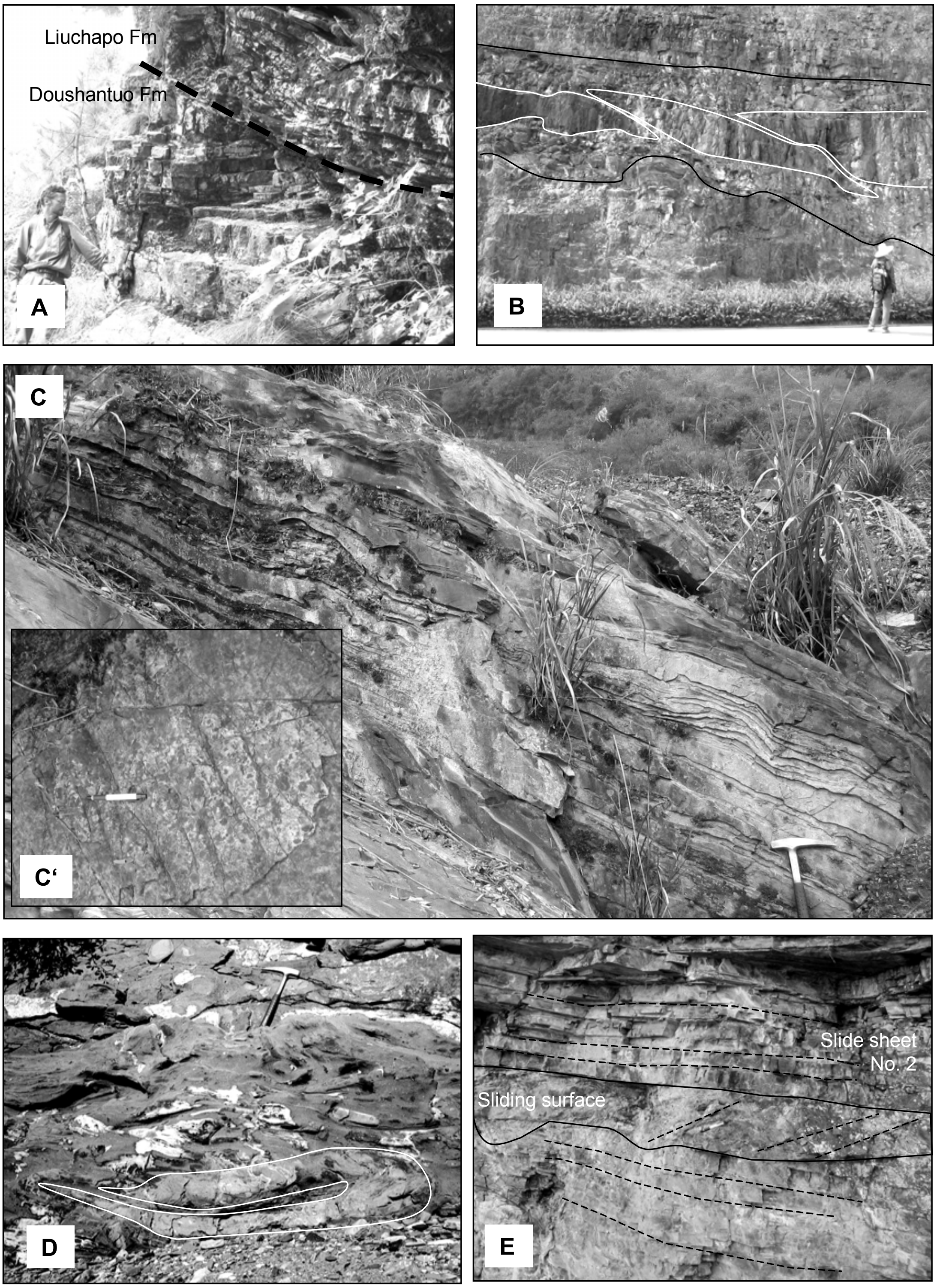


Fig. 42. A: Angular discontinuity between Doushantuo Formation shales and overlying black silicified shales of Liuchapo Formation, representing a slide horizon (Jinjiadong section). B: Elongate silty limestone olistoliths (white lines) in dm-to-m-scale, slump-folded black shale in the upper Doushantuo Formation (Luoyixi section). Note the erosive base of the olistolith and the undeformed overlying beds (black lines). C: Gravity-related deformation in silty limestones of slide sheet No. 3 at Xixi section. C': Cm-sized ripples on the bedding surface of silty limestones in slide sheet No.3 (Xixi section). D: Debrites, showing almost complete loss of cohesion and local plastically deformed, folded bed (white contour) (Sangshuping section). E: Highly deformed sediment interval interpreted as slide surface at the base of slide sheet No.2 (Xixi section, lower Doushantuo Formation).

3. Discussion

3.1. Evidence of large-scale mass displacements

Three criteria serve to identify large-scale slides:

- The laterally correlatable units show the characteristics of gravity movement processes in a logical downdip succession and include the complete spectrum of mass displacement processes (Fig. 42 and 43). In the upslope sections, slumps and slides involving gently folded limestone (Fig. 42C, 42C') above discrete levels of highly deformed basal shear (Coniglio and Dix, 1992), "megatruncation surfaces" (Stewart et al., 1993) or slip surfaces (Stow et al., 1998) predominate (Fig. 42A, 42E). In mid-slope section, slides of decametre thickness and possible km-scale lateral extent and olistostromes involving m-sized blocks (Fig. 42B) increase in abundance. Downdip, the reduction in size of olistoliths (Jinjiadong section) or their absence in the downslope sections (Liuchapo and Xiaoyuanxi sections) may indicate that the olistostromes were replaced by debrites (Fig. 42D) and turbidites (Fig. 43). Meter-scale tight to isoclinal slump folds are common throughout the study area from which their downslope transport direction is inferred.
- Abrupt and erosional facies contacts in stratigraphic profiles without transitional facies from deep-water (autochthonous) facies to shallow-water (allochthonous) facies occur throughout. The slide units are platform carbonates and shallow-water, intra-shelf basin evaporites and phosphorites.
- The allochthonous shallow-water carbonates are correlatable over, at least, 70 km between Luoyixi and Yanwutan sections at the same stratigraphic horizon. This unit may therefore either represent an assemblage of individual blocks exceeding outcrop size (several 100 m) at each of the three adjacent mid-slope locations of Liujiata, Xixi and Yanwutan sections or may form a single, more-or-less coherent body on the mid-slope of approx. 50*100 km in size.

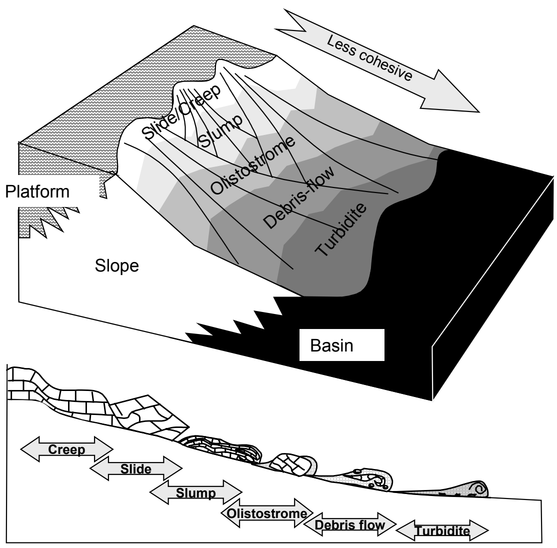


Fig. 43. Schematic ideal sequence of gravity-induced facies occurring on submarine slopes (after Coniglio and Dix, 1992; Whitham, 1993; Stow et al., 1998; Lee and Chough, 2001).

3.2. Slide dimensions, displacement distance, and slope geometry

The largest recent submarine slides are documented from the volcanic flanks of Hawaii (Moore et al., 1995; Cervelli et al., 2002; Ward, 2002) and Tenerife (Hürlimann et al., 2001). Some of these slides consist of > 2000 km^3 of re-mobilized sediment (Ward, 2002). Debrites and turbidites, the most distal deposits of mass wasting, may extend up to several hundred kilometres from their source (Coniglio and Dix, 1992). These processes have been studied using seismic data and sonar imagery along modern slopes. For example, the recent Palos Verdes slide (California) carried about 0.34 km^3 of mass sediment over a distance of 4-5 km (Bohannon and Gardner, 2004). In the North Aegean, Lykousis et al. (2002) documented a slide with a volume of 3-8 km^3, an area of 85 km^2 and a runout distance of approximately 6-7 km. In the Japanese Sea, Lee et al. (1996) studied slide sheets of 10 km long and 50 m thick. The geological records also preserve examples of significantly larger dimensions. Beutner and Craven (1996) described a coherent mass movement of Ordovician carbonates of 1300 km^2 areal extent and several kilometres thickness having moved ca. 30 km on a gently dipping surface. Stewart et al. (1993) document truncation surfaces traceable of 56 km along depositional strike and along 8 km basinward. Large-scale submarine sliding or gravity-induced mass movement can occur along a detachment surface due to a reduced frictional strength; this may have been caused by high pore-water pressure (Spence and Tucker, 1997; Huvenne et al., 2002; Lykousis et al., 2002; Watts, 2003; Martel, 2004), by the dissociation of gas hydrates (Lee et al. 1996), or by the injection of volcanic gases (Beutner and Craven, 1996). The approximate location of the platform margin can be constrained from published data (Bureau of Geology and Mineral Resources 1987, 1988, 1990) (Fig. 37). The most proximal part of slide No. 3 (Luoyixi section) appears to be located approximately 36 km basinward of the assumed platform margin (Figs. 37 and 40). Fragmentation of this slide sheet occurs approximately 130 km basinwards of the platform margin, somewhere upslope of the Jinjiadong section (Fig. 44). Therefore, this slide is estimated to cover an area of approximate 60 × 80 km^2 with a minimal thickness of about 10 m. The volume of displaced sediments is larger than 54 km^3.

Earthquakes (Heubeck, 1992; Hürlimann et al., 2001), previous stress history (Silva et al., 2004), intense storm events (Stow et al., 1998), significant regressions (Lee et al., 1996; Spence and Tucker, 1997), or sediment loading (Coniglio and Dix, 1992; Bosellini et al., 1993; Spence and Tucker, 1997) may have initiated sliding. The presence of evaporites and phosphorites at the base of several large-scale slides may have facilitated their displacement.

4. Conclusions

Our work documents large-scale Ediacaran mass transport on the Yangtze platform slope environment. Three criteria helped to identify slide sheets: (1) correlation between sections of shallow-water-facies carbonates; (2) rapid (and "inconsistent") change in facies separated by thin, highly deformed sediment, interpreted as displacement surface; (3) regional persistence of the unit. The sedimentary facies of the slide blocks allows a crude reconstruction of the platform margin facies, consisting of shallow-water, protected, environment. Displacement may have been facilitated by the presence of low-strength evaporites and brittle phosphorites at the base of the slides and/or by the water and gas accumulation (Spence and Tucker, 1997).

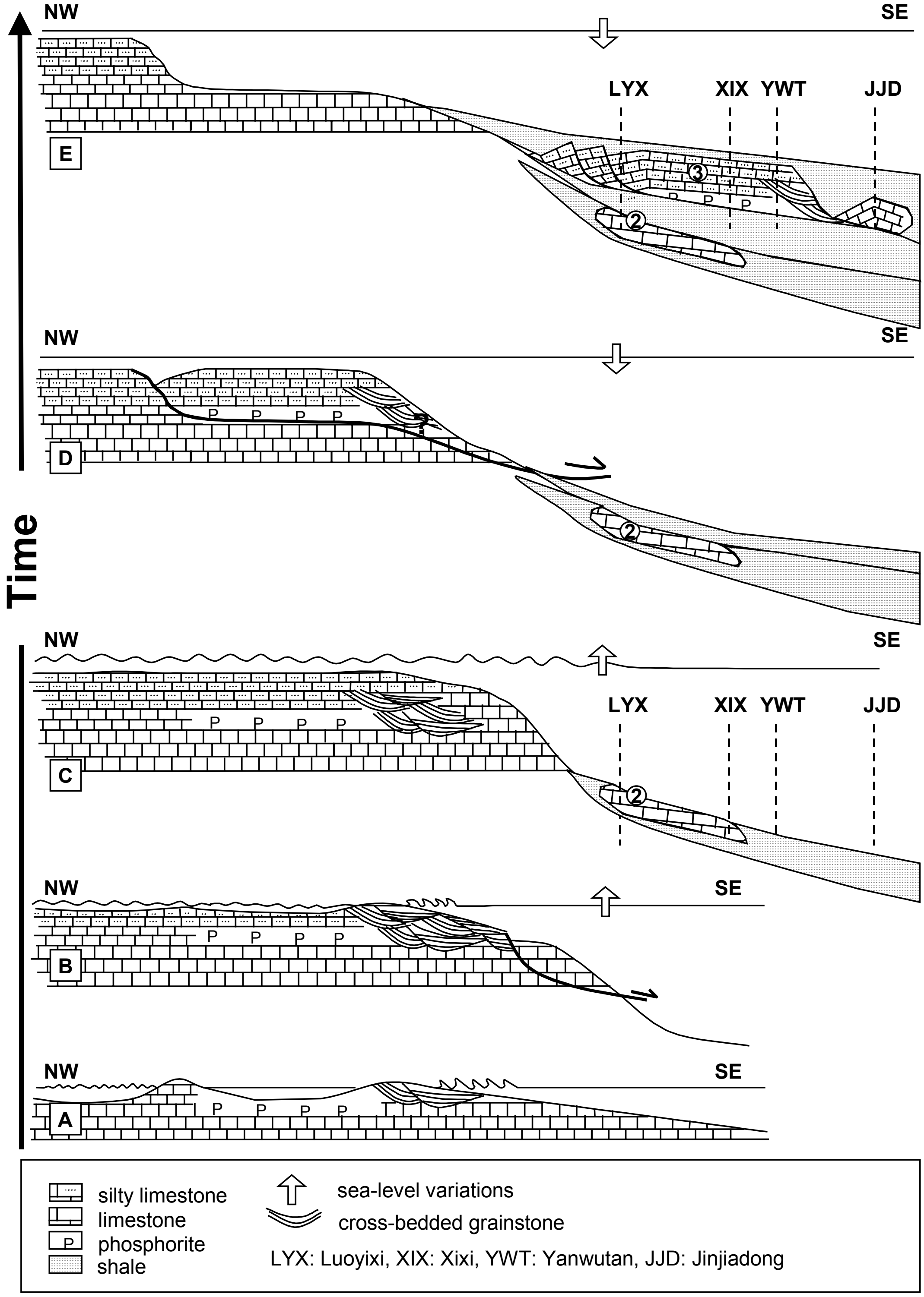


Fig. 44. Proposed sedimentary evolution of the allochthonous deposits on the Ediacaran southeastward-dipping slope of the Yangtze platform.