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Soft-sediment deformation structures induced by rapid sedimentation in Early Cretaceous turbidites, Lingshan Island, eastern China

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3 **eastern China**

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Abstract: Turbidites of the Early Cretaceous Lingshanda Formation on Lingshan Island, eastern China, show numerous soft-sediment deformation structures. The turbidites accumulated in a rift basin plain on the distal part of a low-energy fan, together with autochthonous fine-grained sediments that settled from suspension. Occasionally, sets of both types of sediments slumped down the basin slope. The turbidites were studied in two sections. Paleocurrent directions, measured from sole marks at the base of the sandy turbidites, indicate a slope from SE to NW; this is consistent with the dip direction of the axial planes of the major slump folds. Among the numerous types of soft-sediment deformation structures that are present, two types are of special interest because of their specific genesis, viz. rip-up clasts and dome structures. It appears that rapid sedimentation must be considered as the main trigger behind these deformations: the rapid accumulation of particularly the sandy turbidites resulted in overloading of the underlying beds and then consequently an increase in their pore-water pressure that induced liquefaction/fluidization, which triggered the formation of the rip-up clasts and dome structures. The downslope movement of freshly deposited turbidites after slope failure over the inclined sedimentary surface induced shear stresses, which resulted in the complication of the rip-up clasts and the preferred orientation of some dome structures. Both the dip directions of the axial planes of some of the dome structures and micro-folds within the rip-up clasts are consistent with the paleocurrent direction indicated by the sole marks and the slump folds.

Keywords: soft-sediment deformation structures; turbidites; dome structures; rip-up clasts; Lingshan Island

Introduction

Soft-sediment deformation structures (SSDS; this acronym is used in the present contribution for both singular and plural) include a wide range of sediment deformations with various morphologies; they are preserved in ancient and modern sediments all over the world, in all depositional environments (Allen and Banks 1972; Allen 1977; Owen 1987, 1996; Moretti 2000; Van Loon 2009; Owen et al. 2011). SSDS are of great significance in providing sedimentary records of processes acting on sediments while they were unconsolidated or semi-consolidated during or shortly after deposition (Owen 1987). A sudden decrease or the complete loss of shear strength due to deformation mechanisms in water-saturated sediments allow deformations to occur under the influence of driving-force systems. Sediments behave as viscous or liquid-like materials when they are deformed (Allen 1977; Owen 1987, 1996; Moretti and Ronchi 2011; Suter et al. 2011; Tinterri et al. 2016), thus resulting in deformation in the case of liquefaction and in complete loss of the primary structures in the case of fluidization.

Numerous types of soft-sediment deformation structures, including load structures, convolute lamination and water-escape structures, are commonly present in turbidites (Sanders 1956; Lowe 1975; Allen and Banks 1972; Stromberg and Bluck 1998; Moretti et al. 2001; Tinterri et al. 2016); most of them result from liquefaction and/or fluidization (Allen 1977) of water-saturated sediment after passing the failure threshold due to a rapidly thickened overburden resulting from a high sedimentation rate (Moretti et al. 2001).

During the Early Cretaceous, the area where Lingshan Island (offshore eastern Shandong Province, eastern China) is situated nowadays (Fig. 1) formed part of an inter-arc basin with a tensional tectonic regime (Yang and Van Loon 2016); it was

67 thus affected by active tectonics. This resulted in relatively steep basin slopes and,
68 due to erosion of the hinterland, a vast supply of siliciclastic particles that led to rapid
69 accumulation on the slopes. The combination of these factors favored slope failure
70 and the initiation of turbidity currents, debris flows and hyperpycnal flows (Yang et al.
71 2016). Where these flows came to rest, the weight of the freshly deposited sediments
72 increased the pore-water pressure of the underlying, still unlithified layers, resulting in
73 liquefaction, sometimes followed by fluidization (cf. Allen 1977). Consequently, a
74 wide variety of SSDS originated, due to the sometimes chaotic local stress fields that
75 resulted from the combination of mass-flow activity, reversed density gradients, slope
76 conditions, and liquefaction/fluidization; these SSDS provide insight into the
77 depositional conditions (Yang et al 2016). The presence of tectonic activity (rifting,
78 earthquakes) contributed to the instability of the sediments, thus also resulting in
79 SSDS such as synsedimentary faults, boudins (including domino boudins), etc.,
80 which provide insight into the tectonic regime (Yang and Van Loon 2016). In addition
81 to the more commonly occurring SSDS such as load casts, pseudonodules, water-
82 escape structures, convolutions, etc., which have been described earlier (e.g. Lu et al
83 2011, 2012; Shao et al 2014), two types of SSDS are present that were not earlier
84 described from the Lingshandao Formation, viz. dome structures and rip-up clasts.
85 They are important because the dip directions of the axial planes of some of the
86 dome structures and micro-folds in the rip-up clasts are related to the lateral shear
87 stress that was probably induced by the flow of turbidity current (Moretti et al. 2001),
88 thus indicating the direction of the basin slope. Moreover, the rip-up clasts were not
89 the result of some erosional activity (like normally) but rather a result of a depositional
90 process, and the dome structures are a type of SSDS that has not been detailed

91 before, although some genetically related SSDS (e.g. flames, squeezed structures)
92 have been dealt with previously by, among others, Olivaira et al. (2011).

93 Consequently we focus here on these two specific types of SSDS in the turbidite
94 successions that are well-exposed in the Dengta section (~8 m) and the Qiancengya
95 section (~20 m) (both located in the sea cliffs in the southwest of Lingshan Island)
96 (Fig. 1). We discuss their deformation mechanisms, driving forces and trigger
97 mechanism, with the objective to highlight the significance of rapid sedimentation for
98 the formation of these specific types of SSDS.

99

100 **Geological setting**

101 The turbidite section under study crops out in coastal cliffs on Lingshan Island, an
102 island in the Yellow Sea, about 40.7 km SE from Qingdao City, Shandong Province,
103 eastern China (Fig. 1a). The island covers an area of about 8 km² and its top is about
104 513.6 m above sea level.

105 Lingshan Island is located in the Lingshandao Depression (Fig. 1b-c) (Luan et al.
106 2010), between the Qianliyan High and the Jiaonan High (Wang 2013). The latter
107 belongs to the Sulu Orogenic Belt that developed due to the collision of the North
108 China Plate with the Yangtze Plate in the Triassic (Li 2009). The main faults trend
109 NE-SW and control the spatial distribution of the various tectonic units; secondary
110 faults trend NW-SE and divide the Lingshandao Depression and determine the dip of
111 the sediments.

112

113 **Previous and latest hypotheses**

114 The complex structural setting and the geographically isolated position of the island
115 caused an strong scientific debate about its precise geotectonic, stratigraphic and

sedimentological setting (Faure et al., 2003; Wu et al., 2005; Lu et al., 2011, 2012; Shao et al., 2014; Wang et al., 2014; He et al., 2015; Zhou et al., 2015). Recent research has made clear, however, that the Lingshandao Formation cannot, as previously assumed (SBGMR 1991), be correlated with the uppermost part of the contemporaneous Laiyang Group in the nearby Jiaolai Basin (Wang et al., 2014), but must rather be considered as a different entity. Based on trace-element analysis, it has also become clear that the formation accumulated in a deep-marine environment (Yang et al 2017), rather than in a continental environment as was assumed on the basis of the finds of carbonized plant debris (Zhong 2012); the plants were found by recent investigations to have been washed in by hyperpycnal flows (Yang et al 2016). Further, it was found on the basis of analysis of stress systems that can be deduced from SSDS such as domino boudins, that an overall tensional regime prevailed during sedimentation of the Lingshandao Fm., but that the resulting deformations caused local (fairly small-scale) compression, which is also expressed by specific soft-sediment deformation structures such as small synsedimentary upthrusts.

Sedimentary and structural history

Eastern China was part of the Circum-Pacific tectonic domain during the Early Cretaceous; it became affected by the fast subduction of the Pacific Plate. Distinct lithospheric thinning occurred during the Late Mesozoic (Wu et al. 2005). Magmatic intrusions and volcanic eruptions were particularly frequent and active during Early Cretaceous (Zhou et al. 2015). Rift basins developed in this extensional setting at both sides of the Sulu Orogenic Belt, including the large rift basin in the south that

includes the Lingshandao Depression, and that nowadays trends NE-SW in the offshore region of eastern Shandong (Zhou et al. 2015).

A thick deep-water succession mainly consisting of turbidites (the Lingshandao Fm.) was deposited in the Early Cretaceous. Subsequently, the study area was uplifted and tilted, resulting in the overall ENE dip direction of the strata (Yang and Van Loon 2016). The ongoing regional tectonic uplift caused shallowing of the basin, leading to a change in facies from deep to shallow marine to a continental delta front (Shao et al. 2014). This was accompanied by intense magmatic activity, so that shallow-marine sediments alternate with volcanic material.

Four stratigraphic units (Fig. 1d) are exposed in the coastal cliffs of Lingshan Island (Zhang et al. 2013). The oldest unit is composed of ~90 m of greyish yellow thin-bedded sandstones alternating with dark grey to black shales (Lu et al. 2011; Yang and Van Loon 2016) that correspond to the deep-marine succession accumulated during the Early Cretaceous. This succession constitutes the Lingshandao Formation (Zhang et al. 2013) (mainly comprising turbidites, with some debrites and hyperpycnites). The Lingshandao Formation (Zhang et al. 2013) is overlain by a regionally extensive layer of grayish white rhyolite belonging to the Bamudi Formation, which can be used as a marker bed for stratigraphic correlation. This rhyolite is, in turn, overlain by shallow-water deltaic deposits intercalated by several layered diabase intrusions and pyroclastic flows, indicating gradual regional tectonic uplift and active volcanism. The uppermost unit is composed of volcanic agglomerates and andesites, which also belong to the Bamudi Formation (Zhou et al. 2015).

Characteristics of the Lingshandao Fm.

The turbidites of the Lingshandao Formation, which contain the SSDS that are the main subject of the present contribution, crop out mainly in the south and west of Lingshan Island, and are best accessible on the Dengta and Qiancengya sections (Fig. 1) where the present study was carried out. These sections consists mainly of turbidites, often in the form of beds grading from sandstone to siltstone to mudstone, but fine-grained turbidites form the majority. These fine-grained turbidites tend to show, just like the fine-grained upper parts of the coarse turbidites, millimeter-scale horizontal laminae. These fine-grained allochthonous sediments cannot be distinguished in the field from the autochthonous sediments that settled from suspension.

Groove casts and flute casts occur on the lower bedding planes of the sandstone turbidites (Fig. 2). Locally sets of turbidites were reworked in the form of slumps. These slumps differ in size and contain sometimes complex folds. The axial planes of the major folds in these slumps dip to N120°, consistent with the paleocurrent direction measured from the sole marks mentioned above. Obviously, the complex – and continuously changing – stress systems that exist in a slumping mass, have resulted in numerous smaller faults that show an almost complete spread in dip directions of the axial planes.

The Dengta section

The Dengta section (Fig. 3, upper right) consists of a vertical wall of about 8 m of turbidites (Fig. 3, left); a slump about 0.7 m thick is present at the base of the section (Fig. 3, lower right), and another slump about 2.5 m thick is present in the top part. The sandstones are of the order of a few millimeters to a few centimeters thick, but a few beds are over 10 cm thick. The basal parts of the turbidites tend to show normal

grading, and to erode the fine-grained tops (mainly shales, occasionally mudstones with varying clay/silt ratios) of the underlying turbidites; the more fine-grained upper parts show millimeter-scale parallel lamination, commonly well distinguishable by different weathering colors.

The Qiancengya section

The Qiancengya section (Fig. 4) is about 20 m thick. It consists of grayish yellow sandstone layers and grayish black fine-grained sediments (Fig. 4, left). The sandstone turbidites are centimeters to decimeters thick (Fig. 4, lower right), and commonly show an erosional base and normal grading. The fine-grained parts of these coarse turbidites can also be some centimeters to some decimeters thick, and some of them display millimeter-scale parallel lamination.

Depositional environment

In both sections, the turbidite succession is built by sequences that show thickening- and coarsening-upward units. These sequences are similar to the “sandstone lobes” of meter-scale sandstone packages formed in the outer-fan settings described by Mutti and Ricci Lucchi (1978). Both the sandstone and the more fine-grained turbidites in the Dengta section are thinner than those in the Qiancengya section, possibly indicating deposition in a slightly more basinward (distal) setting.

Lingshan Island occupies an isolated place in the Yellow Sea, so that a clear sedimentological/paleogeographical context is lacking. However, the characteristics of the sediments in the Dengta and Qiancengya sections are diagnostic enough to deduce an outer-fan/basin-plain setting. The slumps in the Dengta section fit into this

picture: Field et al. (1982) demonstrated that such slumps can be triggered by seismic shocks that affect water-saturated sediments on slopes of even less than 1° (cf. Berra et al. 2011). The slumped material consists of successions of turbidites and autochthonous fine-grained sediments that moved downslope after failure of the slope sediments, possibly under the influence of seismic shocks that resulted from earthquakes in the tectonically active basin, although slope failure due to overloading cannot be fully excluded. If seismic activity was responsible, the seismic shocks were apparently not strong enough to initiate the formation of seismites (Yang and Van Loon 2016), and earlier interpretations of SSDS as seismites (Wang 2013) must be considered erroneous as the pertinent layer does not fulfill seismite criteria (Sims 1975; Obermeier 1996; Rossetti 1999; Wheeler 2002; Hilbert-Wolf et al. 2009; Owen and Moretti 2011).

Description of the dome structures and rip-up clasts

Lu et al. (2011) were the first who described the turbidites of the Lingshandao Formation and their SSDS. Several researchers studied these SSDS from then on, and they all attributed them to seismic shocks (Wang 2013; Shao et al. 2014; Feng et al. 2016; Yang and Van Loon 2016). None of these authors, however, described the dome structures and rip-up clasts that are the main subject of the present contribution, and which have – as we will detail further on - a different genesis.

Dome structures

The dome-shaped structures (called 'dome structures' in the following) occur in the lower part of Dengta section. These deformation structures involve the fine-grained top parts of turbidites and the base of the overlying sandstone turbidite (Fig. 5).

These dome-shaped structures are 1-5 cm wide and 1-3 cm high, showing a thickening of the bedding – which is well preserved – from their sides toward the central upper part of the structure. The sandstones surrounding the top of the ‘domes’ show normal grading; a remarkable feature is that some of the coarser grains have sunk into the sag of the underlying fine-grained sediment. Moreover, fragments of this underlying fine-grained sediment (actually millimeter-scale parallel-laminated sediments consisting most probably of both fine-grained turbidites and suspension-derived sediments) occasionally float in the overlying sandstone. Dark mud laminae in the overlying sandstone unit are penetrated by the dome structures. Minor flame structures occasionally develop from the flanks of the dome structures.

Several layers below the deformed level are also affected, as indicated by undulating bedding planes (Fig. 5c). These structures are irregular and the deformed level is laterally discontinuous. The irregular character of these deformed levels gradually disappears laterally within about 2 m.

The rip-up clasts

A level with rip-up clasts (Fig. 6) is present in the Qiancengya section, at the base of the coastal cliff. These structures occur in a level between the upper, laminated fine-grained part of a sandstone turbidite and an overlying sandstone turbidite.

The laminated sediments that are involved have been broken up into fragments of different sizes; these fragments are strongly deformed. Part of the commonly angular fragments float in the sandstone part of the underlying turbidite, whereas other fragments float between laminae inside the fine-grained sediment, in the form of relatively thin clasts (Fig. 6a). Some of these thin fragments are also distorted, stretched and/or folded (Fig. 6b).

Other specimens show laminae that have only been folded. The axial planes of these folds dip to the NNW (Fig. 6c). This direction is consistent with the paleocurrent direction indicated by the flute casts of the turbidites and by the dip of the axial planes of the major slump folds in the succession. Larger folds occur occasionally in some fragments (Fig. 6d).

Interpretation of the dome structures and rip-up clasts

Neither the dome structures nor this type of rip-up clasts have been interpreted previously. For this reason we deal with their genesis in detail here.

Interpretation of the dome structures

The dome structures have several characteristics in common with flame structures, but differ fundamentally from them because of their shape, particularly the length/width ratio. Flame structures form between adjacent descending lobes (load casts) at the contact between two successive layers that show a reversed density gradient (cf. Anketell et al. 1970; Allen 1982). The shape of such flames is controlled by the maturity of the load casts and by the lateral distance between them, but they tend to be more or less vertical and to have length/width ratios of the order of 10-100. Flame structures between seismically induced load structures, as described by, among others, Du et al. (2008), Owen et al. (2011) and Moretti and Ronchi (2011) show commonly much more distortion, depending on the complexity of the seismically induced load casts (which may become increasingly complex if successive seismic shocks affect them). Because of their irregular shapes, it is not well possible to attribute a specific length/width ratio to them, but this value does

commonly not differ substantially from that of the first-mentioned type of flame structures.

The dome structures under study here have a much lower length/width ratio (order of 0.5-1), but they are also more regular than flame structures. In addition, the load structures in the sandy top part between the dome structures cannot have formed due to seismic activity because the layer in that case should show more – and particularly more laterally continuous – deformations. This implies that the dome structures must represent a process due to syn- or metadepositional conditions. The floating fragments consisting of the fine-grained sediment that now occur occasionally in the sandy part of the overlying turbidite must be ascribed to erosion of the parent layer of the fragments; this erosion is interpreted to have taken place under influence of the shearing caused by the downslope running turbidity current. The small kink folds show that the shear stress due to the movement of the turbidity current had a lateral component. Taking all these features into account, it must be deduced that rapid sedimentation of the overlying turbidite triggered the development of the dome structures.

The morphology of these dome structures results from the two main driving forces, viz. the gravitational instability due to a reverse density gradient (cf. Owen 1987, 1996, 2003; Owen et al. 2011; Rossetti 1999) and the lateral shear stress (cf. Mills 1983; Brenchley and Newall 1997; Dasgupta 1998; Moretti et al. 2001). During the rapid accumulation of ever more turbidites, the weight of the overburden caused, after passing a threshold value, partial liquefaction of the still unconsolidated sediments; these started to flow laterally (and partially upwards) together with the pore water, thus forming the dome structures without, however, to have sufficient power to break through the overlying layer. The laminae of the affected sediment

thus became thicker in the domes, while thinning under the descending lobes of the load structure.

The axial planes of some dome structures dip to the WNW and the micro-scale kink folds indicate that the orientation of the shear stress was ESE-WNW; both directions are consistent with the paleocurrent direction measured from the slump folds and the sole marks. The shear stress that played such an important role in the formation of the dome structures was probably induced by the drag of the turbidity current, but it cannot be excluded entirely that the downslope component of the gravitation of the overlying turbidite succession also played a role.

Interpretation of the rip-up clasts

Rip-up clasts are commonly considered to represent a seismically-induced autoclastic mudstone breccia (Wang 2013). Our field examples show clearly, however, that the “clasts” are made up of fragments of the fine-grained sediment that became distorted when it became in immediate contact with the overlying sandstone turbidite. This must be deduced from the fact that the sandy base of the overlying turbidite was involved in a deformation process, whereas the fine-grained, laminated sediment does not show any obvious deformation. This suggest that the deformation occurred already during the deposition of the overlying turbidite. If the deformation were induced by a post-depositional process (such as a seismic shock), the fine-grained top part of the overlying turbidite should also have been deformed, though not necessarily equally strongly. Moreover, the appearance of the fragments is not consistent with that of seismogenic autoclastic fragments which display brittle deformation and which fit harmoniously with each other (Anand and Jain 1987; Plaziat et al 1990; Guiraud and Plaziat 1993; Qiao and Li 2009; Du 2011; Rossetti et

al. 2011). Another argument against a seismogenic origin is that the strongly deformed fragments, which are distorted, stretched, folded and even overturned in a complicated way, are all attributable to the action of lateral shear stress, whereas these features cannot result from seismic shocks. A seismic trigger can consequently be ruled out; on the other hand, although the origin of rip-up clasts can have different origins, including diagenetically induced pressure (e.g. Henares et al. 2016), these types of structure have commonly been suggested to be induced by the passage of a strong flow such as a tsunami (Bondevik et al. 2003; Goff et al. 2004) or a turbidity current (Labaume et al. 1987), which also results in a sudden increase of the lithostatic pressure due to the rapid sedimentation of a turbidity current.

Deformations of the types described above develop when turbidity currents pass under a specific main driving force: lateral shear stress. Moreover, the rapidly thickened overburden resulted in the fluidization of the sandstone part of the underlying turbidite due to the increase of the pore pressure. The fluid/sediment mixture tried to escape upwards and penetrated the laminated fine-grained sediment. Possibly at the same time, the shear stress exerted by the passing turbidity current resulted in the complex deformation of the fragments. It can, however, not be entirely excluded that the shear stress resulting from the downslope component of the turbidites' weight contributed to the shear stress, particularly since some silty laminae in the fine-grained sediment became also liquefied.

Discussion

Numerous natural processes have the potential to trigger the development of SSDS in unconsolidated or semi-consolidated water-saturated sediments. The deformation mechanisms and driving forces can, however, in most cases be

unraveled by analysis of the SSDS (cf. Suter et al. 2011). The interpretation of the most likely trigger mechanism, in contrast, is commonly much more difficult to define, particularly since different triggers can induce SSDS with similar morphologies, whereas it is known already for a long time that one single trigger can result in SSDS with strongly different morphologies (Kuenen 1958; Butrym et al. 1964; Dzulynski and Walton 1965). This makes it difficult to recognize triggers for complex SSDS such as those that characterize, for instance, seismites. It is therefore understandable that contrasting approaches have been proposed to distinguish seismic triggers (criteria-based approach) from non-seismic triggers (trigger-based approach) (Pope et al. 1997; Jones and Omoto 2000; Moretti 2000; Moretti and Sabato 2007; Spalluto et al. 2007; Owen et al. 2011), and even such approaches have to deal with numerous pitfalls (Moretti and Van Loon 2014).

Few criteria have, unfortunately, been developed thus far to identify non-seismic triggers. Moretti and Sabato (2007) suggested to identify them by analyzing each possible trigger using all available information to accept or discard a specific trigger. This approach is, however, not only comprehensive, but it is difficult - if not impossible - to consider all potential triggers for each individual SSDS. Owen et al. (2011) therefore suggested a three-stage approach, combining assessment of (1) the sedimentary facies, (2) likely triggers and (3) available criteria. We follow this approach here.

(1) With respect to the facies assessment, it is clear that the SSDS under study developed in turbidite successions which were deposited in an outer-fan/basin-plain environment. All SSDS are situated at the boundaries between the fine-grained top parts of a sandstone turbidite and the sandstone part of an overlying turbidite. It is remarkable that the fine-grained top part of the latter (the overlying turbidite) is

undeformed, which proves that the deformation must have occurred syndepositionally (i.e. during deposition of the overlying turbidite) or (much less likely) metadepositionally, i.e., before deposition of the overlying turbidite. This close relationship suggests that the trigger is associated with the depositional process so that triggers that are not associated with depositional processes (such as seismic shocks, bioturbation and impacts) can be excluded.

(2) With respect to the trigger assessment, it is important, because we proved above that the trigger was most probably syndepositional and thus should be considered as inherent to the depositional environment, that numerous triggers (particularly rapid sedimentation, storm waves, breaking waves, flow impact, a tsunami, tidal shearing and groundwater movement) need be assessed. According to the water depth in this sedimentary environment, most triggers, such as storm waves, breaking waves, tsunamis and tidal shear can fortunately be discarded. In addition, the deformational structures are not similar with those induced by flow-induced shear or groundwater movement. Therefore, rapid sedimentation remains as the most likely trigger.

(3) With respect to the criteria assessment, some probable criteria have already been proposed to characterize SSDS in turbidite successions that are related to rapid sedimentation. These criteria are based on the characteristics of the SSDS and their sedimentary context, and they include the following situations: (1) the turbidite overlying the level with the SSDS shows no obvious liquefaction-induced feature in its sandstone part; (2) the fine-grained part of the overlying turbidite is still undeformed; (3) the preferred orientation of some structures may have been caused by shear stress, and they are consistent with the paleocurrent direction.

Conclusions

Dome structures and rip-up clasts occur in Early Cretaceous turbidite successions exposed in the Dengta and Qiancengya sections on Lingshan Island, eastern China. The turbidites with these SSDS tend to consist of thin-bedded sandstones that alternate with finely laminated fine-grained sediments. The sediments accumulated in an outer-fan/basin-plain setting characterized by low-energy conditions. The dome structures and rip-up clasts result from liquefaction/fluidization induced by the rapidly increasing weight of the overburden caused by the high sedimentation rate of successive turbidites, which is a common feature in such types of succession.

The dome structures have a genesis (Fig. 7) that is in several respects comparable to that of flame structures: overloading induced by the sudden deposition of a sandy turbidite caused the finely laminated fine-grained, water-saturated sediment to be pushed aside between sagging sand lobes of the freshly deposited layer; this was facilitated because the fine-grained sediment became partially liquefied, enabling them to flow sideways and somewhat upwards into the direction of least pressure (= upwards). The energy of the moving sediment/water mixture was, in contrast to the situation where a zone of weakness allows such a mixture to open a pathway through the overlying layer, relatively small, so that the overlying sediment could not (or only as a very small scale) be penetrated, so that only a dome-shaped accumulation was formed with laminae that thicken towards the axial part. The shear stress exerted by the turbidity current caused a preferred orientation (NW) of some axial planes of the dome structures, consistent with the overall paleocurrent direction.

The rip-up clasts of the finely laminated, fine-grained sediments developed due to the fluidization of the sandstone part of the underlying turbidite caused by the sudden overloading due to the rapidly deposited overlying sandstone turbidite (Fig. 8). The

excess water rushed out, to rupture the fine-grained sediment. The shear stress exerted by the passing turbidity current complicated the deformation process, resulting in stretched, distorted and folded clasts.

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Draft

[Figure captions]

Fig. 1. Geographical and geological setting. (a) Location of the study area, with the Sulu Orogenic Belt between the North China Plate and the Yangtze Plate. (b) Geological setting of the Shandong region, with Lingshan Island (indicated in red) being situated in the Lingshandao Depression. (c) Geological map of Lingshan Island, with locations of the two sections under study. (d) Stratigraphic framework and sedimentological setting of Lingshan Island.

Fig. 2. Paleocurrent data. (a) Stereonet plots of fold axes (open squares) and axial-plane poles (crosses) of the folds in slumps ($n = 20$). (b) Rose diagram of paleocurrent directions measured from flute casts. (c) Rose diagram of paleocurrent directions measured from groove casts.

Fig. 3. The Dengta section. The succession (a) consist mainly of turbidites (b) that each consist of a graded lower sandstone part and a finely laminated fine-grained upper part. Some slumps are also present, ranging from meters thick (b) to some decimeters thick (c). (diameter of the lens cap is 6 cm).

Fig. 4. The Qiancengya section. the succession (a) consists mainly of thin-bedded sandstones alternating with fine-grained layers (b). (c) detail of the succession (diameter of the tape holder is 20 cm).

Fig. 5. Dome structures in the Dengta section. (a) Setting of a well-developed specimen between a fine-grained unit and the sandy basal part of an overlying

turbidite. (b) Detail of the structure in Fig. 5a. (c) Undulating laminae (dashed lines) toward the axial plane of a dome structure. Pen (1 cm in diameter) for scale.

Fig. 6. Rip-up clasts at the base of the Qiancengya section. (a) Partly undeformed fragment (left) and disrupted fragments of broken-up lamination (right) in a fine-grained layer. (b) Deformed (distorted, stretched, folded) fragments of the same layer, also showing layer thickening and thinning. (c) Folded laminae inside the fine-grained laminated bed (the axial plane dips to the NNW). (d) Large folded fragment of the laminated sediment. Pen (1 cm in diameter) for scale.

Fig. 7. Schematic model showing the genesis of the dome structures. (a): deposition of a turbidite on a turbidite substratum. (b) a sand-rich turbidity current flows over the older turbidite. (c) dome structures form in the liquefied sediment due to overloading and lateral shear caused by deposition of the sand-rich lower part of the turbidite. (d) deposition of the fine-grained upper part of the turbidite, preserving the dome structure.

Fig. 8. Schematic model showing the genesis of the rip-up clasts. (a) deposition of a turbidite on a turbidite substratum. (b) escape of water/sediment mixtures; (c) rip-up clasts form in the liquefied sediment due to the erosional power and lateral shear exerted by the sand-rich lower part of the turbidity current. (d) deposition of the fine-grained upper part of the turbidite, preserving the rip-up clasts.

Fig. 1. Geographical and geological setting. (a) Location of the study area, with the Sulu Orogenic Belt between the North China Plate and the Yangtze Plate. (b) Geological setting of the Shandong region, with Lingshan Island (indicated in red) being situated in the Lingshanda Depression. (c) Geological map of Lingshan Island, with locations of the two sections under study. (d) Stratigraphic framework and sedimentological setting of Lingshan Island.

141x140mm (300 x 300 DPI)

Fig. 2. Palaeocurrent data. (a) Stereonet plots of fold axes (open squares) and axial-plane poles (crosses) of the folds in slumps (n = 20). (b) Rose diagram of palaeocurrent directions measured from flute casts. (c) Rose diagram of palaeocurrent directions measured from groove casts.!! †

75x49mm (300 x 300 DPI)

Fig. 3. The Dengta section. The succession (a) consist mainly of turbidites (b) that each consist of a graded lower sandstone part and a finely laminated fine-grained upper part. Some slumps are also present, ranging from meters thick (b) to some decimeters thick (c). (diameter of the lens cap is 6 cm).

146x148mm (300 x 300 DPI)

Fig. 4. The Qiancengya section. the succession (a) consists mainly of thin-bedded sandstones alternating with fine-grained layers (b). (c) detail of the succession (diameter of the tape holder is 20 cm).

141x143mm (300 x 300 DPI)

Fig. 5. Dome structures in the Dengta section. (a) Setting of a well-developed specimen between a fine-grained unit and the sandy basal part of an overlying turbidite. (b) Detail of the structure in Fig. 5a. (c) Undulating laminae (dashed lines) toward the axial plane of a dome structure. Pen (1 cm in diameter) for scale.

161 × 162 mm (96 × 96 DPI)

Fig. 6. Rip-up clasts from the base of the Qiancengya section. (a) Partly undeformed fragment (left) and disrupted fragments of broken-up lamination (right) in a fine-grained layer. (b) Deformed (distorted, stretched, folded) fragments of the same layer, also showing layer thickening and thinning. (c) Folded laminae inside the fine-grained laminated bed (the axial plane dips to the NNW). (d) Large folded fragment of the laminated sediment. Pen (1 cm in diameter) for scale.

161×108 mm (96×96 DPI)

Fig. 7. Schematic model showing the genesis of the dome structures. (a): deposition of a turbidite on a turbidite substratum. (b) a sand-rich turbidity current flows over the older turbidite. (c) dome structures form in the liquefied sediment due to overloading and lateral shear caused by deposition of the sand-rich lower part of the turbidite. (d) deposition of the fine-grained upper part of the turbidite, preserving the dome structure.!! †

134x77mm (300 x 300 DPI)

Fig. 8. Schematic model showing the genesis of the rip-up clasts. (a) deposition of a turbidite on a turbidite substratum. (b) escape of water/sediment mixtures; (c) rip-up clasts form in the liquefied sediment due to the erosional power and lateral shear exerted by the sand-rich lower part of the turbidity current. (d) deposition of the fine-grained upper part of the turbidite, preserving the rip-up clasts.

134x77mm (300 x 300 DPI)