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RESEARCH PAPER

Deep-water gravity flow deposits in a lacustrine rift basin and their oil and gas geological significance in eastern China

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Abstract: The types, evolution processes, formation mechanisms, and depositional models of deep-water gravity flow deposits in a lacustrine rift basin are studied through core observation and systematic analysis. Massive transport of slide and slump, fluid transport of debris flow and turbidity currents are driven by gravity in deep-water lacustrine environment. The transformation between debris flow and turbidity current, and the transformation of turbidity current between supercritical and subcritical conditions are the main dynamic mechanisms of gravity flow deposits in a lake basin. The erosion of supercritical turbidity current controls the formation of gravity-flow channel. Debris flow deposition gives rise to tongue shape lobe rather than channel. Deep-water gravity flow deposits are of two origins, intrabasinal and extrabasinal. Intrabasinal gravity flow deposits occur as single tongue-shape lobe or fan of stacking multiple lobes. Extrabasinal gravity-flow deposits occur as sublacustrine fan with channel or single channel sand body. However, the nearshore subaqueous fan is characterized by fan of stacking multiple tongue shape lobes without channel. The differential diagenesis caused by differentiation in the nearshore subaqueous fan facies belt results in the formation of diagenetic trap. The extrabasinal gravity flow deposits are one of the important reasons for the abundant deep-water sand bodies in a lake basin. Slide mass-transport deposits form a very important type of lithologic trap near the delta front often ignored. The fine-grained sediment caused by flow transformation is the potential “sweet spot” of shale oil and gas.

Key words: turbidity current; debris flow; deep-water gravity-flow deposits; depositional model; oil and gas geological significance; fault lake basin

Introduction

Sand bodies of deep-water gravity-flow deposition in a lacustrine basin refer to sand bodies which are transported and deposited by gravity and distributed below the storm wave base. These sand bodies are the main targets of exploration for lithologic hydrocarbon reservoirs and unconventional hydrocarbon reservoirs in China[1–4]. The formation and distribution of deep-water gravity-flow sand bodies in a lacustrine basin are controlled by multiple factors, including tectonic activities and climate conditions[5–7], and these sand bodies contain abundant information related to paleotectonics and paleoclimatic evolution. Research works related to deep-water gravity-flow deposits in a lacustrine basin are vital for geological researches such as tectonic and paleoclimate evolution, paleogeographic reconstruction and hydrocarbon exploration and development[8–9]. The seminal work of turbidity current proposed in 1950 was the beginning of deep-water gravity-flow research works[10], and then expanded to deep-water gravity-flow deposits theory. Gravity-flow deposits in a lacustrine basin were first mentioned by Forel[11] in studying the transport process of high-density current injected into Lake Geneva in Switzerland. Deep-water gravity-flow deposits caused by

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rework of marine sediments have been the main research objects later, while deep-water gravity-flow deposits in a lacustrine basin have been neglected. In recent years, drawing on the research experience of gravity-flow deposits in marine basins, some progresses also have been made in gravity-flow deposits of lacustrine basin[1, 12–14]. The research on deep-water gravity-flow deposits in a lacustrine basin is a comprehensive study involving the dynamic process of "trigger-transport-deposition" of gravity flow[15], the existing study focus on the identification and distribution of sand bodies, but ignore the analysis of the dynamic process of deep-water gravity-flow in a lacustrine basin. The systematic research works related to the types, evolution processes of gravity flow and formation mechanisms and depositional models of deep-water gravity-flow deposits are relatively weak[2–3, 8–9, 16].

The lacustrine rift basin has the typical characteristics of various geomorphic structural units such as steep slope zone, sub-sag zone and gentle slope zone, and multistage step-shaped fault slopes. The gravity-flow deposits formed under the control of lacustrine rift basin are diverse in type and complex in evolution process, so lacustrine rift basins are ideal places to study the deposition of deep-water gravity-flow in lacustrine basin. Based on systematic analysis of types of deep-water gravity-flow deposits in lacustrine rift basins, the sedimentary evolution processes, depositional models, and hydrocarbon geologic significance of deep-water gravity flow deposits have been discussed in this work, in the hope to provide some theoretical basis for the conventional and unconventional hydrocarbon exploration in deep-water gravity-flow deposits of lacustrine basin.

1. Classification of deep-water gravity-flows in a lacustrine rift basin

A lacustrine rift basin is characterized by strong tectonic activities, large slope gradient, abundant sediment supply, and large water depth. Compared with a marine basin and other types of continental lacustrine basins, a lacustrine rift basin is more likely to have deep-water gravity-flow deposits. A large lacustrine rift basin often has various kinds of deep-water gravity-flow deposits[4]. In this work, based on core observation and analysis of typical deep-water gravity-flow deposits in the Jiyang depression and Weixinan sag, according to the rheologic and sedimentary dynamic features reflected by sediment composition, sedimentary structures and lithofacies associations, combined with deep-water gravity-flow classification schemes in China and abroad, deep-water gravity-flow in a lacustrine basin is divided into debris flow of plastic rheology and turbidity current of Newtonian rheology. In addition, there are two kinds of mass transport deposits, slide and slump associated with deposition of deep-water gravity-flow. According to mud content, debris flows are subdivided into muddy debris flows and sandy debris flows. According to the density and sedimentary structures, turbidity currents are subdivided into high-density turbidity current and low-density turbidity current. Low-density turbidity currents are further subdivided into surge-like turbidity current and quasi-steady turbidity current according to strength of sedimentary dynamic, duration time and depositional succession[17] (Fig. 1).

Sediment particles in muddy debris flow are mainly supported by matrix strength and excess pore-fluid pressure. The deposits of muddy debris flow are mainly composed of matrix supported massive conglomerate and muddy sandstone, which reflect plastic rheology and settling pattern of overall consolidation (Fig. 1③). Sediment particles in sandy debris flow are mainly supported by matrix strength, excess pore-fluid pressure, dispersive pressure, and buoyant. Low in matrix content, sandy debris flow deposits are mostly massive sandstone (Figs. 1④, and 2a). Abundant floating mud clasts and muddy rip-up clasts in the upper part of the massive sandstone indicate plastic rheology and settling pattern of en-massive consolidation.

Sediment particles in high-density turbidity current are mainly supported by dispersive pressure, buoyant, and flow turbulence with relatively low matrix content and weak normal grading. Stratification structures caused by traction carpet and imbrication of pebbles are common in coarse-grained massive deposits of high-density turbidity current (Figs. 1⑤ and 2b), indicating the settling features of stratified transport and vertical stacking[18]. The high-density turbidites are more common in coarse-grained gravity flow deposits of the steep slope zone in a lacustrine rift basin. Some high-density turbidites may misinterpreted as sandy debris flow deposits. It is possible to distinguish high-density turbidites from sandy debris flow deposits by obvious erosional structures and internal grading variation (Figs. 1④, 1⑤ and 2).

Sediment particles in low-density surge-like turbidity current are mainly supported by flow turbulence, and settle according to the grain size from big to small to form complete or incomplete Bouma sequence. The sediments are smaller in grain size and higher in matrix content than the high-density turbidity current sediments. This flow surge-like turbidity current with short duration and is characterized by a sudden increase in flow velocity and energy followed by a rapid decline[17] (Fig. 1⑥). Sediment particles in low-density quasi-steady turbidity current are mainly supported by flow turbulence. The size of the sediment particles is controlling by the energy of the flood, resulting in inverse-normal grading sequence which reflects the increasing then declining of the flood energy. In addition, climbing ripple bedding and continental plant debris are common in these deposits[17]

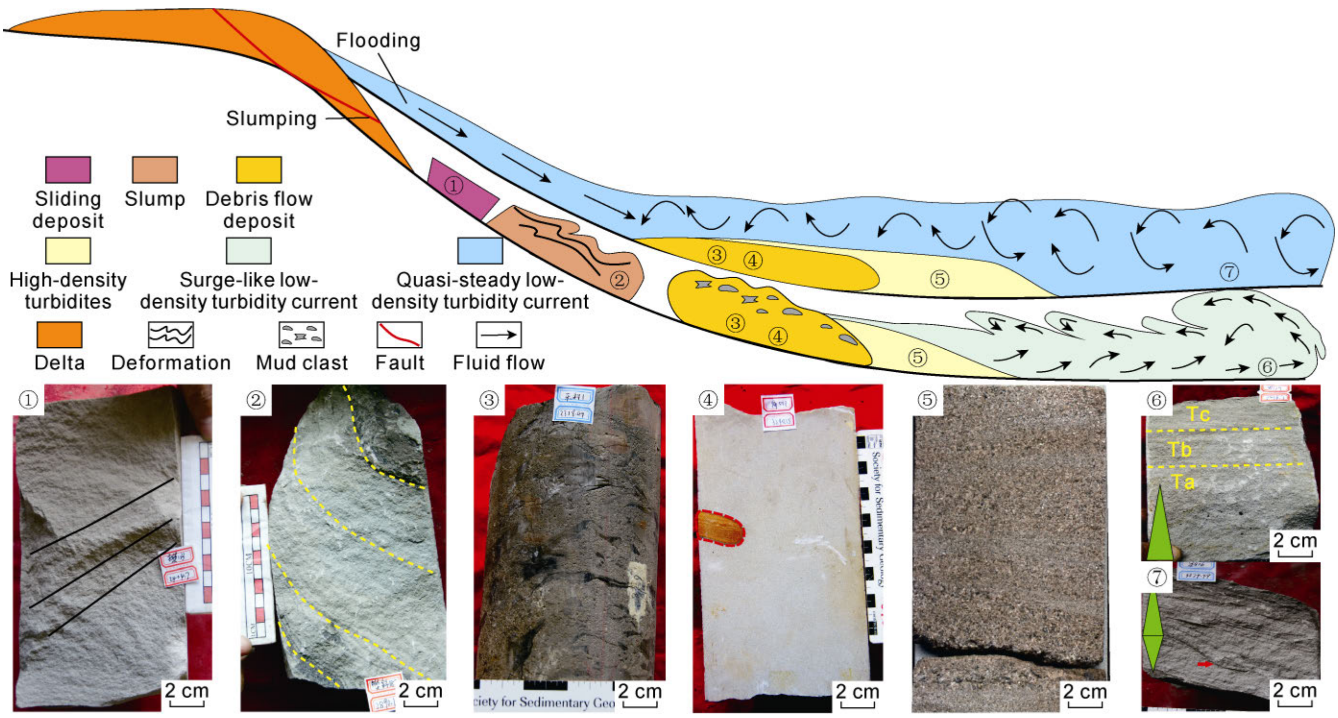

Fig. 1. Types, distribution and sedimentary characteristics of deep-water gravity-flow deposits in a lacustrine rift basin. ① Dongying sag, Well Fan 133, 2404.7 m, sliding block with incompletely modified bed; ② Dongying sag, Well Fanxie 183, 2890.1 m, slumping block with internal deformed structure; ③ Dongying sag, Well Dongke 1, 3348.5 m, massive muddy clasts developing muddy debris flow deposit; ④ Huimin sag, Well Shang 548, 3240.2 m, massive sandy debris flow deposit with floating mud clasts in the top part; ⑤ Dongying sag, Well Shi 100, 3087.7 m, high-density turbidites with stratification structures; ⑥ Dongying sag, Well Shi 129, 3438.7 m, incomplete Bouma sequence deposited by surge-like low-density turbidity current; ⑦ Dongying sag, Well Niu 876, 3374.5 m, inverse-normal grading sequence deposited by quasi-steady low-density turbidity current.

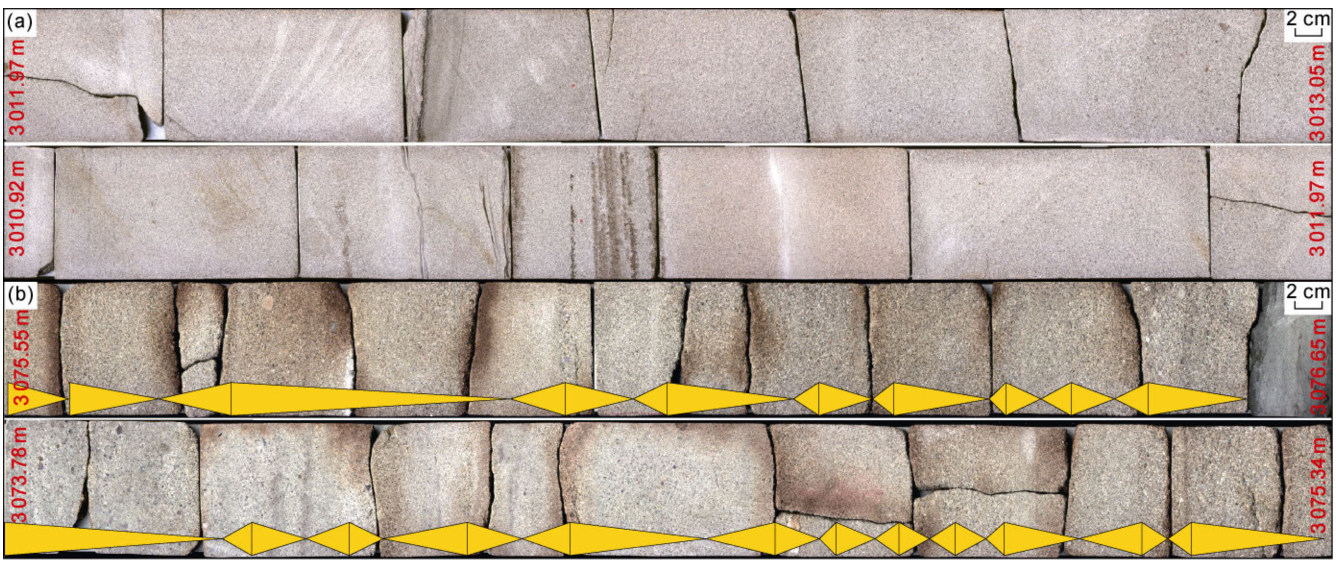

Fig. 2. Characteristics of massive sandstone caused by deep-water gravity-flow in a lacustrine rift basin of the Dongying sag. (a) Well Niu 110, 3010.92–3013.05 m, medium to fine massive sandstone caused by sandy debris flow, uniform in internal composition without obvious sedimentary structures or grain sequence variation; (b) Well Shi 100, 3073.78–3076.65 m, medium to coarse-grained massive sandstone caused by high-density turbidity current, with obviously internal stratified structures and grain sequence variation.

(Fig. 1⑦). The sliding block is characterized by the abrupt contact between internal shallow-water sedimentary structure sandstone and deep water mudstone, and shear slide surfaces in the bottom (Fig. 1①). The slumping block is characterized by internal continuous deformation structures, sandy folds and sand injections (Fig. 1②).

There are also transformation and mixing between debris flow and turbidity current in a lacustrine rift basin, which result in hybrid event bed. To make it easy to understand, hybrid flow isn't regarded as one type of gravity flow, instead it is regarded as a flow transformation process. Grain flow is regard as the extremely condition of sandy debris flow, that is, sandy debris flow without muddy matrix. In this situation, the grains are mainly supported by dispersive pressure. Supercritical state is the dynamic property of fast transporting flow, which is most likely to occur in stratified high-density turbidity current[18–22].

2. Dynamics and sedimentation of deep-water gravity-flow in a lacustrine rift basin

Due to special sedimentary tectonic background, deep-water gravity-flow in a lacustrine rift basin is also unique in dynamics and sedimentation. First, due to large slope angle of the terrain, deep-water gravity-flow is low in transformation efficiency. Second, complex topography and multi-stage stepped ramps lead to multi-stage evolution of deep-water gravity flow. Third, with intense tectonic activities, deep-water gravity-flow of slump origin is common in the front of delta. Fourth, as the deposition area is close to provenance area, deep-water gravity-flow caused by flood is widespread. Fifth, as the transitional zone from shallow water to deep water is narrow, coarse-grained deep-water gravity-flow deposits are more common. Lacustrine rift basins mostly appear as single fault or double faulted grabens controlled by tensile faults. The basin has steep slope zone, gentle slope zone and sub-sag zone in general. Different in slope gradient, source supply and water depth, these zones are different significantly in dynamics and sedimentation of deep-water gravity-flow deposits. The steep slope zone has mainly deep-water gravity-flow deposits triggered by flood. The gentle slope zone or long axis zone have deep-water gravity-flow deposits triggered by both sediment slump and flood.

2.1. Deep-water gravity-flow deposits triggered by flood in the steep slope zone

The steep slope zone in a lacustrine rift basin is formed under the effect of tensional fault with relatively large slope gradient. For example, the northern steep slope zone of Dongying sag has a slope gradient of 18.7°–31.8°[4]. With sufficient sediment supply, the steep slope zone of lacustrine rift basin is the area with deep-water gravity-flow most developed. In the steep slope zone, the room for sediment development is relatively narrow without shallow water sediments, or there are only a small amount of fluvial fan or fan delta sediments in the incised valley. Under the effect of episodic flooding event, continental clasts are transported to the lacustrine basin in the forms of flooding-debris flow through lake-margin incised valley. Therefore, the deep-water gravity-flow deposits in the steep slope zone are mainly debris flow deposits and high-density turbidites, with occasional low-density quasi-steady turbidites (Fig. 3a).

Under the action of its own gravity, the flood-debris flow in the steep slope reaches the deep lake directly along the boundary fault. With high matrix content, high viscosity, and low mixing degree with ambient water, the debris flow often accumulates at the toe of the slope in deep lake. After debris flow settling, the high-density fluid caused by flood plunging carry the sediment ahead further, and the sediment settle gradually under its own gravity. Some of the high-density fluid accelerate under the effect of secondary ramp and increase in erosional ability, eroding the muddy base and transforming into sandy debris flow. Sandy debris flow can transform to high-density turbidity current with the dilution of ambient water and hydraulic jump while transporting ahead. High-density turbidity current would transform into low-density quasi-steady turbidity current due to sediment settling, ambient water dilution, and continual supply of flood (Fig. 3a). As the high-angle boundary faults in the steep slope zone play a major role in controlling the basin floor landform, the dilution and mixing of gravity flow with ambient water are inhibited in the transporting process, and the evolution efficiency of the flow is relatively low. Thus, fan aprons dominated by sandy debris-flow and muddy debris-flow sediments come up around slope toe.

2.2. Deep-water gravity-flow deposits triggered by flood along basin axis or in the gentle slope zone

The long axis or gentle slope zone of rift basin has much smaller terrain height difference than the steep slope zone, so debris flow or high-density sediments caused by flood would settle on land or inshore shallow lake, forming alluvial fan or fan delta etc. Part of the flood with high energy can transport to the deep-water area directly in the form of high-density fluid pass through the inshore shallow lake area, forming deep-water gravity-flow deposits triggered by flood (Fig. 3b). Due to the abundant sediment supply and relatively low density of water, deep-water gravity-flow deposits triggered by flood are more common in the lacustrine basin than in the marine basin[5, 14].

The deep-water gravity-flow deposit in the long axis zone or gentle slope zone of the lacustrine rift basin is mainly controlled by the flood energy and transport process. In the case with relatively strong flood energy, the sediment would settle at proximal end due to gravity difference itself, resulting in small amount of debris-flow sediment and high-density turbidites. With sustaining flood supply and settling of relatively coarse-grained sediments, fine-grained sediments would be transported to the deep-water zone in the form of low-density quasi-steady turbidity current. Shearing and dragging of quasi-steady turbidity current to the high concentration sediments at the bottom is the favorite condition to form traction carpet. Vertical stacking of traction carpets result in massive sandstone[23] (Fig. 3b). Erosion of high-density

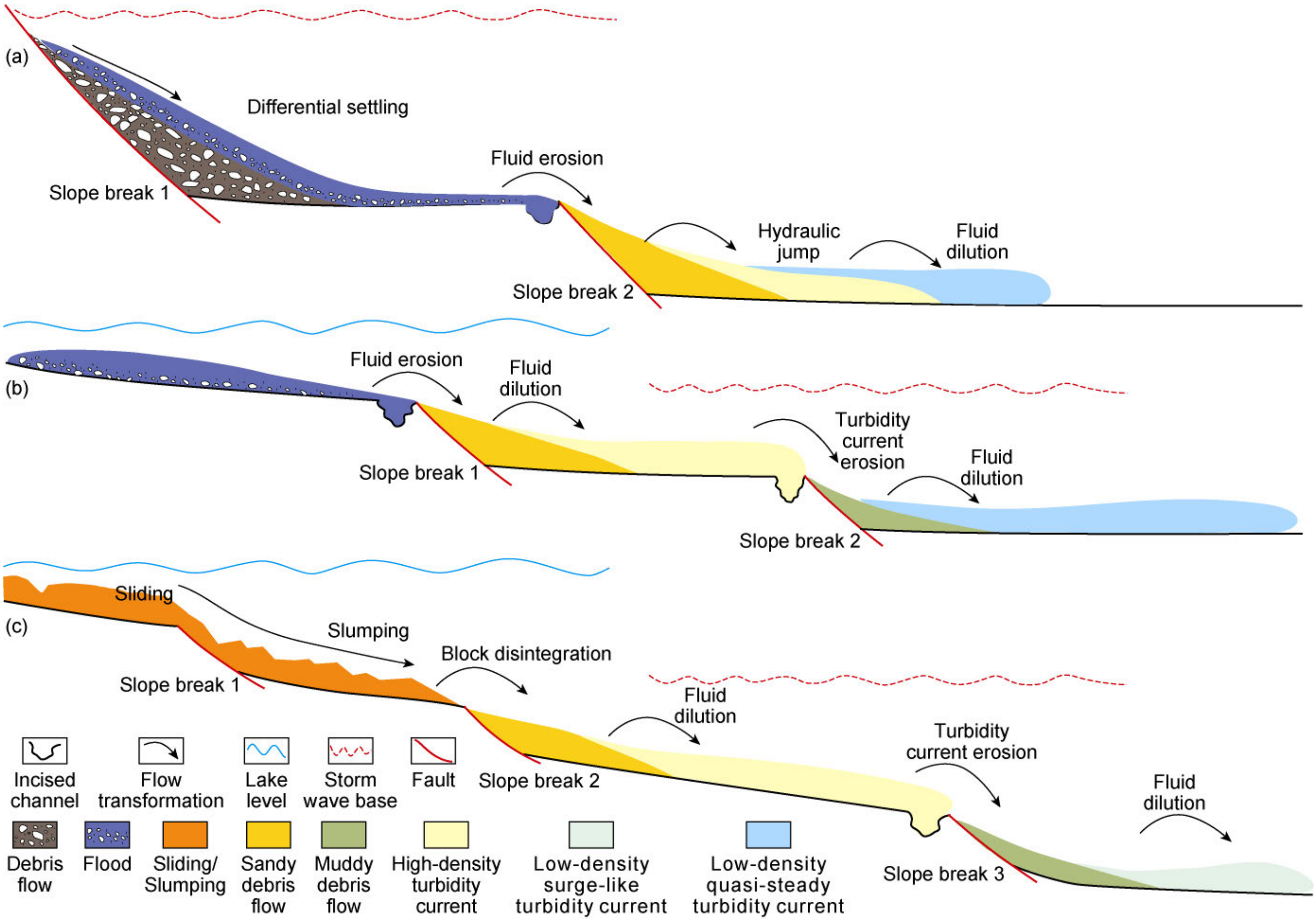

Fig. 3. Models of transport and evolution processes of deep-water gravity-flow in a lacustrine rift basin. (a) The transport and evolution processes of deep-water gravity-flow in the steep slope zone of the lacustrine rift basin; (b) The transport and evolution processes of deep-water gravity-flow caused by flood in the gentle slope zone along long axis of the lacustrine rift basin; (c) The transport and evolution processes of deep-water gravity-flow caused by sediment collapse in the gentle slope zone along long axis of the lacustrine rift basin.

turbidity current to muddy basement would lead to increase of muddy matrix content in the flow. With lower density, the muddy matrix would accumulate in the upper part of the flow, forming small amount of muddy debris flow, and thus hybrid event bed of deep-water gravity flow deposits[19] (Fig. 4). When the slope gradient of the basin is relatively low, low-density quasi-steady turbidity current deposits take dominance. The sedimentary process is controlling by increasing then declining flood energy, correspondingly, inverse grading sequence in lower part then normal grading sequence in upper part is created. With sustaining flood supply, climbing ripple bedding is formed. The different structures of lacustrine rift basin and marine basin caused different sedimentary characteristics of gravity-flow deposits of flood origin in them. The continental shelf of marine basin is broad in general, so coarse-grained sediments carried by deep-water gravity-flow of flood origin largely settle in the continental shelf in marine basin. The left fine-grained sediments would be transported further to the deep-water basin plain. Most previous researches came to the conclusion that gravity-flow caused by flood in a marine basin could only transport sediments with grain size equal to or less than fine sand. In contrast, in a lacustrine rift basin, the transitional zone from shallow water to deep water is narrow, gravity-flow of flood origin would carry sediments of various grain sizes to the deep lake center directly, as this kind of basin has no continental shelf of marine basin or broad gentle slope of large inland depression lacustrine basin. Coarse-grained deep-water gravity-flow deposits are common in this kind of basin (Fig. 2b).

2.3. Deep-water gravity-flow deposits triggered by sediment slumping along long axis or in the gentle slope zone

Fan delta and delta deposits in shallow water zone along the long axis or in the gentle slope zone of lacustrine rift basin are likely to collapse and transport as the result of sediment rapid progradation or other external triggering mechanisms. This is one of the main formation mechanisms of deep-water gravity-flow deposits in lacustrine rift basin. The collapse and transport of shallow water sediments experience sliding, slumping trans-

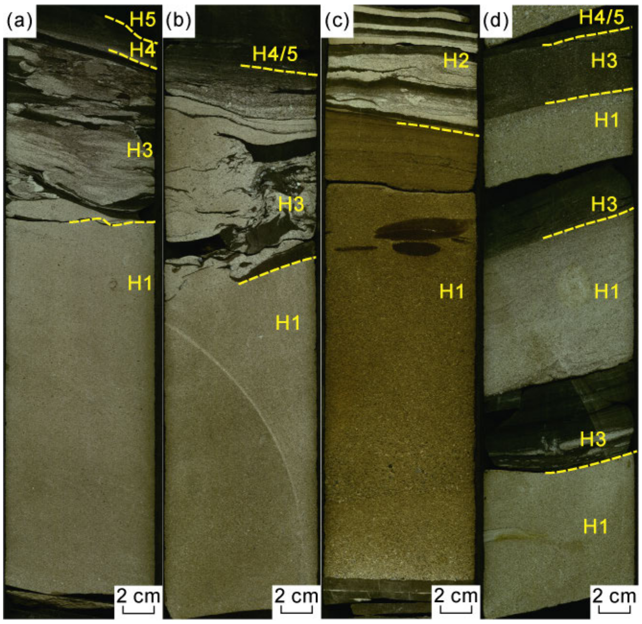

Fig. 4. Hybrid event beds in the lacustrine rift basin in the Weixinan sag of Beibuwan Basin. The yellow dotted line is the boundary of depositional unit; H1–H5 is the depositional unit number of hybrid event beds, modified from [19]. (a) WZ11-7-1, 2508.63–2509.16 m, four-layer structure, with muddy clasts in the upper part; (b) WZ11-7-1, 2512.74–2513.15 m, three-layer structure, with muddy clasts in the upper part; (c) WZ11-7-4, 2171.72–2172.09 m, hybrid event bed in band structure; (d) WZ11-7-1, 2521.61–2521.95 m, two-layer structure, with muddy clasts in the upper part.

port processes in the early stage of flow evolution. With the mixing of ambient water, the blocks disintegrate gradually and transform into debris flow sediments. Debris flow transforms to high density turbidity current with the further mixing of ambient water. As the collapse and transport of sediment lasting a short duration in general is characterized by a sudden increase in flow velocity and energy then a rapid decline later, and finally, the flow evolves into low-density surge-like turbidity current (Fig. 3c).

Although the long axis or gentle slope zone of the rift basin is gentler in terrain than the steep slope zone, multi-stages and multi-types of slope break zones often occur in these areas under the control of sedimentation and tectonic action. The transport and evolution processes of deep-water gravity-flow under the control of multi-stages and multi-types of slope breaks are more complicated than those in the marine basin mainly controlled by continental slope. The slope break in front of the sedimentary body adjacent to lake-shoreline controls the sliding and slumping of early sediments. The subsequent slope break zones shoreline can speed up the disintegration of blocks and flow dilution, and have significant control on the development of debris flow and high-density turbidity current. Under the effect of slope break, hydraulic jump is likely to occur during the transport of high-density turbidity currents, leading to strong erosion and frequently transformation between supercritical flow and supercritical flow and subcritical flow, consequently, the muddy basement would be eroded more rapidly, and the mud content of the flow would increase quickly. This may be the reason for the development of hybrid event beds with muddy debris in the upper part of the deposits. Local topographic relief in the center of the lake basin also has a big influence on the transport and evolution of deep-water gravity-flow. In particular, blocked by local uplifts, the low-density turbidity current would slow down with sediments settled in relatively low position. As the fluid velocity decreases and mud content increases, low-density turbidity current would transform into muddy debris flow. This may be the main reason for the formation of thin hybrid event beds without mud clasts in the upper part of deposits in relatively low position of lacustrine rift basin floor (Fig. 4).

3. Depositional model of deep-water gravity-flow deposits in a lacustrine rift basin

3.1. Formation of deep-water gravity-flow channels

The formation of gravity-flow channel is mainly controlled by the erosion capability of flow. The confluence of erosion and filling processes results in channel-levee system in a deep-water basin. The debris flow with plastic rheology often transports as laminar flow. Due to hydroplaning and basal shear wetting during transport, debris flow has weak erosion to the basement. As a result of strong flow turbulence, turbidity current with Newtonian rheology has stronger erosion to the basement during transport, and the intensity of erosion is in a positive correlation with flow turbulence. Due to relatively weak flow turbulence, low-density turbidity current has weak erosive capacity. The strong flow turbulence and erosion of supercritical high-density turbidity current provide a theoretical basis for explaining the formation and evolution of gravity-flow channel. Geomorphology of modern gravity flow channel and monitoring of gravity flow have proved that the erosion of supercritical high-density turbidity current creates discontinuous linear channel with disk-shaped cross-section and larger width/depth ratio. Then, sustaining action of supercritical high-density turbidity current results in the continuous gravity flow channel, with enhanced downward erosion and smaller width/depth ratio. Under the effect of Coriolis force and secondary circulation, lateral migration and meandering take place in the channel. The erosive ability of the flow enhances further, resulting in V-shaped cross-section with small width/depth ratio. The gravity flow spills over the channel locally, forming distributary channel with the erosion of turbidity current, and the geometry of cross-section would evolve from single V-shape to combination of multi-V shapes[20]. The repetition of above processes would result in complex channel system. In a lacustrine basin, the channel-levee systems are closely related to deep-water gravity flows caused by sustaining flood supply, for example, the lower part of the first member of Shahejie Formation in Banqiao slope of Qikou sag, the lower part of the third member of the Shahejie Formation in east slope of Niuzhuang in Dongying sag etc. With no turbidity currents strong in erosion ability, gravity-flow deposits dominated by debris flow sediments in steep slope zone caused by floods and gravity-flow deposits dominated by sandy debris flow sediments along long axis and in gentle slope zone caused by sediment slumping have fewer gravity flow channels developed.

3.2. Depositional model of deep-water gravity-flow deposits

3.2.1. The extrabasinal deep-water gravity-flow deposits

From the analysis of depositional mechanism and architectural elements of gravity-flow deposits, the depositional model of extrabasinal deep-water gravity-flow deposits mainly include incised valley, channel-levee, channel-lobe transition zone, lobe and so on. From proximal to distal ends, the depositional architectural elements turn up from incised valley, gravity-flow channel-levee, channel-lobe transition zone, lobe in order, forming typical architectural elements associations. Under the control of sedimentary-tectonic setting, some depositional architectural elements may not develop. The types of depositional architectural elements and grain size of sediments are controlled by sediment supply and flood energy jointly. The sediment of this kind has obvious fan shape (Fig. 5).

The incised valley deposit is characterized by strong downward erosion, which is reflected by typical incision-filling reflection characteristic on seismic profile with large width/depth ratio generally. Dominated by matrix supported conglomerate or mud filling, it is the product of sediment bypass or muddy debris flow sediments filling. Channel-levee deposits also exhibit incision-filling reflection characteristic on seismic profile, but are much smaller in width/depth ratio and in band shape. Channel deposits are characterized by massive conglomerate, pebbly sandstone and sandstone with stratification structures. With erosional structures in the bottom, they are the products of high-density turbidity current, and mainly occur in the juncture of incised valley front and slope break. On two sides of the channel are relatively fine sediments, which are the results of spilled deposits carried by flood with strong energy. The fine-grained sediments are developed by low-density quasi-steady turbidity current and settle as levee. Ripples are common in the levee deposits. The channel-lobe transition zone is characterized by intense erosion, which is the depositional architectural element with most developed supercritical turbidite deposits. The lobe deposits are mainly composed of high-density turbidites and low-density quasi-steady turbidites, with small distributary channels developing locally. Migration and superposition of lobes give rise to lobe complexes[21]. Hybrid event beds caused by flow erosion are common in proximal of the lobe, while hybrid event beds caused by flow deceleration and expansion may occur in distal. In particular, in the case that the erosional ability of the flow enhances due to the development of local fault, hybrid event beds would come up extensively.

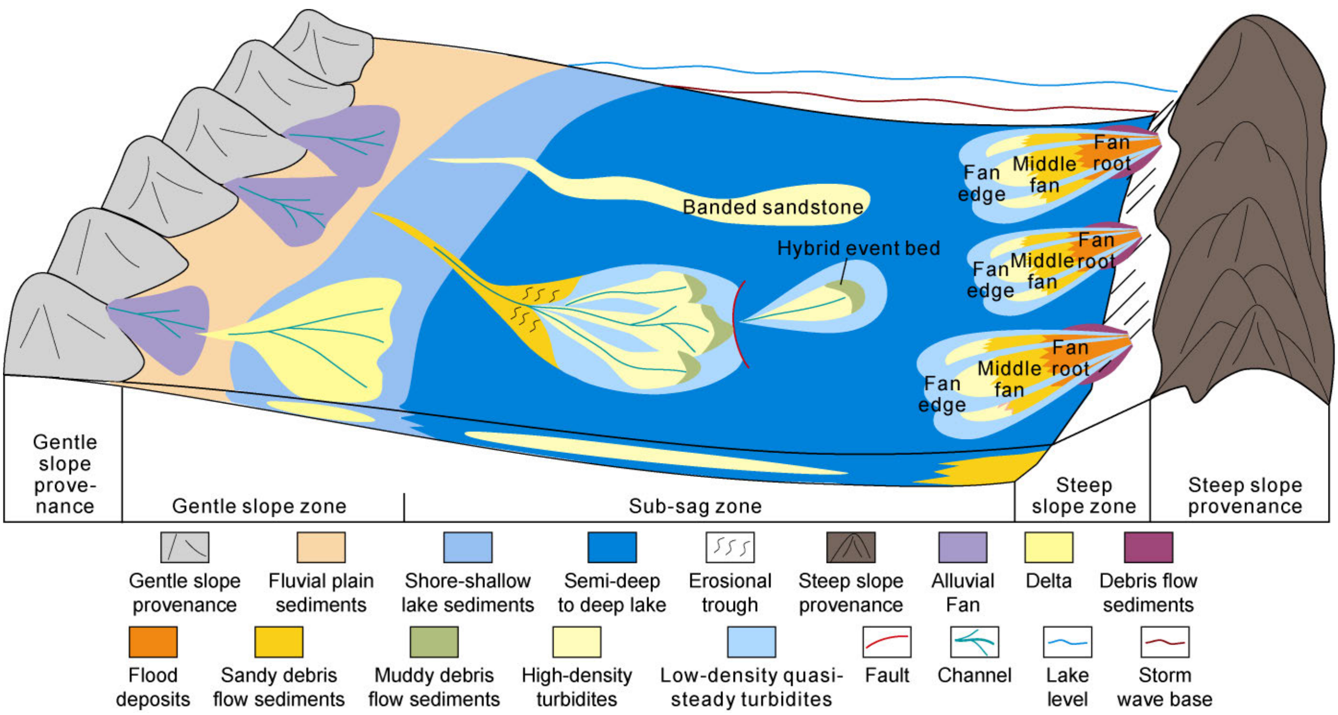

Fig. 5. Depositional model of extrabasinal deep-water gravity-flow deposits.

The river types and related deep-water gravity-flows in different tectonic belts of lacustrine rift basin are various in transporting process and efficiency. Thus, the depositional model of extrabasinal deep-water gravity-flow deposits are also various (Fig. 5). With relatively large topographic height difference, the steep slope zone in rift lacustrine basin has seasonal rivers developed in general. The sediments carried by these rivers are coarse in grain size and have mixed mud, sand and gravel. These coarse-grained sediments would transport to the deep lake rapidly along source channels like incised valleys under the effect of seasonal floods. Due to the large topographic slope gradient, the fluid is low in transporting efficiency and weak in transformation, and the single stage gravity-flow event would give rise to tongue-shaped body dominated by debris flow sediments. Tongue-shaped bodies of different stages could stack over each other to form nearshore subaqueous fans[4]. According to the composition, sedimentary structures, depositional mechanisms, deposit distribution, and depositional architecture elements, the nearshore subaqueous fan can be further divided into three main parts, fan root, middle fan and fan edge. The fan root is located at the slope toe adjacent to the basement fault, where the deposit is dominated by thick massive matrix supported conglomerate formed by muddy debris flow. The middle fan is mainly composed of thick massive particle-supported conglomerate and pebbly coarse sandstone formed by sandy debris flow. Because of the steep topography, the debris flow has no enough time to transform and mix with ambient water while transportation, so the deposits are featured by tongue shape, without channel-levee. The fan edge is dominated by medium to thin bedded silty sandstone caused by low-density quasi-steady turbidite current.

The gentle slope zone and long axis direction of rift lacustrine basin are favorite places for perennial rivers. The sediments carried by the flood in these areas need to be transported long distance over the shore-shallow water to deep lake area. Due to the relatively gentle topography in these areas, the fluid is high in transporting efficiency and thorough in transformation and differentiation. Channel and levee deposits caused by erosion of feeding channel and high-density turbidity current develop in the proximal end. Lobes caused by low-density quasi-steady turbidites are common in the distal end. Channel-lobe transition zone with obvious erosional structures is located in the middle part. The above architecture elements comprise fan-shaped deposits, representing typical sublacustrine fan type. According to the composition, sedimentary structures, depositional mechanisms, distribution characteristics, and depositional architecture elements, the fan-shaped extrabasinal deep-water gravity-flow deposits can be divided into three main parts: inner fan, middle fan and outer fan. The inner fan is mainly composed of massive debris flow sediments in medium-thick bed filling the original confined source channel, corresponding to feeding channel deposits. The middle fan is characterized by distributary channel caused by erosion of high-density turbidity current and related filling deposits, which corresponds to architectural elements of channel-levee and channel-lobe transformation belt. The outer fan is characterized by large-area thin-bedded lobes caused by low-density quasi-steady turbidity current. In the case of weak sediment supply, the differentiation of sedimentary facies is weak, the fan shape isn't obvious, and banded sand bodies caused by low-density quasi-steady turbidity current are most likely to come up. These deposits mainly fill low-lying areas in the basin.

3.2.2. The intrabasinal deep-water gravity-flow deposits

From the analysis of depositional mechanism and architectural elements of gravity-flow deposits, the depositional model of intrabasinal deep-water gravity-flow deposits mainly includes collapse belt of delta front, chaotic deposit, and tongue-shaped sand body, etc. From proximal to distal, the depositional architectural elements of collapse belt to tongue-shape sand body turn up in order, constituting typical association of architectural elements (Fig. 6). With grain size controlled by the grain size of the transported sediments itself, the sediments have no obvious fan shape, and are characterized by stacking of lenticular sand bodies[12].

The collapse belt at delta front features collapse cliff and pit etc. The chaotic deposit in this belt is a mixture of mud, sand and gravels characterized by soft sediment deformation structures of various scales, and are thick layered massive sandstone and muddy sandstone caused by transport of soft sediment after collapse. According to the differences in internal sediment composition and sedimentary structure, the tongue-shaped sand body can be further divided into proximal and distal parts. The proximal deposit is dominated by medium to thick bedded massive sandy debris flow sediments, while the distal deposit is dominated by medium to thin bedded low-density surge-like turbidites with Bouma sequence. In the case of fault developed locally, part of sandy debris flow would transform into high-density turbidity current with higher erosional ability. The high-density turbidity current could give rise to some hybrid event beds in the distal end of tongue-shaped body. Intrabasinal deep-water gravity-flow deposits controlled by various triggering mechanisms and slope gradients are different in distribution characteristics. The collapse of delta front when its own gravity exceeds the critical angle of repose caused by rapid progradation would result in gravity flow of long

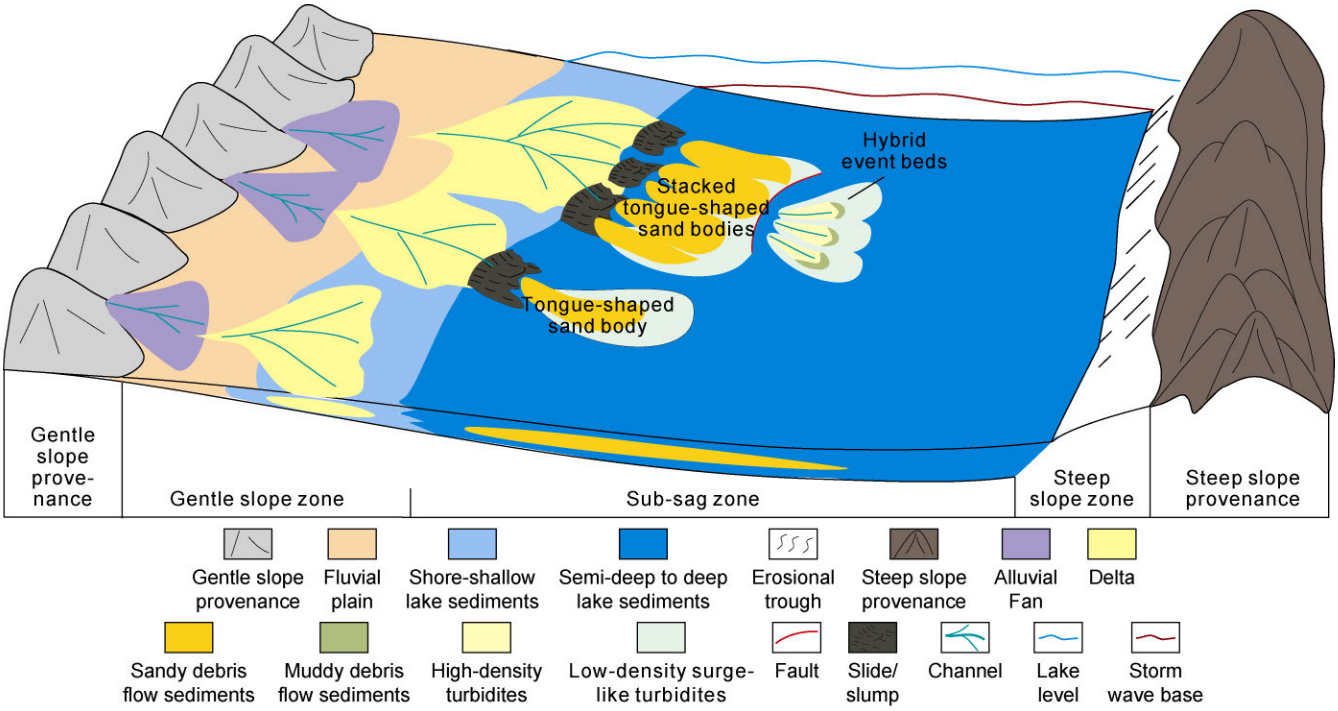

Fig. 6. Depositional model of intrabasinal deep-water gravity-flow deposits.

transport distance and full evolution. Tongue-shaped sand bodies mainly occur far away from the slope break. Intrabasinal deep-water gravity-flow deposits caused by syndepositional faults and earthquakes are very close to the collapse belt of delta front in slope break and composed of chaotic sediments. In the rapid transport of large amount of pre-existing sediments triggered by events, the sediments are not likely to mix with ambient water, thus, the gravity flow has weak transformation degree, and tongue-shaped sand bodies are not well-developed far away from the slope break. Sediment supply also affects the formation and distribution of tongue-shaped sand bodies. Weak sediment supply would result in isolated tongue-shaped sand bodies. On the contrary, sufficient sediment supply would result in multi-stage tongue-shaped sand bodies stacking over each other.

4. Case study of deep-water gravity-flow deposits in a lacustrine rift basin and their petroleum geological significance

4.1. Nearshore subaqueous fan and diagenetic trap

The steep slope zone of lacustrine rift basin is a favorable place for development of nearshore subaqueous fan. With unique formation mechanisms and depositional process, coarse-grained clastic sediments of nearshore subaqueous fan facies are in close contact to high quality source rock laterally in the deep lake, making them favorable oil and gas enrichment sites in lacustrine rift basins. Taking the north steep slope zone of Dongying sag as an example, the nearshore subaqueous fan in the upper part of the fourth member of Shahejie Formation is distributed like an apron due to large topographic height difference and widely developed paleo-gullies. Controlled by transportation and evolution process of flooding of debris flow, the fan root is dominated by massive muddy debris flow sediments of mixed sand, mud and gravels. The middle fan and fan edge are mainly composed of well-sorted sandy debris flow sediments, high-density turbidites and low-density quasi-steady turbidites[22]. During burial evolution, the matrix supported muddy debris flow sediments in fan root weaken in reservoir property as the result of strong compaction and matrix recrystallization, thus becoming good lateral barrier layers. Whereas the well sorted sandstone of sandy debris flow and turbidity current in the middle fan and fan fringe can act as migration channels and reservoirs. Due to different composition and sedimentary structures, fan root, middle fan and fan edge deposits differ in burial diagenetic evolution processes, bringing about near-shore subaqueous fan diagenetic traps and oil and gas enrichment[22]. Under the guidance of this model, a great breakthrough has been made in hydrocarbon exploration in nearshore subaqueous fan of Shengli Oilfield. By 2019, 3.2×10^8 t oil geological reserves have been proved in nearshore subaqueous fan sandy conglomerate.

4.2. Flood triggered gravity-flow deposits and deep-water sand body enrichment

Extrabasinal deep-water gravity-flow deposits developed during the depositional stage of the first member of Paleogene Liushagang Formation (El_1) in WZ11-4N block of Weixinan sag of Beibuwan Basin (Fig. 7a). The Well WZ11-7-1 located in the distal end is characterized by

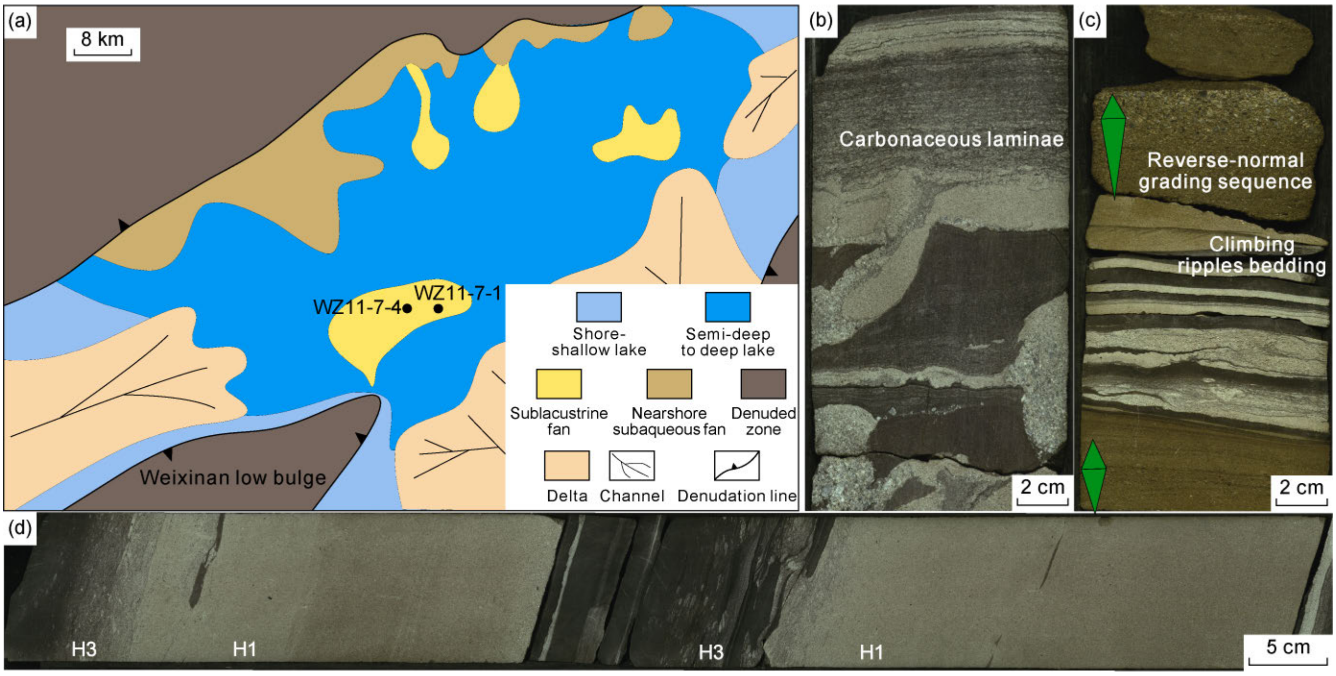

Fig. 7. Distribution of sublacustrine fans in the El_1 of WZ11-4N block of the Weixinan Sag. (a) Plane distribution characteristics of sublacustrine fans; (b) WZ11-7-1, deep-water gravity-flow deposits of flood origin with carbonaceous laminae; (c) WZ11-7-1, inverse-normal grading sequence and climbing ripples bedding in deep-water gravity-flow deposits of flood origin; (d) WZ11-7-1, characteristics of deep-water gravity-flow hybrid event beds, H1—turbidity sediment below the hybrid event beds, H3—muddy debris flow sediments above the hybrid event beds.

stratified carbonaceous clastic interbedded with thin bedded siltstone (Fig. 7b), which is the lofting deposit of distal extrabasinal deep-water gravity-flow. Local reverse-normal grading rhythms and climbing ripples bedding indicate flood triggered gravity-flow deposition (Fig. 7c). The two-layer deep-water gravity flow hybrid event beds in Well WZ11-7-1 further indicate the deposit is in distal deposit of deep-water gravity flow (Fig. 7d) and Weixinan low bulge was the potential provenance area. The Weixinan low bulge suffered uplifting and denudation during El_1 depositional stage, the denudation products were transported to the deep water by flood triggered gravity-flow directly, rather than forming sandbodies in the shallow water around Weixinan low bulge (Fig. 7a). Hence the accumulation of shallow water sediments is not a necessary condition for the formation of deep-water gravity-flow deposits. Extrabasinal deep-water gravity-flow provides a reasonable explanation for the widely developed deep-water-gravity flow deposits, and further expand the understanding on the distribution range of deep-water gravity-flow deposits. The El_1 member of Weixinan sag is rich in oil and gas resources. Based on the calculation, the underlying El_2 member source rock can generate 4.2×10^8 t of oil and gas at least. Therefore, sand bodies of deep-water gravity-flow triggered by flood will become the main targets of hydrocarbon exploration there in the next step.

4.3. Mass transport deposits and lithologic traps in the slope zone

Mass transport deposits developed in the delta front of lacustrine rift basin are important lithologic traps favorable for hydrocarbon enrichment and preservation because they are surrounded by high-quality deep-water source rocks and separated from the delta front. Sliding mass transport deposits developed close to the Jinjia delta during the depositional stage of the middle submember of the third member of Shahejie Formation (Es3z) in Boxing sub-sag of Dongying sag, Bohai Bay Basin (Fig. 8a). The delta front sand bodies are transported to the deep-water basin under the action of external triggering mechanisms, close to the delta front, are mainly sliding mass deposits featuring abrupt contact between thick bedded massive sandstone and dark gray mudstone (Fig. 8b). Due to the incomplete disintegration of pre-existing deposits, this kind of sliding block is very similar to mouth bar deposit of delta front, and even has some sedimentary characteristics of reverse grading sequence of mouth bar preserved. However, as the shearing between the sliding mass transport deposits and the underlying deposits can result in shear zone at the bottom, discontinuous sliding shear surface with relative higher matrix content than the upper part of the block can be seen. Mass transport deposits have massive structure overall, no internal traction structures, and a small amount of bedding after sliding reformation preserved locally. The single beds of sliding block are thicker than those of sandy debris flow deposits and turbidity sediments, making them favorable for hydrocarbon accumulation (Fig. 8b). Hence, they are an important type of lithologic reservoir in delta front has long been overlooked. The understanding that mass transport deposits

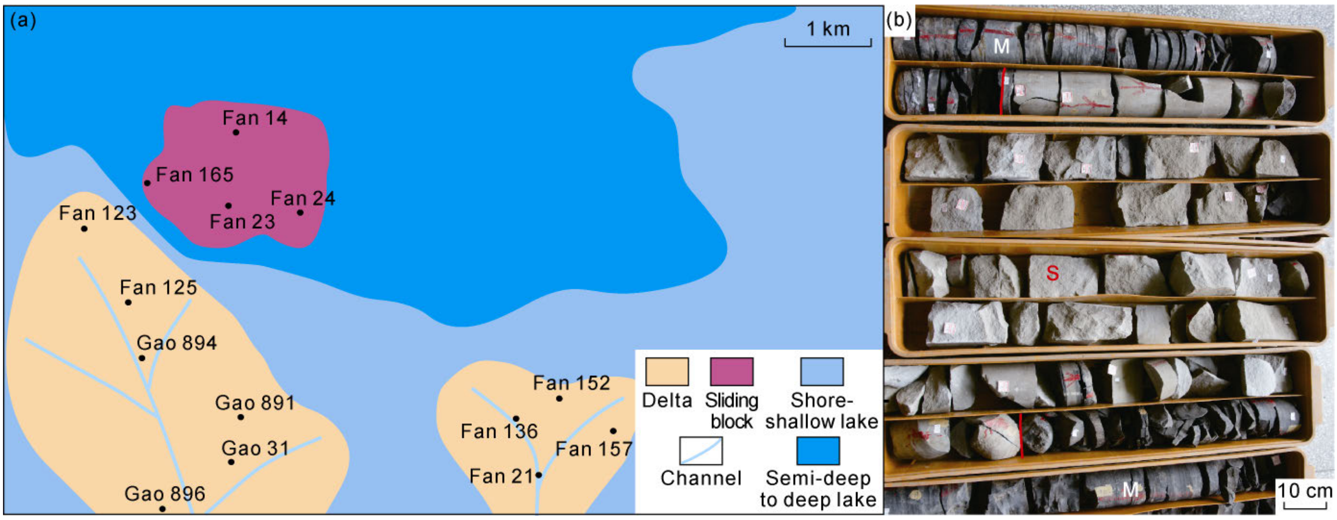

Fig. 8. Mass transport deposits and lithologic traps in the Paleogene Shahejie Formation, Dongying sag. (a) Planar distribution of sliding blocks in the Es3z of Boxing sub-sag, Dongying sag; (b) Well Fan 24, lithofacies association characteristics of sliding block, M—dark gray mudstone, S—massive sandstone.

are well-developed at delta front has overthrown the traditional understanding that delta front is dominated by mouth bar deposits, thus, opening up a new sedimentological perspective for hydrocarbon exploration of lithologic reservoirs widely developed in the depositional slope zone of delta front. In the mass transport deposits of the Es3z in Fan 154 block of Boxing sub-sag, Dongying sag, the geologic oil reserves of 364.98×10^4 t have been discovered, proving that the mass transport deposits are an important type of lithologic trap.

4.4. Fine-grained sediments and shale oil and gas caused by deep-water gravity flow deposits

Deep-water fine-grained sediments in a lacustrine basin are the main carriers for shale oil and gas. In addition to the traditional suspension origin, deep-water gravity-flow as an important formation mechanism of fine-grained sediments has been paid more attention to. Fine sediments can form relatively large flocculated particles by flocculation, which can be transported for a long distance along the basin floor. Deep-water gravity-flow, as an important long-distance transportation mechanism along the slope, plays an important role in the transportation and deposition of fine-grained sediments[23]. Taking the deep-water fine-grained sediment in Well WZ 11-7-4 of Weixinan sag as an example, deep-water fine-grained sediments of four kinds of origins can be identified according to sedimentary structures and lithofacies associations (Fig. 9). The fine-grained sediment of muddy debris flow origin is characterized by thin-bedded massive sandy mudstone, with floating sandy particles, sandy mass, and occasionally floating mud rip-up clasts in irregular shape. These deposits are in abrupt contact with both underlying and overlying suspension mudstone (Fig. 9a). The fine-grained sediment of flow transformation origin is mainly characterized by the hybrid event beds

Fig. 9. Fine-grained sediments of deep-water gravity-flow origin in El_1 member of Well WZ11-7-4, Weixinan sag. (a) Lithofacies association and sedimentary structures of fine-grained sediment of debris flow origin; (b) Lithofacies association and sedimentary structures of fine-grained sediment of flow transformation origin; (c) Lithofacies associations and sedimentary structures of fine-grained sediments of low-density turbidity flow and suspension settling origins.

composed of thin massive sandstone with lower matrix content in the lower part and silty mudstone with rich matrix and organic matter in the upper part. This kind of sediment is the result of low-density turbidity current transforming to muddy debris flow[23] (Fig. 9b). The fine-grained sediment of low-density turbidity current origin is characterized by weak erosion and typical normal grading (Fig. 9c), indicating that the sediment was supported by flow turbulence and settled gradually. The fine-grained sediment caused by superposition featured by laminated thin-bedded mudstone and siltstone interbedded (Fig. 9c). The differences of material composition or seasonal changes result in laminae of different colors.

Fine-grained sediments of different formation mechanisms stack vertically and spread widely on the plane, bringing about widespread fine-grained sediments in deep water of lacustrine basins. Fine-grained sediments of different deep-water gravity-flow transport mechanisms differ significantly in organic matter and silt contents. Thin-bedded normal grading lithofacies association of low-density turbidity current origin has higher silt content but lower organic matter content. Fine-grained sediment of muddy debris flow origin has higher organic matter content but lower silt content. The fine-grained sediment lithofacies association of flow transformation origin has higher organic matter content and higher silt content. Therefore, the fine-grained sediment of flow transformation origin is favorable for oil and gas generation and storage, and has better fracability as well, making it the potential lithofacies association to form “sweet spot” in shale oil and gas. Fine-grained sediments of flow transformation origin mostly turn up in local relatively low-lying areas in the deep-water area of the basin floor. Less than 20 cm in single layer, and up to tens of meters thick cumulatively, this kind of fine-grained sediment is the important target for continental shale oil and gas exploration in the next step. For example, a major breakthrough has been made in shale oil exploration in Jiyang depression, discovering shale oil resources of 98.44×10^8 t; the sandstone thin interlayers of deep-water gravity-flow origin in the depression are the favorable condition for steady flow of shale oil.

5. Conclusions

Two flow types, debris flow and turbidity current, and mass transport process of sliding and slumping are developed in a lacustrine rift basin. The debris flow can be subdivided into muddy debris flow and sandy debris flow. The turbidity current can be subdivided into high-density turbidity current and low-density turbidity current. Low-density turbidity current includes low-density surge-like turbidity current and low-density quasi-steady turbidity current. The transport and evolution processes of deep-water gravity-flow in a lacustrine rift basin are controlled by the concentration and density of sediments. The deep-water gravity flow changes between supercritical and subcritical states at the proximal end of deposition. The erosion or expansion of the fluid decreases in speed at the distal end, leading to transformation of turbidity current to muddy debris flow locally.

Deep-water gravity flow deposits in a lacustrine rift basin are formed in two mechanisms, intrabasinal sediment transport and continuous extrabasinal sediment supply, which correspond to intrabasinal and extrabasinal depositional models respectively. From t proximal to distal, the intrabasinal deep-water gravity-flow deposit consists of three main sedimentary architecture elements, namely, collapse belt, chaotic deposit and tongue-shaped body, and has no obvious fan shape; while the extrabasinal deep-water gravity-flow deposit consists of sedimentary architecture elements such as incised valley, channel-levee, channel-lobe transition zone, and lobe, in an apparent fan shape. Nearshore subaqueous fan with low-fluid transporting efficiency is mainly composed of muddy debris flow sediments. The sublacustrine fan with high-fluid transporting efficiency is dominated by high-density turbidites.

The sedimentary facies differentiation of nearshore subaqueous fans controlled by the transport and evolution processes of gravity-flow is a main cause for the formation of diagenetic trap under deep burial conditions. Sliding mass deposit is a kind of important lithologic trap overlooked before at delta front. The extrabasinal gravity-flow deposits are a reasonable explanation for the widespread deep-water sandstone in lacustrine basins. Deep-water gravity-flow is an important genetic mechanism of fine-grained sediment. The fine-grained sediment of flow transformation origin is the potential “sweet point” for shale oil and gas.

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