Sedimentological characteristics and depositional processes of sediment gravity flows in rift basins: The Palaeogene Dongying and Shahejie formations, Bohai Bay Basin, China

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A B S T R A C T

Sediment gravity flow deposits are common, particularly in sandy formations, but their origin has been a matter of debate and there is no consensus about the classification of such deposits. However, sediment gravity flow sandstones are economically important and have the potential to meet a growing demand in oil and gas exploration, so there is a drive to better understand them. This study focuses on sediment gravity flow deposits identified from well cores in Palaeogene deposits from the Liaodong Bay Depression in Bohai Bay Basin, China. We classify the sediment gravity flow deposits into eight lithofacies using lithological characteristics, grain size, and sedimentary structures, and interpret the associated depositional processes. Based on the scale, spatial distribution, and contact relationships of sediment gravity flow deposits, we defined six types of lithofacies associations (LAs) that reflect transformation processes and depositional morphology: LA1 (unconfined proximal breccia deposits), LA2 (confined channel deposits), LA3 (braided-channel lobe deposits), LA4 (unconfined lobe deposits), LA5 (distal sheet deposits), and LA6 (non-channelized sheet deposits). Finally, we established three depositional models that reflect the sedimentological characteristics and depositional processes of sediment gravity flow deposits: (1) slope-apron gravel-rich depositional model, which involves cohesive debris flows deposited as LA1 and dilute turbidity currents deposited as LA5; (2) non-channelized surge-like turbidity current depositional model, which mainly comprises sandy slumping, suspended load dominated turbidity currents, and dilute turbidity currents deposited as LA5 and LA6; and (3) channelized subaqueous-fan depositional model, which consists of non-cohesive bedload dominated turbidity currents, suspended load dominated turbidity currents, and dilute turbidity currents deposited as LA2–LA5, originating from sustained extrabasinal turbidity currents (hyperpycnal flow). The depositional models may be applicable to oil and gas exploration and production from sediment gravity flow systems in similar lacustrine depositional environments elsewhere.

1. Introduction

Sediment gravity flow deposits have been extensively researched since they were first described by Kuenen and Migliorini (1950), with the prime focus on facies models, such as the ‘Bouma Sequence’ for classic turbidity currents (Bouma, 1962) and the ‘Lowe Sequence’ for high-density turbidity currents (Lowe, 1982). The models have proved to be very useful for studying deep-water sediments, and have considerably improved understanding of sediment gravity flow deposits. However, the much-used Bouma Sequence has been shown to be inaccurate for predicting sand behaviour (Covault et al., 2014), especially in lacustrine basins. Sediment gravity flows are the main mechanism of sediment delivery to deep-water basins (Normark and Piper, 1972; Mulder and Alexander, 2001), and may originate through gravitational collapse of clastic sediments stored in slope areas or material supplied from rivers in flood (Milliman and Syvitski, 1992; Mulder and Syvitski, 1995; Mutti et al., 1999; Zavala and Arcuri, 2016). Single remobilisation events may generate more than one type of flow (Haughton et al., 2009). Conventionally, four basic types of sediment gravity flows have been recognized – turbidity currents, grain flows, liquefied flows, and debris flows – of which turbidity currents and debris flows are the most widely distributed and studied (e.g. Middleton and Hampton, 1973;
Lowe, 1976; Amy et al., 2005; Hodgson, 2009; Talling et al., 2012). However, this classification is limited and problematic; it is difficult to apply it to flows in other materials such as sandy or muddy mass-transport deposits (Stow and Johansson, 2000), thick amalgamated conglomerates, and hyperpycnal flow deposits (Zavala et al., 2011). Furthermore, it has been shown that sediment gravity flows may evolve over time and laterally (Haughton et al., 2009); therefore, the transitional processes between different types of sediment gravity flows cannot be rigorously generalized using simple classifications. Several studies have focused on the architecture and depositional patterns of submarine sediment gravity flow systems in different tectonic settings and climatic conditions, principally to provide information on the distribution of oil and gas reservoirs (Richards, 1994; Stow and Mayall, 2000; Mattern, 2005; Payros and Pujalte, 2008). However, these investigations have not provided a great deal of detail on the sedimentological characteristics and depositional processes of sediment gravity flows, especially in rift basins.

Bohai Bay Basin in eastern China covers an area of about 200,000 km² and is a typical intra-continental rifted basin of the North China Craton, which is controlled by the Tan-Lu fault zone (Liu et al., 2016). Due to the intense tectonic activity induced by the Tan-Lu faults, there are numerous Palaeogene sediment gravity flow sandstones in the region, and they have been investigated using well cores and outcrops (Wang and Liu, 1987; Wang, 1991; Xian et al., 2012, 2013). Sediment gravity flow sandstones have shown the potential to meet the growing demand for oil and gas in China (Li et al., 2009; Mo et al., 2012; Zhang et al., 2014; Yuan et al., 2016). In the eastern oil fields, which are in late-stage production, exploration has switched from structural to lithologic oil-gas reservoirs. In this context, it is essential to strengthen knowledge of sediment gravity flow deposits and to better understand their sedimentological characteristics and related depositional processes.

Sediment gravity flow deposits have been frequently observed in cores from the Palaeogene deposits of the Liaodong Bay Depression (LBD) in Bohai Bay Basin. The typical grain size of the deposits ranges from silty sand to cobble, and they were accumulated by non-cohesive to cohesive sediment gravity flows. The different gravel components and supporting mechanisms indicate that the sediment gravity flows could have various origins or feeder systems. Previous studies in the area have mainly relied on seismic data from the Dongying Formation (Jia et al., 2010; Wu et al., 2012), which has revealed the distribution of reservoirs and sedimentary bodies, however, there has been little analysis of the sedimentological characteristics and depositional processes of sediment gravity flow deposits using core studies and statistics.

The main objectives of this study were: (1) to identify typical sediment gravity flow lithofacies based on lithological characteristics, grain size, and sedimentary structures, and to interpret their origin; (2) to analyse the scales and spatial distribution of sediment gravity flow deposits with consideration of strata and the sedimentary environment; (3) to confirm the lithofacies associations in terms of development scales, spatial distribution, and bounding relationships; and (4) to establish typical sediment gravity flow depositional models taking into account controlling factors, in order to explain sedimentological characteristics and depositional processes within a continental rift basin. The results have potential to play an important role in the lithological study of oil-gas reservoirs in similar tectonic settings and sedimentary environments.

2. Study area

2.1. Geological setting

The LBD is in the northeast of Bohai Bay Basin, China (Fig. 1a), which is surrounded by uplifted Precambrian basement blocks (Huang and Liu, 2014). The NE-trending Tan-Lu faults developed across the depression mean that its structural style differs from the middle and southern areas of Bohai Bay Basin, and from the terrestrial part of the basin (Jia et al., 2015). Multi-stage extensional and strike-slip fault activity has created a deep and narrow rift basin. The Tan-Lu faults bifurcated in the Palaeogene, and the depression was divided into five secondary structural units, from west to east as follows: Liaoxi Sag, Liaoxi Uplift, Liaozhong Sag, Liaodong Uplift, and Liaodong Sag (Fig. 1b). The Liaozhong Sag has the thickest sedimentary sequence, followed by the Liaoxi and Liaodong (Zhu et al., 2008); the tectonic units developed in parallel in a NE direction (Xu et al., 2005; Jia et al., 2015).

The LBD, controlled by the Tan-Lu faults, was subject to three tectonic episodes in the Palaeogene: (1) extension and rifting from the Palaeocene to the middle Eocene (56–38 Ma); (2) post-rift thermal subsidence from the late Eocene to the early Oligocene (38–32.8 Ma); and (3) strike-slip and rifting during the Dongying period of the Oligocene (32.8–24.6 Ma) (Zhao et al., 1996; Zhu et al., 2008; Jia et al., 2015) (Fig. 2). Regional uplift and erosion resulted in a regional unconformity on top of the Dongying Formation, with an eroded thickness of about 300–900 m (Huang and Liu, 2014), recording the transition from rift to depression basin (Cheng et al., 2015). This study focuses on strata of the Shahejie Formation, which represent the first two tectonic episodes outlined above, and the Dongying Formation, however, owing to the unconformity between E2d2 and E2d3 and the lack of core intervals in E2s1, only layers E2s3 to E2d3 were available for investigation (Fig. 2).

2.2. Sedimentological setting and stratigraphy

The Shahejie and Dongying formations record two complete cycles of lacustrine development, recognized by changes in lake level (Fig. 2; Zhu et al., 2008). Two lake level maxima are recorded in E3d2 and E2d3 and correspond to intense rifting and early strike-slip and rifting stages, respectively.

The main lithologies of E2s3 are shale or mudstone deposited as lacustrine facies in the centre of the lake, and medium to coarse-grained sandstones or conglomerates deposited by fan-deltas developed on the edge of the lake basin (Dong et al., 2007; Li et al., 2007). Strata of E2s2 comprise lacustrine facies, carbonate platform, and fan-delta deposits composed of interbedded grey mudstone or shale and medium to coarse-grained sandstones. E2s1 strata comprise lacustrine facies and carbonate platform deposits, intercalated with dark mudstones, shales, and bioclastic limestones or dolostones that can be used for regional correlation (Fig. 2; Dong et al., 2007; Zhu et al., 2008; Chang et al., 2014).

The Dongying Formation has a great thickness, resulting from intensive strike-slip motion, and the related sedimentary environments reflect the transition from lacustrine to deltaic and fluvial facies. The sedimentary deposits of E2d3 are mainly lacustrine facies of dark grey mudstone intercalated with sandstone lenses (Zhu et al., 2008). The strata of E2d2 contain mainly deltaic deposits of thick, medium- to fine-grained sandstones or sublacustrine fan deposits with coarse-grained clastics that formed in a deep lake environment (Zhu et al., 2008; Wu et al., 2011) (Fig. 2).

3. Materials and methods

Interpretation of the sedimentological characteristics and depositional processes of sediment gravity flows in the Shahejie Formation and Dongying Formation deposits of the LBD was mainly based on analysis of core intervals, isopach maps, and fault data obtained by the Tianjin Branch of China National Offshore Oil Corporation. Cores were split lengthwise and digitally photographed (Figs. 3–6). A section of sediment gravity flow deposits approximately 278 m long was identified from 30 wells in the Palaeogene succession (Fig. 1b), covering members E3s3 to E2d3. Macroscopic characteristics of the deposits, such as grain size variation, colour, depositional structure, lithology, and

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fabric, were described in detail (Table 1). Based on seismic reflection boundaries, tectonic, and sedimentary characteristics (Fig. 2), strata from E2s3 to E3d2l have been divided into four sequences (E2s3, E2s2-1, E3d3, and E3d2l). The horizons, lengths, and percentages of the sediment gravity flow lithofacies accounted in the four sequences were described and calculated (Table 2), and used to infer the scale of stratigraphic development of different sediment gravity flow deposits. Isopach maps were constructed to infer the spatial distribution of the dominant lithofacies in different sequences. The field data and key sedimentological logs yielded significant information on lithofacies associations and types of bounding surfaces; depositional models were developed based on the sedimentological characteristics and depositional processes of sediment gravity flow deposits in a continental rift basin.

4. Sedimentological analysis of sediment gravity flows

Fig. 1. Location map and geological framework of the studied region. (a) Location map of the Liaodong Bay Depression in the Bohai Bay basin, China. (b) Geological setting of the Liaodong Bay Depression in the Palaeogene deposits, showing the location of studies wells.

There is a diverse range of subaqueous sediment gravity flows in the study area due to the complex tectonic activity and geomorphology of the basin that results in different trigger mechanisms, sedimentary sources, and kinetic energy. Frequently, tectonic uplift and subsidence
not only leads to the characteristic alternating uplifts and sags, but also results in a diversity of sources for the sediment gravity flows. Taking into account grain size and sedimentary structures, sediment gravity flow deposits were classified into eight lithofacies (Eyles et al., 2007; Henstra et al., 2016) (Table 1), the main features of which are outlined below.

4.1. Lithofacies A (LFA): matrix-supported conglomerates

4.1.1. Description

LFA beds mainly consist of a matrix-supported fabric, integrated with structureless breccias and gravels (Fig. 3a–c), and stack thicknesses may be over 10 m. The breccias and gravels embedded in the matrix are composed of coarse magmatic, metamorphic, and carbonate rock clasts from the bedrock. Extrabasinal clasts are red, ashen, and black in colour. Intrabasinal clasts are derived from early depositional
sandstones and mudstones deposited in deltas or shallow lakes (Fig. 3a and b). Gravels and clasts are poorly sorted and dispersed in an abundant matrix composed of unsorted rock fragments varying in size from silt to fine-grained clasts (Henstra et al., 2016). Some of the gravels are composed of material reworked from earlier conglomeratic rocks. Previously accumulated rocks originating from shallow lakes may break into clasts, along with biodetritus and phytoclasts, under specific trigger mechanisms, e.g. earthquakes, storms, and slumping (Fig. 3b). LFA also comprises amalgamated diamictite (Fig. 3c), which shows fairly low maturity and poor sorting, angular–subangular or subangular–subrounded grain morphologies, and no preferential orientation. The gravels in are faintly graded or structureless beds, and breccia size ranges from 2 to over 100 mm.

4.1.2. Interpretation

The high clay content of LFA suggests cohesive behaviour and a freezing depositional mechanism typical of cohesive debris flows (Mulder and Alexander, 2001). LFA is usually interpreted as a special manifestation of cohesive debris flow deposit generated by earthquakes or seasonal floods (Zheng et al., 2012), also referred to as ‘true debris flows’ by Middleton and Hampton (1973). Deposits with diverse parent rocks like LFA (Fig. 3a–c) have also been described as ‘polymictic conglomerates’ by Socci and Smith (1990). The range of roundness, compositions, and sorting characteristics shown by the gravels indicates a complex debris flow transport history. The erodible and slope content of some lithified clasts implies they originated from subaerial erosion, and were then transported by a debris flow from the intermontane area to the centre of the lake. The immature, angular characteristics of most clasts that make up LFA suggest a proximal provenance. The high matrix strength of LFA allowed larger clasts to be maintained within the flow and not sink to the bottom (Quiquerez et al., 2013).

4.2. Lithofacies B (LFB): clasts-supported conglomerates

4.2.1. Description

This lithofacies has a higher clast content and lower matrix percentage compared with LFA (Fig. 3d–f). Bed thickness ranges from 10 to more than 100 cm, and grain size ranges from 2 to 50 mm. LFB is dominated by massive and crudely stratified conglomerates. Conglomeratic layers are stacked vertically, with various sizes of gravels. Poorly sorted clasts exhibiting subangular–subrounded morphology are packed into a muddy-silty matrix. The lower part of the massive conglomerates shows normal or inverse graded bedding with low-angle asymptotic cross-stratification (Celma, 2011) (Fig. 3d and e). Some
conglomerates have a gradual internal contact with overlying sandstones (Fig. 4f). A minor proportion of deformed muddy clasts were also observed in conglomeratic layers. Large clasts appear to have moved freely at the base of conglomerate beds and commonly appear imbricated.

4.2.2. Interpretation

Although massive bedding clasts-supported conglomerates such as LFB with boulder sized, poorly sorted clasts have been attributed to deposition from concentrated density flows (Lowe, 1976; Lash, 1984; Krapež and Hand, 2008), they could also have accumulated as bedload at the base of sustained turbidity currents (Zavala et al., 2011). The absence of muddy matrix indicates that the currents were non-cohesive (Henstra et al., 2016). Clasts imbrication is common, suggesting a fluid flow (Newtonian) where clasts could freely rotate. The occasional occurrence of basal erosive surfaces indicates a high velocity flow. The composition of the gravels suggests both extrabasinal and intrabasinal provenance (Fig. 3d–f), and the higher roundness and grain sorting imply a relatively farther transport distance compared with LFA. Beds with faint inverse grading at the base of the conglomerates are interpreted as being deposited from non-cohesive and highly-concentrated flows with high internal shear (Postma et al., 1988; Manville and White, 2003).

4.3. Lithofacies C (LFC): Massive fine to medium-grained sandstones

4.3.1. Description

LFC is composed of light to dark, fine- to medium-grained, massive structureless sandstones with ‘floating’ muddy clasts and gravels (2–10 cm) (Fig. 4a–c). The sandstones commonly comprise monotonous and very thick successions with little stratification and bioturbation, internally exhibiting subtle and gradual grain size variations. Most of the ‘floating’ muddy clasts are rip-up type, dark in colour, and aligned, and are concentrated at the top of LFC (Fig. 4a and c). The superimposition of pure, massive, fine-grained sandstones and massive sandstones with numerous muddy clasts is ubiquitous, and they are usually stacked vertically and associated with banded sandstones. The mean bed thickness of LFC varies from 0.3 to 5 m, and the total stacked thickness may exceed 10 m. Basal and upper contacts are sharp, and commonly erosive to non-erosive (Fig. 4b).

4.3.2. Interpretation

The massive sandstones were accumulated under decreasing capacity from a decelerating sand-rich turbulent flow attributed to suspend load deposits of a hyperpycnal flow system (Zavala et al., 2011; Zavala and Arcuri, 2016). Large scale, thick stacked massive sandstones are interpreted as recording gradual deposition from sustained turbidity currents (Kneller and Branney, 1995; Krapež and Hand, 2008). Clasts appear aligned due to hindered settling. Progressive aggradation is thought to be an important factor preventing the formation of primary
sedimentary structures (Kneller and Branney, 1995; Sumner et al., 2008; Zavala et al., 2011). The plastic deformation of the muddy rip-up clasts implies that the sediment gravity flow event may have occurred during the syn-diagenetic stage. The dark colour of the clasts indicates that they were deposited in a semi-deep lake environment. The minor component of less rounded muddy and sandy gravels may have originated from distributary channels on the deltaic plain, and could have been conveyed to the foreslope under seasonal sustained floods or gravitational collapse. One of the features considered diagnostic for identification of hyperpycnal deposits is the abundance of plant debris, including entire leaves (Zavala et al., 2011; Zavala and Arcuri, 2016).  

4.4. Lithofacies D (LFD): Graded sandstones with parallel and ripple bedding  

4.4.1. Description  

LFD exhibits various depositional structures and characteristics, including normal grading, parallel and ripple bedding (Fig. 4d–g), and is relatively rare in the study area. Individual beds are very thin (less than 10 cm), which may be due to the limited size of core samples rather than a true reflection of the field situation. Graded light-coloured pebbly conglomerates and gravelly sandstones display relatively poor sorting and low clay content, while dark sandstones have a high clay content (Fig. 4e). Sandstones with parallel and ripple bedding commonly are found above normally graded fine-grained sandstones (Fig. 4d–f). The sandstones display incomplete Bouma Sequences. The stacked thickness of LFD reaches up to 50 cm (Xu et al., 2016), and it displays a sharp contact with the underlying bed. Scour-fill structures are also observed in the cores (Fig. 4f and g).

4.4.2. Interpretation  

Normally graded sandstones are interpreted as turbidity current deposits and usually identified as Tₐ in the Bouma Sequence, representing deposition by suspension settling or grain-to-grain interactions resulting from the decrease of fluid kinetic energy (Bouma, 1962; Lowe, 1982). Sandstones with parallel and ripple bedding represent deposition by traction currents plus fallout from turbulent suspensions and are represented by Tₕ and Tₗ in the Bouma Sequence. Stratification may be formed by freezing of the traction (Henstra et al., 2016). Sandstones with parallel and ripple bedding are usually vertically developed with normally graded sandstones, indicating a common origin. Sandstones in LFD appear to be controlled by fluctuations in the
velocity of overpassing turbulent flow (Zavala et al., 2011), hence, we interpret LFD as accumulation from turbidity currents. Turbidity currents are turbulence supported, which may led to erosion of underlying beds. The relatively high grain concentration of LFD could account for the limited preservation of groove casts, flute casts, or other deformation structures in the cores.

4.5. Lithofacies E (LFE): Chaotic sandstones and mudstones with glide planes

4.5.1. Description

LFE has a thickness of up to 50 cm, but it was the least observed facies due its limited distribution in the well cores. LFE is composed of chaotic coarse-grained sandstones with numerous deformed and
4.5.2. Interpretation

LFE deposits formed from sediment failure and subsequent slumping and sliding (Covault et al., 2009). Deformation structures with a glide-surface are attributed to slope deposit instability and acceleration under gravity. Deformation could be caused by numerous mechanisms, e.g. earthquakes, storms, and slumping. Massive plastic muddy breccias and deformation structures indicate that sediment slumping occurred during the synsedimentary stage. Overlying sediments in a semi-consolidated state are able to slide along the shear surface under the influence of gravity. The underlying fine-grained sediments could be involved in this sandy slumping, leading to the low compositional and structural maturity of these chaotic sandstones. The arbitrary nature of deformed muddy clasts suggests that they experienced drastic rotation during transport, which supports the slumping units being formed by discrete basal shears (Nardin et al., 1979; Coleman and Prior, 1988).

4.6. Lithofacies G (LFG): Pebbly mudstones

4.6.1. Description

LFG is characterized by interbedded very fine-grained sandstones and mudstones/siltstones exhibiting horizontal bedding. Extensive groove casts, flute casts, bioturbations, phytoclasts, and other deformation structures were also observed in LFB (Fig. 5d–f). The thickness of individual beds ranges from 1 to 5 cm, and they are commonly stacked vertically as rhythmic bedding (Fig. 5d and e) with the thickness reaching 10–50 cm. The contact between the mudstones and underlying sandstones is sharp, and there is inconspicuous scouring on the contact surface. The sandstones are composed of fine-grained sand, and no muddy clasts were observed in the cores.

4.6.2. Interpretation

LFF may have formed from dilute turbidity currents, and is characterized by larger grain sizes and greater structural sorting than LFC. The numerous deformation structures could be caused by loading of laminated sand deposits and underlying muddy deposits or seismically induced liquefaction (Liu et al., 2016). The thin interbedded sandstones-siltstones/mudstones could correspond to the Td and Te intervals of the Bouma Sequence (Lowe, 1982; Gagnon and Waldron, 2011). Sandstone-mudstone couplets are also indicative of transport by hypercyclical flows, in which deposits accumulate by normal settling when flow ceases (Zavala et al., 2011). Consequently, LFE could be used to indicate the boundary between different turbidity currents or hypercyclical events.

4.7. Lithofacies H (LHF): Massive mudstones

4.7.1. Description

LHF comprises mudstones with poorly sorted pebbles, usually less than 30 cm thick (Fig. 6a–c). The mudstones are typically lenticular in shape and of limited lateral extent. LFG exhibits a gradational basal contact with massive fine-grained sandstones or interbedded sandstones–siltstones/mudstones (Fig. 6c). Numerous small floating and scattered clasts of different compositions and sizes (< 2 cm), originating from sandstones, mudstones or carbonates, are embedded in the mud matrix (Fig. 6a and b). In addition, pebbles are concentrated and distributed parallel to bedding. The muddy matrix is generally structureless, but may exhibit flow and deformation structures.

4.7.2. Interpretation

The numerous embedded clasts indicate the high matrix strength of LFD, which is likely to have resulted from increasing buoyancy where extraformational clasts are supported by a laminar flow (Nardin et al., 1979; Lowe, 1982; Middleton and Hampton, 1973). This type of lithofacies is usually interpreted as originating from a mudflow or muddy debris flow (Mulder and Alexander, 2001). The presence of coarse-grained clasts within a muddy matrix suggests that they accumulated together, without sorting (Tamura and Masuda, 2003). Indeed, the clay content in LFG is more than 60%, which implies that the muddy debris flow lacking adequate sand support.

4.8. Lithofacies H (LHF): Massive mudstones

4.8.1. Description

LHF is composed of massive, dark mudstones with phytoclasts and fossil fragments, showing weak horizontal lamination (Fig. 6d and e). The mudstones show great lateral extension and LHF can reach thicknesses of several to tens of metres. Very few interbedded siltstones were observed in the massive mudstones. At the base, the mudstones commonly display a gradational contact with the underlying LFB, LFC, or LFD. Massive mudstones are commonly eroded by all the previously described sediment gravity flow facies.

4.8.2. Interpretation

The presence of dark mudstones in LHF suggests a quiet subaqueous depositional environment. The weak horizontal lamination suggests that mud deposition resulted from fallout of suspension particles in an extremely low-energy offshore, probably basin floor, setting. The minor siltstone in mud deposits may also be interpreted as the product of very dilute turbidity currents (Mutti et al., 1999; Zavala et al., 2011; Henstra et al., 2016).

5. Discussion

5.1. Development scales and spatial distribution of sediment gravity flow deposits

5.1.1. Development scales

The development scales of the different types of sediment gravity flow deposits in the Shahejie and Dongying formations, based on thickness data for cores from 30 wells, are as follows: LFC and LFF predominated, followed by LFA, LFB, LFH, and finally LFD, LFE, and LFG (Table 2; Fig. 7). This suggests turbidity currents are the main depositional mechanism of sediment gravity flows in the study area. Although the thicknesses of individual beds of dilute turbidity deposits ranges from 1 to 5 cm, the total thickness is 71.5 m, which further supports that they comprise the greatest number of beds. The smallest total thickness is for muddy debris flow deposits, reaching only 2.4 m,
formed from suspended load dominated turbidity currents.

The percentage of sediment gravity flows varies in the different stages of the formations. LFA only occurs in the Shahejie Formation, while LFB, LFC, LFF, and LFH are observed in every stage of the Shahejie and Dongying formations (Table 2; Fig. 7). This implies that the formation of LFA is closely linked to the sedimentary environment, tectonic activity, and climatic conditions of the Shahejie Formation. Furthermore, the distribution ratios of the four lithofacies found
throughout the Shahejie and Dongying formations vary. The percentage of LFB in E2s3 and E3d3 is higher than that in E2s2–E2s1 and E3d2, which may be due to intense tectonic activity during the former. The percentage of LFC, LFF and LFH, which dominate sediment gravity flow deposits in the study area, gradually increases after E2s3.

5.1.2. Spatial distribution of sediment gravity flow deposits

The distribution and thickness of sediment gravity flow accumulations for the four stages E2s3, E3d3, E2s2–E2s1, and E3d2, is shown in isopach maps (Fig. 8). The maps highlight depocentres and sedimentary gradients. The majority of sediment gravity flow deposits are found along the Tan-Lu faults, which suggests that tectonic fault activity is the main factor influencing their distribution. Slope-break belts formed by faults provide accommodation space and subaqueous environment for sediment gravity flow deposits (Fig. 9a). Differences in gradient across the slope-break belts, which are due to fluctuations in the intensity of fault activity, may cause transport rates towards the depocentre to vary. Sediment failure in delta-front settings may benefit from the specific gradients, with consideration of the impact of gravity provided by the inclined glide plane (Fig. 5). Other styles of sediment gravity flows are directly linked to the topographic differences. Furthermore, fault activity may be related to seismicity, which plays an important role in triggering sediment gravity flows, although it is not associated with a specific depositional process (Liu et al., 2016). Sand dykes, synsedimentary faults, and other seismically induced soft-sediment deformation structures can be observed under, above, or within the sediment gravity flow deposits (Fig. 9b and c) suggesting that they may be induced by paleoearthquakes. However, the sediments are still classed as sediment gravity flow deposits because of the numerous coarse grains, slumping, and other confirmed sediment gravity flow features.

Analysis of the lithofacies distributions show that all the sediment gravity flows identified in the LBD are distributed near faults, on slopes, or near the adjacent basin plain (Fig. 8), as follows:

1. Intervals dominated by LFB and LFC, which are interpreted as being accumulated by bedload dominated turbidity currents and suspended load dominated turbidity currents, are distributed on the proximal slope. They usually exhibit particularly steep dips and correspond to the base of the fault scarp (Surlyk, 1978; Henstra et al., 2016).

2. Intervals dominated by LFC (and LFF) with interbedded LFD, which are interpreted as turbidity current deposits, are distributed in the main body of the slope. Strata display more modest dips. This zone is comparable to the coarse-rich fan slope of Richards et al. (1998).

3. Intervals dominated by LFF and LFH, which were probably formed from dilute turbidity currents, are distributed at a distance from the basin margin. This zone is interpreted as the base of the slope-break zone or basin plain and exhibits horizontal strata at the distal end (Henstra et al., 2016).

4. Intervals including interbedded LFE, which originate from sandy slumping, are distributed in front of the delta or in the proximal slope.

5. Intervals dominated by LFA, which are interpreted as cohesive debris flow deposits, are distributed in the nearby uplifts.

Fig. 9. Core examples evidencing paleoearthquakes and a deep water setting. (a) Sulphide, indicating deep water setting. Well D22-1-1, at 3003 m, in LFF. (b) Synsedimentary faults developed below turbidity current deposits. Well D21-1-2, at 3628.7 m, in LFC. (c) Seismically induced soft-sediment deformation structures (injectites). Well A1-1-1, at 2753.6 m, in LFF.
Intervals comprising LFD and LFG are rare, and their distribution is mainly concentrated on the slope.

5.2. Lithofacies associations and depositional processes

Due to the vertically- and laterally-restricted nature of the available core intervals, it is not possible to use adjacent or connecting well sections to accurately constrain downstream or across-stream sedimentary facies changes of the sediment gravity flows. However, based on previous research on the depositional elements of sediment gravity flows (Walker, 1978; Richards, 1994; Krapež and Hand, 2008), together with information on the spatial distribution, characteristics, and bounding relationships of lithofacies in more than 10 wells (Fig. 10), it is possible to group the lithofacies associations of the studied sediment gravity flow deposits into six types reflecting transformation processes and depositional morphology (Fig. 11).

5.2.1. Lithofacies association 1 (LA1): Unconfined proximal breccia deposits

This association consists of massive, multiple LFA that exhibit sharp contacts with interbedded LFH (Fig. 11a). The total vertical thickness of LA1 reaches tens of metres. LA1 is predominantly composed of thick-bedded, disorganized, and amalgamated LFA with thin-bedded LFH. Contacts between amalgamated units are faint and non-erosional, and are demonstrated by major changes in average clast size (Krapež and Hand, 2008). Upward transition into other lithofacies is rare except for LFH. LA1 is only identified in proximity to the fault system that forms the uplifted margin (Fig. 9).

The coarse-grained and poorly sorted breccias and conglomerates are indicative of proximal accumulations from cohesive debris flows. The occurrence of thick beds and muddy matrix suggests the sediment gravity flows were related to seasonal floods. The lack of erosional features within amalgamated conglomerates implies an unconfined apron-like morphology and gravel-rich environment, such as found at mountain front. The presence of dark interbedded mudstones indicates that the coarse-grained deposits were carried directly into the lake. LA1 was mainly observed along the border of basin-controlling faults, which is in accordance with characteristics proposed by Krapež and Hand (2008), and is interpreted as representing a subaqueous talus apron environment (Henstra et al., 2016).

5.2.2. Lithofacies association 2 (LA2): Confined channel deposits

LA2 is dominated by massive, thick, and multiple LFB in which vertical thickness reaches 5 m (Fig. 11b). Conformable clast-supported conglomerates exhibit structureless beds with variable gravel size and sharp contacts and scouring surfaces with the underlying fine-grained sediments. The high proportion of LFB in LA2 is used to differentiate it from LA3.

The coarse-grained and thick-bedded deposits of LA2 imply formation in a powerful hydrodynamic environment. An array of coarse clasts with rounding and preferential sorting implies that sediment sources were abundant and relatively distant. The moderate scouring surfaces within the amalgamated conglomerates suggest origin in a continuously intense flow, while the scouring surface on the underlying sediments suggests a confined channel depositional environment such as upper slope-break zone or inner apron.

5.2.3. Lithofacies association 3 (LA3): braided-channel lobe deposits

LA3 is mainly composed of clast-supported conglomerates (LFB) that transition upwards into massive (LFC) and normally graded sandstones (LFD) (Fig. 11c). The thick coarse-grained bedded sandstones could have formed as either LFC (structureless graded beds) or LFD (normal graded beds). Thin LFG layers are occasionally observed above LFC with no sharp contact. LFB mainly occupies the lower part of
LA3, comprising conglomeratic beds that are typically 1–3 m thick and with scours at the base of individual beds. The upper part of LA3 comprises stacking conglomerates and sandstones beds of LFC and LFD, which are typically 5–10 m in thickness. Core intervals dominated by LA3 are distributed more widely than those dominated by LA2, and more remotely from the basin margin.

The widely distributed coarse amalgamated conglomerates and thick-bedded sandstones with basal scouring surfaces are considered to represent braided-channel fill in middle apron settings. This implies that turbidity currents were not confined in fixed position channels. The lack of sharp contacts between the lower conglomeratic beds and overlying sandstone beds indicates a continuous and sustained depositional process and suggests that each conglomerate-sandstone association corresponds to a single sedimentary unit (Clifton, 1984; Cronin and Kidd, 1998).

5.2.4. Lithofacies association 4 (LA4): Unconfined lobe deposits
LA4 is composed of massive, thick, and fine to medium-grained LFC with thin, interbedded LFF (Fig. 11d). Single massive sandstone beds are typically less than 1 m in thickness, but they are usually vertically stacked and can reach 5 m, with overall thickness of LA4 exceeding 5 m. The lower part of LA4 comprises LFC and the upper part LFF. In contrast to LA2 and LA3, scour surface evidence is absent in LA4, and bedding contacts are planar and laterally continuous.

The fine grain size and limited thickness of LFC in LA4 suggest that the massive sandstones were transported over longer distances than those in LA3. The lack of scour surfaces in LA4 suggest a continuous depositional process, which implies it originated from unconfined sediment gravity flows and has a sheeted geometry (Krapež and Hand, 2008; Jackson et al., 2009). The aggradation of massive sandstone occurred at, or close to, the mouths of proximal-lobe braided channels. Upward fine-grained suspended load dominated turbidity current deposits formed sheet-like beds due to decelerating turbulent flow (Krapež and Hand, 2008; Henstra et al., 2016).

5.2.5. Lithofacies association 5 (LA5): Distal sheet deposits
LA5 consist of massive, dark mudstone beds with fine interbedded sandstones and siltstones deposited as LFH and LFF, respectively (Fig. 11e). Individual beds, which are embedded in massive mudstones, are tabular and laterally extensive, and there are numerous phytoclasts and bioturbations in the mudstones. This lithofacies association is interpreted as hemipelagic or dilute turbidity current deposits.

LA5 accumulated in low-energy depositional environments, as suggested by the dominance of massive mudstones. This indicates a
distal environment dominated by a hemipelagic settling. LA5 is interpreted as deposition towards the edge of unconfined lobe deposits on the basin plain as well as in upper apron settings around channels.

5.2.6. Lithofacies association 6 (LA6): Non-channelized sheet deposits

The LA6 association, which is also mainly composed of LFC and LFF, is similar to LA4 (Fig. 11f), but is distinguished by the presence of LFE, which formed by sandy slumping. The thickness of LFE, however, is limited (usually less than 1 m). The total thickness of LA6 is lower than that of LA4, and the grain size is smaller. LFE exhibits a sharp contact and evidence of erosion with the underlying fine-grained sediments and is gradually replaced by LFC and LFF without a sharp break. Another distinguishing characteristic of LA6 is the fine- to medium-grained, laterally extensive sandy sediments that exhibit a sheeted geometry rather than a wide lobate geometry (Xu et al., 2016).

LA6 is interpreted as non-channelized sheet deposits that formed in front of a delta. The limited thickness of LFE may be due to the steep slope where preservation of liquefied sediments with deformed muddy clasts is challenging. The continuous depositional process between sandy slumping and massive sandy sediments implies that the coherent sandy slumping can be transformed into a more fluid sediment gravity flow (cf. Iverson et al., 1997). Owing to the influence of surrounding water, suspended load dominated turbidity currents can be sequentially transformed into dilute currents (Stow and Johannson, 2000; Mulder and Alexander, 2001); therefore, deposits of LA6 are interpreted as resulting from a deltaic slumping system rather than a stable and sustained supply source. The more limited thickness of LA6 compared to LA4 was due to the slumping process. Flows generated by sediment failure accelerated down the steep basin-margin slope and then rapidly decelerated and were deposited at the break of slope (Walker et al., 1995; Covault et al., 2009). The trigger for sediment failure was gravity instability induced by earthquakes or inherent periodic collapse of accumulated deposits close to the delta front.

5.3. Inferred sediment gravity flow depositional models

Numerous depositional models of subaqueous sediment gravity flows have been proposed (Normark, 1970; Walker, 1978; Richards, 1994; Tanaka and Maejima, 1995; Krapež and Hand, 2008; Zhang and Scholz, 2015; Xu et al., 2016; Zavala and Arcuri, 2016), but there is no consensus over their applicability and new data are still necessary to revise and improve the models. Compared to marine basins, sediment gravity flow facies in continental rift basins have several distinctive features: (1) Owing to intense, complex tectonic activity and limited transport distance, sediment gravity flow deposits usually exhibit coarser grain sizes; (2) The limited extension and complex geomorphology of continental rift basins means that sediment gravity flows in cannot extend as far as those in marine basins; and (3) The rapid and multi-type evolution and development of continental rift basins might lead to a number of sediment gravity flow depositional models coexisting in the same basin. Based on the depositional environment, lithofacies, development scales, spatial distribution, and lithofacies associations of sediment gravity flows deposits, we propose three depositional models reflecting the sedimentary characteristics and depositional process of sediment gravity flows in continental rift basins.

5.3.1. Slope-apron gravel-rich depositional model (M1)

M1 is similar to Richards (1994) depositional model which involves coarse-grained materials and a non-channelized geomorphology (Fig. 12). It describes a slope-apron gravel-rich depositional environment that develops close to mountain areas and uplifts bounded by active faults (Inenson, 1989; Tanaka and Maejima, 1995). Individual brecciated units, or more rarely, conglomeratic units, are deposited as sheets, which is characteristic of slope-apron environments (Nelson et al., 1991). M1 is mainly composed of LA1, with rare LA5, described as unconfined proximal breccia deposits. The combination of lithofacies associations in this model is relatively simple. Coarse-grained deposits form as LA1, with decreasing grain size and decreasing variety of breccia components from the proximal slope to the base of the slope. Ultimately, massive mudstone lithofacies (LFH) develop towards the basin plain. Usually, deposits accumulated in M1 are recognized in close to proximity to the basin-controlling faults. Owing to the steep slope and proximity of source materials, the development scale of M1 deposits is limited. With consideration of the depositional environment, lithofacies associations, and development scale, we can infer that M1 is mainly composed of cohesive debris flows with numerous ‘floating’ breccias, resulting from discontinuous floods in the intermontane region. From the above analysis (Figs. 7 and 8), we propose that sediment gravity flows in the Shehejie Formation formed according to M1; this may be due to the prevailing humid climate, bedrock erosion, and intense fault activity.

5.3.2. Non-channelized surge-like turbidity current depositional model (M2)

M2 is a specialized depositional model, partly analogous to traditional ‘surge-like’ turbidite currents (Mutti et al., 1999) or intrabasinal turbidites (Zavala and Arcuri, 2016), but with no evidence for granular flow. Also, in the study area, neither obvious channels nor wide lobate sands were observed. M2 mainly comprises LA5 and LA6 from the proximal slope in front of the delta to the distal basin plain. This implies that M2 deposits can be divided into non-channelized sheet deposits and distal sheet deposits (Fig. 13). Surge-like turbidity currents are initiated as cohesive debris flows (sandy slumping) from the delta front, which progressively transform into suspended load dominated turbidity currents, and finally accumulate as dilute turbidity currents at, or near, the toe of a regional slope. Transformations between plastic and Newtonian flows are the consequence of acceleration and entrainment of ambient water in slope areas. In this model, sediment gravity flows result from delta front slumping, which leads to fine-grained and laterally extensive, thin sediment gravity flow deposits. From Figs. 7 and 8, M2-type sediment gravity flow deposits are mainly developed in E5d2, E6d1, and E6d3, when the LBD was in a post-riparian thermal subsidence stage, with partial characteristics of a depression basin resulting in the development of a lacustrine environment (Jia et al., 2014). In the LBD, sediment gravity flows formed under M2 are mainly controlled by abundant sediment input and the periodic gravitational collapse of slope deposits (Hampton, 1972; Zavala and Arcuri, 2016). Although the acceleration of surge-like subaqueous sediment gravity flows is more sensitive to depositional gradient, sediment abundance may partly compensate for the relatively gentle slope gradient in E5 to E6d1.

5.3.3. Channelised subaqueous-fan depositional model (M3)

M3 is composed of LA2–LA5 and resembles the classic submarine fan or hyperpycnal system model (Walker, 1978; Zavala et al., 2011); as such, M3 can be divided into four sections, from the proximal slope to the distal basin plain: confined channel, braided-channel lobe, unconfined lobe, and distal sheet lobe (Fig. 14). Deposits formed under M3 originate from sustained bedload dominated hyperpycnal flows that evolve into more dilute turbidity currents, resulting in the accumulation of coarse-to-fine-grained deposits. The occurrence of diamictites in the conglomeratic lithofacies suggests a complex transport process. Based on the grain size, lithology, and depositional structure, sediments formed as M3 can be divided into three groups (bedload, suspended load, and lofting deposits), following the concept of Zavala et al. (2011) and Zavala and Arcuri (2016). Under M3, accumulations of sediment gravity flow deposits originate from sustained intermontane rivers that bypassed shallow lakes or deltaic areas, and are then transported within channels into the basin. Ultimately, these sediments are deposited on the basin plain as sheet lobe fans.

In the study area, sediment gravity flow deposits formed as M3 developed during E5d2 to E6d1 and represent the most pervasive
depositional style, accumulating on steep and gentle slopes. Hence, the slope break is not a decisive control on sediment gravity flow deposits accumulated as M3. The proximal confined channel may have developed along a river in a delta system when the supply source was sufficient with low accommodation, or incised into underlying sediments owing to lacustrine regression. The resulting deposits may range from thick and internally complex beds of conglomerates and sandstones to graded shales with plant remains, depending on the distance from provenance to depositional (Zavala and Arcuri, 2016). The final thickness and extension of the deposits depend on the duration of the sustained turbulent flows and on the palaeogeomorphology of the depositional basin. Sediments deposited under M3 may represent a favourable reservoir for oil and gas.

6. Conclusions

(1) Eight lithofacies are recognized from analysis of sediment gravity flow deposits in approximately 278-m-long core intervals from 30 wells in the Liaodong Bay Depression: cohesive debris flows (matrix-supported conglomerates), non-cohesive bedload dominated turbidity currents (clasts-supported conglomerates), suspended load dominated turbidity currents (massive fine-grained sandstones and graded sandstones with parallel and ripple bedding), sandy slumping (chaotic sandstones and mudstones with glide planes), dilute turbidity currents (interbedded sandstones–siltstones/mudstones), muddy debris flows (pebbly mudstones), and very dilute turbidity currents (massive mudstones).

(2) Based on sedimentological logs and the bounding relationships of

Fig. 12. Slope-apron gravel-rich depositional model.
sediment gravity flow deposits in 10 key wells, along with their spatial distribution, the eight lithofacies are grouped into six lithofacies associations (LA) that reflect their processes of transformation and depositional morphology: unconfined proximal breccia deposits (LA1) in proximity to the fault system that forms the uplift margin; confined channel deposits (LA2) widely developed at the lacustrine basin margin; braided-channel lobe deposits (LA3) distributed in the proximal slope; unconfined lobe deposits (LA4) distributed remotely from the basin margin; distal sheet deposits (LA5) distributed in the base of the slope or basin plain; and non-channelized sheet deposits (LA6) distributed in the slope of the delta front.

(3) Three depositional models are proposed for the Palaeogene Dongying and Shahejie formations in the Liaodong Bay Depression that reflect the sedimentological characteristics and depositional processes of the sediment gravity flows: a slope-apron gravel-rich depositional model (M1), a non-channelized surge-like turbidity current depositional model (M2), and a channelized subaqueous-fan depositional model (M3). M1 is composed of cohesive debris flows deposited as LA1 and dilute turbidity currents deposited as LA5, and mainly developed in the Shahejie Formation. Sediment gravity flows in M1 usually formed under a humid climate, bedrock erosion, and fault activity. M2 is composed of sandy slumping, suspended load dominated turbidity currents, and dilute turbidity currents deposited as LA5 and LA6, and mainly developed in E2s2, E2s1, and E3d3 strata. Sediment gravity flows in M2 are usually triggered by inherent sediment failure or earthquakes. M3 is composed of deposits of non-cohesive bedload dominated turbidity currents, suspended load dominated turbidity currents, and dilute turbidity currents deposited as LA2–LA5, and mainly formed in E3d2 to E3d1 strata, representing the most pervasive depositional style. Sediment gravity flows in M3 are usually formed by sustained
seasonal flood and lacustrine regression.

Overall, our results have allowed us to revise previous classifications of sediment gravity flow deposits and to improve understanding of their depositional processes. Furthermore, since deep-water sediment gravity flow sandstones are currently the focus of attention regarding oil and gas exploration, this work may provide a useful basis for future research and exploration campaigns.

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