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Review Paper

New progresses of fine-grained sediment gravity-flow deposits and their importance for unconventional shale oil and gas plays

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ABSTRACT

Fine-grained sediments are widely distributed and constitute the most abundant component in sedimentary systems, thus the research on their genesis and distribution is of great significance. In recent years, fine-grained sediment gravity-flows (FGSGF) have been recognized as an important transportation and depositional mechanism for accumulating thick successions of fine-grained sediments. Through a comprehensive review and synthesis of global research on FGSGF deposition, the characteristics, depositional mechanisms, and distribution patterns of fine-grained sediment gravity-flow deposits (FGSGFD) are discussed, and future research prospects are clarified. In addition to the traditionally recognized low-density turbidity current and muddy debris flow, wave-enhanced gravity flow, low-density muddy hyperpycnal flow, and hypopycnal plumes can all form widely distributed FGSGFD. At the same time, the evolution of FGSGF during transportation can result in transitional and hybrid gravity-flow deposits. The combination of multiple triggering mechanisms promotes the widespread development of FGSGFD, without temporal and spatial limitations. Different types and concentrations of clay minerals, organic matters, and organo-clay complexes are the keys to controlling the flow transformation of FGSGF from low-concentration turbidity currents to high-concentration muddy debris flows. Further study is needed on the interaction mechanism of FGSGF caused by different initiations, the evolution of FGSGF with the effect of organic-inorganic synergy, and the controlling factors of the distribution patterns of FGSGFD. The study of FGSGFD can shed some new light on the formation of widely developed thin-bedded siltstones within shales. At the same time, these insights may broaden the exploration scope of shale oil and gas, which have important geological significances for unconventional shale oil and gas.

1. Introduction

With the ongoing advancements in conventional oil and gas exploration and development, unconventional oil and gas resources have gradually become the key target for oil and gas exploration and development (Zou et al., 2019a, 2019b; Hussain et al., 2021). As an important unconventional oil and gas resource, shale oil and gas have become the research focus (Liu et al., 2018a,b; Zou et al., 2019a, 2019b). Shale oil and gas are mainly developed in deep-water (water depth below storm wave base) fine-grained sedimentary rock successions (DeReuil and Birgenheier, 2019; Peng, 2021). Therefore, exploring the formation mechanism of deep-water fine-grained sediments (Abouelresh and Slatt, 2011; Könitzer et al., 2014; Yuan et al., 2015; Yang et al., 2017a, 2017b; Peng, 2021), deciphering the distribution patterns (Yuan et al., 2015; Zou et al., 2019a, 2019b; Emmings et al., 2020), as well as understanding organic matter enrichment in deep-water fine-grained sedimentary rock succession (Liu et al., 2018a,b; Hussain et al., 2021; Peng et al., 2021, 2023; Hussain and Al-Ramadan, 2022; Cunningham and Arnott, 2023; Talling et al., 2024), are of great significance to realize the efficient exploration and development of shale oil and gas (Zou et al., 2019a, 2019b).

Fine-grained sediments refer to clay- and silt-sized sediments with a particle size of less than 62.5 μm. They are widely distributed and account for about two thirds of the global sedimentary rocks

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(Stow and Piper, 1984a,b; Schieber et al., 2010; Aplin and Macquaker, 2011). Studying the formation and distribution of fine-grained sediments is also important for reconstruction of paleoenvironment (Stow et al., 1984; Stow and Piper, 1984a,b; Arthur and Sageman, 1994), global sediment transportation (Macquaker et al., 2010; Schieber, 2016; Mutti, 2019), and carbon cycle process (Arthur and Sageman, 1994; Galy et al., 2007). Deep-water sediment gravity-flows are one of the most important dynamic mechanisms for transporting sediments along slopes to deep-water basin areas (Talling et al., 2012; Yang et al., 2017; Hizzett et al., 2018; Mutti, 2019; Hage et al., 2019). Fine-grained sediment gravity-flows (FGSGF) are rich in clay minerals and organic matter (Hovikoski et al., 2016; Fildani et al., 2018; Boulesteix et al., 2019; Mutti, 2019). Therefore, their sediment characteristics, transportation, evolution processes, and distribution patterns differ from traditional coarse-grained sediment gravity-flows (Baas et al., 2009, 2016a, 2016b; Baker et al., 2017; Craig et al., 2020; Zeichner et al., 2021). On the one hand, the FGSGF consists of smaller particles, and its formation and transportation conditions are easier to attain compared to those of coarse-grained sediment gravity flow. Therefore, fine-grained sediment gravity flow deposits (FGSGFD) are widely developed in the fine-grained sourced sediment gravity-flow systems and the distal end of the coarse-grained sediment gravity flow systems (Hizzett et al., 2018; Mutti, 2019). On the other hand, FGSGF are rich in clay minerals and organic matter. The increase in clay mineral or organic matter content can enhance the flow cohesion, thereby changing the overall rheological properties (Baas and Best, 2002; Sumner et al., 2009; Haughton et al., 2009). The increase of flow cohesion is one of the most important reasons for transforming low-density turbulent flows into muddy debris flows (Malarkey et al., 2015; Baas et al., 2009, 2016a, 2016b, 2019; Baker et al., 2017). It further controls the transportation and evolution of flow and the preservation and enrichment of organic matter (Cai et al., 2007; Blattmann et al., 2019; Craig et al., 2020).

At the current stage, the overall understandings of FGSGFD remains limited, including the sedimentary identification marks, the formation mechanisms, the transport and evolution processes, and the distribution patterns. The aims of this paper are (1) to provide a comprehensive overview of the recent advancements in global FGSGFD research, (2) to clarify the future research prospects of FGSGFD, and (3) to explore the significance of FGSGFD for unconventional shale oil and gas exploration and development.

2. Terminology

The terminology related to the FGSGF and their deposits in this study abides by the definition of Mutti et al. (1996, 1999, 2003), Bouma (2000), Haughton et al. (2009), Talling et al. (2012), Yang et al. (2019, 2020, 2023a, b), and Zavala (2020).

Fine-grained sediment gravity-flow (FGSGF): the FGSGF associated with these events are caused by excessive sediment density and dominated by fine-grained sediments. One FGSGF event may contain different types of FGSGF, including muddy debris flows, low-density turbidity currents and so on (Talling et al., 2012).

Low-density turbidity current: a turbulent Newtonian fluid in which sediment grains are supported by the turbulent fluid (Lowe, 1982). In this kind of current, clay-to fine-grained sand-sized particles that can be fully suspended as individual grains by flow turbulence (Lowe, 1982).

Muddy debris flow: a laminar, non-Newtonian Bingham plastic flow in which sediment is predominantly supported by the matrix strength, excess pore pressure, and buoyancy (Talling et al., 2012). A driven down-slope due to their weight and momentum is the key feature of debris flows (Talling et al., 2012). It usually results in massive mud or argillaceous sandstone with floating mud clasts or granules.

Hyperpycnal flow: a density flow originated by direct plunging of a fluvial discharge into a lacustrine or marine basin. The density of the incoming flow is higher than that of the receiving water body due to the high concentration of sediment contained in the flow. Where the basin is sufficiently deep, this type of flow will move along the basin floor (Mulder et al., 2003).

Wave-enhanced gravity flow: a density flow with the energy to maintain sediment in suspension is provided by orbital motion of surface gravity waves, instead of gravity-induced turbulence, as for classical turbidity currents (Macquaker et al., 2010). This kind of flow is capable of propagating downslope on gradients as low as 0.5 m km^{-1} (Macquaker et al., 2010).

Hybrid event beds (HEBs): deposits of hybrid sediment gravity flows, composed of turbidity current in the lower part and debris flows in the upper part at a fixed point (Haughton et al., 2009; Southern et al., 2017). Hybrid event beds typically comprise a basal clay-poor sandstone (non-stratified or stratified) (H1) overlain by banded sandstone (H2), with clay-rich non-stratified argillaceous sandstone at the bed top (H3) (Talling, 2013).

Transitional gravity flow: refers to the turbulence structure developed as the flow transits from high to low or low to high Reynolds number (Haughton et al., 2009). This kind of flow can be subdivided into turbulence-enhanced transitional flow, lower and upper transitional plug flow as clay concentration increases (Baas et al., 2009).

Hypopycnal plumes (overflows): A less dense flow where sediment-laden fluid moves out over the surface of denser fluid filling the basin, as in the case of a stream discharging into the ocean or lakes (Bates, 1953). Vertical mixing is inhibited because of stability between the layers, and the flow pattern is that of the plane jet (Bates, 1953).

3. Research history of FGSGFD

Previous studies mostly proposed that fine-grained sediments were the products of suspension settling in low-energy environments (Moore, 1969; Piper, 1972). However, many studies showed that low-density turbidite currents are an important transportation and deposition mechanism for laminated mudstones based on the turbidity current theory (Stow and Bowen, 1978; Stow and Bowen, 1980). Then, sedimentary sequences of four types of fine-grained turbidite are established, including silt turbidite, muddy turbidite, biogenic turbidite, and mixed-structure turbidite (Stow and Shanmugam, 1980; Stow and Piper, 1984a,b). With the development of deep-water gravity-flow theory, processes such as low-density turbidity current, muddy debris flow, and mass transport are suggested to play an important role in the transportation and deposition of deep-water fine-grained sediments (Gorsline, 1984; Stow and Piper, 1984a,b; Stow, 1985). Recently, fine-grained mud-rich gravity-flow depositional systems have begun to receive further attention. The fine-grained mud-rich gravity-flow depositional system mainly refers to these dominated by shales or silty mudstones, and they comprise at least 70% of the total succession (Bouma, 2000; Stelting et al., 2000). Due to the high mud content of the fine-grained mud-rich gravity-flow depositional system, their sediment characteristics, transportation, evolution processes, and distribution patterns differ from traditional coarse-grained mud-poor gravity-flow depositional systems (Stelting et al., 2000). There are many unsolved problems about the formation mechanisms and transportation process of FGSGF at that time (Stow et al., 2001).

With the advancement of flume tank simulation experiments and direct monitoring observation technologies, new understandings about the mechanism of FGSGFD and related flow transportation evolution processes are emerging (Schieber, 2016). In addition to mass transport deposits, muddy debrites, and low-density turbidites formed by sediment failure, numerous studies have shown that low-density muddy hyperpycnal flow (Parsons et al., 2001; Bhattacharya and MacEachern, 2009) and wave-enhanced gravity flow (Macquaker et al., 2010) can transport fine-grained sediments to deep-water basins for relatively long distances. The latest direct monitoring observation of gravity flow shows that hypopycnal plumes can be gradually transformed into low-density turbidity current, resulting in FGSGFD (Hizzett et al., 2018; Hage et al., 2019). A combination of multiple triggering mechanisms explains the possibility of FGSGFD formation in different environments (Stow, 1985; Boulesteix et al., 2019). The flume tank simulation experiment further confirmed that the fine-grained sediments may reach the size of coarse silt level through flocculation, and can be efficiently transported to the deep-water basin through gravity-flow in the form of bedload (Schieber et al., 2007, 2019). The FGSGF transported in the form of bedload further effectively interacts with the soft muddy substrate (Hovikoski et al., 2016), increasing the mud content in the flow. Therefore, the low-density turbidity current may be transformed into muddy debris flow, forming hybrid and related transitional gravity flow (Baas and Best, 2002; Haughton et al., 2003). The flow transformation from low-density turbidity current to low concentration muddy debris flow makes the evolution process of FGSGF and distribution patterns of FGSGFD more complicated (Hovikoski et al., 2016; Boulesteix et al., 2019; Mutti, 2019). These latest findings further demonstrate the crucial role of gravity flow in the transportation and deposition of fine-grained sediments (Peng, 2021; Hussain et al., 2021; Peng et al., 2022).

4. New progresses of FGSGFD

The deep-water FGSGF process is involving overall 'triggering-transporting-settling' of gravity-flow, also known as gravity-flow event (Talling et al., 2012). Gravity-flow events are characterized by various triggering mechanisms, several different types of flow, and a common occurrence of downflow transformation (Fisher, 1983; Mutti, 1992; Waltham, 2004; Felix and Peakall, 2006; Baas et al., 2009; Talling et al., 2012; Boulesteix et al., 2019; Dodd et al., 2019). Therefore, a single gravity flow event may form multiple types of gravity flow sediment assemblages, resulting in extremely complex sediment characteristics and distribution patterns (Haughton et al., 2003; Talling et al., 2004; Hovikoski et al., 2016; Mutti, 2019; Baas et al., 2021).

On the one hand, deep-water gravity-flows of different origins can effectively transport and deposit fine-grained sediments (Stow and Mayall, 2000; Piper and Normark, 2009). Mechanisms such as gravity-flows resulting from sediment failures, hyperpycnal flood flows, and the settling of hypopycnal plumes play crucial roles in the transportation and depositional of fine-grained sediments (Hovikoski et al., 2016; Boulesteix et al., 2019; Mutti, 2019; Hage et al., 2019; Wells and Dorrell, 2021) (Table 1). Therefore, distinguishing formation mechanisms of FGSGFD through their compositions or sedimentary structures is still very difficult (Jiang et al., 2013; Liu et al., 2015; Xian et al., 2016; Clare et al., 2016; Hage et al., 2017; Hussain et al., 2020, 2021; Stevenson et al., 2020).

On the other hand, the involvement of clay minerals and organic matter in FGSGF can effectively enhance the cohesion and viscosity of the flow. Therefore, the turbulence of the low-concentration fine-grained turbidity current at the distal end of the deposition is damping and transforms into a high-concentration transitional flow or hybrid gravity-flow (Baas et al., 2009, 2016a, 2016b, 2021; Sumner et al., 2009; Baker et al., 2017; Craig et al., 2020; Stevenson et al., 2020; Hussain et al., 2021). Transitional or hybrid gravity-flow deposits are an important part of deep-water FGSGFD (Hovikoski et al., 2016; Boulesteix et al., 2019, 2020; Mueller et al., 2021; Baas et al., 2021) (Table 1). The identification of fine-grained transitional and hybrid gravity-flow deposits at distal depositional areas is an important reason to reevaluate the heterogeneity of fine-grained sediments and the differential enrichment of organic matters (Baas et al., 2016b; Craig et al., 2020; Emmings et al., 2020; Hussain et al., 2021).

4.1. Sedimentary characteristics of FGSGFD

Deep-water FGSGFD often look uniform, but they contain many sedimentary details (Stow and Piper, 1984a,b; Jiang et al., 2013). High-precision microscopy techniques and in-situ composition analysis techniques are significant in revealing the genetic mechanism of FGSGFD (Hovikoski et al., 2016; Boulesteix et al., 2019, 2020; Mutti, 2019; Yang et al., 2019; Stevenson et al., 2020). In addition to massive bedding common in muddy debrites, normal graded bedding, and horizontal bedding that are common in low-density turbidites, and some sedimentary features of genesis indications have been discovered based on XRF element scanning (Yang et al., 2019; Hussain et al., 2020, 2021), polished rock samples (Hovikoski et al., 2016; Yang et al., 2019), and microscopic observations (Hovikoski et al., 2016; Boulesteix et al., 2019). In addition, some case studies indicate early diagenetic calcareous nodules developed in fine-grained sediments can effectively preserve original sedimentary composition and sedimentary structures from the alteration caused by subsequent intense mechanical compaction and chemical diagenesis (Otharán et al., 2022). Therefore, sedimentary structures in fine-grained sediments preserved by those nodules are significant for understanding the depositional processes associated with fine-grained sediment gravity-flows (Schieber, 2016; Otharán et al., 2022).

FGSGFD caused by hyperpycnal flow or wave-enhanced gravity flow exhibits distinct sedimentary characteristics. The inverse then normal grading of fine-grained sediments, and the combination of clastic particles and carbonaceous clasts observed in polished rock samples or under the microscope can be used as important identification marks of muddy hyperpycnites (Fig. 1(a), (b)) (Soyinka and Slatt, 2008; Zavala et al., 2012; Wilson and Schieber, 2014, 2015, 2017; Zavala and Arcuri, 2016; Song et al., 2017; Yang et al., 2017a; Jin et al., 2021; La Croix et al., 2021). These inverse then normal grading indicate the waxing then waning of hyperpycnal flow (Mulder et al., 2003; Zavala and Arcuri, 2016). Sandy ripples and lenticular laminae in shale at a thin-section scale are important evidence for bedload transportation by hyperpycnal flows or bottom currents (Stow et al., 2001; Schieber and Southard, 2009; Schieber et al., 2010). The tripartite bed of curved sandy ripples and mud clasts at the bottom, wavy horizontal laminae in the middle, and massive mudstone in the upper part indicates wave-enhanced gravity flow deposits (Macquaker et al., 2010). FGSGFD can be effectively distinguished from the background mudstone (pelagic or hemipelagic mudstone) through in-situ XRF scanning analyses of trace element content and distribution (Hussain et al., 2020).

FGSGFD that indicate origins of flow transformation exhibit distinctive sedimentary characteristics. The characteristics of dewatered structures, loading structures, contact relationships, and composition difference developed in the fine-grained sediments, exhibit as thin-bedded sandstone and argillaceous sandstone interbedded layers (Fig. 1(c)–(e)), can be used as important identification marks of hybrid event beds (HEBs) (Haughton et al., 2009; Hovikoski et al., 2016; Yang et al., 2017b, 2018, 2019; Boulesteix et al., 2019; Hussain et al., 2020; Dodd et al., 2022). Moreover, the banded structure that can be described in detail often shows significant differences in the material composition of transitional

Table 1
Summary of new progresses of fine-grained sediment gravity-flow deposits (FGSGFD).

Type of FGSGFD	Sedimentary characteristics	Formation mechanisms	Transport process	Distribution pattern	Organic matter enrichment	References
Low density turbidites	Normal graded bedding, and horizontal bedding	Settling of low-density turbidity current caused by sediment failure	Dilution and waning	Levee deposits and distal lobe deposits	Organic matters rich in the upper part of gravity-flow sequence, Td division of the Bouma sequence	Lowe (1982); Bouma (2000); Talling et al. (2012)
Muddy debrites	Massive bedding, floating sandy balls, and mud clasts	Frozen of cohesive massive muddy debris flow caused by sediment failure	Dilution and waning	Traceable elongated distribution pattern in proximal part of basins	Determined by the accumulation of organic matter in parent deposits	Sumner et al. (2009); Talling et al. (2012)
Muddy hyperpycnites	Inverse then normal grading, carbonaceous clasts, climbing ripples	Direct plunging of a fluvial discharge into a lacustrine or marine basin	Waxing then waning	Elongated geometry ranges from proximal to distal part of basins	Rich in terrestrial organic matters in lofting deposits	Bates (1953); Mulder et al. (2003); Wilson and Schieber (2014)
Wave-enhanced sediment-gravity flow deposits	The tripartite bed of curved sandy ripples and mud clasts at the bottom, wavy horizontal laminae in the middle, and massive mudstone in the upper part	The energy of the flow to maintain sediment in suspension is provided by orbital motion of surface gravity waves	Dilution and waning	Distributed mainly in continental shelves	Organic matters rich in the upper part of the sequence	Macquaker et al. (2010); Wilson and Schieber (2017)
Hypopycnal plume deposits	Finger-like structures, “cloudy” structures, water escape structures, sandy ripples and climbing cross-bedding	A less dense flow where sediment-laden fluid moves out over the surface of denser fluid filling the basin and transform to hyperpycnal flow	Flow concentration increases with flow run-out and then decreases.	Distributed mainly in distal part of basins.	Organic matters rich in clay dominates in deposits.	Bates (1953); Mutti (2019)
Hybrid event beds	Bipartite or tripartite bed structures, with clean silt in the lower part and argillaceous sandstone in the upper part	The transformation of low-density turbidity current to muddy debris flow caused by turbulence damping at a fixed point	Flow concentration increase with flow run-out.	Distributed in the distal or relatively low-lying regions of basins.	Muddy debrites in the upper part of the bed rich in organic matters.	Haughton et al. (2009); Southern et al. (2017)
Transitional gravity flow deposits	Banded structure, normal sandy current ripples, large current ripples, and low-amplitude bed-waves	Flow transits from high to low or low to high Reynolds number	Transitional between flow concentration increases and decreases.	Distributed in the distal or relatively low-lying regions of basins.	Organic matters rich in dark bands of banded structures.	Haughton et al. (2009); Baas et al. (2009)

gravity flow deposits (Yang et al., 2019; Hussain et al., 2020). The differences in composition (Fig. 1(f)) and the occurrence of normal sandy current ripples, large current ripples, and low-amplitude bed-waves (Fig. 1(g)) can be used as diagnosing criteria for transitional gravity flow deposits (Southern et al., 2017; Boulesteix et al., 2019; Koo et al., 2020; Baker and Baas, 2020; Stevenson et al., 2020). In the fine-grained sediments with frequent sand and mud interbeddings, the occurrence of finger-like structures due to the local sinking of sandy sediments and cloud-like structures formed by local dewatering is common (Fig. 1(h) and (i)). These distinctive structures coupled with the development of sandy ripples and climbing cross-bedding, may indicate sediments transform from hypopycnal plumes (Parsons et al., 2001; Hizzett et al., 2018; Mutti, 2019; Wells and Dorrell, 2021).

4.2. Formation mechanisms of FGSGFD

In addition to FGSGFD caused by earthquake induced sediment failure and re-transportation, wave-enhanced gravity flow, low-density muddy hyperpycnal flow, and gravity flow caused by hypopycnal plumes settling are all important transportation and deposition mechanisms of fine-grained sediments (Fig. 2) (Macquaker et al., 2010; Hovikoski et al., 2016; Boulesteix et al., 2019; Mutti, 2019; Hage et al., 2019; Wells and Dorrell, 2021). Hyperpycnal flow primarily constitutes a density flow that originates from the direct plunging of a fluvial discharge into a deep-water basin. The density of the incoming flow is higher than that of the receiving water body due to the high sediment concentration in the flow (Mulder et al., 2003) (Fig. 2(b)). The flow will plunge and move along the basin floor. Due to the ongoing influx of floodwaters, the muddy hyperpycnal flow experiences extensive transportation from shallower to deeper water regions (Parsons et al., 2001; Bhattacharya and MacEachern, 2009). The resulting fine-grained sediments are rich in terrigenous carbonaceous clasts (Zavala and Arcuri, 2016). The gravity flow caused by the settling of the hypopycnal plume is formed by the river influx in the sedimentary basin during the non-flood period (Fig. 2(c)). The dilute plume accumulates continuously in the estuary area and is transformed into gravity flow through convection, which driven by fluid diffusion and subsidence (Davarpanah Jazi and Wells, 2020; Wells and Dorrell, 2021; Lu et al., 2022). Therefore, these gravity flows have the capacity to transport and deposit thin interbedded fine-grained sediments in deep-water basins (Hizzett et al., 2018; Hage et al., 2019; Mutti, 2019). Wave-enhanced gravity flow is caused by re-suspended fine-grained sediments in the relatively shallow water area with wave modifications (Fig. 2(d)). The increasing suspended fine-grained sediments triggered by waves initiates gravity flow and deliver sediments to deep-water basins (Piper and Normark, 2009; Macquaker et al., 2010; Schieber, 2016). On the one hand, the combined effect of different genetic mechanisms leads to the development of FGSGFD from shallow-to deep-water environments with or without earthquakes or floods as triggers (Hizzett et al., 2018; Hage et al., 2019). On the other hand, the gravity flow formed by different formation mechanisms may

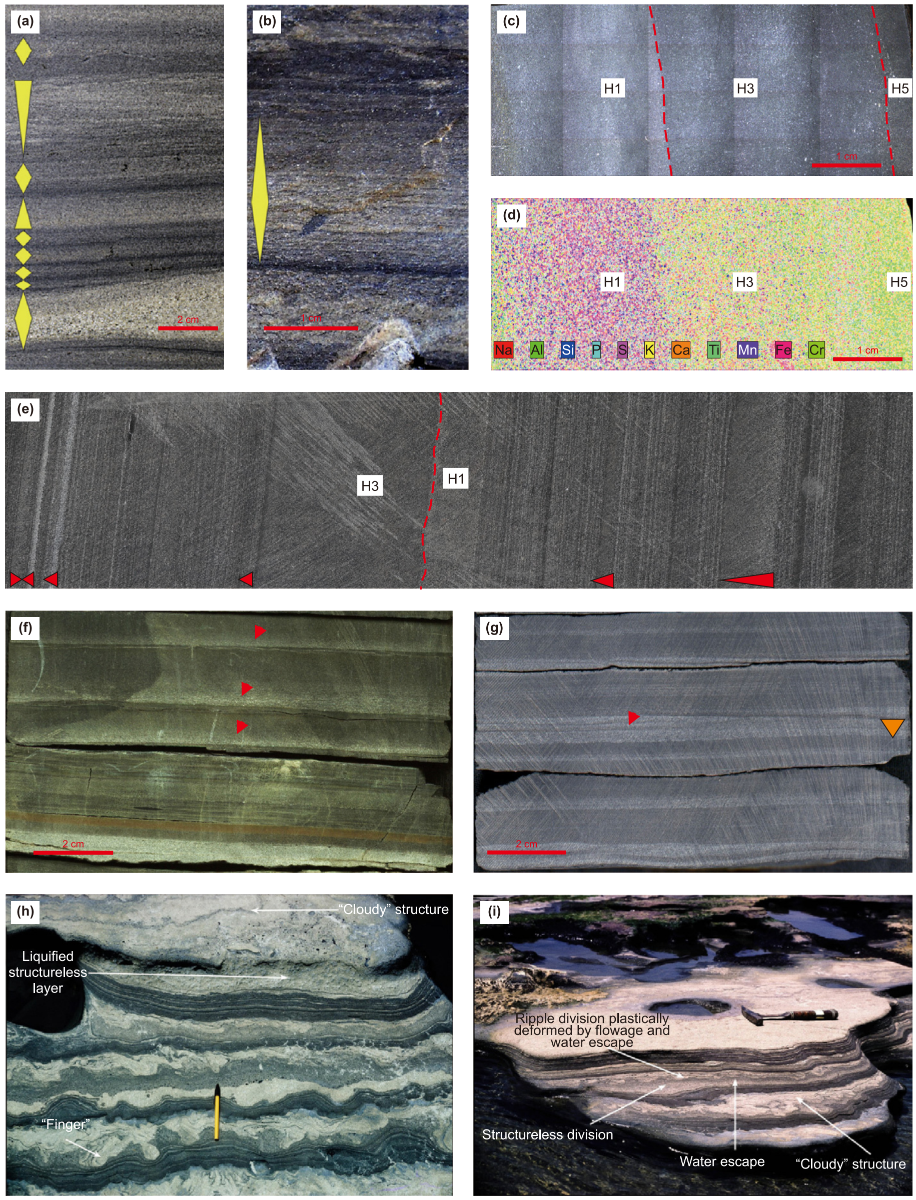

Fig. 1. Typical sedimentary characteristics of FGSGFD. **(a)** Vertical stacking of inverse then normal grading sequence caused by hyperpycnal flow. Normal grading or inverse grading are also internally observed. Cretaceous deposits from Utah (Schieber, 2016). **(b)** Symmetrical inverse then normal grading sequence with abundant carbonaceous clasts. Cretaceous deposits from Utah (Schieber, 2016). **(c)** Thin-layer tripartite structure hybrid event bed. Cretaceous from Lingshan Island. **(d)** μ-XRF element scan of picture (c), Cretaceous from the Lingshan Island. **(e)** Vertical stacking of fine-grained sediment gravity-flow deposits. Cretaceous from the Lingshan Island. **(f)** Vertical stacking of quasi-laminar plug flow deposits, WZ11-7-4 well core, 2175.79–2175.85 m. **(g)** Vertical stacking of upper transitional plug flow deposits, Ch 96 well core, 1991.20–1991.28 m. **(h)** Local preservation of finger-like features, commonly obliterated into a cloudy structure (Mutti, 2019). **(i)** Cloudy structure and ripple division are deformed by flowage and water escape (Mutti, 2019). H1–H5, the depositional unit of hybrid event bed of Haughton et al. (2009), the red dotted line is the boundary of different depositional units.

transform into different flow types with the mixing of ambient water and the interaction with the muddy substrate during the transportation (Haughton et al., 2003; Talling et al., 2004). These processes will result in different flow types during deposition, which further complicates the sedimentary characteristics and distribution patterns of FGSGFD (Hovikoski et al., 2016; Boulesteix et al., 2019).

4.3. Transport and evolution processes of FGSGFD

The evolution of FGSGF and the transformation relationships between various flow types during the transportation process pose challenges in current research (Hovikoski et al., 2016; Baas et al., 2016b, 2021; Boulesteix et al., 2019; Baker and Baas, 2020; Craig et al., 2020). Previous transformation models, based on fluid dilution theories, postulated that the evolution of deep-water FGSGF often involves a transition from high-concentration debris flows to low-concentration turbidity currents (Fisher, 1983; Mutti, 1992; Shanmugam, 2013). On the contrary, recent researches have revealed opposite phenomena. The transformation of low-concentration turbidity current into high-concentration muddy debris flow is widely developed in the distal depositional environment due to the suppression of fluid turbulence during the evolution of FGSGF (Haughton et al., 2003, 2009; Talling et al., 2004; Talling, 2013; Hussain et al., 2020, 2021).

The erosion of turbidity currents, the collapse and mixing of

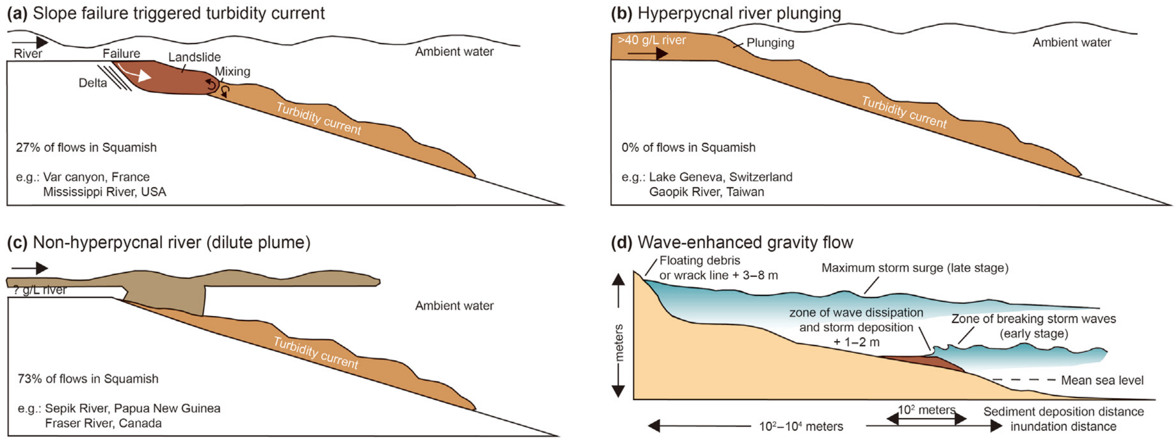

Fig. 2. The dynamic mechanism of FGSGFD (Abouelresh and Slatt, 2011; Hage et al., 2019). **(a)** FGSGF caused by sediment failure. **(b)** FGSGF caused by flooding (hyperpycnal flow). **(c)** FGSGF caused by settling of hypopycnal plume; **(d)** Wave-enhanced FGSGF. **(e)** Fine-grained muddy debris flow.

local muddy sediments, and the floating and accumulation of fine-grained sediments increase mud content (Haughton et al., 2003; Talling et al., 2004; Hussain et al., 2020, 2021). These are the primary factors driving the transformation of low-concentration turbidity currents into high-concentration muddy debris flows (Talling, 2013). Numerical simulation experiments have demonstrated that small changes in flow concentration can lead to major changes in flow properties (Talling et al., 2012, 2015). When the initial sediment concentration is 0.9 mg/L, the flow exhibits characteristics of a turbidity current; when the initial sediment concentration increases to 1.0 mg/L, the flow exhibits debris flow characteristics (Talling et al., 2015). Flume tank simulation experiments further reveal that the type and concentration of clay minerals are the main reasons controlling the transformation of low-concentration turbidity current into a high-concentration muddy debris flow in FGSGF (Baas et al., 2009, 2016b). This transformation further results in transitional and hybrid gravity flow deposits (Baas and Best, 2002; Sumner et al., 2009; Haughton et al., 2009), alternative interpretation is the vertical stratification of debris flows in distal (Talling et al., 2004; Sumner et al., 2009; Hussain et al., 2021). When the volume fraction of kaolin in the low-density turbidity current is greater than 22%, the flow can be transformed into a muddy debris flow (Baker et al., 2017). When kaolin replaced by montmorillonite with a higher matrix strength, this value is reduced to 16% (Baas et al., 2009, 2011; Baker et al., 2017). The latest research shows that microbial organic matter (extracellular polymer EPS) also plays an important role in controlling the transportation and evolution of fine-grained sediment deposits (Malarkey et al., 2015; Parsons et al., 2016; Chen et al., 2017a,b, 2019; Baas et al., 2019; Zeichner et al., 2021) (Fig. 3). Therefore, research works that separated the transportation and depositional processes of detrital particles from organic matters may be far away from the actual conditions of FGSGF (Zhang et al., 2016; Chen et al., 2017a,b, 2017b, 2018, 2019; Baas et al., 2019; Cai et al., 2019).

4.4. Distribution pattern of FGSGFD

Fine-grained sediment gravity-flow deposits are accumulated by various depositional mechanisms and may have different distribution characteristics (Wilson and Schieber, 2014; Steel et al., 2016; Pierce et al., 2018; Koo et al. al., 2020). The edge of the muddy shelf collapses and then experiences slide and slump transformation into medium-to high-strength muddy debris flows. Due to the high contents and high strengths of muddy matrix, these debris flows are difficult to mix and be diluted by the ambient water along the transportation process (Talling et al., 2012; Talling, 2013). As a result, it often forms fine-grained deposits with large thicknesses and a traceable elongated distribution pattern (Talling et al., 2012; Talling, 2013). In a gravity-flow system caused by collapse and re-transportation of sand-rich sediments, the fine-grained sediments mostly spill out of the channel to form levee deposits characterized by thin-bedded sand and mud interbeddings (Hansen et al., 2015, 2017). With coarse-grained sediments settling in the channel, fine-grained sediments are further transported to deep-water basins, forming lobe deposits that occupy large areas (Boulesteix et al., 2020) (Fig. 4). During the transportation process of muddy hyperpycnal flow in marine and saline basins, buoyancy reversal inhibits the lateral diffusion of fluids (Bhattacharya and MacEachern, 2009; Wilson and Schieber, 2014; Steel et al., 2016), in combination with fluid stratification (Kneller et al., 2016), results in long-distance transportation into deep-water basins. As a result, the fine-grained sediments formed by hyperpycnal flow mostly have an elongated geometry (Steel et al., 2016; Kneller et al., 2016; Yang et al., 2017a, 2017b; Wells and Dorrell, 2021) (Fig. 4).

FGSGFD caused by hybrid or transitional gravity flows are mainly distributed in the distal or relatively low-lying regions of the basins, and the distribution area is relatively limited compared to that of coarse-grained turbidites (Southern et al., 2017; Patacci et al., 2020; Hussain et al., 2021; Baas et al., 2021). Turbidity currents are transformed into muddy debris flows due to a local erosion of the muddy substrate or due to the reduced velocity of turbidity currents entering the relatively low-lying regions of the substrate (Haughton et al., 2009; Talling, 2013). The resultant silt-mud interbedded fine-grained sediments are generally bulls-eye patterns, distributed, or filled in relatively low-lying regions of the basin (Fig. 4) (Haughton et al., 2003; Talling, 2013). Turbidity currents may transform into muddy debris flows due to fluid expansion and deceleration during the late stage of transportation resulting in interbedded silt and mud (Haughton et al., 2003; Talling et al., 2004). These FGSGFD generally surround the edges of the flow and are distributed in rings (Fig. 4) (Talling et al., 2007; Davis et al., 2009). Wave-enhanced gravity flow and hypopycnal plume triggered gravity flow can transport and deposit fine-grained sediment for a long duration (Hizzett et al., 2018; Hage et al., 2019; Mutti, 2019). Therefore, their deposits are featured by fine-grained silt and mud interbeddings (Mutti, 2019).

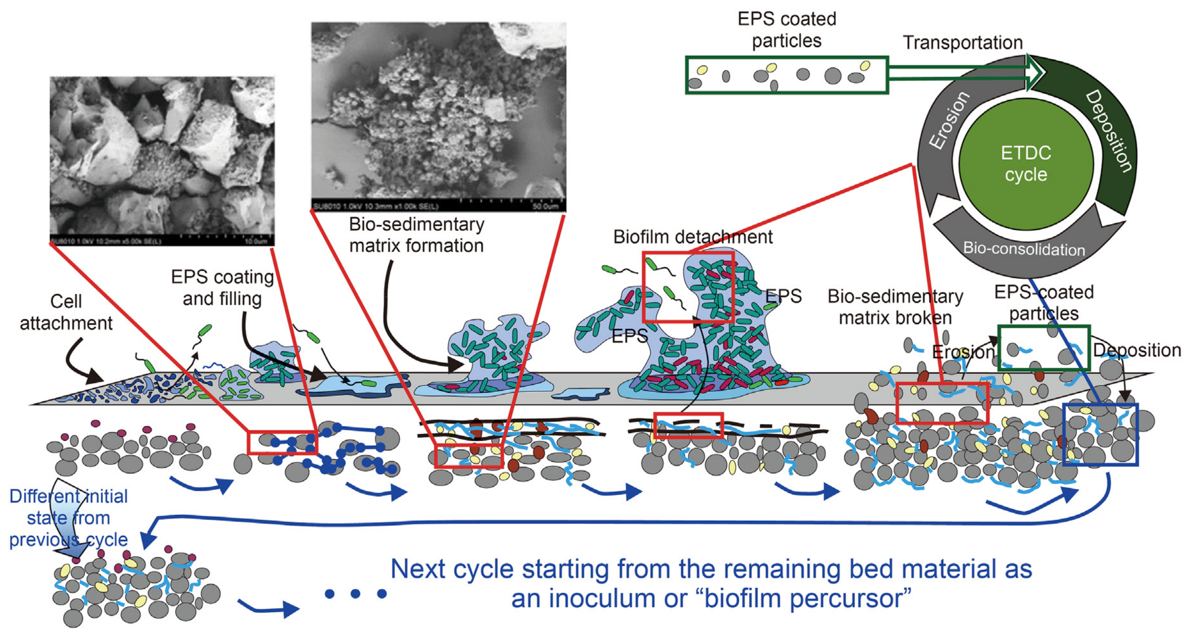

Fig. 3. The control effect of organo-clay complexes on the transport and evolution of fine-grained sediments (Chen et al., 2019).

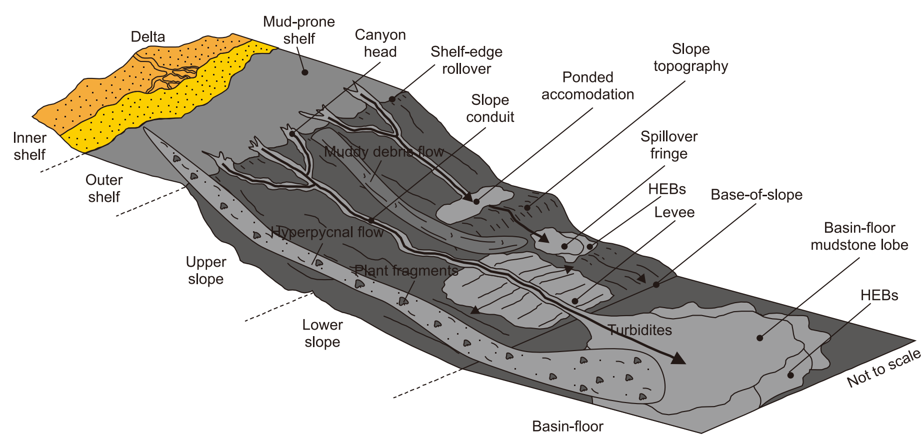

Fig. 4. The distribution pattern of FGSGFD in marine and lacustrine basins (Boulesteix et al., 2020). HEBs-Hybrid event beds.

4.5. Organic matter enrichment in FGSGFD

Previous studies suggested that organic matter is commonly preserved in argillaceous sediments caused by suspension settling (Hage et al., 2020; Hussain and Al-Ramadan, 2022), but the latest researches show that the efficient transportation and rapid burial, and the preservation of organic matter by FGSGFD are also an important reason for the enrichment of organic matters (Saller et al., 2006; Galy et al., 2007; DeReuil and Birgenheier, 2019; Hage et al., 2020; Hussain and Al-Ramadan, 2022). Due to the hydrodynamic sorting and density fractionation in the transportation process of gravity flow (Hage et al., 2020), the organic matter carried by gravity flow with mixed particle size is mostly enriched in the upper part of the flow during the transportation process. Therefore, the Td division of the Bouma sequence dominated by fine-grained sediments is enriched with organic matters (Hage et al., 2020; Hussain and Al-Ramadan, 2022). The upper part of the Td division is mostly covered by muddy sediments and quickly buried to avoid oxidation (Hage et al., 2020). Therefore, the organic matter is enriched in the upper part of gravity-flow sequence dominated by fine-grained sediments (Saller et al., 2006; Hage et al., 2020) (Fig. 5(a)). For example, in the modern gravity flow deposits in the Canadian fjords, the total organic carbon content of the Td division is 2%–5%, which is much higher than that in the adjacent mudstone deposits (Hage et al., 2020). FGSGFD of Upper Miocene in the Kutei Basin, Indonesia, has a total organic carbon content of 4%–7% (Saller et al., 2006). Compared with wave-enhanced gravity flow deposits and FGSGFD caused by sediment failure, muddy hyperpycnal flow, and hypopycnal plume triggered gravity flow are rich in terrestrial organic matter and mostly form FGSGFD with high organic matter content (Zavala and Arcuri, 2016; Mutti, 2019). At the same time, due to the sedimentary differentiation in the transportation process, bedload sediments are the main type at proximal areas, where traction structures mostly develop, and organic matter content is relatively low (Zavala and Arcuri, 2016). On the contrary, the distal part of the deposition is dominated by suspended-load sediments. Organic matter is enriched due to floating and is dominated by humic kerogen (Wilson and Schieber, 2014, 2015; Jin et al., 2021).

In addition to the organic matter carried by the gravity flow

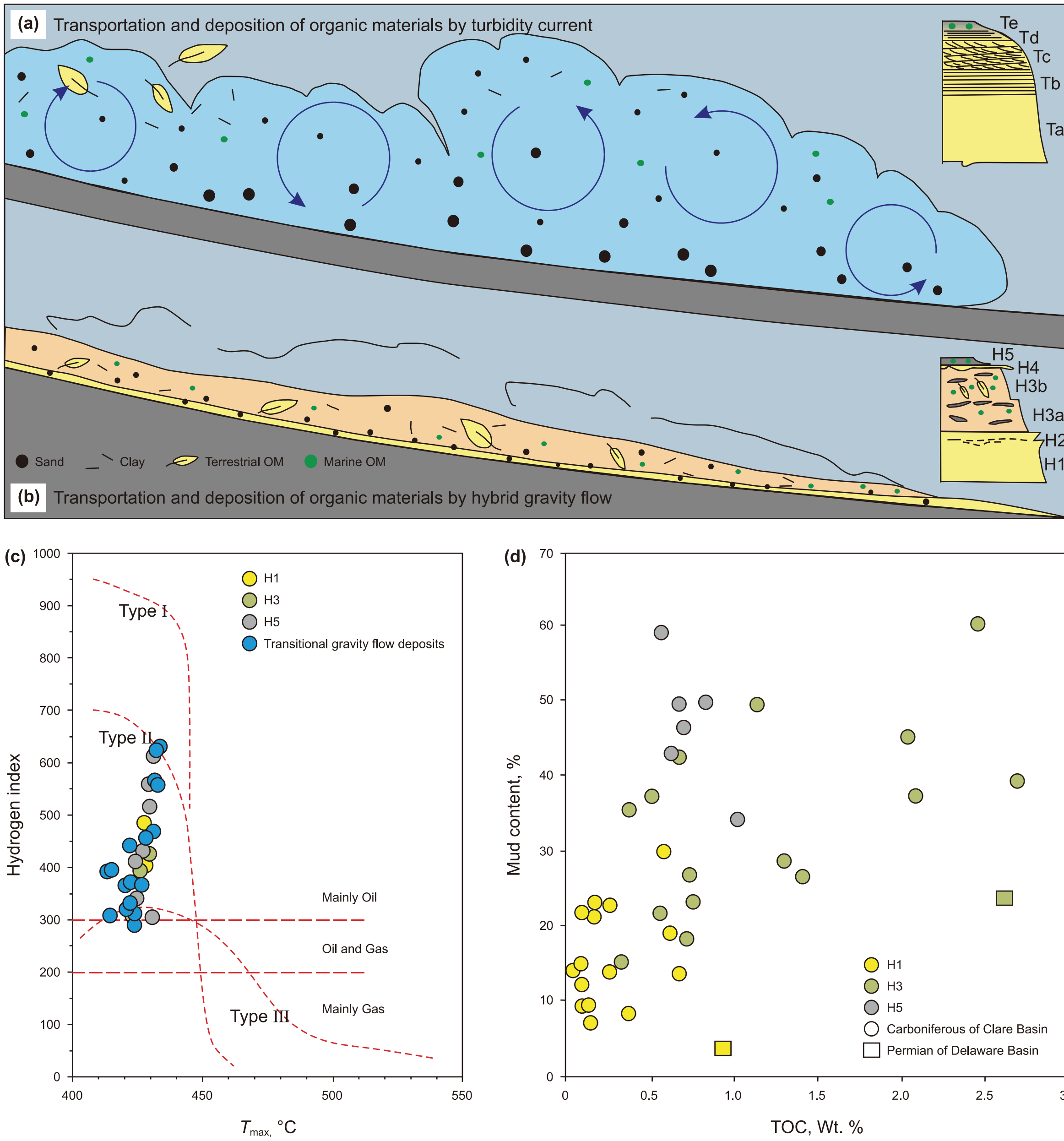

Fig. 5. Transportation and enrichment of organic materials of FGSGFD (Hovikoski et al., 2016; Kvale et al., 2020; Hussain et al., 2021; Hussain and Al-Ramadan, 2022). **(a)** Transportation and deposition of organic materials by turbidity currents (Hussain et al., 2021; Hussain and Al-Ramadan, 2022). **(b)** Transportation and deposition of organic materials by hybrid gravity flow (Hussain et al., 2021; Hussain and Al-Ramadan, 2022). **(c)** Organic matter types in the hybrid event beds and transitional gravity flow deposits of Paleogene lacustrine gravity flow deposits in the Honghe Basin, Vietnam (Hovikoski et al., 2016). **(d)** The total organic carbon content of the different depositional units of HEB (Kvale et al., 2020; Hussain et al., 2021).

itself, the interaction with the muddy substrate during the transportation process will further increase the content of clay and organic matter in the flow, resulting in the transformation of the fine-grained gravity flow and the enrichment of organic matters (Hovikoski et al., 2016; Boulesteix et al., 2019; DeReuil and Birgenheier, 2019; Hussain et al., 2021). Hybrid or transitional gravity flow results from a low-density turbidity current which can transform into a muddy debris flow with increased clay and organic matter content (Haughton et al., 2009; Baas et al., 2009). This muddy debris flow caused by flow transformation is mostly rich in clay matrix and organic matter (Hovikoski et al., 2016; Kvale et al., 2020; Hussain et al., 2021). The organic matter is generally dominated by liptinite kerogen (Fig. 5(b)) (Hovikoski et al., 2016; Boulesteix et al., 2019; Hussain et al., 2021). For example, the H3 division of HEBs and transitional gravity flow deposits widely developed in the Paleogene lacustrine gravity flow deposits in the Honghe Basin, Vietnam (Hovikoski et al., 2016). Those deposits are mainly characterized by rich saprophytic kerogen (Fig. 5(c)) (Hovikoski et al., 2016). HEBs developed in both the Permian in the Delaware Basin, USA, and the Carboniferous in the Northwestern Clare Basin of Ireland are one of the important causes of the enrichment of organic matter (Fig. 5(d)) (Kvale et al., 2020; Hussain et al., 2021).

5. Prospects for research of FGSGFD

5.1. Interaction mechanisms of FGSGFD

The formation mechanisms of FGSGFD are diverse and overlap in temporally and spatially, which will inevitably lead to the mutual interaction of FGSGFD caused by different genetic mechanisms (Piper and Normark, 2009). However, the interaction mechanisms are still unclear (Piper and Normark, 2009; Yang et al., 2020a,b). On the one hand, FGSGFD have variable origin genesis, and deciphering their genesis through sedimentary structures and facies analyses is still uncertain (Boulesteix et al., 2019; Stevenson et al., 2020; Peng, 2021). For example, polished rock samples reveal that FGSGFD of the Chang 7 oil member of the Yanchang Formation in the Ordos Basin is rich in tripartite hybrid event beds (Fig. 6(c), (d)) and transitional flow deposits (Fig. 6(e)) (Niu et al., 2023). The traditionally recognized mudstone rip-up clasts rich sandy debrites (Fig. 6(a)) and normal graded low-density turbidites (Fig. 6(b)) are also developed (Niu et al., 2023). In addition, two types of HEBs were recognized, including mud clasts developed in the upper H3 division of HEBs (Fig. 6(c)) and the absence of mud clasts in the upper H3 division of HEBs (Fig. 6(d)). Two types of banded structures, a feature of the transitional flow deposits, are developed (Fig. 6(e)) (Niu et al., 2023). One of them contains frequent light-dark bands with approximately the same thickness and significant differences in material composition (Fig. 6(e)). The other shows a significant difference of the material composition between the thin bottom layer and the upper layer (Fig. 6(e)). Microscopic observations further reveal that the thin layer of fine-grained sediment gravity-flow sediments has different vertical stacking patterns. There are vertical stacks of low-density turbidite with obvious normal grading (Fig. 6(f)) and vertical stacks of transitional flow deposits with an obvious bipartite structure (Fig. 6(g)). The features mentioned above indicate the complexity and genetic diversity of FGSGFD (Niu et al., 2023). In addition, the fine-grained sediments formed by hypopycnal plume settling have long been regarded as the distal or marginal deposits of the FGSGFD caused by the collapse and re-transportation of the sediments or the continuous flooding rivers (Mutti, 2019). How to effectively distinguish them remains to be studied (Mutti, 2019; Wells and Dorrell, 2021).

On the other hand, in sedimentary environments where FGSGFD caused by different formation mechanisms are common, the interactions between FGSGF of different origins are not clear (Piper and Normark, 2009; Yang et al., 2020a,b). It is unclear that whether the development of hyperpycnal flow will further trigger the failure and re-transportation of sediments (Fig. 7). At the same time, it is controversial that whether FGSGF caused by hyperpycnal flow, or hypopycnal plume settling is only determined by river discharge (Mutti, 2019; Wells and Dorrell, 2021). The interaction between hyperpycnal flow and hypopycnal plume needs to be further studied (Jin et al., 2021; Steel et al., 2018).

5.2. Evolution process of FGSGF with the effect of organic-inorganic synergy

The transportation and evolution of FGSGF represents 'minerals-organic matter-microbes-water' interaction, in which the organic-inorganic (mainly clay minerals) synergy plays a key role in controlling flow properties and evolution (Craig et al., 2020). Microbial organic matter such as extracellular polymer substrates (EPS) plays

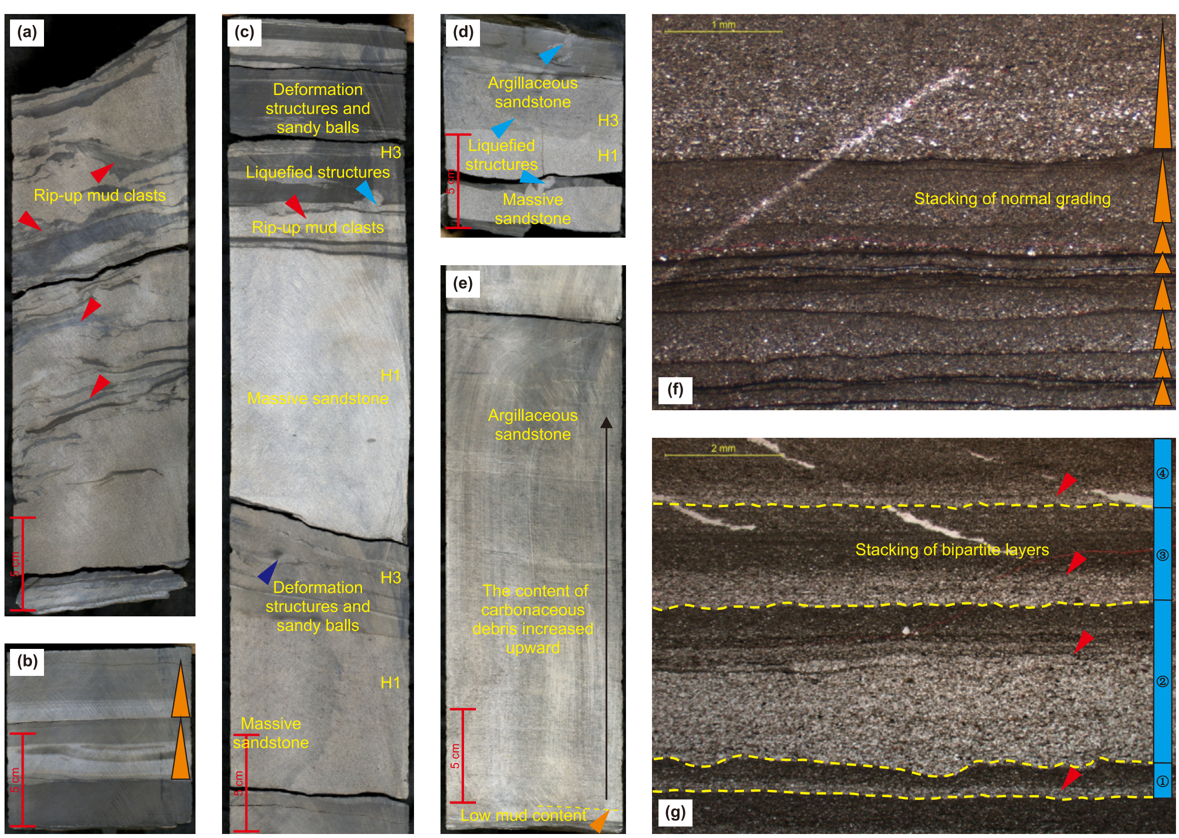

Fig. 6. The characteristics and types of deep-water FGSGFD in the Chang 7 oil member of the Yanchang Formation in Well Cheng 96 in the Ordos Basin (Niu et al., 2023). **(a)** Sandy debrites. **(b)** Low-density turbidites. **(c)** Stacking of hybrid event bed. **(d)** Bipartite structure hybrid event bed. **(e)** Upper transitional plug flow sediment. **(f)** Thin section scale low-density turbidites with vertical stacking of normal grading. **(g)** Thin section scale transitional flow deposits vertical stacking of banded structures.

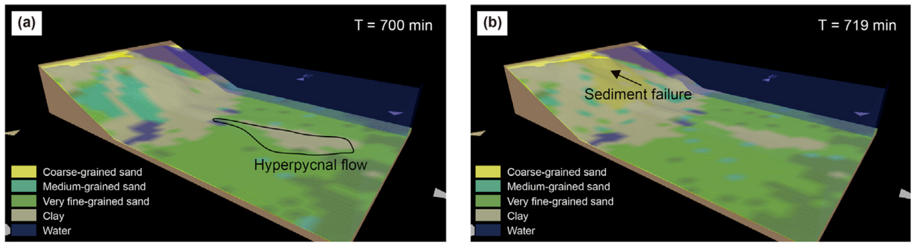

Fig. 7. Numerical simulation according to Sedsim indicated the interaction of gravity flow deposits of multi triggering mechanisms. **(a)** The deposition of hyperpycnal flow show as elongated sandy body in front of delta. **(b)** Delta front collapse after hyperpycnal flow development, which indicated interaction between hyperpycnal flow and gravity flow caused by sediment failure.

an important role in controlling the transportation and evolution of fine-grained sediments (Malarkey et al., 2015; Parsons et al., 2016; Chen et al., 2017a,b; 2018, 2019; Baas et al., 2019; Zeichner et al., 2021). Clay minerals are easily adsorbed into organic matter to form organo-clay complexes (Wang and Wan, 1993; Cai et al., 2007; Dong et al., 2009; Blattmann et al., 2019; Zeichner et al., 2021). Thus, the electrochemical properties of clay minerals and organic matter are changed, controlling the flow types and evolution process of FGSGF during the transportation (Blattmann et al., 2019; Zeichner et al., 2021). Several scholars have considered the comprehensive influence of the type and content of clay minerals and the organic matters on the evolution of FGSGFD while transportation (Baker et al., 2017; Baas et al., 2019; Craig et al., 2020). However, the organo-clay complex caused by the adsorption of organic matter into clay minerals is not a simple mechanical mixing of organic matter and clay minerals (Zeichner et al., 2021). The properties of organo-clay complexes formed by the organic-inorganic synergy of different clay minerals and organic matter are significantly different (Blattmann et al., 2019) (Fig. 8). Therefore, the evolution process of FGSGF during transportation under the control of organo-clay complexes needs to be studied systematically. At the same time, the development of organo-clay complexes also significantly contributes to the enrichment of organic matter in FGSGFD. This mechanism is of great significance in deepening our understanding of global carbon burial and cycling processes (Craig et al., 2020).

Fine-grained sediment gravity-flow deposits have typical characteristics, such as fine-grained detrital particle size, abundant clay minerals, enrichment of organic matter, and strong microbial influence (Zhang et al., 2016; Zhang et al., 2017; Liu et al., 2018a,b; Zou et al., 2019; Cai et al., 2019). Taking FGSGFD of the Chang 7 oil member of the Ordos Basin as an example, the organic matter is enriched, and the TOC is generally 6%–14% (Yuan et al., 2015). At the same time, volcanic ash hydrolyzes after deposition to form a large number of clay minerals, with an average content of more than 50% (Yuan et al., 2015). These clay minerals are dominated by illite and smectite mixed layer and illite (Yuan et al., 2015), which are favorable for the extensive development of organo-clay complexes because attractive van der Waals forces (Talling et al., 2012; Baas et al., 2016b; Baker et al., 2017). However, the transportation and evolution of FGSGF under the influence of organo-clay complexes formed through the interaction of various clay mineral with sedimentary or microbial organic matter remain unexplored (Malarkey et al., 2015; Zhang et al., 2016; Baas et al., 2016a, 2019; Hovikoski et al., 2016; Cai et al., 2019). In addition, the types and contents of both clay minerals and organic matters in ancient sedimentary rocks may change due to burial diagenesis (Yuan et al., 2015). Therefore, based on the analyses of sedimentary rocks, some important information may be missing for understanding the FGSGF transport and evolution under the control of organo-clay complexes. A combination of case study and flume tank experiment analysis may be an effective method to solve this problem (Baas et al., 2019; Craig et al., 2020).

5.3. The controlling factors of the distribution pattern of FGSGFD

The combination of multiple triggering mechanisms promotes the widespread development of FGSGFD, without temporal and

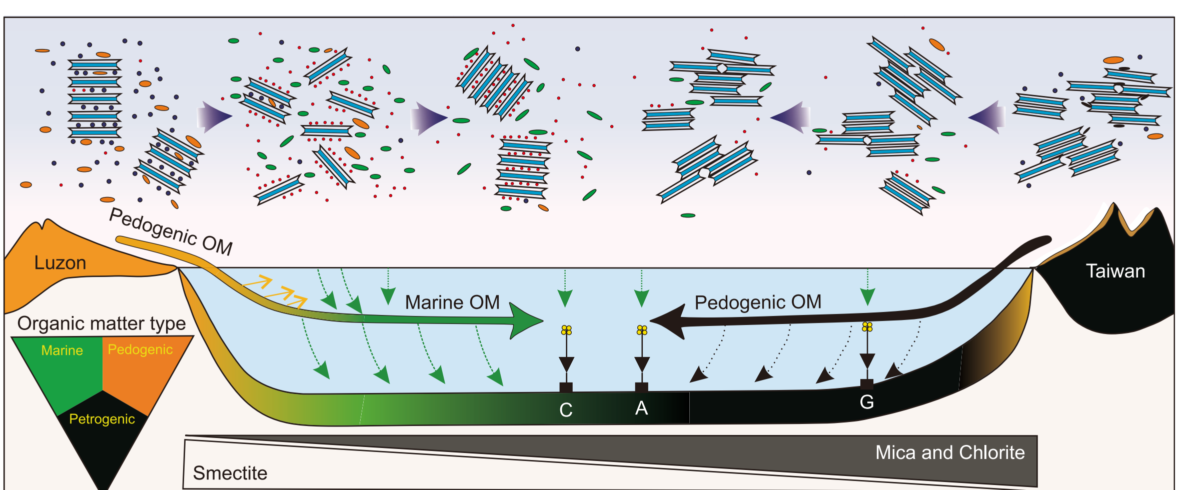

Fig. 8. The transportation process of organo-clay complexes in the river-ocean system (Blattmann et al., 2019).

spatial limitation (Piper and Normark, 2009; Hage et al., 2019). That means the formation of FGSGFD is not limited by a specific time (specific triggering mechanisms) (Hizzett et al., 2018; Mutti, 2019; Hage et al., 2019; Davarpanah Jazi and Wells, 2020; Wells and Dorrell, 2021). Meanwhile, FGSGFD is common in both shallow- and deep-water conditions (Dou et al., 2021; Hizzett et al., 2018). However, the autogenic or allogenic factors controlling the distribution of FGSGFD of different formation mechanisms need further study (Fig. 9). Specifically, how allogenic factors such as the type and intensity of sediment supply, climate, tectonic activity, and the fluctuation of sea (lake) level, control the formation distribution of FGSGFD is unclear (Yang et al., 2019). In addition, how autogenic factors such as slope, the topography of basin floor, and ambient water properties control the formation and distribution of FGSGFD need more evaluation (Boulesteix et al., 2019) (Fig. 9). For example, it is unclear whether FGSGFD caused by sediment failure and hyperpycnal flow is more common in the background of low-stand systems tract with sufficient sediment supply, humid climate, and strong tectonic activities (Boulesteix et al., 2019). On the contrary, whether FGSGFD caused by wave-enhanced gravity flow and hypopycnal plume settling is more developed in the background of highstand system tract with insufficient sediment supply, dry climate, and weak tectonic activities (Boulesteix et al., 2019). In addition, a more systematic investigation is needed to understand how FGSGFD with diverse formation mechanisms and distribution patterns reflect the evolution of source-to-sink systems and the influence of relatively long-scale astronomical cycles (Tian et al., 2021) (Fig. 9).

In particular, whether different types and contents of clay minerals and organic matter are the main reasons or not for the formation and distribution variation of hybrid event beds and transitional gravity flow deposits in different regions remains to be further studied (Kvale et al., 2020; Emmings et al., 2020; Stevenson et al., 2020; Hussain et al., 2021). At the same time, different types of organo-clay complexes play distinct roles in the effective preservation of organic matter during burial (Kennedy et al., 2002, 2014; Blattmann et al., 2019; Hussain et al., 2021; Hussain and Al-Ramadan, 2022). Therefore, whether the types and contents of organo-clay complexes predominantly contribute to the disparate enrichment of organic matter in FGSGFD, consequently governing their distribution, necessitates systematic exploration.

Moreover, FGSGFD in marine and lacustrine basins may have their special characteristics because of different depositional environments (Yang et al., 2020a,b). It is believed that muddy hyperpycnites are more common in lacustrine basins than in marine basins because only small particle concentrations are necessary for plunging in lacustrine basins (Mulder et al., 2003; Mulder and Chapron, 2011). The hypopycnal plume is easy to transformed into hyperpycnal flow in lacustrine basins as settling-driven convection is more common in lakes than in the ocean (Davarpanah Jazi and Wells, 2020). On the contrary, wave-enhanced gravity flow deposits are common in marine basins with wide continental shelves (Macquaker et al., 2010). It is not clear whether wave-enhanced gravity flow deposits are also developed in lacustrine basins. As for hybrid event beds and transitional gravity flow deposits, case studies indicate they are developed in both marine and lacustrine basins (Haughton et al., 2009; Hovikoski et al., 2016). However, there are only a few examples in lacustrine basins, and more case studies are needed to reveal the differences of hybrid event beds and transitional gravity flow deposits in marine and lacustrine basins (Dodd et al., 2022).

6. Unconventional shale oil and gas significances of FGSGFD

6.1. Origin of thin-bedded siltstones within shales

Thin-bedded siltstones within shale are favourite place for shale oil and gas accumulation (Yuan et al., 2015; Hovikoski et al., 2016; Kvale et al., 2020; Peng, 2021; Peng et al., 2022). Most of those thin-bedded siltstones are FGSGFD (Hovikoski et al., 2016; Kvale et al., 2020; Peng, 2021). Taking the shale oil of Chang 73 oil member of the Yanchang Formation in the Ordos Basin as example, these shale oil are mainly composed of organic-rich shale intercalated with thin-bedded siltstones (Yuan et al., 2015; Xi et al., 2020). The development of thin-bedded siltstones has a very obvious controlling effect on the enrichment of shale oil and gas (Yuan et al., 2015; Xi et al., 2020). Therefore, many researches have been done on the formation mechanisms of thin-bedded siltstones (Yuan et al., 2015). Early studies proposed that thin-bedded siltstones are deposited by turbidity currents (Yang et al., 2014). Subsequently, numerous researchers indicated that thin-bedded siltstones are primarily dominated by sandy debrites with a minor presence of low-density turbidites (Wang et al., 2020; Yu et al., 2021). A consensus has been reached that those thin-bedded siltstones belong to FGSGFD (Yang et al., 2014; Lv et al., 2017, 2018). Current researches indicated that hyperpycnal flow, hybrid gravity-

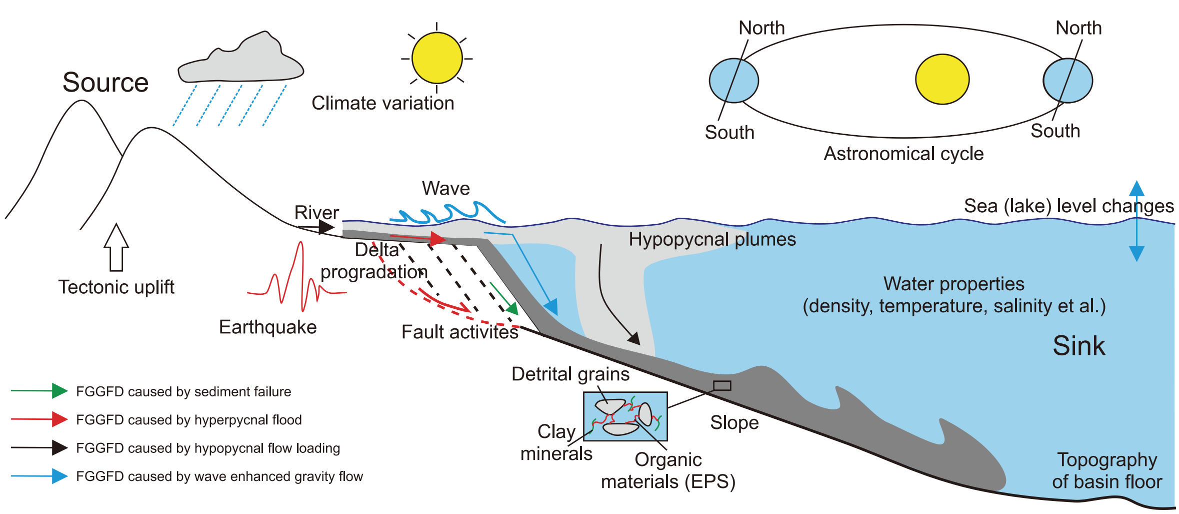

Fig. 9. Comprehensive controlling factors of FGSGFD distribution.

flow, and the transitional gravity flow may have played a more obvious controlling role in the accumulation of thin-bedded siltstones interbedded with shale in deep-water systems (Hovikoski et al., 2016; Boulesteix et al., 2019; Wells and Dorrell, 2021; Yang et al., 2021; Peng et al., 2022). Hyperpycnal flow is controlled by lateral flow replenishment and floating accumulation, which may be an important dynamic mechanism explaining the long-distance transportation of these fine-grained sediments (Zavala and Arcuri, 2016; Steel et al., 2016; Peng et al., 2022). During the transportation of fine-grained sediments by gravity-flows, the increase of mud and organic content in the fluid caused by the interaction between fluid and a muddy substrate could be the reason for flow transformation to hybrid, or transitional gravity flows (Hovikoski et al., 2016; Boulesteix et al., 2019). This flow transformation may be one of the important reasons for deposits dominated by thin-bedded siltstones interbedded with shales (Baas et al., 2019; Craig et al., 2020; Baker and Baas, 2020; Peng, 2021).

6.2. Expand shale oil and gas exploration scopes relatively

Thin-bedded siltstones interbedded with shales formed by gravity-flow transformation in deep-water basins are potential areas for developing sweet spots of shale oil and gas (Yang et al., 2017b, 2019, 2020; Kvale et al., 2020; Peng, 2021). The development of clay and organic matter is the main factor that promotes the transformation of gravity flow. The resultant hybrid event beds or transitional flow deposits are features by bipartite structure of silty sediments in the lower part and muddy sediments in the upper part (Fig. 6(g)). Those thin-bedded siltstone and shale interbedding successions are richer in organic materials than pure low-density turbidities (Hovikoski et al., 2016; Craig et al., 2020; Peng, 2021), such as research work in Upper Pennsylvanian organic-rich Cline Shale by Peng (2021) indicated that massive to ripple cross-laminated sandy mudrocks caused by low-density turbidity currents with average TOC of 0.6 wt%, while planar laminated argillaceous fine mudrocks may cause by flow transformation with average TOC of 4.97 wt%. As a result, the upper muddy sediments are enriched in clay and organic matter, providing a material basis for generating oil and gas (Hovikoski et al., 2016; Peng, 2021). Furthermore, the lower silty deposits are adjacent to the upper muddy deposits, providing potential storage space for the oil and gas generated on the upper part (Fig. 6(g)). At the same time, those thin-bedded siltstone and shale interbeddings are easier to break up than pure muddy deposits, which is benefit for fracture and development (Yang et al., 2019; Emmings et al., 2020). Stable flow transformation may form thin-bedded siltstone and shale interbedding with a cumulative thickness of tens of meters to hundreds of meters (Lowe and Guy, 2000; Hovikoski et al., 2016). These sediments may be the dominant sedimentary lithofacies of 'sweet spot' developed in shale oil and gas (Hovikoski et al., 2016; Kvale et al., 2020; Emmings et al., 2020; Stevenson et al., 2020; Hussain et al., 2021; Peng, 2021). The relationship between flow transformation deposits and shale oil and gas enrichment needs further research works. This study may shed new light on fine-grained shale oil and gas exploration and development.

7. Conclusions

(1) FGSGFD of different formation mechanisms have their special sedimentary characteristics. Low-density turbidites are featured by normal grading; muddy debrites are dominated by clasts rich massive mudstone; wave-enhanced gravity flow deposits have a typical tripartite beds; low-density muddy hyperpycnites are common in inverse then normal grading and carbonaceous clasts; hypopycnal plume deposits have finger-like features and cloudy structures; hybrid event beds have typical bipartite beds; transitional gravity flow deposits are characterized by large current ripples and low-amplitude bed-waves.

(2) Sediment failure triggered gravity flow, wave-enhanced gravity flow, low-density muddy hyperpycnal flow, and hypopycnal plumes can all form widely distributed FGSGFD. Clay minerals, organic matter, and organo-clay complexes of different types and contents are the main controlling factors for the transformation of low-concentration turbidity current into high-concentration muddy debris flow in FGSGF. It is also the reason for the formation of transitional gravity-flow and hybrid gravity-flow deposits.

(3) The interaction mechanism of FGSGF caused by different initiations, the evolution of FGSGF with the effect of organic-inorganic synergy, and the controlling factors of the distribution patterns of FGSGFD need to be further studied.

(4) The study of FGSGFD can shed some new light on reasonably explaining the formation of widely developed thin-bedded siltstones in shale and expanding the exploration scope of shale oil and gas. It has important significance of shale oil and gas exploration and development.

CRediT authorship contribution statement

Tian Yang: Conceptualization, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Ying-Lin Liu:** Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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