Deepwater Turbidite Lobe Deposits: A Review of the Research Frontiers

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Abstract: Deepwater/deep-marine turbidite lobes are the most distal part of a siliciclastic depositional system and hold the largest sediment accumulation on the seafloor. As many giant hydrocarbon provinces have been discovered within deepwater lobe deposits, they represent one of the most promising exploration targets for hydrocarbon industry. Deepwater exploration is characterized by high cost, high risk but insufficient data because of the deep/ultra–deepwater depth. A thorough understanding of the deepwater turbidite lobe architecture, hierarchy, stacking pattern and internal facies distribution is thus vital. Recently, detailed outcrop characterizations and high–resolution seismic studies have both revealed that the deepwater lobe deposits are characterized into four–fold hierarchical arrangements from “beds”, to “lobe elements”, to “lobes” and to “lobe complex”. Quantitative compilations have shown that hierarchical components of lobe deposits have similar length to width ratios but different width to thickness ratios depending on different turbidite systems. At all hierarchical scales, sand–prone hierarchical lobe units are always separated by mud–prone bounding units except when the bounding units are eroded by their overlying lobe units thus giving rise to vertical amalgamation and connectivity. Amalgamations often occur at more proximal regions suggesting high flow energy. A mixed flow behavior may occur towards more distal regions, resulting in deposition of “hybrid event beds”. These synthesized findings could (1) help understand the lobe reservoir distribution and compartmentalization therefore benefit the exploration and development of turbidite lobes within the deep marine basins (e.g. South China Sea) and (2) provide rules and quantitative constraints on reservoir modeling. In addition, the findings associated with deepwater turbidite lobes might be a good starting point to understand the sedimentology, architecture and hierarchy of turbidites in deep lacustrine environment.

Key words: deepwater, turbidite lobes, architecture, hierarchy, quantitative characterization, hybrid event beds

1 Introduction

Since the pioneering study on turbidite currents by Kuenen and Migliorini (1950), research on deepwater turbidite currents and their resulting deposits (i.e. turbidites) has continued up to date. Turbidity current is considered as a non-cohesive Newtonian fluid and characterized by its incremental (layer-by-layer) depositional manner, distinguishing itself from the cohesive debris flow which is characterized by en masse (freezes) settling and other types of deepwater gravity flows (Mutti and Normark,1991; Mulder and Alexander, 2001; Haughton et al., 2009; Talling et al., 2012). The concept of “turbidites” was firstly used by Kuenen (1957) to represent the deposits generated by turbidity current. Kuenen’ student Bouma studied the Annot Sandstone outcrops of France in detail and proposed a conceptual vertical facies model of turbidites, which has become the standard turbidite model known as the “Bouma sequence” (Bouma, 1962). However, it has been recognized that not every deepwater sedimentary cycle has the fabric of Bouma sequence, leading to various controversies concerning the deepwater sedimentary processes and classifications (e.g. Shannugam, 2000, 2002; Talling et al., 2012). The development history of deepwater turbidite research has been compiled by Bouma (2000), Stow and Johansson (2000), Stow and Mayall (2000), Shannugam (2000), Mutti et al. (2009), Mulder and Etienne (2010), Mulder et al. (2011) and Talling et al. (2012), thus it is not discussed in detail herein.
Deepwater turbidite lobe deposits represent the most distal part of a siliciclastic depositional system (Mulder and Etienne, 2010). They are currently a major focus of academic research since they represent the largest sediment accumulation on the seafloor and hold a wealth of proxy information associated with past climate, eustatic and tectonic forcing (e.g. Bouma, 2004; Covault and Graham, 2010). Meanwhile, with great lateral continuity and high sand volume, deepwater lobe reservoirs have become the most promising target for oil and gas exploration over the past decade, and large volumes of hydrocarbons accumulated within deepwater lobes have been discovered worldwide (e.g. Gulf of Mexico, North Sea, offshore Brazil and Southeast Asia).

The term “lobe” was firstly used by Normark (1970) to describe a series of sedimentary bodies which generally have ovoid morphologies and convex–up topographies within the modern Navy and San–Lucas turbidite fans. The term “fan” is to represent a deepwater depositional system (modern and/or ancient) consisting of deposits resulting from various gravity flows but primarily turbidity currents. “Lobes” could be mixed with “fans” because they are both used to describe similar plan–form geometry (lobe–like, fan–like), causing ambiguous terms such as “fan lobe” (Bouma et al., 1985; Shanmugam and Moiola, 1991). In the current paper, “lobes” are those sedimentary bodies which are located at the most distal part of a given deepwater turbidite system. They generally display lobate shapes in plan–view and are commonly deposited at low topographic reliefs.

The deep water depth under which the turbidite lobes often lie has impeded the development of research on them and, at least in part, been responsible for the associated controversies (Normark et al., 1993). Despite the recent development of geophysical technologies (e.g. multi-beam sounders and side–scan sonar), to obtain useful information (e.g. continuous cores, seismic data) effectively characterizing the deepwater depositional systems is still difficult and expensive. Thus, the deepwater turbidite lobes are still insufficiently studied, whilst the need to explore the hydrocarbon resources in deepwater is rapidly increasing. The aims of this paper, as with the need to explore the hydrocarbon resources in deepwater turbidite lobes are still insufficiently studied, whereas deepwater fan down–dip the channel systems. They generally show lobate geometries in plan–view and are commonly deposited at low topographic reliefs.

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2 Architecture and Hierarchy

As with fluvial systems (Allen et al., 1983; Miall, 1985), the architectural–element approach has been applied to deepwater fan systems to represent a particular suite of processes/elements that share similar sedimentary characteristics (e.g. external and internal geometry, bounding surfaces and facies association), such that they can be recognized and mapped in most deepwater fan systems (Mutti and Normark, 1987; Mutti and Normark, 1991; Chapin et al., 1994; Clark and Pickering, 1996; Sullivan et al., 2000; Posamentier and Kolla, 2003; Pyles, 2007; Lin Yu et al., 2014). Due to different scales of observations and methodologies used in these studies, different classifications of deepwater architectural elements and corresponding terminologies exist. Despite that, main architectural elements within deepwater fan systems include canyons, channels, lobes, levees and overbank areas, slumps and marine shales (e.g. Normark et al., 1993; Posamentier and Kolla, 2003). Each element may occur at a range of scales and within a hierarchy of similar features. Channels and lobes are the two architectural elements where most sand–prone deposits can accumulate, and are therefore the most promising targets for hydrocarbon exploration (e.g. Mayall et al., 2006; Saller et al., 2008). Considerable efforts have been made to study deepwater channels during the last decade for their excellent reservoir potentials (e.g. Mayall et al., 2006; Fildani et al., 2013; Xiao Bin et al., 2014), whereas deepwater lobes that have larger sand volumes remain less understood.

2.1 Architectural and morphological characteristics

In existing deepwater fan depositional models (Normark, 1970; Walker, 1978; Reading and Richards, 1994; Richards et al., 1998; Saller et al., 2008; Prelat et al., 2009), lobes generally occur in the most distal part of a given deepwater fan down–dip the channel systems. They generally show lobate geometries in plan–view and overall convex–up morphologies with flat bases in vertical profile, in contrast to turbidite channels which display sinuous, ribbon–like geometries in plan–form and overall concave morphologies with irregular/erosional bases in vertical profile. In addition, turbidite lobes have much higher width to thickness ratios than turbidite channels, providing another direct basis for differentiating these two deepwater architectural elements. Note that deposits with similar characteristics (but different terminologies) may occur within the deepwater slope depositional model as proposed by Shanmugam (2000), although this model is interpreted to be debris flow-dominated.

Lobes represent the largest deposition of sands within a
Reading and Richards (1994) and Richards et al. (1998) have proposed the stratigraphic architecture of lobes with respect to the entire deepwater fan systems and distinguished their vast differences when the source systems (i.e. point source fans, multiple source ramps, linear source slope aprons) and grain size of sediments (i.e. gravel–rich, sand–rich, sand/mud–rich, mud–rich) vary.

As the development of high–resolution 3D seismic surveying technologies (e.g. Saller et al., 2008) and subsurface imaging (e.g. Jegou et al., 2008), recent work has further revealed the variability and complexity of deepwater fan system. Morphologically, the terminal lobes have various interaction patterns with the up–dip channel systems. Two morphological end–members of lobes are recorded (Mulder and Etienne, 2010): lobes occurring directly down–dip channels and lobes occurring down–dip a transitional zone which lies at the end of channels. In large mud–rich deepwater fan systems along passive margins, lobes occur at the end of the upstream feeder canyon or channel–levee systems (e.g. Twichell et al., 1992; Posamentier and Walker, 2006). In contrast, in smaller sand–rich deepwater turbidite systems (e.g. the Valencia Fan and Laurentian Fan), a transitional zone named “Channel Lobe Transition Zones” (CLTZ) exists between the up–dip canyon/channels and the down–dip lobes (Mutti and Normark, 1991; Wynn et al., 2002; Hofstra et al., 2015). This CLTZ is characterized by a bypass/erosion area (“detached lobes of high efficiency systems” of Mutti, 1992) dominated by erosional features such as furrows, scours and sand waves. Irrespective of the interactions with up–dip systems, deepwater lobes start to develop at a certain point (e.g. breach of channel mouth) and spread down flow.

2.2 Stratigraphic hierarchy
Previous studies described lobes as homogeneous sheet–like systems which gradually become thinner and mudrier distally (e.g. Mutti and Normark, 1991). Yet recent work on deepwater lobe deposits using side scan sonar and high–resolution seismic data (Gervais et al., 2006; Deptuck et al., 2008; Saller et al., 2008), and detailed outcrop characterizations (Prelat et al., 2009; Zhang et al., 2013; Grundvag et al., 2014) have all concluded that lobe deposits are structured into a hierarchical manner (Fig. 1a). For example, using 3D seismic datasets, Deptuck et al. (2008) recognized four hierarchical levels of compensational stacking, with “beds” stacking to form “lobe elements”, “lobe elements” stacking to form “composite lobes” and “composite lobes” stacking to form “lobe complexes”. Such hierarchical subdivisions were primarily based on the abruptness of the shift between the thickest parts of successive bodies, and secondarily on the basis of bounding discontinuities and the amount of drapes between depositional bodies. Outcrop studies generally allow high–resolution vertical observations and the definitions of the hierarchy derived from outcrop studies are commonly based on fine–grained bounding units separating depositional bodies. Prelat et al. (2009), for example, have recognized a four–fold hierarchy (Fig. 1b) from “bed” to “lobe element” to “lobe” to “lobe complex” for the deepwater lobe deposits in Tanqua Karoo Basin, South Africa, based on the characteristics and geometry of fine–grained bounding units (e.g. “inter–lobes”). In these studies, and the current work as well, lobe complexes represent the highest hierarchical blocks and they can be equivalent to “fans” in some cases (e.g. Prelat et al., 2009). However, “fans” and “turbidite systems” are more likely used to describe the deepwater “source–to–sink” system (e.g. Somme et al., 2009) and therefore should be hierarchically higher than “lobe complexes”.

2.2.1 Bed
The fundamental and smallest building block in a deepwater turbidite system is “bed” (sandstone bed), representing a single depositional event. Sandstone beds in deepwater systems have thickness ranging from 0.02m to 3.5 m (e.g. Zhang et al., 2015), and can extend 0.2 km to 2 km long and wide (e.g. Grundvag et al., 2014). Beds within deepwater lobes are characterized by stacking of massive (0.5–3 m thick), amalgamated, structureless sandstone beds (e.g. the top part of Fig. 2a) at proximal to medial lobe region and thin (0.02–0.5 m thick), less/non–amalgamated, ripple–laminated to parallel–laminated sandstone beds interbedded with mudstone beds at more distal region. In deepwater turbidite lobes, beds are often organized into “thickening–upward cycles” (Fig. 2a) on vertical profile (e.g. Mutti and Sommino, 1981; Pickering et al., 1989; Macdonald et al., 2012: Zhang et al., 2013; Grundvag et al., 2014). An important feature of beds in deepwater turbidite lobes is the sand amalgamation (Fig. 2b). In terms of reservoir potential and connectivity, sand amalgamation represents a scenario that overlying permeable sandstones erode impermeable shale baffles and barriers away thus connect to the otherwise separated underlying sandstones. Therefore, high degree of sandstone bed amalgamation generally implies high reservoir connectivity. This issue will be discussed in
Fig. 1. Deepwater lobe hierarchical scheme.
(a), Cartoon showing the four–fold hierarchy for lobe complexes, modified from Prelat et al. (2010). Note that the relative scale and the number of objects at the different hierarchical levels are highly variable. No scales are inferred; (b), Schematic log showing the vertical stacking of hierarchical elements, modified from Prelat et al. (2009).

Fig. 2. Outcrop photos of turbidite lobe deposits.
(a), One typical thickening–upward package of the Ross Sandstone, Western Ireland (modified from Macdonald et al., 2012); (b), Turbidite successions in Mt. Messenger Formation, Taranaki Basin, New Zealand where the sandstone beds (grey) erode mudstones (pale) away and show obvious amalgamations as highlighted by red arrow (modified from Manzocchi et al., 2007).
detail in later part of this paper.

2.2.2 Lobe element

One or several genetically related beds/bed–sets stack to form a “lobe element”. Lobe elements generally have lobate plan–geometry (Fig. 3a). A compilation of global lobe elements shows that the average length, width and thickness of lobe elements are 2km, 1.3km and 3m respectively (Zhang et al., 2015). Vertically, beds in a lobe element often display a thickening–upward trend (Fig. 2a, Fig. 3b) at certain locations (mainly proximal–medial lobe regions), making it an important criterion to interpret lobe element deposition. Detailed outcrop studies (e.g. Prelat et al., 2009; Zhang et al., 2013) have revealed that, if not amalgamated, lobe elements are separated by laterally extensive (at least at the scale of lobe element dimension), thin siltstones and/or shale units which are named “inter–lobe element” herein. Like the shales eroded by sandstone beds, these inter–lobe elements can be locally eroded away causing lobe element amalgamation, but such lobe element amalgamations are less frequently observed than bed amalgamations (Prelat et al., 2009; Straub and Pyles, 2012; Zhang et al., 2013; Grundvag et al., 2014). Generation and stacking of lobe elements are interpreted to be controlled by autogenic factors. For example, Deptuck et al. (2008) have ascribed the position shifts of lobe elements to the change in distributary channel–mouth position because of small–scale avulsions or channel migrations.

2.2.3 Lobe

One or several genetically related lobe elements stack to form a “lobe”. Early outcrop studies (e.g. Mutti and Normark, 1987) described deepwater turbidite lobes as sand–prone deposits including generally tabular, non–channelized bodies from 3 to 15m thick. Recent quantitative compilation of over 200 deepwater lobes from 23 different deepwater systems (Zhang et al., 2015), however, has demonstrated that the average lobe length, width and thickness is 12km, 4.8km and 10m respectively. Lobes are bounded by particular fine–grained units named “inter–lobes” (Fig. 1b; Fig. 4b), which can maintain their lithofacies and thickness for a long distance (possibly the entire lobe scale or even longer) and are often used as marking beds for correlation of outcrop sections. Local amalgamations of inter–lobes can also occur (e.g. Fig. 4b), but are probably less frequent than the lobe element amalgamations (Zhang et al., 2013; 2015).

The internal architectural and hierarchical characteristics of lobes are intensively studied, however, to understand what factors controlling the lobe development and the stacking patterns remains a research frontier. Detailed mapping of lobes in the Tanqua Karoo Basin, South Africa suggests the development of lobes within a lobe complex corresponds well to allogenic factors such as relative sea level change (e.g. Hodgson et al., 2006). Yet another interpretation (e.g. Deptuck et al., 2008; Prelat et al., 2009, 2010; Zhang et al., 2013; Grundvag et al., 2014) tends to relate the deposition of lobes to autogenic avulsion of the feeder channels. The mechanism and stacking pattern of lobes will be discussed in the following section of this paper.

2.2.4 Lobe complex

One or several lobes stack to form a “lobe complex” (Fig. 4a, 4b). A “lobe complex” is the highest building block in the current work, with average length, width and thickness of 52 km, 20 km and 47.5 m (Zhang et al., 2015). Lobe complexes are bounded by pelagic/ hemipelagic shales several meters to tens of meters thick implying long sedimentation hiatus. In the sequence stratigraphic perspective, these thick pelagic/hemipelagic shales are condensed sections and each lobe complex may represent a fourth–order sequence (e.g. Booth et al., 2003; Pyles, 2008; Zhang et al., 2013).

Deepwater lobe deposits are structured into a four–fold hierarchy including lobe complex, lobe, lobe element and bed (Fig. 1; Fig. 4b). At each hierarchical scale, sand–prone lobe components are always separated by their particular mud–prone bounding units (e.g. lobes separated by inter–lobes, Fig. 4b). From thin shale bed representing short hiatus between a single rapid depositional event to thick inter–lobe complex representing long episodes of fan shutdown, each of these mud–prone bounding units has unique dimension and duration, which in fact is the key to correctly interpret the entire lobe hierarchy. For example, detailed bed–to–bed correlation of the deepwater turbidite lobe successions in the Ross Sandstone, western Ireland suggests that, although the system is very sand–rich with Net–to–Gross ratio (NTG) about 80% and sand bodies have great lateral continuity and connectivity, the key to understand reservoir performance and internal heterogeneities is the distributions of fine–grained units which work as baffles and barriers due to their impermeable nature (Martinsen et al., 2008; Zhang et al., 2013). However, when it comes to real exploration of deepwater turbidite lobe reservoirs, these important muddy units are too thin (except some inter–lobe complexes) to be captured by seismic data. To date, detailed outcrop characterizations appear the only way to quantitatively study these fine–grained bounding units. Therefore, more detailed outcrop studies on deepwater turbidite lobes are hereby suggested to further the understandings of this issue.
In summary, as an important architectural element of deepwater turbidite fan, deepwater turbidite lobe is structured into hierarchical architectures leading to unique hierarchical stacking pattern of sand bodies. To understand the detailed hierarchical arrangements is the key to predict reservoir compartmentalization and thus reservoir performances. Benefited from the fast–growing technologies such as high–resolution seismic and side–scan sonar, studies on deepwater turbidite lobes have evolved magnificently over the past decade. Recent research frontiers concerning deepwater turbidite lobes include more detailed/quantitative studies on lobe

Fig. 3. Examples of lobe elements.
(a), Seismic slice showing six lobe elements within a lobe in Kutai Basin, offshore Indonesia in plan–view (modified from Saller et al., 2008); (b), Outcrop photo showing two lobe elements vertically stack in a lobe of the Ross Sandstone, Western Ireland (modified from Pyles et al., 2014). Note the vertical thickening upward trend.

Fig. 4. Examples showing stacking pattern of different lobe hierarchical objects.
(a), Plan–view map showing eighteen lobes (A–N) within a Pleistocene lobe complex in Kutai Basin with lobe A being the oldest and lobe R being the youngest (modified from Saller et al., 2008); (b), Schematic cartoon showing vertical stacking of four lobes within a lobe complex in Central Spitsbergen, Norway, note the lobe amalgamation and the extent of fine-grained bounding units (modified from Grundvag et al., 2014).
sedimentology; turbidite deposition process; the more distal, heterogeneous facies of lobe deposits resulting from hybrid flows and better characterization of their reservoir connectivity using novel numerical modeling methods.

3 Research Frontiers

3.1 Quantitative characterizations

A notable research trend regarding deepwater turbidites is the change from qualitative description to quantitative characterization. Deepwater channels, for example, have been intensively studied in a quantitative fashion in order to better predict the channel reservoir compartmentalization (e.g. Clark and Pickering, 1996; Mayall et al., 2006) and constrain numerical modeling (e.g. McHargue et al., 2011). Only recently geologists started to quantitatively characterize deepwater lobes, in specific, the dimensions and geometries of hierarchical objects and their amalgamations.

3.1.1 Dimension and geometry

The dimensions and geometries of deepwater lobe reservoirs in the Golo basin, offshore Corsica (Gervais et al., 2006; Deptuck et al., 2008) and the Kutai basin, offshore Indonesia (e.g. Saller et al., 2008) are well measured and documented. Such quantitative documentations can greatly help constrain predictions of reservoir distribution (e.g. well correlations) and provide input parameters for numerical modeling work.

Prelat et al. (2010) have systematically compared lobes from six different deepwater systems. Focusing on the lobe scale, their analysis shows that lobes can be grouped into two categories: one has thicker but smaller lobes (“confined”) and the other has thinner but larger lobes (“unconfined”), reflecting the influence of the local topography. In addition, they have revealed that lobe volumes lie within a very close range irrespective of their grain size and source system, thus hypothesized that there might be an autogenic factor forcing lobe deposition to terminate at a certain point. Later, Zhang et al. (2013; 2015) compiled the dimensional and geometric characteristics of deepwater turbidite lobes over 23 deepwater systems at bed, lobe element, lobe and lobe complex scales. Their results have demonstrated that the shapes of lobe units are very similar at each hierarchical scale. The average length to width ratio of lobe elements, lobes and lobe complexes are all about 2:1 (Fig. 5a), yet hierarchically higher elements have dimensions a magnitude larger. In addition, hierarchical objects in a particular deepwater system are likely to lie on a very close width to thickness ratio trend (Fig. 5b), suggesting the depositional mechanisms of lobe elements, lobes and lobe complexes are somehow similar, hierarchically smaller objects might be just smaller versions of hierarchically larger objects.

3.1.2 Amalgamations

The phenomenon of sand beds amalgamated to form composite beds has been frequently observed in many deepwater turbidite systems (both channels and lobes). A well-known example is the widely studied Kilclogher Cliff section of the Ross Sandstone in western Ireland, which shows “amalgamated sheet sandstone” overlying “layered sheet sandstone” (e.g. Chapin et al., 1994; Sullivan et al., 2000). In most cases, this sand–on–sand amalgamation was described in a qualitative manner, such as “highly amalgamated, moderately/amalgamated, layered (indicating no amalgamation)” (e.g. Elliott, 2000; Hodgson et al., 2006; McHargue et al., 2011). However, an increasing number of studies have reported the

Fig. 5. Quantitative characterization of different lobe hierarchical objects.

(a), Global compilation of length and width data for lobe element, lobe, lobe complex and fan. Data of fans are from Somme et al. (2009). 1:1 length to width ratio is highlighted as red dashed line; (b), Width to thickness data for lobe element, lobe, lobe complex in Kutai Basin, Karoo Basin and Ross Sandstone respectively. Both plots are modified from Zhang et al. (2015).
amalgamations within deepwater turbidite deposits in a quantitative manner (Chapin et al., 1994; Stephen et al., 2001; Mattern, 2002; Manzocchi et al., 2007; Romans et al., 2009; Zhang et al., 2013, 2015). Chapin et al. (1994) firstly quantified the degree of sand amalgamation by defining a term amalgamation ratio as the fraction of sand-on-sand contacts relative to the entire bed contacts when examined on a 1D vertical profile. Stephen et al. (2001) applied this definition to 2D numerical modeling and demonstrated that the amalgamation ratio has logarithmic and linear relationships with the single-phase upscaled ratio of horizontal to vertical permeability and the fraction of mobile oil recovered respectively. Manzocchi et al. (2007) expanded the definition of amalgamation ratio as the fractional lengths of amalgamation surfaces with respect to the entire bed lengths. They compiled the Net-to-Gross ratio (NTG) vs amalgamation ratio of different turbidite successions, suggesting that different lobe depositional environments can be characterized by different relationships of NTG and amalgamation ratio. Further, they used both NTG and amalgamation ratio as inputs to a novel object-based modeling approach and they proposed that the amalgamation ratio rather than the NTG, is the most vital control on reservoir connectivity. Later, Zhang et al. (2013; 2015) suggested that the amalgamation ratio should be studied in a hierarchical manner and used new data to reveal that the amalgamation ratio increases as the lobe hierarchical level decreases (Fig. 6). Using this finding as a key constraint, their novel object-based modeling work has revealed that the amalgamation ratio at different scales is the key control on static connectivity and dynamic performance.

Quantitative documentation of the amalgamation ratios remains difficult and relatively overlooked. There are several reasons for this: (1) amalgamations can only be recognized in high-quality outcrops and cores whereas impossible to observe using well-logging and seismic data; (2) the importance of the sand amalgamations has not been fully recognized thus few geologists have quantitatively measured the amalgamation ratio. It is therefore advocated that more attention should be paid to this particular property especially quantitative characterization in the future work, since it is the vital control for both static reservoir connectivity and dynamic flow performance.

3.2 Turbidity lobe depositional process

To date, it appears not easy to establish a commonly-accepted deepwater turbidity lobe deposition process model, since many aspects of deepwater gravity flows such as transport process, rheology, sediment support mechanism and depositional model remain contentious (Lowe, 1982; Mutti et al., 1999; Shanmugam, 2000; Mulder and Alexander, 2001; Haughton et al., 2009; Mutti et al., 2009; Talling et al., 2012; Li Xiangbo et al., 2013; Xian Benzong et al., 2013). Nevertheless, there seems to be a consensus that turbidite lobe deposition is dominated by downslope turbidity current characterized by an overall unconfined, distributive pattern (Mutti and Normark, 1987; Posamentier and Kolla, 2003; Mulder and Etienne, 2010). As stated above, lobes start to develop at the end of channel-mouth or CLTZ. Progressive sediment elutriation suggests that the flow becomes sand-dominated towards the channel mouth (Normark, 1970). Consequently, levee heights gradually decrease until they cannot confine the high-density part of the flow, resulting in the radial flow splay and lobe deposition (Posamentier and Kolla, 2003). Flows with high-velocity, high sand fraction and low shear resistance result in deposition characterized by lobes with dense channel network at top (i.e. channelized lobe). Then, flows decelerate and rapid deposition occurs which are dominated by thick, highly amalgamated sandstones interbedded with thin mudstones with an overall sheet-like geometry. They gradually transit into lobe fringes which are characterized by thick mudstones interbedded with thin sandstones with very limited degree of amalgamation. The bypass/transition zone which is developed upstream of sandy lobes becomes a hot research topic due to its large influence on the morpholocy of lobes. This transition zone (CLTZ) is dominated by scours and has been discovered in many deepwater turbidite systems (e.g. Wynn et al., 2002; Posamentier and Kolla, 2003; Hofstra et al., 2015). In addition, deposition resulted from along
slope processes such as bottom currents and their complex interactions with turbidity current processes is another rapidly developing research topic (Rebesco et al., 2014). Reviews on such along slope processes are beyond the scope of the current work and can be found in Stow et al. (2002); Wang et al. (2007) and Rebesco et al. (2014). Despite its rapid development, studies on the interactions between along slope processes and particularly turbidity lobes are still scarce and most studies focused on the slope environment dominated by contour current in the Gulf of Cardiz. For example, Habgood et al. (2003) and Hanquiez et al. (2010) demonstrated that certain contourite processes can trigger and directly feed turbidite lobes in the Gulf of Cardiz. Marchez et al. (2010) revealed that the interaction between contour current and turbidity process is strongly controlled by climate variations and relative sea-level changes, and the perched lobes mixed with contourites could show good reservoir potential. Indeed, the along slope process is an emerging research area, yet more work is needed to unravel its complex interactions with downslope process, especially the turbidite lobe depositional process.

3.3 Hybrid event beds

Recent studies based on observations on modern sea floor (e.g. Talling et al., 2007), cores (Haughton et al., 2003, 2009) and deepwater facies correlations at outcrop (e.g. Hodgson et al., 2006; Talling et al., 2013; Grundvag et al., 2014) have recognized evidences for abrupt/or progressive changes in deepwater gravity flow behaviors, suggesting the interrelationships of multiple gravity flows (e.g. turbidity currents, debris flows). These observations have resulted in new classifications associated with the mixed flow behaviors, such as the “linked debrites” (Haughton et al., 2003), “hybrid event beds” (Haughton et al., 2009) and “hybrid submarine flows” (Talling, 2013). This issue has been a research hot point. Notably, Haughton et al. (2009) have proposed an “ideal” five-division hybrid event bed vertical profile with basal cleaner, sandier portion grading upwards into dirtier, muddier divisions (Fig. 7). Argillaceous sandstones commonly associated with mud clasts (linked debrites, H3) overlie either transitional flow deposits (banded sandstones, H2) and/or structureless sandstones (high-density turbidity deposits, H1) with abundant dewatered features, suggesting the development of turbulent, transitional and laminar flow behavior in different parts of the same flow. A trailing low-density turbulent cloud H4 and mud suspension fallout H5 may cap the H1–H2–H3 divisions, implying a return to non-cohesive behavior before the start of a mud background. Overall, the principle underlying these classifications (e.g. the five-division classification) is that turbidity currents are not simply digesting into water and becoming increasingly dilute until

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<th>DIVISIONS</th>
<th>INTERPRETATION</th>
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<td>Pseudonodular and/or massive mud</td>
<td>Suspension fallout ± shearing</td>
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<td>Parallel and ripple cross-lamination</td>
<td>Traction by dilute turbulent wake</td>
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<td>Muddy sand: ± mud clasts, sand patches, injections, oozed granules, shear fabrics. Often segregation of carbonaceous fragments to top where they can be laminated.</td>
<td>Cohesive debris flow, locally modified by sand injection from beneath, and partly reworked at top.</td>
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<td>Alternating lighter and darker sands, with loading at base of lighter layers, sheared dewatering pipes and sheets.</td>
<td>Transitional flow with intermittent turbulence suppression due to near bed dispersed clay and internal shearing.</td>
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<td>Isolated mud clasts surrounded by clean sandstone.</td>
<td>Progressive aggradation beneath non-cohesive high density turbidite current.</td>
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Fig. 7. Conceptual log showing “ideal” organization of a typical five-division (H1–H5) hybrid event bed. Note that not all divisions are present or have consistent character. Modified from Haughton et al. (2009).
runout, instead, they may evolve to more cohesive nature as they expand laterally and distally. In other words, hybrid event beds tend to occur at the more distal part of a deepwater turbidite system where lobes are predominant rather than channels.

To understand the hybrid event beds is significant since (1) they may lead to an improved lobe facies model; (2) they have great influence on reservoir heterogeneity and recovery efficiency (e.g. Haughton et al., 2003; Davis et al., 2009; Kane and Ponten, 2012); (3) the occurrence of such hybrid event beds in deepwater lobe deposits may reflect the wider fan system behavior and style. Haughton et al. (2009) have summarized four hybrid event bed distribution styles (Fig. 8): (1) hybrid event beds dominate the entire distal fan stratigraphic, implying the up–dip slope system was continually out of grade by tectonic activities (e.g. Upper Jurassic turbidites of the North sea); (2) hybrid beds are restricted to sections representing fan initiation, suggesting the sea floor is irregular due to gravity sliding or salt tectonics (e.g. Paleocene Forties fan, North sea); (3) hybrid beds occur sporadically within the fan deposits, perhaps representing elastic systems develop upon previous carbonate–constructed basin margins (e.g. Carboniferous Ross Sandstone, Ireland); (4) hybrid event beds dominate the fan retrogression phase (upper part), indicating large volume flows penetrate deep into muddy distal basins (e.g. Lower Cretaceous Britannia system, North sea).

3.4 Stacking patterns of turbidite lobe deposits

There seems to be a consensus on the hierarchic arrangements of deepwater lobes, yet how the lobe hierarchical components stack to each other remains disputed. Despite different mechanisms of lobe stacking were proposed, a vertical thickening–upward pattern is continued to be observed in different deepwater systems. Therefore, how lobe stack sequentially and how the repeated thickening upward cycles are formed remains a notable research frontier.

Hodgson et al. (2006) proposed a three–phase lobe development model (progradation to aggradation to retrogradation) according to the relative sea–level change, based on observations of outcrops and cores of Karoo Basin, South Africa (Fig. 9). In this model, lobes initiate, grow and retreat sequentially corresponding to the early, middle and late stage of a typical lowstand system tract (LST). However, whether this typical model can be applied to other deepwater systems requires further testing since other studies suggest lobes can also develop during transgressive system tract (TST) and highstand system tract (HST) (e.g. Bourget et al., 2010) and aggradation may be more important than progradation because accommodation is always available (Hiscott, 1981; Chen and Hiscott, 1999).

Macdonald et al. (2012) proposed a continual–progradation lobe element deposition model within a lobe, based on outcrop studies of the Ross Sandstone, western Ireland, to account for the constant thickening–upward trend and the associated “megaflute” structures observed in lobe elements (Fig. 10). This particular thickening upward cycle has formed by lobe element progradation mechanism which are supported by many workers (e.g. Mutti and Ricci–Lucchi, 1978; Walker, 1978; Shanmugam and Moiola, 1988; Mattern, 2002; Macdonald et al., 2012; Grundvag et al., 2014). In contrast, another group of workers have used statistical analysis to argue that the lobes show no consistent vertical patterns (Hiscott, 1981; Chen and Hiscott, 1999). In addition, lobe elements retrogradation, rather than progradation and aggradation, can also occur within a lobe. Within the last lobe of the Rhone Neofan, 7 youngest lobe elements clearly show retrogradation whist 4 oldest ones display progradation (Jegou et al., 2008; Mulder and Etienne, 2010).

Despite the different mechanisms, deposition of lobes appears to show a particular “compensational stacking pattern” (Mutti and Sonnino, 1981), with the thickest locus of later lobes shifted a few hundreds of meters away from the thickest locus of older lobes, suggesting the deposition of later lobes tends to “avoid” the highs and “favor” the lows created by older lobes. The principle of compensational stacking has been suggested to be widely developed at various scales of lobe deposition from beds to lobe complexes (e.g. Mutti and Sonnino, 1981; Pickering et al., 1989; Gervais et al., 2006; Deptuck et al., 2008; Prelat et al., 2009; Bourget et al., 2010; Prelat et al., 2010; Straub and Pyles, 2012; Prelat and Hodgson, 2013; Pyles et al., 2014; Zhang et al., 2015).

Notably, quantitative characterizations are also used to better distinguish the stacking patterns of deepwater lobes compared to deepwater channels. Mattern (2002) has complied the amalgamation ratios in different deepwater un–channelized and channelized successions, suggesting channelized successions have higher amalgamation ratio and therefore higher flow energy and less depositional nature. Straub and Pyles (2012) have used statistical analysis of a quantitative measurement (i.e. the “compensational index”) to demonstrate that the deepwater lobes show a higher degree of compensation than deepwater channels. Further, Zhang et al. (2013, 2015) have revealed that, at a given NTG, deepwater channels have higher amalgamation ratio than deepwater lobes, in accordance with the findings of Mattern (2002) and Straub and Pyles (2012). In addition, at a given NTG, hierarchically higher objects are less amalgamated (Fig. 6), suggesting they are more likely to avoid eroding into
Fig. 8. Summary of four geological scenarios resulting in different distributions of hybrid event beds at system scale (modified from Haughton et al., 2009).
previous ones, in other words, more compensational.

3.5 Numerical modeling methods

To build reservoir models realistically representing the architecture and heterogeneity of deepwater lobe deposits is a research focus, and an increasing number of numerical modeling methods (all stochastic) have been proposed. In general, such modeling work includes process–based (Groenenberg et al., 2010; Aas et al., 2014), process–oriented (Elfenbein et al., 2005), surface–based (Pyrcz et al., 2005; Zhang et al., 2009; Bertoncello et al., 2013), multiple point statistics (MPS, e.g. Pyrcz et al., 2008) and object–based modeling methods (Stephen et al., 2001; Manzocchi et al., 2007; Zhang et al., 2015). With specific pros and cons, these modeling studies have unique aims and focus on vastly different scales of depositional architectures. For instance, the process–oriented modeling work can realistically represent millimeter scale bedding structures (Elfenbein et al., 2005), whereas novel object–based modeling studies focus on the beds but could be applied to the entire lobe complex (e.g. Manzocchi et al., 2007; Zhang et al., 2015). The rapidly developing numerical modeling approaches have incorporated many architectural and hierarchical characteristics of lobe deposits and greatly benefited the understandings of deepwater lobe deposits both for academia and industry. Novel methods of numerical modeling of deepwater lobes are an emerging research trend, and this issue will be discussed in detail in other publications.

4 Discussion

4.1 Terminology

As the development of research on deepwater turbidite
lobes, many terminologies have arisen yet some of them are confusing and even contradictory. Among them, a few terminologies are particularly mentioned. The first one is “Fan lobe”, which was used by Bouma et al. (1985) to describe the fan-shaped sedimentary body within the Mississippi turbidite system. “Fan lobe” may cause confusion between the “fan” and one of the architectural elements (i.e. “lobe”) within a fan, therefore it is suggested this term should not be used anymore. Another one is “sheet”, which was commonly used to describe those sand bodies with tabular external form, high width-to-thickness ratio (aspect ratio) (greater than 500:1), few erosional features, good lateral continuity and thus potentially good vertical connectivity (e.g. Mutti and Normark, 1987; Chapin et al., 1994; Mahaffie, 1994). This term may also introduce confusion because (1) some
workers define “sheet” as an independent deepwater architecture element, for example, Galloway (1998) defined “turbidite lobes”, “sheet turbidite” and “debris flow lobes and sheets”; (2) lobes are sheet–like and most of the sheet–like successions examined by previous workers are in fact lobes, however, depositional channel deposits could also appear sheet–like geometry in some cases (e.g. Elliott, 2000). In short, the term “sheet” should be used with caution; we suggest “sheet” should be strictly used to describe a specific kind of geometry (e.g. sheet–like lobe; sheet–like channel). Similarly, the term “mound” should also be strictly used to describe a sort of geometry, rather than a type of architecture element.

4.2 Implications for deepwater exploration and development

Three–dimensional seismic reflection and well data are the most commonly used data types to support the hydrocarbon exploration. For deepwater reservoirs, the drilling expense is very high in most cases, but the wells are too sparse to characterize the reservoir distribution. Three–dimensional seismic reflection and side–scan sonar methods can help describe the reservoir geometry, stacking pattern at inter–well regions. However, due to the lack of vertical resolution, they cannot always characterize the subtle but vital characteristics such as recognition of the thin (centimeter– a few meters) but laterally continuous fine–grained units that generally drape the coarse–grained reservoirs. In contrast, outcrops can provide excellent high–resolution analogs which cannot be attained otherwise. The recognition of laterally continuous fine–grained bounding units at outcrops has significantly improved the understanding of deepwater lobe architecture and hierarchy (e.g. Prelat et al., 2009). In turn, this new understanding can be used to guide subsurface studies.

With gigantic discoveries being made in deepwater provinces such as Gulf of Mexico basins and offshore Brazil, industrial focus has gradually moved to the South China Sea basins, to be specific, the Cenozoic slope areas of Pearl River Mouth Basin and Qiongdongnan Basin (e.g. Wang Yongfeng et al., 2012; Zhu Weilin et al., 2012; Li Shengli et al., 2016). A brief review of the lobe architecture, stratigraphic hierarchy, facies distributions especially in the distal regions, stacking patterns and modeling methods can provide a big picture to understand deepwater lobes and benefit deepwater exploration, both at the appraisal stage when the number of wells are limited and at the development stage when drillings are highly expensive. Large deep–lacustrine turbidite reservoirs have also been discovered in many non–marine basins in China, for example the Mesozoic Songliao basin (e.g. Feng Zhiqiang et al., 2010). Although the knowledge associated

with deepwater turbidite lobes are mainly concerning deep–marine environment, they might be a good starting point to explore the sedimentology, architecture and hierarchy of turbidites in deep–lacustrine environment.

5 Conclusions

(1) Due to the deep water depth and the difficulty of obtaining useful information, the deepwater turbidite lobes which have great reservoir potentials, require further studies. This paper focuses on the research regarding deepwater turbidite lobes such as their architectures, hierarchies, and depositional mechanisms.

(2) With lobate geometries in plan–form and vertical convex–up profile, lobes occur in the most distal part of a given deepwater fan. Two morphological end–members exist: lobes occur directly down–dip channel–levee systems in large mud–rich system; and lobes occur down–dip of a transitional “Channel Lobe Transition Zone” (CLTZ) which lies down–dip the channel systems and is dominated by erosive and bypass features.

(3) Deepwater lobe deposits are structured into a four–fold hierarchy from beds, lobe elements, lobes and lobe complexes. At each hierarchical scale, sand–prone lobe components are separated by mud–prone bounding units with unique characteristics.

(4) The average length to width ratio of lobe elements, lobes and lobe complexes are all about 2:1 and hierarchical objects at different hierarchical scales in a particular deepwater system tend to have an approximate width to thickness ratio. Amalgamation ratio, a quantitative measurement of the degree of amalgamation, has been demonstrated to be the key control on reservoir connectivity and to increase as the lobe hierarchical level decreases.

(5) Sedimentologists have noticed the interactions of different flows especially at the distal/lateral fringe of deepwater fan systems, leading to new classifications of hybrid event beds. Detailed descriptions of such hybrid event beds are significant since they can help understand the flow origin, sequence stratigraphic framework and reservoir heterogeneity.

(6) Stochastic modeling of deepwater lobes provides an irreplaceable approach to unravel the complex lobe depositional mechanisms, to mimic the stacking pattern of hierarchical lobe components, and to minimize the risk for hydrocarbon explorations.

(7) The knowledge gained from this review could improve the understanding of the deep marine turbidite lobes and perhaps benefit the exploration and development of turbidite lobes developed within deep lacustrine basins in China.
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