Research paper

Mudflow gully characteristics, formation and impact on reservoir heterogeneity – A gas field in the Yinggehai Basin, South China Sea

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Abstract

Mudflow gullies are well developed in offshore areas and on the upper deepwater slope. In this paper, we discuss the formation and characteristics of mudflow gullies in a gas field in the Yinggehai Basin along the northwestern South China Sea margin, and address their impacts on sand body distribution, reservoir heterogeneity, and hydrocarbon accumulation.

The geological setting and sedimentary characteristics indicate that the sedimentary environment of the study intervals is located in an area between lower shore face and offshore. The gullies are several meters to a few tens of meters wide, and are filled mainly with thick mudstones interbedded with thin siltstones. Gully fills show an overall fining upward depositional trend, and exhibit a high value, low-amplitude linear GR wireline log shape. Mudflow gullies always incise the underlying sand bars or sand sheets, are overlain by offshore shales and are therefore considered to have developed in a transgressive setting. They are of three basic types, i.e., deep-, moderate- and shallow-classes according to the incision depth. The mudflows developed in offshore environment with rapidly varying topography, and deeply cut the underlying sand bars in lower shore face environment. Influenced by diapiric events, plastic mud-rich sediments were apt to slump, yielding the studied gullies. Gullies can converge to generate a lobe at front of them. In particular, during marine transgression, due to the high depositional rate of muddy sediments and tectonic activity, marine transgression offered the most favorable scenario for the development of these gullies. The mudflows also slumped down the slope into the deep water areas of the basin.

Because of the incision of mudflow gullies and transgressive wave ravinement from the southeast, the pre-existing sand bars on the lower shore face were reworked by waves and oriented in a NE–SW direction, perpendicular to the east shoreline to Hainan Island. The sand bars were affected by the mudflow gullies and diapir faults, often isolated from each other, resulting in a weak sand connectivity vertically and laterally. The degree of erosion of the sand bodies by mudflows decreases with depth. In addition, diapiric activity not only induces the formation of mudflow, but also causes CO2 in the deep buried intervals to migrate into gas reservoir attached by faults. The mudflow gullies are important causes of gas reservoir compartmentalization. CO2 filling process and gully development in the area resulted in more heterogeneity than the areas without them. Therefore, mudflow gullies control not only the reservoir compartments but also the gas content in the reservoir.

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1. Introduction

Mudflows are composed of cohesive fine grained sediments and water (Roberts, 1985; Huang and Aode, 2009), found in many sedimentary environments, such as glacial, fluvial, lake, desert, coastal area include deltas, offshore and deep water. They are fine grained, and are thus likely to originate in the areas far away from the sediment provenance, such as offshore and deep water depositional environments (Coleman et al., 1980).

Gully is an incised channel caused by a wide variety of factors (Schumm et al., 1984; Menéndez-Duarte et al., 2007). Gullies with erosional forms are responsible for significant soil loss, sediment...
production, and landscape evolution (Menéndez-Duarte et al., 2007). The scale of a gully is less than that of a canyon or channel (Stow and Mayall, 2000). Many gullies are linked down to submarine fans on the continental slope, and often finally evolve into sand-rich canyons, troughs or channels if sandy debris sediments are abundant (Reading and Richards, 1994). Dowdeswell et al. (2006) studied the morphology and sedimentary processes on the continental slope of Amundsen Sea, and recognized many sand-rich gullies on the slope. But the gullies on some continental slopes can also generate mud-rich fans (Reading, 1998). Coleman et al. (1980, 1998) put forward a pattern of mudflow gullies and lobes for the mudflows between offshore and continental slope based on a study on the subaqueous sediment instability in the offshore Mississippi river delta. Several mechanisms were proposed to interpret the creation of mudflow gullies in a number of environments, including heavy rainfalls in deserts (Heldmann et al., 2008) or semi-arid areas (Desir and Marín, 2013), ice sheet sliding and slumping in the ocean with some glaciers (Bowles et al., 2003), unstable shelf edges associated with tectonic movement and fast sedimentation rate of delta or calcareous mud in the areas adjacent to continental slopes (Coleman et al., 1993; León et al., 2007; Roberts, 1985). However, mudflow gullies developed in shore face to offshore remain poorly documented, because there are usually low slope gradients and coarse grained sediments. In this work, we recognize mudflow gullies developed from the lower shore face to the offshore in the DF1-1 gas field of the Yinggehai Basin, South China Sea (Fig. 1), and that they could have slumped to the lower part of continental slope. Due to marine transgression, the depositional setting in the gas field changed from lower shore face-to-offshore-environment. Mudflows originated mainly in latter but

Fig. 1. Location of the study area. The Yinggehai Basin is located at the southwest of the continental shelf of South China Sea (A and B). DF1-1 gas field is in the Yinggehai depression of the basin (B) and it is one of a series of mud diapirs and these diapir structures are mainly distributed from northeast to southwest (C), redrew from Yin et al., 2000). Note: In order to show major gas bearing intervals, we merged geological data of three wells (i.e., W2, W4, and W5, their locations are shown in Fig. 2A) in Fig. 2B.
incised into the former and formed multiple gullies along the lower shoreface.

Due to the fine grain-size, the steeply changing geomorphology, and the high sedimentation rate, mudflow gullies are commonly on the uppermost continental slope areas, such as the case of the Gulf of Mexico (Coleman, 1976). In particular, when volcano activity is intense, mudflow gullies can be generated in the continental slopes, e.g., the cases of the Black Sea and Mediterranean ridge mud volcanoes (Ivanov et al., 1996), mud flows at Håkon Mosby Mud Volcano (Jerosch et al., 2007), submarine gullies on Italian upper slopes (Chiocci and Casalbore, 2011). From shore face to offshore, most gullies form as sandy channels due to relatively coarse sediments and low-gradients, e.g., the case of Sunda shelf in offshore Indonesia (Darmadi et al., 2007). Although it is not very easy to form mudflow gullies from shore face to offshore, it is also possible under suitable geological conditions, such as high sedimentation rate of muddy sediments (Roberts, 1985), marine hydrodynamic changing (Traykovski et al., 2000), and intensive tectonic events (Nemeth and Cronin, 2007).

Most studies on mudflow have focused on sedimentary environments, hydrodynamic features, paleoclimate or hazard, etc (e.g., Coleman et al., 1980; Desir and Martin, 2013; Bowles et al., 2002). The relationship between mudflow gullies and petroleum reservoirs on the offshore or shelf edge remains obscure. In this paper, we document the characteristics of mudflow gullies in the Yinggehai Basin in the northern part of the continental shelf of South China Sea (Fig. 1). In addition, we discuss the formation of mudflow gullies and geological conditions for their generation. Finally, the impact of mudflow gullies on the sand bar distribution and the heterogeneities of reservoirs are discussed, helping to obtain a better understanding of gas accumulations in the reservoir.

2. Geological setting and methodology

2.1. Geological setting

As part of the continental shelf of the South China Sea, Yinggehai basin is located to the east of Hainan island, and extends from northwest to southeast (Fig. 1A and B). Toward Vietnam and Hainan Island, the basin overlaps with fault terraces or gentle slope deposition (Sun et al., 1995). In the Yinggehai Basin, the maximum thick strata (8000–10,000 m) probably developed in the basin’s depocenter since the Neogene (Li et al., 1998). The evolution of the Yinggehai Basin which is an extensional basin is influenced by the mantle upheaval as well as dextral strike slip (Li et al., 1998). The basin experienced three stages of evolution namely early rift extension, broad downwarping during thermal subsidence, and final repeated extension (Zhang and Hao, 1997; Gong et al., 2011, 2014, 2015). The study interval, the Yinggehai Formation (Pliocene), was in the third stage when it suffered from numerous well developed mud diapiric structures. These diapirs can be divided into five N–S trending zones (Fig. 1C), and most of them are anticlinal structures (Yin et al., 2000). Located in the Yinggehai Depression of Yinggehai Basin, DF1-1 Structure is one of such anticlines. The anticline is dome-like with a 21 km-long macro axis, 12 km-long minor axis, an area over 200 km² and trap closure height over 200 m (Fig. 2A). The best gas bearing interval (the 2nd Member of Yinggehai Formation) in DF1-1 Gas Field can be divided into five Beds (Fig. 2B). Constrained by mud diapirs and faults, these gas reservoirs also include several stratigraphic traps (Fig. 2C).

Since the Middle Miocene, mud-rich sediments were deposited from the coast to the deepwater slope of the Yinggehai Basin. Shan and Dong (1996) termed these mud-rich layers mud sources and believed that they collectively resulted from maximum marine transgressions. In seismic profiles, numerous gullies were discovered in the 2nd Member of Yinggehai Formation (Figs. 3–5). They are mainly filled by mudstones as seen from coring, electrical well-logging and seismic data (Figs. 5 and 6).

2.2. Data and methodology

Wireline logs from 18 wells, including 10 exploratory and appraisal wells and 8 development wells were collected. Among these wells, cores (Fig. 6), and laboratory test data, such as the lithology (Table 1), physical property and gas content data were collected from 11 wells. 3D seismic data were also available and covered the entire study area (Fig. 2A).

Combined with the above geological background, the depositional environment was analyzed using the cores and ichnofossils. Seven ichnofossil types (Figs. 6 and 7) and their mutual relationship (Table 2, Table 3 and Fig. 6) in the target formation were analyzed. On the basis of the lithology, the sedimentary structures, the biological remnants, and sedimentary setting, 10 lithofacies can be recognized (Table 4). Seven basic lithofacies assemblages composed of these lithofacies from the lower shoreface to offshore are summarized (Table 5).

The identification of the mudflow gullies was achieved through cores, wireline-logs, and seismic data. The mudflow gullies were depicted in detail (Figs. 5, 6 and 8), and the sedimentary patterns (Fig. 9) were analyzed. The TWTT (two way traveltime) thickness and plain-view distribution of the documented mudflow gullies were determined through seismic horizon tracing (e.g., Figs. 3 and 4). The basal bounding surfaces of the studied sandstones have been traced throughout the study area, and sandstone thickness was calculated (Fig. 10) and sandstone/mudstone ratios were calculated (Fig. 11). Sandstone/mudstone ratio distribution patterns were then established combining the sandstone/mudstone ratio above and that in wells. Finally the distribution of sedimentary facies and mudflow gullies (Figs. 12 and 13) could be obtained based on lithofacies association classification (Table 5) and sandstone/mudstone ratio contour (Fig. 11). In addition, the control of mudflow gullies on the reservoir distribution and heterogeneity were analyzed on the basis of mudflow gully distribution (Figs. 12 and 13). Finally, the impact of mudflow gullies on the sandstone connectivity and gas distribution is discussed. It should be pointed out that we use S1, S2U, S2L, S3U, S3L and S4 to refer to bed or interval, whereas we refer to boundary, we add –T after it to describe its top boundary. For instance, S1-T shows the top boundary of Bed S1.

3. Sedimentary environment

The Pliocene Yinggehai Basin was basically in the same stage of tectonic evolution (i.e., in the stage of repeated extension as discussed above) as it is at present (Sun et al., 1995; Zhang and Hao, 1997). The basin is surrounded by continental areas except in southeast where it faces the open ocean. The Red River from Vietnam and the Changhua River from Hainan Island (Fig. 1) constitute the ultimate feeder river systems (Xie et al., 2004; Sun et al., 2013). The deltas of these rivers in the northwest and northeast are the main feeders for the studied clastic sediments (Xie et al., 2004). The Pleistocene Yinggehai Formation consists of two major gas bearing intervals, i.e., the first and second members from top to bottom (He et al., 2006). The second member of Yinggehai Formation which is the gas bearing in the study area contains fine sandstones, siltstones and mudstones (Table 1, Fig. 6), and represents a distal fine-grained setting.

The sedimentary environments in the DF1-1 gas field were initially interpreted as offshore because of the long distance from sediment provenance and the fine-grained nature of the sediments.
However, this interpretation is disfavored here by the high content of fine sandstones and siltstones in cores of the study interval (Fig. 2B and C). The ichnofossil assemblages in Beds S1 and S2U–S3U are totally different (Table 3). In Bed S1, the ichnofossil assemblage is mainly composed of Phycosiphon, Thalassinoides, Planolites, and Zoophycos, indicating quiet, deep and mud-rich offshore or continental shelf environments. But the ichnofossil assemblages from S2U to S3U are made up of Ophiomorpha, Arenicolites, Skolithos, Zoophycos, and Phycosiphon, i.e., increasing siltstone, shallow and higher energy lower shore-face deposits. The different seismic reflection characteristics (Fig. 3) also indicate the difference of depositional environment between Bed S2U and Bed S1.

In addition, if the sediment supply to a shelf is abundant (especially from the fast progradation of large deltas) the continental shelf gradually builds and accretes far toward the sea (Porebski and Steel, 2006), i.e., sediment supply (and not necessarily sea level) is likely to be the key factor on the growth of shelf margins (Carvajal et al., 2009). With the progradation of shelf, shore face sediments could also migrate seawards during the early stage...
of 2nd member of Yinggehai Formation. And then, because of fast marine transgression, the sea level ascended quickly (Jiang et al., 2012), depositional environment changed from shoreface during Bed S2U to offshore during Bed S1 (Fig. 6).

4. Identification of mudflow gullies

In the DF1-1 gas field, the gullies are easily identified on seismic sections with drilled wells (Figs. 2, 3 and 6). According to the lithology in Well Wd1 (with gullies), these gullies are mainly filled with mudstones, regardless of the size of the gullies. The cores and wireline logs in the gas field suggest mudflow gully characteristics as follows: mudstone, gradual upper and abrupt lower contacts, the mud infill cuts down into underlying sandstone; lower shore face sand sheets underly the mudflow gullies and offshore mudstone overlies them (Fig. 6).

The documented mudflow gullies were aggradationally filled by muddy fines (Fig. 5). They mainly consist of mudstone with a few
Fig. 5. A typical mudflow gully between Well W3 and Well Wd2 (The positions of drilled wells are shown on Fig. 2A) is shown in the middle of the seismic section. Deduced from Well Wd1 data, the gully was filled with mudstone, which eroded the underlying sand bar. Note: The well log on the left side of each well is AC (acoustic) curve and that on the right side is GR curve. CDP = seismic CDP number. The blue rectangle is the interval with cores. The lithology, sedimentary structures and fossils are shown in Fig. 6. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 6. The lithofacies association of mudflow gully and the lower shore face. Note: Bed S2U was totally eroded by a mudflow gully in the diagram. The lithofacies code acronyms are listed in Table 4.
sandy sediments (Figs. 6 and 8). Due to the erosion of gullies, the deposited sand bars are reshaped and show convex and concave shapes in the cross sections (Figs. 5 and 8). And then, these gullies acted as conduits for relatively low concentration fluid mud flows derived from the muddy continent shelf. This kind of mud flow gully is quite different from the common gullies filled with sandstones in shelf environment, e.g., the Taranaki basin turbidite system (King and Thrasher, 1992). In the study area, sandy slumps are often seen as lateral accretion complexes, which were mainly filled by lateral accretion patterns in seismic profiles (Zhuo et al., 2013).

According to the incision depth, these gullies can be divided into three types, i.e., shallow-, moderate-, and deep-gullies (Fig. 8). Shallow and narrow gullies are often distributed in the places where they begin to form; deep gullies are well developed when several shallow and narrow ones merge into one gully; the moderate ones

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**Table 1**
Grain-size and texture of different Beds. Data were collected from 14 wells in DF1-1 gas field. Grain sizes mainly consist of silt and mud with moderate sorting, which indicates relatively far away from sediment provenance.

<table>
<thead>
<tr>
<th>Well Name</th>
<th>S1</th>
<th>S2U</th>
<th>S3U</th>
<th>S3L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample Quantity</td>
<td>43</td>
<td>29</td>
<td>15</td>
<td>67</td>
</tr>
<tr>
<td>Grain-size</td>
<td>Mainly silt, mud</td>
<td>Very fine sands, mud</td>
<td>Silt and very fine sands, mud</td>
<td></td>
</tr>
<tr>
<td>Sorting</td>
<td>Poorly sorted – moderately sorted</td>
<td>Well sorted – moderately sorted</td>
<td>Moderately sorted</td>
<td></td>
</tr>
<tr>
<td>Roundness</td>
<td>Subrounded – subangular</td>
<td>Subrounded</td>
<td>Subangular – subrounded</td>
<td></td>
</tr>
<tr>
<td>Grain Fabric</td>
<td>Matrix-supported – grain-supported</td>
<td>Grain-supported</td>
<td>Grain-supported</td>
<td></td>
</tr>
<tr>
<td>Grain Contact</td>
<td>Isolated – point to point</td>
<td>Point to point</td>
<td>Point to point</td>
<td></td>
</tr>
</tbody>
</table>

**Table 2**
The relationship between main ichnofossils and the sedimentary environments. Seven types ichnofossils were recognized. The ichnofossils show the sedimentary environment of the study area is from shallow water to relatively deep water.

<table>
<thead>
<tr>
<th>Ichnofossil</th>
<th>Beds</th>
<th>Sedimentary environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ophiomorpha</td>
<td>S2L</td>
<td>Shallow water, high energy clear sandstone</td>
</tr>
<tr>
<td>Phycosiphon</td>
<td>S1</td>
<td>Deep water turbidite mudstone</td>
</tr>
<tr>
<td>Thalassinoides (Fig. 7C, D)</td>
<td>S1, S2L</td>
<td>If they have some vertical branches, it could be high energy environment. If they mainly have horizontal branches, it should be quiet environment without storm.</td>
</tr>
<tr>
<td>Arenicolites</td>
<td>S2L</td>
<td>Relatively quiet environment without storm.</td>
</tr>
<tr>
<td>Zoophycos</td>
<td>S1, S2U</td>
<td>Deep water, oxygen-poor layer without turbidite</td>
</tr>
<tr>
<td>Planolites</td>
<td>S1</td>
<td>Deep water, relatively quiet without turbidite</td>
</tr>
<tr>
<td>Skolithos</td>
<td>S1, S2U</td>
<td>Shallow water, high energy clear sandstone</td>
</tr>
</tbody>
</table>
in Well W1 on S2U (Figs. 3 and 8) have relief of deeper than 100 m (Figs. 4 and 8) and a moderately deep one is shown in Well Wd1 (Fig. 5). The deep gullies often eroded S2U thoroughly and they even incised into the S2L (Figs. 3 and 4). Mudflow gullies appearing in S2U and S2L are mostly moderate and shallow ones, e.g., a gully in Well W1 on S2L is nearly 30 m (Fig. 3).

The shallow mudflow gully usually appears at a higher elevation of structure on S2U-T, like that in Well W2 (Figs. 3 and 4), whereas the moderate and deep gullies occur lower in the field structure. For example from Well W2 to Well W5 the depth of gullies increases gradually (Fig. 4). Mudflows with high relief with varying gradient can incise the underlying strata. In a flat area the mud flow velocity would become slow, and might gather together to form wide sedimentary bodies. The lower shore face and offshore sandstones reworked by the mudflows gradually become isolated sand bars (Figs. 8 and 9).

5. Mudflow gully origin

In the study area, the muddy sediments were quickly deposited due to the high sedimentation rates in Yinggehai Basin since the Neogene (Shan and Dong, 1996; Li et al., 1998; Xie et al., 2004). DF1-1 gas field is located in the transitional belt between lower shore face and offshore, where it is far from sediment provenance as discussed above. In this case, fine-grained sandstones, siltstones and mudstones were formed and remained relatively unconsolidated. The strata formed under these conditions are extremely unstable and apt to slump and generate gullies.

From the wells and seismic profiles we could see the erosion of S2U caused by mud diapir movement (Figs. 2C–4) which is one of the important mudflow gully generating factors. There was dextral strike slip movement and N–S fault belts during Pliocene to Quaternary triggered the extensive breakthrough of an abnormal high pressure compartment with thermal fluid in it, which in turn led to mud diapirism distributed along N–S direction in central Yinggehai Basin (Li et al., 1998; Xie et al., 1999). These diapirs were emplaced regularly along the fault belts as several trends taking on NE and NNE (Yin et al., 2000). The intensive upwelling of thermal fluid from mud diapirs (Wang et al., 2004; He et al., 2004) resulted in the high local relief difference, which provided proper dynamic and gradient conditions for the mudflow. Influenced by the mud diapirs and slope gradients, the mud flow energy would have increased in steep slopes, thus formed mud gullies. These gullies appear in both

Table 3

<table>
<thead>
<tr>
<th>Ichnofossil type</th>
<th>Quantity in the Beds of DF1-1 gas field. The ichnofossil type and content in Bed S1 differ from those of Bed S2L ~ S3L. It indicates the differences of their sedimentary environments.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sk Zo Ph Op Th Ar Pi</td>
<td></td>
</tr>
<tr>
<td>++ + ++ ! +++ + !</td>
<td></td>
</tr>
<tr>
<td>++ ++ ++ ! + + !</td>
<td></td>
</tr>
</tbody>
</table>

+++ mainly appeared in the Beds; ++ Often appeared but not unique; + rare; ! Only appeared in the Beds.

Note: Sk – Skolithos; Zo – Zoophycos; Ph – Phycosiphon; Op – Ophiomorpha; Th – Thalassinoides; Ar – Arenicolites; Pi – Planolites.

Table 4

Lithofacies codes and descriptions in the study area. 10 types of lithofacies were recognized, which also indicates the study area is far away from sediment provenance.

<table>
<thead>
<tr>
<th>Lithofacies code</th>
<th>Lithofacies description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fsm Masssive fine sandstone</td>
<td></td>
</tr>
<tr>
<td>Fsc Fine sandstone with compound bedding</td>
<td></td>
</tr>
<tr>
<td>Fsbd Fine sandstone with bioturbation structure</td>
<td></td>
</tr>
<tr>
<td>Fbd Siltstone sandstone with bioturbation structure</td>
<td></td>
</tr>
<tr>
<td>F Fl siltstone sandstone with bioturbation structure</td>
<td></td>
</tr>
<tr>
<td>Fl Fi fine line siltstone</td>
<td></td>
</tr>
<tr>
<td>Fw Siltstone with wave ripple bedding</td>
<td></td>
</tr>
<tr>
<td>Mbd Mudstone with bioturbation structure</td>
<td></td>
</tr>
<tr>
<td>Mh Mudstone with horizontal lamination</td>
<td></td>
</tr>
<tr>
<td>M Mudstone</td>
<td></td>
</tr>
</tbody>
</table>

have the intermediate characteristics (Fig. 8). Based on well and seismic data, depth of the deep mudflow gullies is usually more than 100 m; moderate ones are between 20 and 50 m; shallow ones are less than 20 m. The width of one single mudflow gully is usually less than 1 km (Figs. 3, 4 and 10), and it is consistent with the views of Galloway and Hobday (1996) that mudflow gully is narrow and deep, namely with a low width/depth ratio. From deep to moderate to shallow types, the width shows the trend of gradually decreasing (Figs. 3–5), which is different from regular river channels. Channels with great width often have shallow incised depth (Galloway and Hobday, 1996). However the mudflow gullies in the study area show an opposite trend.

Mudflow gullies are well developed above the bottom part of Bed S1 (Figs. 2C–4) on the S2U-T. Deep mudflow gullies occurring

Table 5

Sendimentary environment and lithofacies characteristics in the study area. The lithofacies associations of twofold environments identified according to sedimentary features and electrobarcal well logging curve. The genesis of them is listed in the last column of the table.

<table>
<thead>
<tr>
<th>Environment Association</th>
<th>Lithofacies</th>
<th>Sedimentary characteristics</th>
<th>Gamma ray well log curve</th>
<th>Genesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Shoreface (S3L ~ S2U)</td>
<td>Sand Bar</td>
<td>Light gray or light greyish-green fine sandstone, small scale symmetrical wave ripple, coarsening upward lithology, vertical or oblique burrows with relatively big size.</td>
<td>Slightly serrate funnel shape</td>
<td>Wave Winnowing</td>
</tr>
<tr>
<td>Sand Sheet</td>
<td>Light greyish-green fine shale siltstone or fine sandstone, wave ripple or structureless, intense bioturbate structure. Occasionally, shells can be found.</td>
<td>Serrate cylindrical shape with small amplitude Line shape slightly serrate</td>
<td>Marine Flooding</td>
<td></td>
</tr>
<tr>
<td>Mudstone</td>
<td>Light gray or light greyish-green silty shale or shale silt, horizontal burrows with small size</td>
<td>Smooth funnel</td>
<td>Wave Winnowing</td>
<td></td>
</tr>
<tr>
<td>Offshore (S1)</td>
<td>Sand Bar</td>
<td>Gray or dark gray shaly fine sandstone or siltstone, small scale asymmetrical wave ripple, coarsening upward, moderate bioturbation.</td>
<td>Serrate cylindrical shape with small amplitude</td>
<td>Vertical Accretion Marine Flooding</td>
</tr>
<tr>
<td>Sand Sheet</td>
<td>Gray or dark gray shaly siltstone, mainly coarsening upward, sometimes moderate bioturbation, with few single burrow.</td>
<td>Smooth line shape</td>
<td>Vertical Accretion Storm Influence Marine Flooding</td>
<td></td>
</tr>
<tr>
<td>Mudstone</td>
<td>Dark gray mudstone or shale siltstone, horizontal laminar or massive structure. Occasionally, very small burrows could be found.</td>
<td>Smooth line shape or bell shape</td>
<td>Gravity Flow</td>
<td></td>
</tr>
</tbody>
</table>
lower shore face and offshore as well as the upper slope below the shelf edge.

The rapid transgression was another trigger for the mudflow gully formation because it resulted in stronger ravinement. Mudflow gullies were mainly generated after the depositions of S2L and S2U, mainly in early S1 (above S2U boundary, Figs. 3–6), when the sedimentary environment changed abruptly from S2U to S1 (Figs. 6 and 9). The Pliocene witnessed frequent icehouse global sea level changes, meaning the multiple rapid rise and decline of sea level (Haq et al., 1988). It was verified that the sea level change during Pliocene in South China Sea was basically the same as with global change (Pang et al., 2005; Xie et al., 2012). The transgression led to erosion, which in turn caused varieties of incised channels, like canyon, trough, gully (Stow and Mayall, 2000). When mud

![Diagram of three types of mudflow gully. Type 1: deep gully, incised the sand bar to the bottom; Type 2: moderate gully: moderately incised the sand bar; Type 3: slightly incised the sand bar. Generally, from the proximal position to distal area, the shallow gully will vary to moderate or deep gully. And when it gets to the relatively flat area, a lobe will be formed due to the decrease of flow energy.](image1)

![Sedimentary pattern from shore face to deep water area. The mudflow gullies were generated at lower shore face and slid to offshore, which were induced by mud diapir. And some mudflows could have slumped to the downslope area. The sand bars in the lower shore face and offshore could be reconstructed to change their initial distribution pattern by the mudflow gullies. Note: -Hypothetical mudflow fans. According to deep-water fan sedimentary patterns (e.g., Reading and Richards, 1994; Coleman et al., 1998; Shanmugam, 2003), we assumed that mudflow fans exist in the basin floor below the slope.](image2)
sediment dominated the incised channel, mudflow gullies appeared. At the same time the erosion of mudflow gullies caused absence of the underlying layers. For instance the variety of mudflow gullies on the boundary of S2U-T lead to apparent absence of S2U sandstone bodies (Figs. 2C–4 and 12). It is significant that the blank area in Fig. 12 is the result of mudflow gullies and mudstone formed during S1, which could also represent the lack of S2U (Figs. 2–4).

Therefore, the generation of mudflow gullies in the Yinggehai Basin was closely related to high sedimentary rates of thick mud sediments, stronger transgression and structural diapirs. When the mudflow gullies were generated, the sand sediments were still weakly consolidated and easily eroded by mudflow sediments with low density. In this way not only were gullies generated but also the sand body distribution pattern had been modified (Fig. 9).

6. Reservoir characterization

6.1. Sand bar distribution

The seismic sections clearly indicate that the mudflow gullies have influenced the Beds of S2U and S2L (Figs. 3 and 4), whose main reservoirs lie in sand bars and sand sheets in lower shore face environment as discussed above. The sand thickness (Fig. 10) and sandstone/mudstone ratio (Fig. 11) indicate that the continuity of higher-value in the north district is better than that in the south because of the separation for sandstone caused by gullies. Based on sandstone/mudstone ratio in wells, this study defines 60% as the threshold to differentiate sand bar and sand sheet (Figs. 12 and 13). Obviously reformed by the mudflows, the sand bars mostly present a NE–SW trend which is the main extension/elongate direction of the mudflows (Figs. 12 and 13). Because of the transgression direction from south to north (Xie et al., 2012; Jiang et al., 2012; Zhang et al., 2013) and mudflow gullies generated from north to south (Fig. 9), the initial sand bars along shoreline with NW–SE trend were usually transformed to distribute in NS or NE–SW direction (Figs. 12 and 13). Beds S2U and S2L are separated by the mudflow gullies and divided into two blocks, i.e., the gas field in the South and W7 well area in the North (Fig. 12). The gullies exert more control on the southern part (Figs. 3, 12 and 13), which can be deduced by the more obvious gullies and non-permeable barriers in the center and margin of the sand bodies. One reason is that the uplift structure caused by mud diapirism mainly appears in the south (Fig. 2A); the other reason is that mudflow genesis pattern (Fig. 9) shows that north district is more close to shoreface, and south district is more close to offshore and deepwater slope. However from shoreface to offshore and slope which leads to better developed mudflow gullies in the south (Fig. 12). Consequently the sand bars become sand sheets in this district and the sand bars reflect more apparent
belt-like features in N–E direction.

The mudflow gullies on S2U reduce the scale and extension of sand sheets and sand bars in lower shore face. The sand sheets and sand bars in the northeastern part were well preserved, only slightly reworked (Fig. 12), while those in the west are strongly reformed by the intensive incision of the later gullies, then turn into irregular and discontinuous bars, finally pinch out or terminate. These gullies destroy the large sand bars in SW–NE direction generating new smaller sand bars in lower shore face (Fig. 12).

The sand bars on S2L were mainly affected by the gullies in the Northern and Eastern parts (Fig. 12) and sand bars in the southern part are much larger than those in S2U (Figs. 12 and 13). The sand body scale difference between S2L and S2U is another evidence for the fact that the gullies were formed later than the sand bars and the incision weakened with increasing depth.

6.2. Reservoir connectivity and heterogeneity

S1 contains limited sandstone and widely deposited mudstone (Figs. 2B and 6). The offshore sandstones are characterized by thin layers and weak continuity (Fig. 2C). The mudstone interlayers formed in the offshore area were so well developed that the sand bodies in Bed S2U were isolated from each other due to the incision of mudflow gullies formed in Bed S1 (Figs. 3–5).

S2U bed was often eroded by the abundant gullies (such as W1, W2, W3, Wd1, Wd2 well area) (Fig. 12). Highly influenced by the mudflow and faults in this Bed, sand bodies are distributed as isolate islands. These sand bodies enhance the heterogeneity but impair the horizontal connectivity and continuity. The sand-body thickness is affected by the incision depth, interlayer amount, and thickness. To be specific, the deeper the gully incises, the thinner the preserved reservoirs. Less influenced by the gullies, sand bars in the S2L in general have better connectivity and continuity than S2U. This is the main reason why the S2L has more gas bearing sand bodies than S2U (Figs. 2C, 12 and 13).

The mud flow gullies will eventually affect the gas distribution. It can be known from the gas component figures that the CO2 content in the northern part is higher than that in the southern part in Bed S2U (Fig. 12). It is partly because of different tectonic altitudes (see Fig. 2A, the highest point of the diapir anticline is in the
southern part) and the sealing process from faults. Due to gravity differentiation, CO₂ is likely to be enriched in the lower part of structure. That is why Bed S2L contains more CO₂ than Bed S2U (Figs. 12 and 13). The faults can be the pathways for CO₂ migration from deep buried intervals into gas reservoirs. In Bed S2L (Fig. 13) faults developed intensively. Due to the faults, CO₂ was able to reach higher part of structure, then accumulated (Figs. 13 and 2A). Undoubtedly it is also closely related with the increasing mud diapirism and subsequent mudflow gullies.

The mudflow gullies can separate the reservoirs and finally they cause the gas component differentiation in the whole reservoirs (Figs. 12 and 13). The mudflow gullies have more influence on the heterogeneity and gas content (the area between Well W5 and Well Wd2 in S2L, shown in Figs. 5 and 13, the area between Well W5 and Well E4h, shown in Fig. 12). Although the two wells are quite close, the mudflow gullies still result in the weak connectivity between sand bodies and obvious component diversity of natural gas.

7. Conclusions

When there is widespread transgression to provide extensive mud cover that is deposited rapidly, along with diapiric mud movement to cause relief changes on the surface, mudflow gullies are apt to be generated in offshore areas. The relief generated in turn triggers gully formation and unlike many river systems, the wider gullies are also deeper, but become narrower and shallower upstream.

The mudflow gullies formed later than shoreface, and so the gullies have most reworking influence on the shallower sands. Mudflow gullies have obvious influence on the connectivity and continuity the sand reservoirs. Gullies of varying scales exert different influence on the distribution of reservoirs and even affect the natural gas content of the reservoirs. We recommend careful mapping of mudflow gullies on shoreface and offshore areas, in time and space, for the evaluation of reservoir distribution and heterogeneity.
Fig. 13. Sedimentary facies of Bed S2U. The mudflow gullies mainly eroded the north and east of the gas field. As described before (Fig. 5), the gullies between W3 and Wd2 have separated the sand bodies. Therefore, the gas bearing characteristics of the two wells are different in Bed S2L. The blank areas are mudflow gullies or mudstone.

Acknowledgments

This work was supported by “the Fundamental Research Funds for the central universities (2-9-2013-97)” and “the Chinese National Natural Science Fund Project (41272132)”. We are grateful to acknowledge the Zhanjiang Division of CNOOC (China Offshore Oil Company) Ltd. for providing the basic data, sharing their ideas about geological setting and for the permission to publish this paper. The authors also want to thank professor Ronald J. Steel in University of Texas at Austin for his valuable improvements to the manuscript.

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