Sandy Debris Flow Sedimentary Characteristics and Patterns in the Meishan Formation of Northern Lingshui Sag, Qiongdongnan Basin

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Abstract. Based on drilling core descriptions and micro sedimentary features, combined with regional paleogeographic features, imaging logging and 3D seismic attribute analysis, the sedimentary characteristics and representative identification mark of sand debris flow sandstone in Meishan formation of northern Lingshui Sag, Qiongdongnan basin are discussed in detail, and the sand debris flow sedimentary pattern in the study area is established. Meishan formation sandy debris flow sandstone in the study area is mainly consist of 2 lithological associations, thick massive siltstone to very fine sandstone without sedimentary structure on the upper part and silty mudstone, mudstone and siltstone interbeds with abundant contemporaneous deformation structure on the lower part, and the “mud-encased sand” structure in massive sandstone can be used as an important symbolic evidence to identify the sand debris flow deposits. The distribution of sandy debris flow sandstone is controlled by shelf slope break, and the area with relatively gentle, constructive slope, where the slope break line is characterized by "bulge" form to the sea, is the most favorable area for the development of sandy debris flow sandstone reservoirs.

1. Introduction
Deep water sandy debris flow sandstone has become a hot field of the deep water sedimentology and global oil and gas exploration [1-3]. Shanmugam (1996) discussed the support mechanism and the rheological characteristics of grain flow and debris flow, pointing out that the sandy debris flow was a Bingham plastic fluid between low density turbidity flow and mud debris flow, and established the slope sedimentation model based on the concept of sandy debris flow [4-5]. The theory of sandy debris flow could better explain the genetic mechanism of unstratified massive sandstone in deep water environment, was an important supplement to the traditional deep water deposition theory, and obtained more and more scholar's approvals gradually [6-8].

In recent years, natural gas discovery in the Meishan formation deep water gravity flow sandstone of northern Lingshui sag, Qiongdongnan Basin has drawn our attention of further petroleum exploration. However, due to the controversy of the formation mechanism of sandstone reservoir and the distribution of favorable reservoir, the natural gas exploration work progress was slow [9-11]. It is urgent to carry out detailed study on the formation mechanism, sedimentary characteristics and distribution pattern of high-quality reservoirs of the Meishan formation gravity flow sandstone.
Through comprehensive analysis of core description, core slice observation and grain size data, imaging logging and 3D seismic data, it is believed that the Meishan formation gravity flow sandstone in the study area belongs to sandy debris flow. In combination with areal palaeogeomorphology and seismic facies study, the sedimentary structure characteristics, identification mark and sedimentary pattern of the Meishan formation sandy debris flow sandstone in northern Lingshui Sag are discussed in details, in order to provide efficient reference for further oil and gas exploration in the study area.

2. Regional geology background
Lingshui sag is located in the western part of the Qiongdongnan basin, covers an area of about 1 x10^5km^2. The tectonic evolution of Lingshui Sag can be divided into three stages: regional rifting stage from Eocene to Oligocene, basement fault controlling the fault block activation; post-rift thermal subsidence stage during Miocene and Neotectonic stage from Pliocene to Quaternary. The typical continental shelf and slope system of Lingshui Sag had formed since the middle Miocene, the Meishan formation sedimentary period. During this period, the center of Lingshui Sag below the slope break was dominated by bathyal mudstone deposits, and on the continental shelf were mainly shallow marine deposits and large deltas from Hainan Island [12-13].

![Figure 1. The structure location of Lingshui Sag, Qiongdongnan Basin.](image)

3. Sedimentary characteristics of sandy debris flow

3.1. Paleogeographic Background
The physical simulation experiments suggest that the critical slope of 6m/km is sufficient to generate sandy debris flow, and there is a strong complementarity between the terrain elevation difference and topographic slope when sandy debris flow is formed. Steep slope or relatively large terrain elevation difference is conducive to the deposition of sandy debris flow [14-15]. During the Meishan formation sedimentary period, the paleogeographic feature of the northern Lingshui sag showed a widely slope which was lower in the south and higher in the north, and the slope break was NE~SW trending.
reaching 120km in length, and the maximum slope of shelf slope was 60-80m/km, which could have been the paleogeographic background of forming sandy debris flow deposits.

3.2. Sedimentary structure characteristics
The Meishan formation sandy debris flow sandstone consists of the upper part and the lower part, showing a two-stage, reverse grain bedding sedimentary sequence that is generally coarser upward and a variety of representative sedimentary phenomena of sandy debris flow.

| CR | Depth (m) | Lithology | Sedimentary facies | Sedimentary structures | Petrographic description | Typical core photos |
|----|-----------|-----------|-------------------|-----------------------|-------------------------|---------------------|
| 3792 | - - - | - - - | Massive sandy debris flow sandstone with multiple thin layers of wavy bedding and grey argillaceous laminae (rigid raft flow section) | Cross-bedding muddy lamina | Non-directional grey-black mudstone tearing debris at the top, with the thickness ranging from 10 to 20cm | |
| 3794 | - - - | - - - | Massive sandy debris flow sandstone with multiple thin layers of wavy bedding and grey argillaceous laminae (rigid raft flow section) | Cross-bedding muddy lamina | Non-directional grey-black mudstone tearing debris at the top | |
| 3798 | - - - | - - - | Massive sandy debris flow sandstone with multiple thin layers of wavy bedding and grey argillaceous laminae (rigid raft flow section) | Cross-bedding muddy lamina | Non-directional grey-black mudstone tearing debris at the top | |
| 3802 | - - - | - - - | Massive white- light grey siltstone without sedimentary structure. Non-directional grey-black mudstone tearing debris at the top | Cross-bedding muddy lamina | Non-directional grey-black mudstone tearing debris at the top | |
| 3804 | - - - | - - - | Grey or grey-black silty mudstone with abundant gravity slump, with sand ball and sand pillow structures | Cross-bedding muddy lamina | Grey or grey-black silty mudstone with abundant gravity slump, with sand ball and sand pillow structures | |
| 3806 | - - - | - - - | Massive grey- light grey siltstone without sedimentary structure, with monolayer thickness ranging from 20 to 70cm, and a small amount of non-directional grey-black mudstone tearing debris. Multiple thin layers of wavy bedding and grey argillaceous laminae at the top | Cross-bedding muddy lamina | Massive grey- light grey siltstone without sedimentary structure, with monolayer thickness ranging from 20 to 70cm, and a small amount of non-directional grey-black mudstone tearing debris. Multiple thin layers of wavy bedding and grey argillaceous laminae at the top | |

Figure 2. Sedimentary structure characteristics of sandy debris flow sandstone.

1) Lithologic abrupt surfaces in sandy debris flow
The plastic rheological property of the sandy debris flow allows the fluid to maintain the "frozen" feature during transport-deposit process, so the top interface is mainly characterized by abrupt contact with the overlying mudstone.
Hydroplaning and basal shear wetting effect are important mechanism that sandy debris flow can overcome the drag of shear friction with the underlying bed, so that sandy debris flow can carry out long distance underwater transportation at low angle slope, with little or no erosion to the underlying sediment, forming discontinuous parallel bedding shear plane [16-17]. In the sandy debris flow sandstone core of the study area, there are many high angle lithologic abrupt contact surfaces and sandstone “concave and convex” contact surfaces, without scour and erosion phenomena, which reflects the process of slide and shear in the “frozen” transportation and accumulation of sandy debris flow sandstone.

![Figure 3. Lithologic discontinuity surface and shear surface in sandy debris flow cores.](image)

(2) Typical “mud-encased sand” structure in sandy debris flow sandstone

The “mud-encased sand” structure, which is spindle shaped about 4 cm long, with “concave and convex” uneven shape cladding of grey silty mudstone in the outer surface, and smoothing elliptic siltstone tuberculosis with the argillaceous flattening deformation texture at the bottom in its internal, is suspended in thick massive grey siltstone.

![Figure 4. “Mud-encased sand” in sandy debris flow sandstone cores.](image)
This kind of “mud-encased sand” structure is similar with “argillaceous parcel” structure which was founded in the Ordos basin by Xiangbo Li (2014) [18-19]. It’s formation mechanism is that the early sandy debris flow firstly produce liquefaction shear deformation on the underlying argillaceous sediment, then in the process of transportation the upper sand sediments is also involved. Mudstone often torn into crumbs and flakes scattered in the massive sandstone because its shear strength is weak, while the sand balls and pillows in mudstone will continue to show the rigid physical properties because its shear strength is similar to the surrounding sandstone, and eventually the “mud-encased sand” structure could be preserved. This “mud-encased sand” structure still maintains a double-layer structure after long-distance transportation, which proves that the sediment transporting process did not undergo traction current or turbidity current washing, and maintained the plastic rheological property. Therefore, this “mud-encased sand” structure can be used as an important symbolic evidence to identify the sand debris flow deposition.

(3) Massive sandstone and gravity flow characteristics
The upper part of sandy debris flow deposit in the study area mainly consists of thick layer, light grey, massive siltstone or extremely fine sandstone, with monolayer thickness ranging from 20 to 70cm, and a small amount of non-directional grey-black mudstone tearing debris can be seen locally, showing the typical characteristics of rigid raft flow section of sandy debris flow. At the top of massive sandstone, there are multiple thin layers of wavy bedding and grey argillaceous laminae, with the thickness ranging from 10 to 20cm. The imaging logging data indicate that the paleocurrent direction is NE-SW, which is parallel to the trend of slope break zone, and it is speculated that the wavy bedding layers and argillaceous laminae are caused by the transformation of abyssal current.

The lower part is mainly grey or grey-black silty mudstone with abundant gravity slump structures and light grey-white massive siltstone with crumple structures and mudstone tearing debris, which is the characterization of laminar flow section of sandy debris flow. The grey and grey-black silty mudstone in the lower part is characterized by a large number of sliding and simultaneous deformation, as well as gravity flow sedimentary structures such as drainage structures. Generally, there are 2-3cm diameter sand ball and sand pillow structures, and quartz gravel can be seen locally.

3.3. Petrological characteristics
The sandy debris flow sandstone in Meishan formation in the study area is mainly quartz sandstone, followed by lithic quartz sandstone. The rock detrital composition is mainly quartz, feldspar and lithoclast, and the quartz content is from 46% to 68.5%, the potassium feldspar content is from 5 ~ 7.5% and the lithoclast content is from 3 to 9%.

Rock interstitial materials are mainly argillaceous matrix, cements and autogenous minerals which are unevenly distributed. Argillaceous matrix is mainly formed by I/S mixed-layers, illite and chlorite, containing a small amount of kaolinite. The cements mainly consist of ferric calcite and siderite, and the micrite siderite occurred in aggregate. The cementation type is mainly pore cementation. Authigenic glauconite is abundant and elliptic between grains. The porosity of sandy debris flow sandstone is from 10% to 25%, and the permeability is from $0.3 \times 10^{-3}$um$^2$ to $20 \times 10^{-3}$um$^2$.

The pore type are mainly primary intergranular pores and secondary dissolution pores (including intergranular dissolved pores, feldspar dissolved pores and intergranular dissolved pores), especially intergranular pores and moldic pores are relatively rich. The grain size probability cumulative curves is roughly consisted of two segments, showing mainly suspended particulate contents and few saltating particulate contents, without rolling contents. The intersection of these two curves fall at about 3.5 ~ 4.0 Φ, reflecting that the sediments grain size is generally fine and mainly consisted of argillaceous siltstone, silty sandstone with certain characteristics of traction current particle size distribution. The reason for this phenomenon is that the sandy debris flow sediments largely inherited the provenance of delta front and front delta sediment particle size distribution characteristics above the slope because of its fast “frozen” overall transport and deposition mechanism. In the C-M diagram, the C and M values of the sandy debris flow sandstone in the study area are mainly concentrated in the
S-R uniform suspension section, and the whole C-M is roughly parallel to the baseline of C=M, reflecting typical gravity flow deposition characteristics.

Figure 5. The grain size distribution of sandy debris flow sandstone in the Meishan formation.

3.4. Geophysical characteristics

The logging curve characteristics of the Meishan formation sandy debris flow sandstone is mainly funnel-shaped with abrupt interface on the top, reflects lithology coarsening upwards of graded bedding features, and has obvious difference with the turbidity channel sandstone which is typical high amplitude box-like or bell-shaped curve. The sandy debris flow sandstone is relatively isolated strong amplitude reflection on the seismic profile; in contrast the surrounding bathyal facies mudstone shows weak reflection. It does not have a traditional submarine fan “lenticular body” and bidirectional downlap characteristics, reflects the “frozen” sliding forming mechanism. It often truncates the parallel-subparallel, weak amplitude strata of the first member of Sanya formation. Therefore, the top interface of Sanya formation in the study area is mainly manifested as truncated interface.

Figure 6. Typical seismic reflection characteristics of sandy debris flow sandstone in the northern Lingshui Sag (section position as shown in Fig.1, A-A').
4. Sedimentary pattern of sandy debris flow
Sandy debris flow sandstone in Meishan formation of northern Lingshui sag mainly comes from Hainan Island. The NEE-SWW direction continental shelf delta with an obvious foreset feature in the seismic profile distributes in the area near the slope break. In the process of delta construction, the blanket sandstone, mouth bar and distal bar sand-rich deposits are unstable due to the steep slope break and the self-construction. Once affected by external trigger factors such as earthquake or wave, sand-rich deposits on the continental shelf always slides down along the slope break at a high speed with sea water lubrication. Thus, large tongue-like sandy debris flow deposits are formed.

The minimum amplitude attribute and variance volume attribute slices of 3D seismic data can better reflect the distribution of slope break and gravity flow deposition system of Meishan formation in the study area. As shown in Figure 7, there is a corresponding relationship between the gravity flow deposits in the Meishan formation and the landform of slope break in the study area: in the area with a relatively steep slope, where the slope break line is characterized by "concave" form to the sea, incised valley of continental shelf is often formed, thus generating submarine fan turbidity current deposit with supply channel under the slope break. And in the area with relatively gentle, constructive slope, where the slope break line is characterized by "bulge" form to the sea, sandy debris flow deposits were mainly formed in tongue shape near the slope break, without incised valley on a higher place. In addition, the "frozen" sliding of sandy debris flow makes the deposits mainly preserves the original particle size, structure, characteristics of the sediments above the slope. In a period of massive sea level decline, the coarse elastic material from Hainan Island can promote further towards the Lingshui sag, thus more coarse-grained sandy debris flow sandstone may deposit under the slope break.

![Figure 7. Superimpose of seismic attribute and slice of variance cube of Meishan Formation in the northern Lingshui Sag.](image)

5. Conclusion
Through fine drilling core descriptions and micro sedimentary features, it is verified that there is a sandy debris flow sandstone deposits in the Meishan formation of northern Lingshui Sag, Qiongdongnan basin, and discusses the sedimentary characteristics of sandy debris flow sandstone in detail, putting forward “Mud-encased sand” structure as its representative identification mark.
Combined with paleogeography research results, the petrological characteristics and the 3D seismic data, the sedimentary pattern of the Meishan formation sandy debris flow sandstone is established that the area with relatively gentle, constructive slope, where the slope break line is characterized by "bulge" form to the sea, is the most favorable area for the development of sandy debris flow sandstone reservoirs.

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