Acta Geologica Sinica (English Edition), 2021, 95(1): 167–176

Geological Interpretation and Hydrocarbon Exploration Potential of Three Types of Mound-shaped Reflectors in the Meishan Formation, Southern Qiongdongnan Basin

FENG Yangwei[1, 2, 3, 4], REN Yan[1, *], LI Zengxue[2] and JIN Li[4]

[1] *School of Geographical Science and Tourism, Nanyang Normal University, Nanyang, Henan 473061, China*
[2] *Shandong Key Laboratory of Depositional Mineralization & Sedimentary Mineral, Shandong University of Science and Technology, Qingdao, Shandong 266590, China*
[3] *School of Earth Sciences, East China University of Technology, Nanchang 330013, China*
[4] *PetroJindian (Beijing) Sci-Tech Co., Ltd, Beijing 100000, China*

Abstract: Many mound-shaped reflectors with different features and shapes are evident in the Upper Member of the Meishan Formation from seismic profiles taken in the deep-water area of the Southern Qiongdongnan Basin. Based on the drilling, 2D and 3D seismic data from the study area, descriptions of the seismic reflection characteristics as well as the geometric shape, wave impedance inversion, analogy and comparative analyses are carried out. Taken in conjunction with research on the paleostructure and paleosedimentary background, we consider that the mound-shaped seismic reflectors are distributed in the Southern Slop belt and the Southern High-rise of the Qiongdongnan Basin, which can be subdivided into three types: reefs, contourite mounds and magmatic diapirs. The first type, reefs, includes patch reefs, platform marginal reefs and pinnacle reefs. Patch reefs present mound-shaped seismic facies with medium frequency and a moderately strong amplitude, being distributed at the uplift of the fault control platform on the Southern Slop belt. The platform marginal reefs have flat mound-shaped seismic facies with strong amplitude and medium frequency, developing at the margin of the carbonate platform in the Southern High-rise. The pinnacle reefs have mound-shaped seismic facies with strong amplitude and medium frequency and are developed on an isolated volcanic cone. The boundaries between individual reefs are clear on the seismic section, with reef ridge and reef ditch developed, the phenomenon of ‘front product’ being visible within, two-way superelevation between wings is developed and they exist visibly as mounds in any viewed direction of the cross-section. They are slightly asymmetrical in the direction perpendicular to the paleodepth, the reef body being steep near the deep-water side, while being gentle near the shallow water side. The wave impedance of a patch reef is about 7 $kg/m^3 \times m/s$, while the wave impedance of a platform marginal reef is about 7.5 $kg/m^3 \times m/s$. The second type - contourite mounds - are mainly developed under the slope break of the southern slope fault control platform’s edge. They are subdivided into two types: conical and flat. The former has mound-shaped seismic facies with medium-strong amplitude and low frequency, the latter having mound-shaped seismic facies with medium amplitude and low frequency. The internal texture of the mounds is not clear on the seismic section, with the boundaries between contourite mounds being blurred. They are mound-shaped only in cross-section, being banded in the extending direction. The upper surface of a single contourite mound is relatively gentle near the deep-water side, while being steep near the shallow water area. The wave impedance of contourite mounds is about 5.8 $kg/m^3 \times m/s$, which is speculated to represent a marly to calcareous clastic deposit. The third type is the magmatic diapir, which has ‘roots’. They have a dome-shaped upper boundary, are bottomless, with a chaotic interior. They penetrated multiple formations, opening towards the base. There are two major accumulation assemblages of reefs, one is the platform margin reef accumulation assemblage with distant source rocks and long-distance migration through an unconformity surface in the Southern High-rise, the other is the patch reef accumulation assemblage with twin sources and short distance migration through faults in the Southern Slop belt near the Central Depression zone. The latter is the main exploration targets at present. There are contourite mound accumulation assemblages with nearby source rocks and short distance vertical migration through faults, which are potentially important targets. The magmatic diapirs pierce the overlying strata and form good hydrocarbon traps and migration pathways, thus representing potential prospecting targets.

Key words: deep-water area, mound-shaped reflectors, reef, contourite mound, accumulation assemblage

Citation: Feng et al., 2021. Geological Interpretation and Hydrocarbon Exploration Potential of Three Types of Mound-shaped Reflectors in the Meishan Formation, Southern Qiongdongnan Basin. Acta Geologica Sinica (English Edition), 95(1): 167–176. DOI: 10.1111/1755-6724.14636

* Corresponding author. E-mail: 542771805@qq.com

http://www.geojournals.cn/dzxbcn/ch/index.aspx; https://onlinelibrary.wiley.com/journal/17556724

1 Introduction

The global oil and gas exploration areas include onshore, shallow water and the deep-water area. The deep-water area has become one of the hotspots of global oil and gas exploration (Jin, 2006), being as large as 2400 × 10^4 km^2 (Zhang et al., 2019a), with 44% of the world's offshore oil resources distributed there (Zhang et al., 2015a), the equivalent of hundreds of billions of tons of oil. Thus far, about 1500 oil and gas fields have been discovered in the world's deep-water area, the equivalent of an annual oil and gas output of 400–500 million tons of oil. Mound-shaped geological bodies, such as reefs, contourite mounds and magmatic diapirs, have attracted extensive attention, because they have the potential to become important exploration targets for oil and gas in the deep-water area.

The reef reservoir is one of the most important reservoirs (Zhao et al., 2009). The Ghawar oilfield of the Persian Gulf (10.74 billion tons) is the largest oil and gas field in the world, its reservoir being the reef beach body (Salih et al., 2005). The reservoir of the Reforma oilfield (4.09 billion tons) in the Gulf of Mexico is a shelf marginal reef (Henry and Paul, 2007). A series of reef-type oil and gas fields, such as the Tupi oilfield (5–8 billion recoverable barrels), have been found under the salt beds in the Santos basin, eastern continental margin of Brazil (Zhang et al., 2019a). Many reef-type oil and gas fields have been discovered in the South China Sea (Gong, 2009; Feng et al., 2016a). The L gas field on the western slope of the Zengmu Basin is the largest natural gas field in Asia, its reservoir being the pinnacle reef (Zhao et al., 2009). The Liuhua 11-1 oilfield in the Pearl River Mouth Basin is the largest reef reservoir in China, the reservoir being platform marginal reef.

The contourite reservoir should be the focus of future petroleum exploration and development. The empirical data of modern contourites show that it has the potential to develop caprock and source rock (Shanmugam, 2017). So far, contourites have been less discussed from the perspective of petroleum geology. Nevertheless, contourites can be good reservoirs and source rocks, some important discoveries having already been made around the world. The argillaceous clastic contourites in the outer ridge of the Great Antilles Islands demonstrate a TOC value of 2% (Tucholke, 1975), while the argillaceous contourite samples affected by the bay current near the Bermuda uplift show a TOC value of 0.35% (Shanmugam, 2017). The Cretaceous contourite mounds at the continental margin of the Arabic craton formed a large oil and gas accumulation (Bein and Weile, 1976). The sandy contourites accumulated near the Great Bahamas Shoal exhibit a maximum porosity and permeability of 40% and 9881×10^3 μm^2, respectively. Flemming (1980) studied the geomorphology reworked by the Agulhas ocean current at the southeastern shelf margin of South Africa and found that clastic sandy and gravel contourites near the shelf margin can form reservoirs with high porosity and high permeability, being dozens of kilometers long and 5 km wide, parallel to the shelf margin. The measured porosity and permeability of Pliocene–Pleistocene sand bodies reworked by contourite currents in the Ewing Bank of the Gulf of Mexico are 25–40% and (100–1800) ×10^{-3} μm^2, respectively (Shanmugam et al., 1993).

Many geological bodies have a mound-shaped seismic reflection, with random, blank, progradational or horizontal interior seismic response characteristics, such as irruptive rock, extrusive rock, salt (mud) domes, buried hills, mud mounds, torso mountains, single sand bodies, low dip reverse fault constructions, slump subsea aprons and turbidite fans of imbricate arrangement (Zhao et al., 2005; Zhao et al., 2009; Zhang et al., 2020). The identification of the geological body types underlying mound-shaped reflectors is a difficult problem. Seismic profiles from the deep-water area of the Southern Qiongdongnan Basin indicate that there are many mound-shaped reflectors present in the upper member of the Meishan Formation. Geological interpretations of these mound-shaped reflectors have varied in the past, with some researchers interpreting mound-shaped reflectors as reefs（Wu et al., 2009; Ma et al., 2011; Feng et al., 2016b), while others considered them to be contourite mounds (Zhao et al., 2013), the result of sediment wave deposition (Li et al., 2017), channel deposition (Tian et al., 2016; Li et al., 2019), or the consequence of water-rock reaction diagenetic transformations and fluid-filling along the fault zone (He et al., 2012).

The degree to which oil and gas exploration has occurred is low in the deep-water area of the southern Qiongdongnan Basin, with only a few oil and gas drilling wells active at present. The total length of the 2D seismic line is about 12,000 km, the seismic network density being roughly 6 km × 8 km, but varying to 4 km × 6 km and 8 km × 16 km in some areas. The total area of the 3D seismic work area is about 3,000 km^2. In this study, the mound-shaped reflectors in the upper segment of the Meishan Formation are taken as the research object. Based on drilling, 2D and 3D seismic data, through description of the seismic reflection characteristics and geometric shape of these mound-shaped reflectors, wave impedance inversion, analogy and comparative analysis are carried out. In conjunction with research on the paleostructure and paleosedimentary background, this paper focuses on the reasonable interpretation of mound-shaped reflectors from the geological point of view. Through comprehensive analysis of the oil and gas geological conditions of various mound-like geological bodies, the exploration potential is then discussed. This research work is useful in treating a variety of types of mound-shaped reflectors differently in oil and gas exploration in the offshore deep-water realm with few wells or no wells, so as to improve exploration efficiency. It is also helpful in improving the understanding of Miocene paleoceanography in the Qiongdongnan Basin, China South Sea.

2 Regional Geological Setting

The Qiongdongnan Basin is located at the northwest shelf of the South China Sea, which is a Cenozoic marginal sea type passive continental margin rift basin (Zhang et al., 2015b; Wang et al., 2020). According to the thickness of the strata, in conjunction with the main faults controlling the development of the basin, the Qiongdongnan Basin can be divided into three first-order structural units, namely the Northern Uplift zone, Central Depression zone, and Southern Uplift zone(including Southern Slop belt and Southern High-rise).. The deep-water area refers to the vast area south of the 300 m depth contour, an area of about 9×10^4 km^2 (Zhang et al., 2007; Zhang et al., 2011) (Fig. 1).

The basement of the Qiongdongnan Basin consists of Precambrian metamorphic rocks, Mesozoic volcanic and sedimentary rocks, while the caprock is a thick-bedded Cenozoic deposit (Wu, 2016; Feng et al., 2017a; Zhang et al., 2020). Faults developed in the Qiongdongnan Basin (Zhu et al., 2009), the strike of the main fault being basically consistent with that of the structural line in the study area, being in NE, EW and NW directions. Volcanic activity has continued from the Eocene to today in the Qiongdongnan Basin, some manifesting in the form of volcanic diapirs.

The tectonic evolution of the Qiongdongnan Basin has experienced four stages, specifically the pre-rift stage prior to the Late Cretaceous, the pift stage from the end of the Cretaceous to the Paleogene (divided into fault depression stage and rifting–subsiding stage), the thermal subsidence stage in the Early–Middle Miocene, then finally the accelerated subsidence stage, in effect since the Late Miocene (Dong et al., 2008; Neng et al., 2013; Gao et al., 2016; Shao et al., 2019; Zhang et al., 2019b). Four sets of sedimentary-filling sequences are correspondingly developed, namely the pre-rift sequence (below T_g), rift sequence (T_g–T_{60}), depression sequence (T_{60}–T_{40}) and subsidence wedge-shaped flexure sequence (T_{40}–T_0). The Meishan Formation is located in the depression sequence, the upper and lower interfaces being T_{40} and T_{50} respectively. Taking T_{41} as the boundary, the Meishan Formation is divided into the Upper Meishan Formation (T_{40}–T_{41}) and Lower Meishan Formation (T_{41}–T_{50}).

3 Seismic Facies Distribution of the Upper Meishan Formation

A seismic facies is the seismic response of geological bodies (Sun et al., 2002; Chen et al., 2012). According to the four parameters of external shape, internal structure, amplitude and frequency of geological bodies, there are five seismic facies that are recognizable in the Upper Meishan Formation of the southern Qiongdongnan Basin, namely progradation, wedge, sheet, dish and mound (Fig. 2).

Central depression zone: the mid-low frequency parallel -subparallel sheet seismic facies developed at the Lingshui Sag, Songnan Low Bulge, Songnan–Baodao Sag and Changchang Sag. At the junction of the Central Depression zone and Northern Uplift zone, there is a weak amplitude, medium frequency, divergent, wedge-shaped seismic facies, distributed in strips in an east–west direction. There are near east–west intermittent narrow strips of imbricate or S-type progradational seismic facies in the northern Central Depression zone. Dish seismic facies with medium-strong amplitude and low frequency are developed at the border region of the Lingshui Sag, Beijiao Bulge and Beijing Sag. A large range of mound-shaped seismic facies are developed at the southern high-rise, Beijiao Bulge, Beijiao Sag and on the marginal slope of the Songnan Low Bulge (Fig. 2).

4 Results of Geological Interpretation of Mound-shaped Teflectors

The research object of this study was the mound-shaped reflectors in the deep-water area of the southern

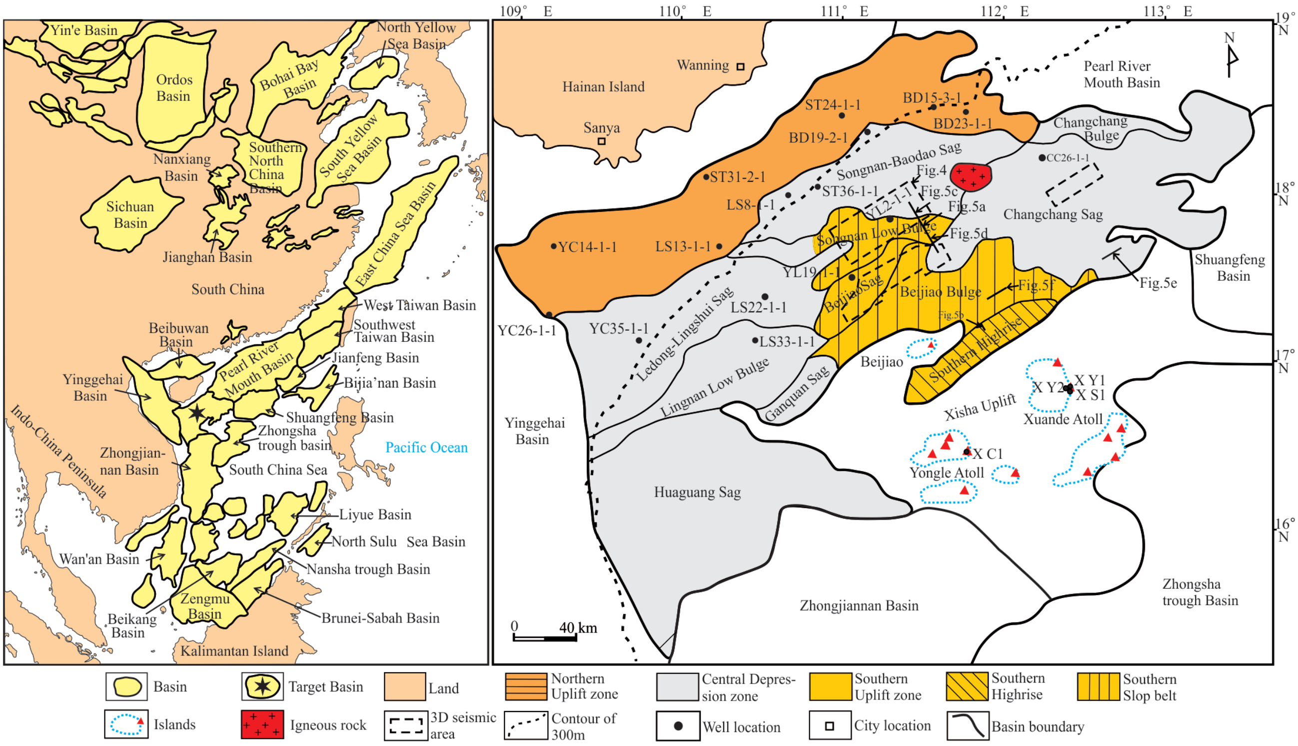

Fig. 1. Generalized geological map of the Qiongdongnan Basin (Modified from Zhang et al., 2015; Feng et al., 2017a.).

Qiongdongnan Basin. Taking into account the seismic reflection characteristics and geometric shape descriptions and using analogy, comparative analysis, wave impedance inversion and forward modeling were targeted then carried out. Combined with research on the paleostructure and paleosedimentary background, the mound-shaped reflectors can be reasonably interpreted to fall into the following three types of geological bodies; reefs, contourite mounds and magmatic diapirs (Fig. 3). Among them, reefs include patch reefs, platform marginal reefs and pinnacle reefs (Fig. 4).

4.1 Reefs

(1) Patch reefs

Patch reefs developed over a large proportion of the margin of the fault-controlled terraces in the Southern Slop belt, presenting as a mound-shaped seismic facies with medium-strong amplitude and medium frequency (Figs. 3, 4 and 5a). Patch reefs are developed in paleogeomorphological highlands, the strata thickness

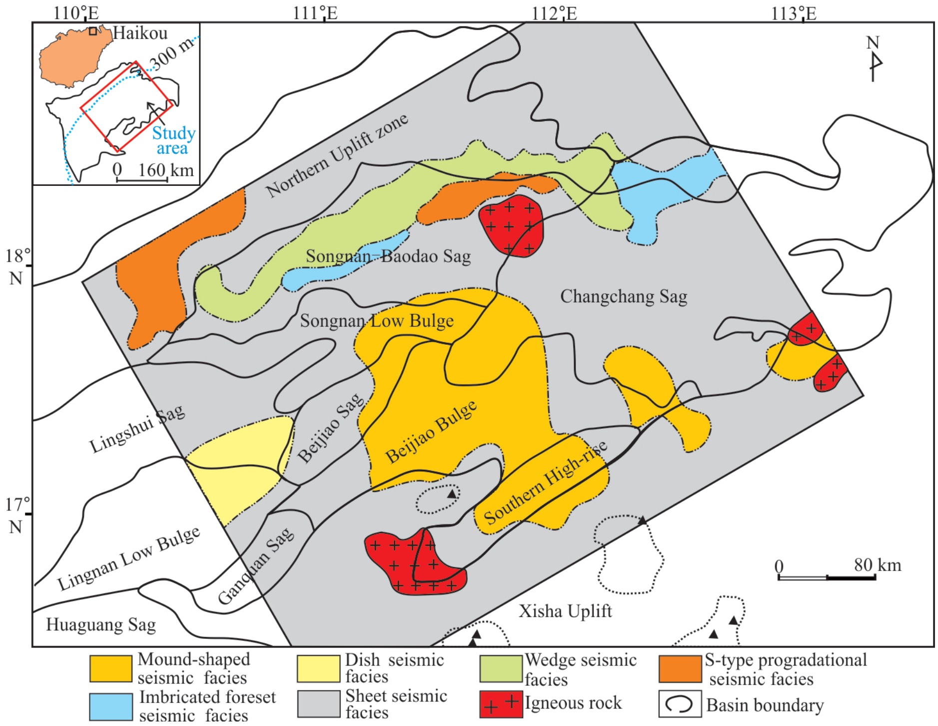

Fig. 2. Plane map of seismic facies of the upper Meishan Formation in the Qiongdongnan Basin (location shown in Fig. 1).

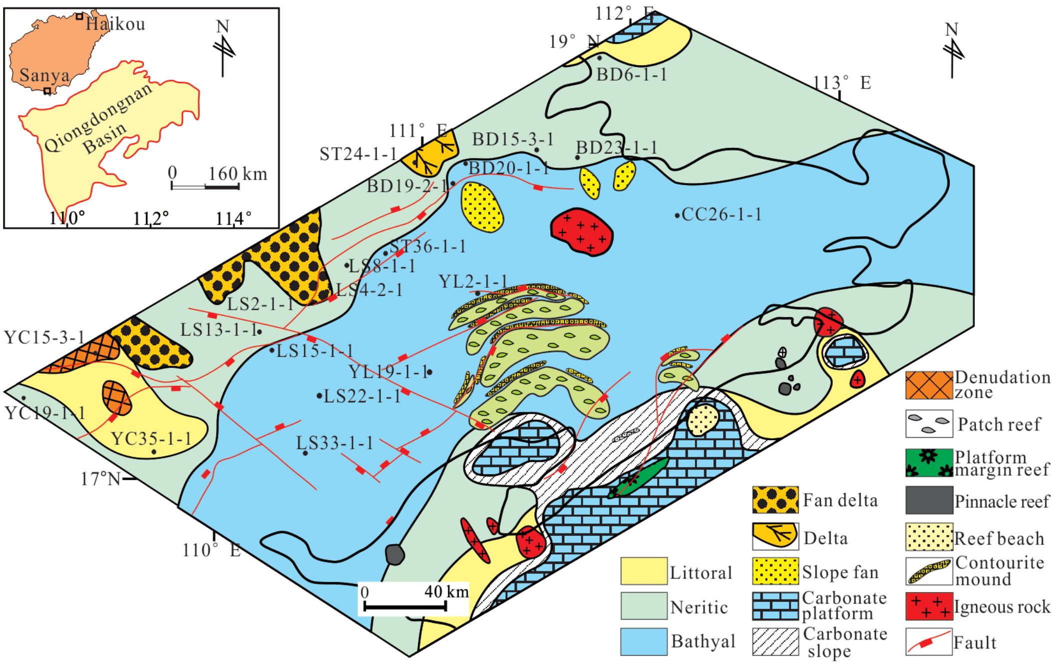

Fig. 3. Sedimentary facies and mound-shaped reflector distribution in the upper Meishan Formation of the southern Qiongdongnan Basin.

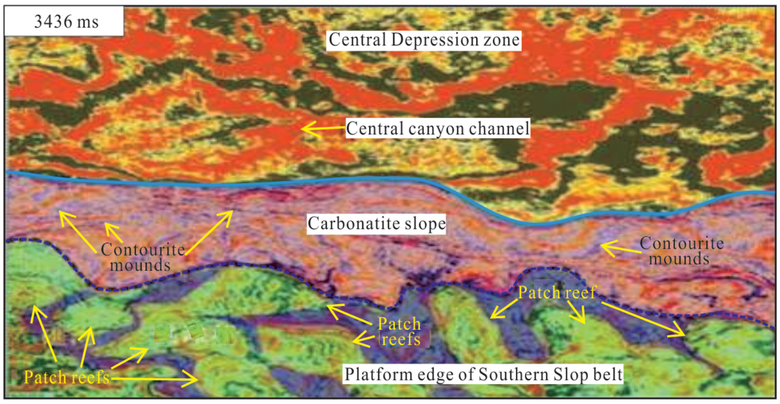

Fig. 4. 3436-ms time-slice of the Meishan Formation in the 3D seismic work area at the northern edge of the southern uplift zone in the southeastern part of the Qiongdongnan Basin (location shown in Fig. 1).

being greater than that of the surrounding strata over the same depositional period. They consist of a reef ridge and a reef ditch, both the upper and lower reflections being strong and uniform, producing a clear outline. From time slice displays of the 3D seismic work area, the outlines of patch reefs are clear and visible, with interlacing distributions of reef ridges and reef canals being evident on the platform (Fig. 4). One single reef is mound-shaped, progradation phenomenon can be seen inside, two-direction overlap being visible between the wings. It has the characteristics of an upper boundary positive reflection coefficient interface (Fig. 5). The height of a single patch reef is around 80–270 m, the slope of the mound wing ranging from 20° to 35° and the density being about 2–3 per 10 km^2. The front reef and back reef are slightly asymmetrical in a direction perpendicular to the paleo-deep-water depth, being steep on the deep-water side, whilst being relatively gentle on the side near the shallow water. Paralleling the paleo-water depth, the patch reef bodies are symmetrical to slightly asymmetrical.

The assemblage of reef bodies is in the shape of an adjacent cone or mound aligned NE–E, distributed in four strips on the plane (Fig. 3). The wave impedance inversion profile shows that the reef top and bottom are uniform and continuous, the wave impedance value reaching about 7 $kg/m^3 \times m/s$ while basically approximating 6 $kg/m^3 \times m/s$ inside, thus meeting the requirements of reef limestone with its high impedance value. In this context, it is very similar to the reef of the Cenozoic Kais Formation as confirmed by drilling in the Salawati Basin, Indonesia (Zampetti et al., 2004). The analogy between them supports the rationale of the interpretation of the patch reef in the Upper Meishan Formation.

(2) Platform margin reefs

Platform margin reefs developed at a paleo-tectonic uplift of the flat-platform edge of the Southern High-rise, with a flat mound-shaped seismic facies with strong amplitude and medium frequency. The shape of one single reef is flat mound-shaped, with reef ridge and reef ditch, two-directional overlap being visible at the reef ditch. The upper and lower reflections are both strong and uniform, the interior almost being layered. The width of the platform margin reef is about 2–8 km, with a length of about 30 km. The height of one single reef is about 100–150 m, the length:height ratio being about 3/1–5/1, the slope of the mound wing ranging from 10° to 15°, with a density of about 1–2 per 10 km^2. The wave impedance inversion profile shows that the wave impedance value of the reef top and bottom is about 7.5 $kg/m^3 \times m/s$, the impedance values being basically about 6.3 $kg/m^3 \times m/s$ within (Fig. 5). Its reflection morphology and wave impedance are very similar to the Liuhua 11-1 platform margin reef, which has been demonstrated by drilling the Dongsha platform in the Pearl River Mouth Basin (Feng et al., 2017a). The Liuhua 11-1 reef has a flat mound-shaped seismic facies with strong amplitude and medium frequency, the top and bottom interfaces displaying a strong and uniform reflection, the interior being layered and continuous, with impedance values of about 8.0 $kg/m^3 \times m/s$ (Mi et al., 2011; Sattler et al., 2004). Large-scale carbonate platforms developed in the Miocene in the Xisha Islands area, where suitable conditions occur for the development of carbonate rocks. XY 1 Well, which encountered a Miocene reef, is located at Xuande Atoll in the Xisha Islands area, which is only about 40km away from the Southern High-rise (Wei, 2007). These are strong pieces of supporting evidence for the development of platform margin reefs in the Southern High-rise of the Qiongdongnan Basin.

(3) Pinnacle reefs

Pinnacle reefs developed on isolated volcanic cones, which are constituent components of tower reef complexes. The reef body is mound-shaped, with a chaotic interior. Pinnacle reefs growth is inherently multiphase, its features being easy to identify. Several large pinnacle reefs, growing on volcanic cones, developed at the southern margin of the Changchang Sag, Qiongdongnan Basin (Fig. 5e).

4.2 Contourite mounds

Contourite mounds primarily developed under the slope break zone of the fault control platform margin in the southern slope belt. According to the geometric shape of the contourite mounds and the relationship between the contourite mounds and the overlying strata, the contourite mounds can be divided into two categories. Type I contourite mounds are conical, with a mound-shaped seismic facies with medium-strong amplitude, low continuity and low frequency. The top of a single mound has a strong reflection, with sub-parallel clutter reflection inside. Multiple contourite mounds form a uniform and continuous lower boundary. The top of the contourite mounds are sharp, the two wings of a mound being asymmetrical. The gullies between contourite mounds are V-shaped and deep. The left wing is steep, while the right wing is gentle. The slope is mostly at 10°–20°, the maximum being over 30°. The ratio of width to height is about 1–2. The boundary between contourite mounds is blurred, some contourite mounds on the right partly

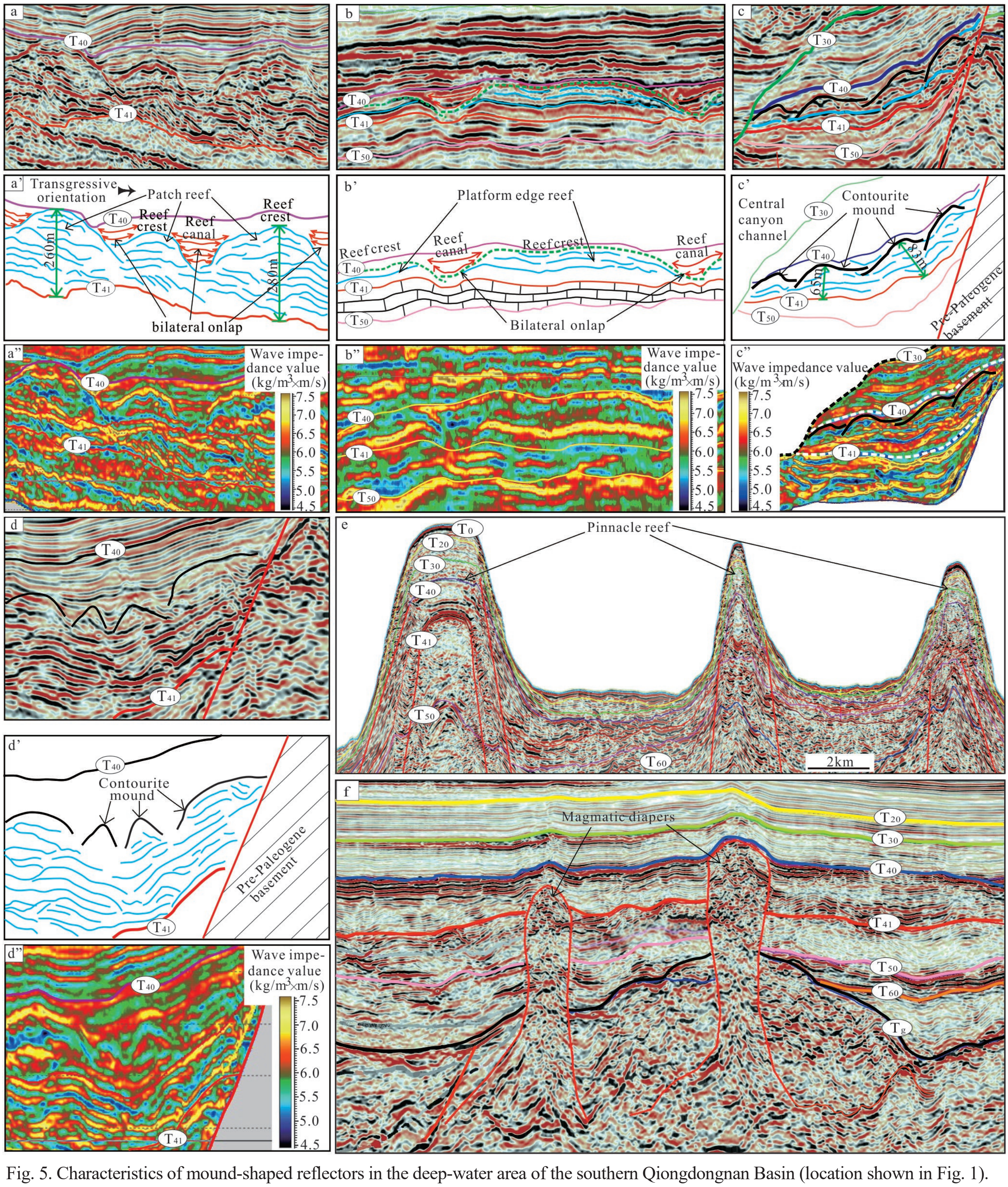

Fig. 5. Characteristics of mound-shaped reflectors in the deep-water area of the southern Qiongdongnan Basin (location shown in Fig. 1).

covering the ones on the left, some almost connecting with each other and appearing as a huge contourite mound (Fig. 5c). Type II contourite mounds are flat, having a mound-shaped seismic facies with medium amplitude, medium continuity and low frequency. The top of a single flat contourite mound is weakly reflective, with sub-parallel clutter reflections inside. There is neither uniformity nor continuity of the upper and lower boundaries for flat contourite mounds. The top of the mound is a gentle arc. The mounds are closely connected, the gullies being shallow. Two wings are symmetrical to micro-asymmetrical. The slope is gentle and mostly at 5°–10°. The width of contourite mounds is 100–1000 m, the height being 50–800 m, producing a ratio of width to height of

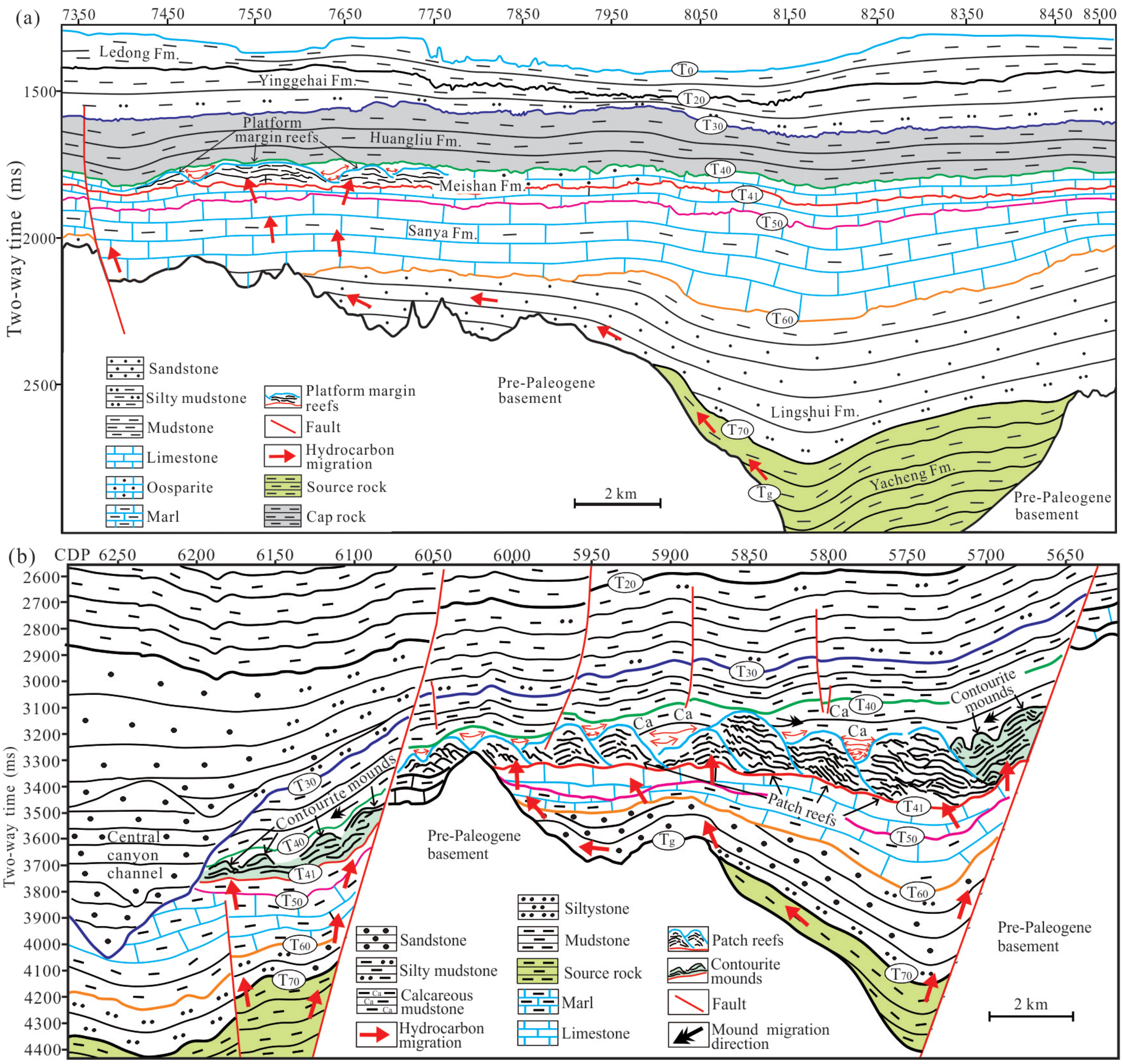

Fig. 6. Accumulation in upper Meishan Formation of mound-shaped reflectors in the southern Qiongdongnan Basin.
(a) Reservoir model of platform margin reefs in the southern high-rise zone; (b) reservoir model of patch reefs and contourite mounds in the southern slope belt.

about 2–5. There is a clear draped relationship between contourite mounds. The contourite mounds are only mound-shaped in north–south cross-section, while they are banded in an east–west extensional direction. The upper surface of one single contourite mound is relatively gentle near the northern paleo-deep-water area, while it is relatively steep near the southern paleo-highrise zone.

The wave impedance inversion profile shows that the wave impedance value of the contourite mounds upper surface reaches about 6.2 kg/m^3×m/s. It is speculated that fine-grained calcareous sediments developed in the later stage of contourite deposition. The wave impedance value of the contourite mounds lower surface is about 6.6 kg/m^3×m/s and it is speculated that the underlying strata consist of bioclastic deposits. The wave impedance values range from 4.6 kg/m^3×m/s to 6.8 kg/m^3×m/s inside, the average being about 5.8 kg/m^3×m/s, which it is interpreted may indicate that the inside of the contourite mounds are marly calcareous clastic deposits.

4.3 Magmatic diapirs

Some magmatic diapirs developed sporadically in the Upper Meishan Formation in the southern Qiongdongnan Basin. A magmatic diapir is characterized by a ‘root’, a mound-shaped upper surface, poor continuity, disordered interior and no lower boundary. Magmatic diapirs open towards the underlying rocks, so that there is always a divergent shape pointing downward. Magmatic diapirs penetrated multiple layers, thus locally changing the continuity of the rock layers (Fig. 5f).

5 Discussion

5.1 Oil and gas exploration potential of reef mounds

The oil and gas geological conditions of reef mounds are superior in the Upper Meishan Formation in the southern Qiongdongnan Basin, which has the characteristics of a near-source, excellent reservoir with a good seal. The central depression zone is a large inherently hydrocarbon-rich depression, the coal measures with carbonaceous mudstone of the Yacheng Formation and the Eocene deep-lacustrine mudstone both having good oil and gas generating capacity (Fu et al., 2020; Magoon and Dow, 1994; He et al., 2012; Feng et al., 2017 b). The reef mounds developed in the southern slope belt and southern high-rise zone, which was semi-surrounded by the large inherently hydrocarbon-rich depression of the Central Depression zone.

The Miocene Kais Formation reefs in the Salawati Basin, Indonesia, are very similar to the patch reefs in the Upper Meishan Formation, the porosity of the reef reservoir in the Kais Formation being about 18%, with oil and gas saturation of about 60% (Zampetti et al., 2004). There was a large-scale sea-level decline at the end of the Meishan Formation sedimentation period, reef mounds becoming exposed and transformed through precipitation leaching, the physical properties of the reservoir thus improving. Thick mudstones developed during the upper Miocene to Quaternary in the southern Qiongdongnan basin, which is a proven regional caprock.

There are two major accumulation assemblages of reefs, one is a platform margin reef accumulation assemblage, with distant-source rocks and long-distance migration through an unconformity surface in the southern high-rise (Fig. 6a). The other is a patch reef accumulation assemblage with twin sources and a short distance migration through faults in the southern slope near the central depression zone (Fig. 6b).

Extensional faults developed in rift layers, which reactivated and extended into the Meishan Formation during the depression stage that provided channels for oil and gas vertical migration. T_{60} is the boundary between the Upper and Lower Cenozoic, which is a regional unconformity formed by the South China Sea movement, acting as a good channel for long-distance oil and gas lateral migration. As shown in Fig. 5a, the favorable hydrocarbon generating area on the right is the Changchang Sag, oil and gas mainly migrating laterally along the T_{60} unconformity to the platform margin reef reservoirs developed in the Southern High-rise. As shown in Fig. 5b, patch reef reservoirs developed in the high part of the Songnan Low Uplift, the Songnan-Baodao Sag on the left and Beijiao Sag on the right being favorable hydrocarbon-generating depressions. A high-angle normal fault is an important channel for short distance oil and gas vertical migration in favorable hydrocarbon-generating depressions. Overpressure is widely-developed in favorable hydrocarbon-rich sags, while patch reef reservoirs in the high part of the Songnan Low Bulge are under normal pressure, oil and gas accumulating in the patch reef reservoirs as a result of the excess pressure (Zhang et al., 2007).

5.2 Oil and gas exploration potential of contourite mounds

The Meishan Formation contourite mounds in the Qiongdongnan Basin are prospective oil and gas resources. The contourite development zone extends from the Xisha Uplift to the Central Depression zone in the hinterland of the basin, adjacent to the proven gas-rich source kitchen. In these proven large-scale inherently hydrocarbon-rich sags, the Yacheng Formation marine–continental transitional coal measures and Eocene deep lake mudstone are the main source rocks (Magoon et al., 1994; Zhu, 2010). Since the Pliocene, the Central Depression zone has been in a ‘hot basin’ state; the strata are very thick and uncompacted and the source kitchen is subject to overpressure, due to fluid thermal expansion along with hydrocarbon generation through heating (Tang et al., 2014). The Meishan Formation contourite drifts constitute the reservoir, which surrounds the southern uplift zone in many belts. Contourites have good reservoir properties in the areas of discovery around the world; the Meishan Formation contourites might have been exposed for a short time and weathered and leached when the global sea-level declined rapidly at the end of the middle Miocene; regional transgression occurred in the Qiongdongnan Basin since the late Miocene, ensuring that the Meishan Formation contourites were overlain by a regional thick mudstone caprock. Thus, a good assemblage of lower source rocks, upper reservoir rocks and caprock is available. Controlled by the S–N extensional fault during the tectonic evolution of the Qiongdongnan Basin, the E–W extensional faults are developed in the basin, and they provide channels for the vertical migration of oil and gas. In Fig. 6b, the left contourites are close to the gas-rich Songnan-Baodao Sag, while the right contourites communicate with the gas-rich Changchang-Baodao Sag. These gas-rich sags are generally in overpressure, while the Songnan Low Bulge is at normal pressure. Driven by excess pressure, the gas generated by the source kitchen migrated a short distance vertically to accumulate in the contourite reservoirs along the direction of decreasing fluid potential.

5.3 Oil and gas exploration potential of magmatic diapirs

Magmatic diapirs pierce the overlying layers, forming good oil and gas traps. The contact zone between magmatic diapirs and the surrounding rocks can also be used as a good channel for oil and gas vertical migration. It therefore represents good prospects for oil and gas exploration.

6 Conclusions

The mound-shaped seismic reflectors can be subdivided into three types: reefs, contourite mounds and magmatic diapirs. Reefs developed in the clear water environment of the paleogeomorphic highlands, including patch reef, platform marginal reef and pinnacle reef. The shape of the reef is mound-shaped and like a convex lens, with strong reflection at both top and bottom. The outline of the reef is clear, the progradation phenomenon can be seen inside and a slight asymmetry exists between the front reef and the back reef. There are two types of reservoir models of reef, one is the reservoir model of platform margin reefs in the southern high-rise zone, the other is the reservoir model of patch reefs in the Southern Slop belt. They are the main exploration targets at present.

There are two types of contourite mounds, conical and flat. Contourite mounds developed under the slope break zone of the fault control platform margin in the Southern Slop belt. The gullies between the contourite mounds are V-shaped. The outline is unclear, with sub-parallel clutter reflection inside. The contourite mounds are only mound-shaped in north–south cross-section, while they are banded in an eas–west extensional direction. There are contourite mound accumulation assemblages with nearby source rocks and short distances of vertical migration through faults, which are potentially important targets.

Magmatic diapirs developed sporadically, characterized by their 'root'. Magmatic diapirs penetrated multiple layers, forming good oil and gas traps, providing good channels for oil and gas vertical migration. They constitute good prospects for oil and gas exploration.

Acknowledgements

This study was funded by the National Natural Science Foundation of China (41872172,42072188), Jiangxi Provincial Natural Science Foundation (20202BABL211019), Open Fund Project of the Key Laboratory of Sedimentary Mineralization and Sedimentary Mineral Resources in Shandong Province (DMSM 2019008), Thanks are expressed by the authors for the hard work of the editors as well as the constructive opinions and suggestions from the peer reviewers.

Manuscript received May 22, 2020
accepted Nov. 7, 2020
associate EIC: ZHANG Gongcheng
edited by Jeff LISTON and FEI Hongcai

References

Bein, A., and Weile, R.Y., 1976. The Cretaceous Talme Yafe Formation: A contour current shaped sedimentary prism of calcareous detritus at the continental margin of the Arabian Craton. Sedimentology, 23(4): 511– 532

Chen, H.Q., Zhu, X.M., Zhang, G.C., Zhang, X. L., and Zhang, Q., 2012. Seismic facies in a deepwater area of a marine faulted basin: Deepwater area of the Paleogene Lingshui Formation in the Qiongdongnan Basin. Acta Geologica Sinica (English Edition), 86(2): 473–483.

Dong, D.D., Wu, S.G., Zhang, G.C., and Yuan, S.Q., 2008. Rifting process and formation mechanisms of syn-rift stage prolongation in the deepwater basin, northern South China Sea. Chinese Science Bulletin, 53(23): 3715–3725.

Feng, Y.W., Qu, H.J., Zhang, G.C., and Pu, R.H., 2017a. Seismic interpretation and exploration direction of Miocene Meishan formation reef in Southern Qiongdongnan Basin, Northern South China Sea. Journal of Palaeogeography, 6(3): 206–218.

Feng, Y.W., and Zhang, G.C., 2017b. Tectonic evolution and controls on source rock development in global deep-water area at passive continental margin. Marine Origin Petroleum Geology, 22(1): 14–24 (in Chinese with English abstract).

Feng, Y.W., Zhang, G.C., and Qu, H.J., 2016a. Development regularity and hydrocarbon exploration potential of Cenozoic reef reservoir, South China Sea. China Petroleum Exploration, 21(6): 18–25 (in Chinese with English abstract).

Feng, Y.W., Qu, H.J., Zhang, G.C., and Pu, R.H., 2016b. The seismic facies analyzing of deep water area of Miocene Meishan formation in Qiongdongnan Basin, northern South China Sea. Journal of Mineralogy and Petrology, 36(3): 82–95 (in Chinese with English abstract).

Flemming, B.W., 1980. Sand transport and bedform patterns on the continental shelf between Durban and Port Elizabeth (southeast African continental margin). Sedimentary Geology, 26(1/2/3): 179–205.

Fu, N., Bian, L.Z., Cao, J., Yang, H.Z., and Wang, K., 2020. Macrobenthic red algae and their hydrocarbon generation characteristics in the Oligocene source rocks in the deep water area, Qiongdongnan Basin, China. Petroleum Exploration and Development, (06): 1–10 (in Chinese with English abstract).

Gao, J.W., Wu, S.G., Mcintosh, K., Mi, L.J., Liu, Z., and Spance, G., 2016. Crustal structure and extension mode in the northwestern margin of the South China Sea. Geochemistry Geophysics Geosystems, 17(6): 2143–2167.

Gong, Z.S., 2009. Reef-important exploration field in deepwater area of of northern continental margin in South China Sea. China Offshore Oil and Gas, 21(5): 289–295 (in Chinese with English abstract).

He, Y.L., Xie, X.N., Lu, Y.C., Li, X.S., Xu, W., and Zou, H.C., 2012. Origin of high-amplitude reflections in Meishan Formation of the southern Qiongdongnan Basin and its significance in hydrocarbon exploration. Acta Petrolei Sinica, 33(4): 617–624 (in Chinese with English abstract).

Henry, S.P., and Paul, W., 2007. Deepwater remains immature frontier. Offshore, 20 the new prospecting targets of northern continental Margin of South China Sea. Acta Petrolei Sinica, 62 (10): 48–50.

Jin, Q.H., 2006. Petroleum in deep water is major prospecting hot spot nowadays. Scientific Chinese (11): 18–20 (in Chinese with English abstract).

Li, Y.F., 2019. The characteristics and origin of unidirectionally migrating channels of Meishan Formation in the Beijiao Sag, Qiongdongnan Basin. Haiyang Xuebao, 41(1): 72–86 (in Chinese with English abstract).

Li, Y.F., Pu, R.H., Hu, B.Q., Fan, X.W., Li, B., Deng, D., Wang, F., and Guo, R.C., 2017. The characteristics of seisimic reflections on the top of the Meishan formation in the Beijiao sag of Qiongdongnan basin. Haiyang Xuebao, 39(12): 53–62 (in Chinese with English abstract).

Ma, Y.B., Wu, S.G., Lv, F.L., Dong, D.D., 2011. Seismic characteristics and development of the Xisha carbonate platforms, northern margin of the South China Sea. Journal of Asian Earth Sciences, 40: 770–783

Magoon, L.B., and Dow, W. G., 1994. The petroleum system-from source to trap. AAPG Memoir 60.

Mi, L.J., and Zhang, G.C., 2011. Strategic investigation and evaluation of oil and gas resources in deepwater area of northern continental margin, South China Sea. Beijing: Geological Publishing House.

Neng, Y., Wu, J.F., Qi, J.F., Zhang, G.C., He, Y.P., and Chen, W.C., 2013. Three structural layers and its evolution of Cenozoic Basins in deep water area of Northern Margin, South China Sea. Acta Geologica Sinica (English Edition), 87 (3): 403–414

Salih, S., Khattab, A.H., and Dogan, P., 2005. Surface expressions of the Ghawar structure, Saudi Arabia. Marine and Petroleum Geology, 22: 657–670.

Sattler, U., Zampetti, V., Schlager, W., and Immenhauser, A., 2004. Late leaching under deep burial conditions: a case study from the Miocene Zhujiang Carbonate Reservoir, South China Sea. Marine and Petroleum Geology, 21: 977–992

Shanmugam, G., 2017. Contourites: Physical oceanography, process sedimentology, and petroleum geology. Petroleum Exploration and Development, 44(2): 177–195.

Shanmugam, G., Spalding, T.D., and Rofheart, D.H., 1993. Process sedimentology and reservoir quality of deep-marine bottom-current reworked sands (sandy contourites): An example from the Gulf of Mexico. AAPG Bulletin, 77(7): 1241–1259.

Shao, L., Cui, Y.C., Stattegger, K., Zhu, W.L., Qiao, P.L., and Zhao, Z.G., 2019. Drainage control of Eocene to Miocene

sedimentary records in the southeastern margin of Eurasian Plate. GSA Bulletin, 131(3–4): 461–478.
Sun, J.Z., and Li, L.B., 2002. Comprehensive Interpretation Course of Seismogeology. Wuhan: China University of Geosciences Press.
Tang, X.Y., Hu, S.B., Zhang, G.C., Liang, J.S., Yang, S.C., Shen, H.L., Rao, S., and Li, W.W., 2014. Geothermal characteristics and hydrocarbon accumulation of the northern marginal basins, South China Sea. Chinese Journal of Geophysics, 57 (2): 572–585 (in Chinese with English abstract).
Tian, J., Wu, S.G., Wang, D.W., Lü, F.L., Wang, B., and Zhang, X., 2016. Characteristics of periplatform channels of the Xisha area, northern South China Sea. Marine Sciences, 40(6): 101–109 (in Chinese with English abstract).
Tucholke, B.E., 1975. Sediment distribution and deposition by the western boundary undercurrent: The Great Antilles Outer Ridge. Journal of Geology, 83(2): 177–207.
Wang, P.C., Li, S.Z., Suo, Y.H., Guo, L.L., Wang, G.Z., Hui, G.G., Santosh, M., Somerville, I.D., Cao, X.Z., and Li, Y., 2020. Plate tectonic control on the formation and tectonic migration of Cenozoic basins in northern margin of the South China Sea. Geoscience Frontiers, 11(4): 1231–1251.
Wei, X., 2007. Characteristic of reef carbonatite and hydrocarbon exploration foreground in Xisha waters. Beijing: Geological Publishing House (in Chinese with English abstract).
Wu, B.W., 2016. The Cenozoic stratigraphy in deepwater area of Southern Qiongdongnan basin. Journal of Stratigraphy, 40(1): 63–66 (in Chinese with English abstract).
Wu, S.G., Yuan, S.Q., Zhang, G.C., Ma, Y.B., Mi, L.J., and Xu, N., 2009. Seismic characteristics of a reef carbonate reservoir and implications for hydrocarbon exploration in deepwater of the Qiongdongnan Basin, northern South China Sea. Marine and Petroleum Geology, 26: 817–823
Zampetti, V., Schlager, W., Konijnenburg, J.H.V., and Everts, A.J., 2004. Architecture and growth history of a Miocene carbonate plateform from 3D seismic reflection data: Luconia province, offshore Sarawak, Malaysia. Marine and Petroleum Geology, 21: 517–534
Zhang, G.C., Mi, L.J., Qu, H.J., Feng, Y.W., and Fan, Y.H., 2011. A basic distributional frame of global deepwater basins and hydrocarbon characteristics. Acta Petrolei Sinica, 32(3): 369–37 (in Chinese with English abstract).
Zhang, G.C., Qu, H.J., and Feng, Y.W., 2015a. An introduction to the petroleum geology of deepwater settings. Beijing: Science Press (in Chinese with English abstract).
Zhang, G.C., Qu, H.J., Zhang, F.L., Chen, S., Yang, H.Z., Zhao, Z., and Zhao, C., 2019a. Recent major discoveries of oil and gas in global deepwaters and enlightenment. Acta Petrolei Sinica, 40(01): 1–34, 55 (in Chinese with English abstract).
Zhang, G.C., Shao, L., Qiao, P.J., Cao, L.C., Pang, X., Zhao, Z.G., Xiang, X.H., and Cui, Y.C., 2019b. Cretaceous–Paleogene sedimentary evolution of the South China Sea region: a preliminary synthesis. Geological Journal, 55(8): 1–22.
Zhang, H., Shao, L., Zhang, G. C., Cui, Y. C., Zhao, Z., and Hou, Y., 2020. The response of Cenozoic sedimentary evolution coupled with the formation of the South China Sea. Geological Journal, 1–22. https://doi.org/10.1002/gj.3856
Zhang, W., Liang, J.Q., Yang, X.H., Su, P.B., and Wan, Z.F., 2020. The formation mechanism of mud diapirs and gas chimneys and their relationship with natural gas hydrates: insights from the deep-water area of Qiongdongnan Basin, northern South China Sea. International Geology Review, 62 (7–8): 789–810.
Zhang, G.C., Mi, L.J., Wu, S.G., Tao, W.X., He, S.B., and Lü, J.J., 2007. Deep water area-the new prospecting targets of northern continental margin of South China Sea. Acta Petrolei Sinica, 28(2): 15–21 (in Chinese with English abstract).
Zhao, T.L., Pu, R.H., Qu, H.J., Zhang, G.C., Liang, J.S., and Feng, Y.W., 2013. An origin discussion of mound-shaped reflections in Miocene, southern Qiongdongnan Basin. Haiyang Xuebao, 35(4): 112–120 (in Chinese with English abstract).
Zhao, Z.Z., Zhao, X.Z., and Wang, Y.M., 2005. Theory and practice of reservoir seismic prediction. Beijing: Science Press (in Chinese with English abstract).
Zhao, B.L., and Du, X.D., 2009. The geologic feature and physics identify of reef. Beijing: Petroleum Industry Press (in Chinese with English abstract).
Zhu, M.Z., Graham, S., Pang, X., and Mchargue, T., 2010. Characteristics of migrating submarine canyons from the middle Miocene to present: Implications for paleoceanographic circulation, northern South China Sea. Marine and Petroleum Geology, 27(9): 307–319.
Zhu, W.L., Huang, B.J., Mi, L.J., Wilkins, R.W.T., Fu, N., and Xiao, X.M., 2009. Geochemistry, origin, and deep-water exploration potential of natural gases in the Pearl River Mouth and Qiongdongnan basins, South China Sea. AAPG Bulletin, 93(6): 741–761.

About the first author

FENG Yangwei, male, born in 1987 in Shaanxi Province; Ph.D.; graduated from Northwest University; lecturer, Master Instructor. He is now interested in the study of marine petroleum geology. Email: 2005130009@163.com. phone: 19838725688.

About the corresponding author

REN Yan, female, born in 1987 in Henan Province; graduated from Henan Normal University; assistant experimentalist. She is now interested in the study of seismic interpretation and laboratory management. Email: 542771805@qq.com.phone: 16679050178.