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Seismic analysis of early-mid Miocene carbonate platform in the southern Qiongdongnan Basin, South China Sea

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Abstract
The southern uplift of the Qiongdongnan Basin is a deepwater area in which no wells have beens drilled. The Miocene-Quaternary strata in the Xisha Islands, which are located 40–100 km to the south, are composed of carbonate reef formations. Paleotectonic and paleogeographic analyses of the basin suggest that the southern uplift experienced favorable geological conditions for the development of carbonate reefs during the Miocene. The high-impedance carbonates have high amplitudes and low frequencies on seismic profiles. The reefs are distributed on paleotectonic highs and are thicker than the contemporaneous formations. A forward model of the variation in carbonate thickness based on lithological and velocity information from wells in nearby regions can simulate the seismic response of carbonates with different thicknesses. We identified several important controlling points for determining the thickness of carbonates from seismic profiles, including the pinchout point, the $\lambda/4$ thickness point, and the $\lambda/2$ thickness point. We depict a carbonate thickness map in the deepwater area of the southern Qiongdongnan Basin based on this model. The carbonate thickness map, the paleotectonic and paleogeographic background, and the seismic response characteristics of reefs suggest that the carbonates that developed on the southern uplift of the Qiongdongnan Basin during the Miocene were mainly an isolated carbonate platform peninsula and ramp deposits. It consisted of gentle ramp platform, steep slope platform, platform depression, gravity flow, and reef bank facies.

Key words: forward model, carbonate rock, thickness, facies distribution, Qiongdongnan Basin

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1 Introduction

Carbonate rocks are both source and reservoir rocks and important in oil and gas exploration. Analysis of seismic data is the major method of studying deepwater areas with no wells. However, identifying carbonate platforms solely based on seismic data is risky. Carbonate platforms, folds, tilted fault blocks, volcanoes, and basement uplifts may all show similar seismic responses (Burgess et al., 2013). Especially it is more difficult if we attempt to identify an isolated carbonate platform by means of seismic interpretation.

The deepwater area of the southern uplift of the Qiongdongnan Basin has favorable growth conditions for carbonate reefs and banks. The four wells on the Xisha Islands in the southern basin, including Wells Xiyong 1, Xichen 1, Xiyong 2 and Xishi 1, all show massive Miocene-Quaternary biogenic reef carbonates directly overlying pre-Cenozoic basement, which indicates that this area has always been a carbonate depositional environment (Fig. 1). The Qiongdongnan Basin mainly received distal terrigenous fine clastic deposits in the Miocene. During the deposition of the Sanya Formation, the southern uplift subsided slowly and was in a littoral-neritic sea depositional environment, and the highland on the uplift became an underwater ridge. During this period, the shallow-water area surrounding the Beijiao low-uplift and the Yongle uplift developed carbonate platforms and biogenic reefs (Qiu and Wang, 2001; Wei et al., 2006; Wu et al., 2009; Zhang et al., 2011; Zhou et al., 2013; Xi et al., 2014). The slopes surrounding uplifts developed mixed de posits of carbonates and terrigenous clastic rocks. The southern uplift is located only 40–100 km from the carbonate platform in the Xisha Islands to the south. The Miocene strata in the Lingshui depression and Changchang depression to the north of the uplift are all composed of terrigenous clastic rocks (Fig. 2). Clastic sediments are much more common in Yongle depression which is closer to the southern uplift. The southern uplift between these depressions is likely a transition zone between carbonates and clastic rock deposits during the Miocene (Yang et al., 2010; Ma et al., 2012; Tang et al., 2013).

2 Evidence for carbonate development in the southern uplift during the Miocene

The southern uplift region is a distal pelagic area. No wells have yet revealed the reflections of the high-amplitude. Based on the reflection characteristics of reef and carbonate, we suggest that the high-amplitude reflections of the Miocene series on the ancient uplift in the southern deepwater area of the Qiongdongnan Basin represent a carbonate formation that contains biogenic reefs and banks. First, the Miocene was an important period in which the South China Sea extensively developed carbonates and

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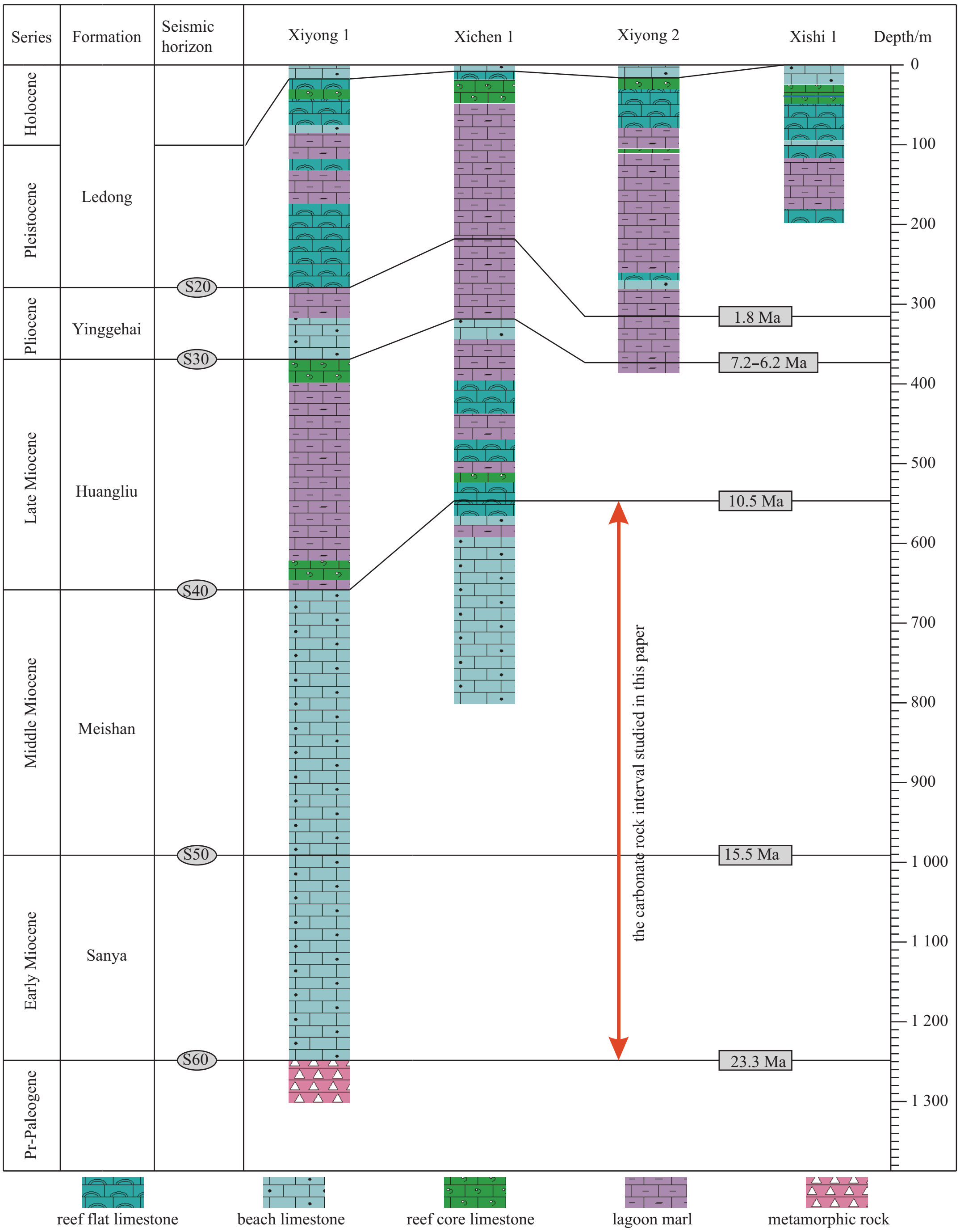

Fig. 1. Sedimentary facies map of the Xisha Islands area. Modified from Zhao (2010).

biogenic reefs (Liu et al., 2003; Zampetti et al., 2004; Fyhn et al., 2013; Steuer et al., 2014; Zhang et al., 2015). Many reef reservoirs that have been discovered in the South China Sea are in Miocene strata that were located on ancient uplifts, including the southern uplift of Qiongdongnan Basin (Chen et al., 2011, 2015). The carbonates have high-amplitude reflections on seismic profiles (Lu et al., 2010; Mi et al., 2013), which become low-amplitude reflections as the carbonates thin and transform to sands and shales from the platform margin to the interior of the depressions. Second, we observed typical carbonate and biogenic reef reflections on seismic profiles in the deepwater area of the southern uplift (Figs 3 and 5). They overlain on ancient basement highs and had typical dune shapes that were thicker than the bilateral contemporaneous strata, which reflects the biogenic reef built up first, and the bilateral strata later overlap the reef from the sides. Figure 4 shows a schematic geological profile along survey Line A. Third, the high-amplitude reflections of the Miocene strata on the southern uplift have similar polarity to the positive reflection of the seafloor. On positive-polarity profiles, the high-amplitude responses have upper peak lower trough (90° phase angle) or one peak two troughs (0° phase angle) (Brown, 1996). The high amplitudes are likely caused by high-velocity carbonates that are thinner than the tuning thickness (approximately 40 m in the study area). Finally, since the Miocene high-amplitude reflections of the southern uplift of the Qiongdongnan Basin are located near the Miocene carbonate platform (Xisha

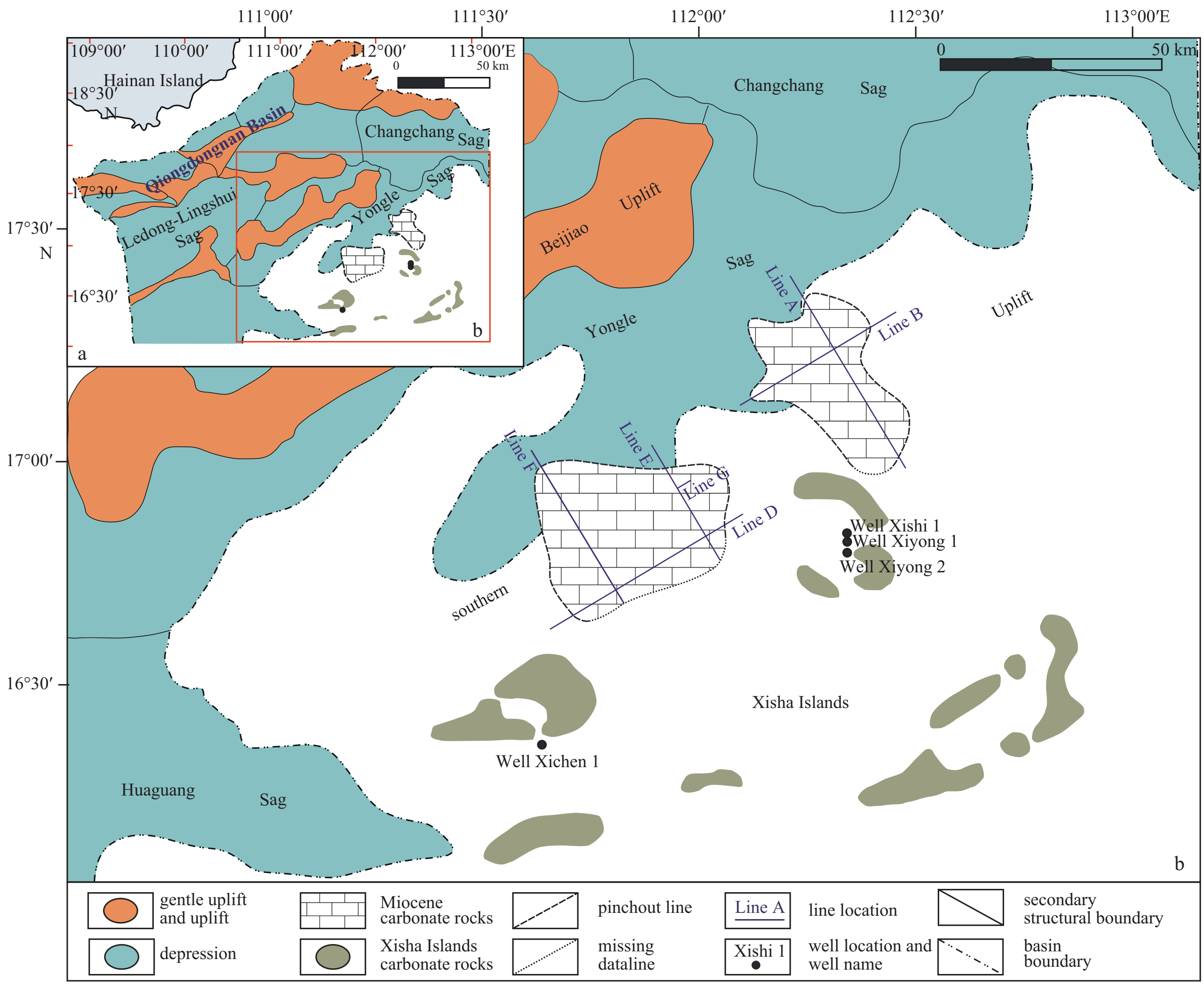

Fig. 2. Location of Qiongdongnan Basin (a) and distribution of carbonate platforms in the southern uplift of Qiongdongnan Basin (b). The red square in Fig. 2a is the location of Fig. 2b.

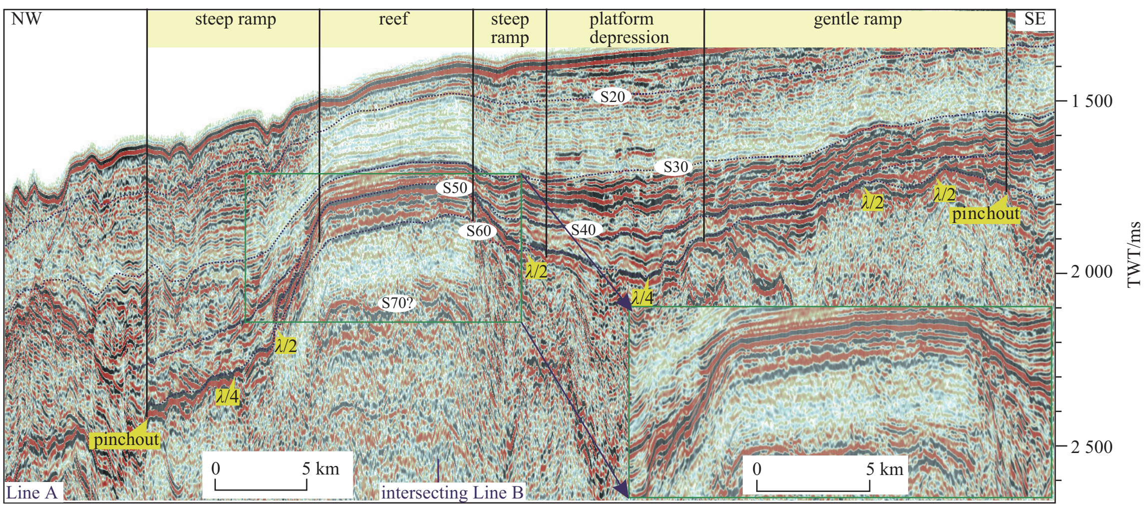

Fig. 3. Seismic responses of the carbonate reefs, fore-reef steep ramp deposits, and back-reef gentle ramp deposits of the Sanya Formation (S60–S50) on the southern uplift in the Qiongdongnan Basin. Deposits S50–S40 are missing from this platform.

Uplift) (Fig. 2), the two may be connected, and the reef carbonate deposits of the former may be a northern extension of the latter.

Based on the 4 km×16 km two-dimensional seismic network

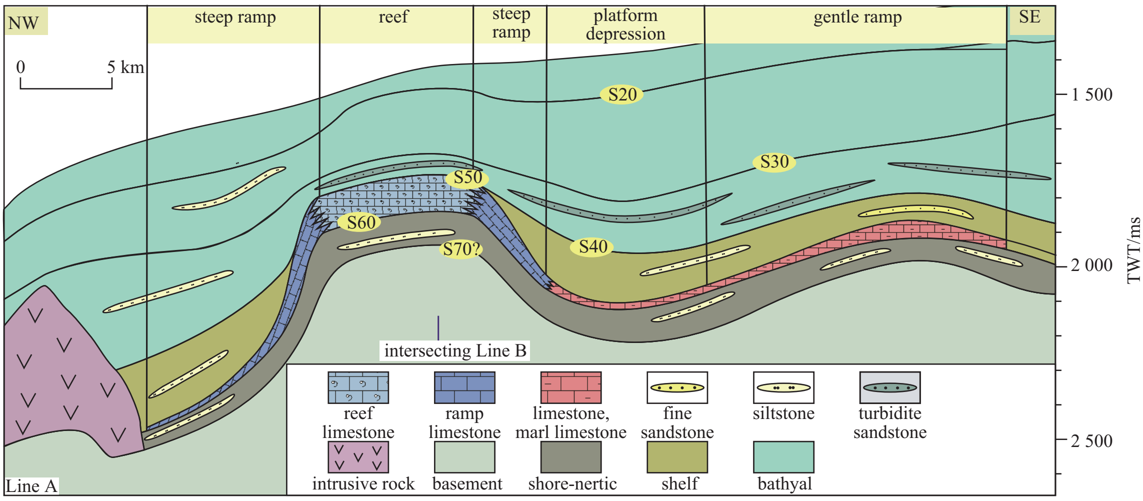

Fig. 4. Schematic geological profile of the carbonate platform of the Sanya Formation (S60–S50) on the southern uplift in the Qiongdongnan Basin.

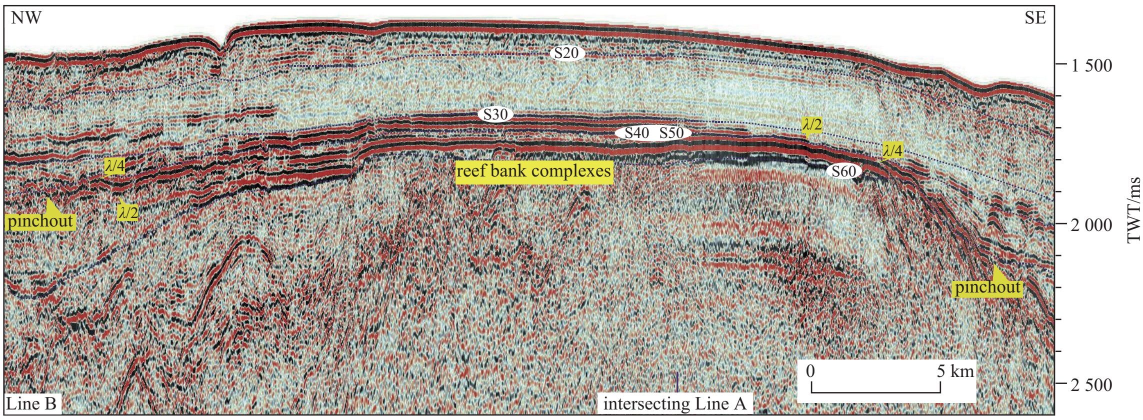

Fig. 5. Reflection of the Miocene carbonate platform reef bank on the southern uplift of the Qiongdongnan Basin. Deposits S50–S40 are missing from this platform.

data in this region, the paleotectonic and paleogeographic analyses of the conditions of carbonate deposition, and the relationship between the response characteristics of carbonates of different thicknesses and the sedimentary environment, we mapped the Miocene carbonate thickness and facies distribution of the southern uplift.

3 Seismic response model of carbonate thickness

The degree of agreement between forward models and the subsurface conditions depends on the prior understanding of the subsurface parameters. We obtained the parameters of the lithology, thickness, and velocity of the strata based on wells in nearby regions. The velocity of the Miocene Sanya Formation (S60–S50) carbonates is about 4 700 m/s, the velocity of sandstone is between 2 500 and 3 700 m/s, and the velocity of mudstone is 2 400–3 600 m/s. The main frequency of the seismic wavelet in the study region is approximately 35 Hz, and the wavelength (λ) is approximately 160 m. The corresponding tuning thickness is approximately 40 m (Fig. 6). Based on the Widess wedge seismic response model (Widess, 1973), we developed a geological model in which the massive carbonates at Xisha thin northward and then selected several key points that caused variations in the amplitude and waveform, such as the carbonate pinchout point, the $\lambda/4$ thickness point, and the $\lambda/2$ thickness point. When the thickness of a carbonate layer is $\lambda/2$ (approximately 80 m), the waveforms that are reflected from the top and bottom boundaries of the carbonate are barely separated and form two peaks and two troughs. When the thickness of the carbonate is greater than $\lambda/2$, the waves form multiple peaks and troughs with a constant amplitude. When the thickness of the carbonate is $\lambda/4$, which is approximately 40 m, the wavelets that are reflected from the top and bottom of the carbonate layer constructively interfere (a tuning effect), and the relative amplitude of the composite waveform reaches a maximum. When the thickness is less than $\lambda/4$, the amplitude decreases with decreasing thickness. When the carbonates pinch out, the seismic event ends. The reflection waveform and amplitude characteristics of these thickness-control points are the basis for estimating the thickness of the carbonates from two-dimensional seismic profiles in this region (Fig. 6).

In addition, the seismic profiles in this region are in positive-polarity displays. As shown in the forward model (Fig. 6), high-impedance carbonates that are less than $\lambda/4$ thick generally form reflections with one peak two troughs or upper peak lower trough. When the thickness of the carbonate layer is greater than the half wavelength, the top boundary shows a reflection with

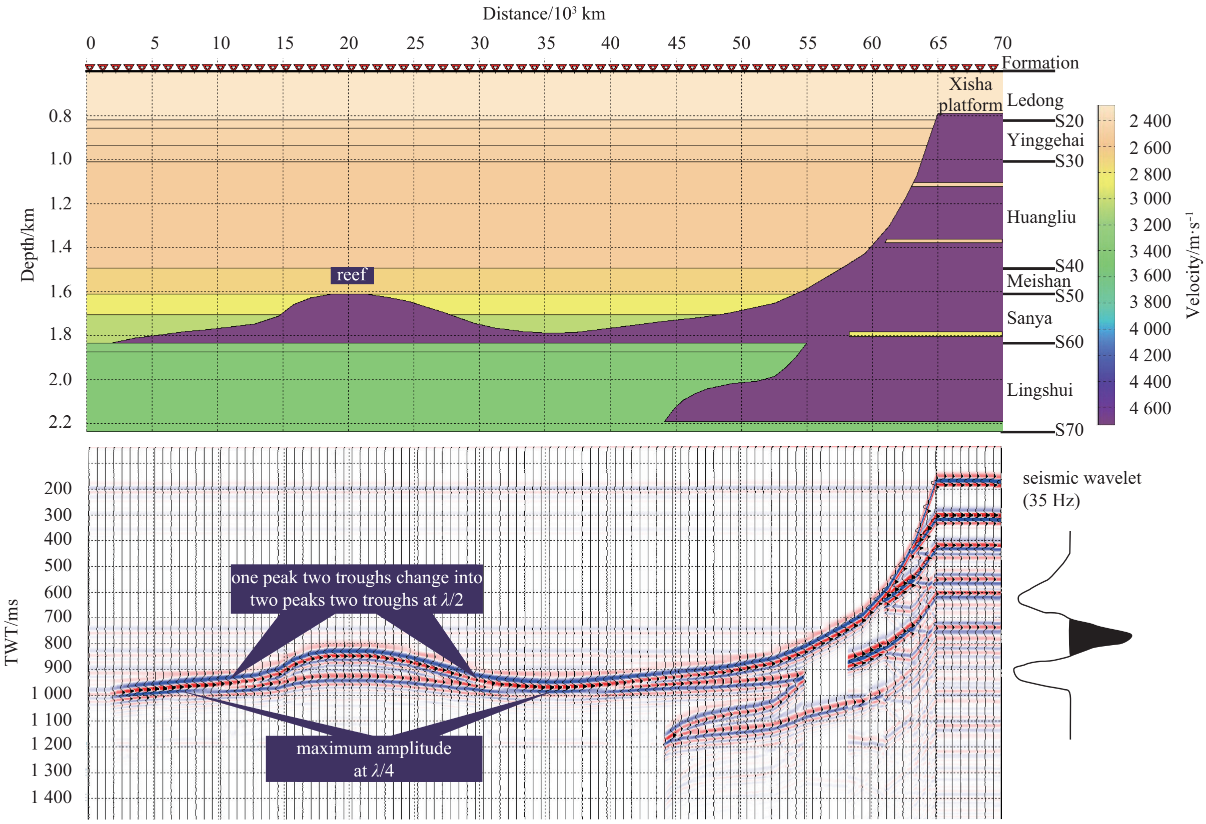

Fig. 6. Forward model of carbonate thickness.

one peak two troughs or upper peak lower trough, the bottom boundary shows a reflection with upper trough lower peak or one trough two peaks, and the interior shows low amplitudes or a blank reflection. This is one of the important evidence that distinguishes low-velocity mudstone from high-velocity carbonates and indicates the presence of carbonates.

For example, on the seismic profile along the northwest-southeast-oriented survey Line C, the strong reflection nearly below the S50 interface is formed by carbonates. Based on the forward model, we can identify the pinchout points and points with thicknesses of 40 m and 80 m in the carbonate layer nearly below S50 on the seismic profiles (Fig. 7).

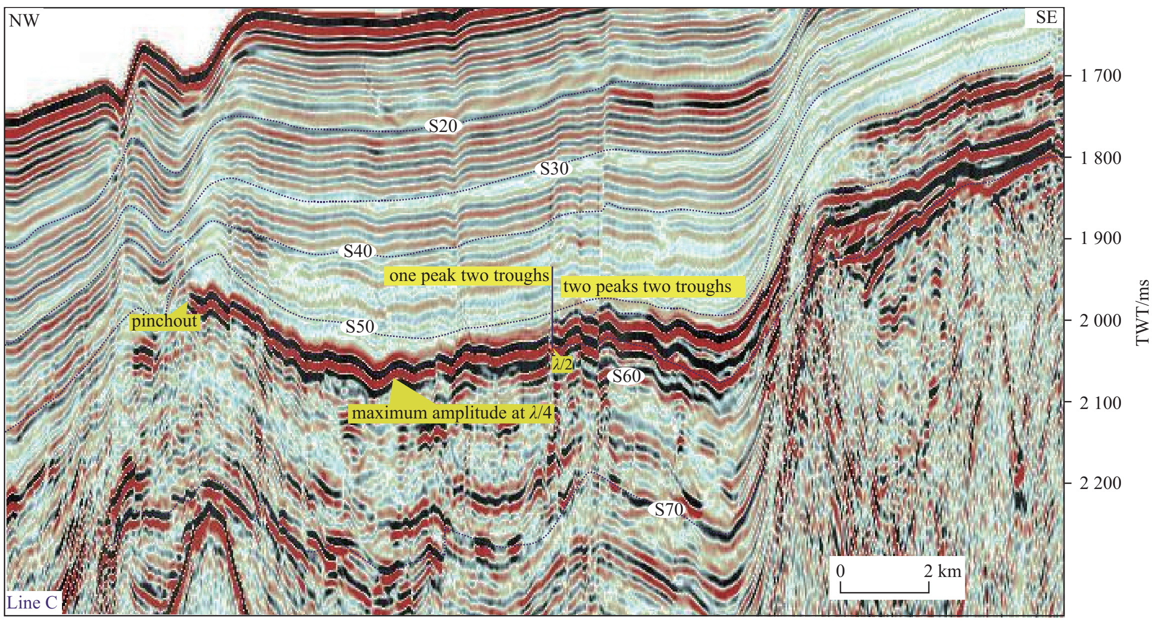

Fig. 7. Seismic response characteristics of variations in carbonate thickness on the seismic profiles. The locations of the pinchout point, tuning thickness point and half-wavelength point are indicated.

4 Making a carbonate thickness map

We first identified carbonates on the seismic profiles in the southern uplift region based on the high-amplitude reflections from the S60 to S40 interfaces. We then identified pinchout points (0 m), $\lambda/4$ points (40 m), and $\lambda/2$ points (80 m). In the regions that were thicker than $\lambda/2$ (approximately 80 m) (i.e., regions with two peaks two troughs or multiple peaks multiple troughs), we can distinguish the top and bottom boundaries of the carbonates on the seismic profiles. The thickness is calculated by time-depth conversion formula inferred from nearby well data. The points on the profiles at which one peak one trough change to two peaks two troughs were the $\lambda/2$ points (80 m). The points within regions with one peak one trough with the maximum relative amplitude were the $\lambda/4$ points (40 m). We identified two layers of carbonates on the profiles along survey Lines D (Fig. 8) and F (Fig. 9), calculated the single-layer thickness of each, and added them together. The amplitudes decreased in the mixed deposit segments in the depression or slope regions, but the reflection's thickness increased. The carbonate thickness is roughly taken as approximately half of the thickness of the corresponding strata segments. The contours between them were determined by interpolation. Finally, we synthesized these methods to construct the carbonate thickness map (Fig. 15). The carbonates on the southern uplift of the Qiongdongnan Basin were distributed in two blocks (eastern and western). The carbonates in the eastern reef was the thickest (approximately 200 m), followed by the carbonate ramp gravity flow in the western block, which was approximately 140–160 m thick. The carbonates in the other regions were generally 20–120 m thick.

5 Sedimentary characteristics of the platform ramp

Two types of ramp (steep and gentle) developed on the sides of the eastern platform on the southern uplift (Figs 3 and 5). The steep ramp might have occurred carbonate gravity deposits, but because of their small size, they still showed layered reflection features.

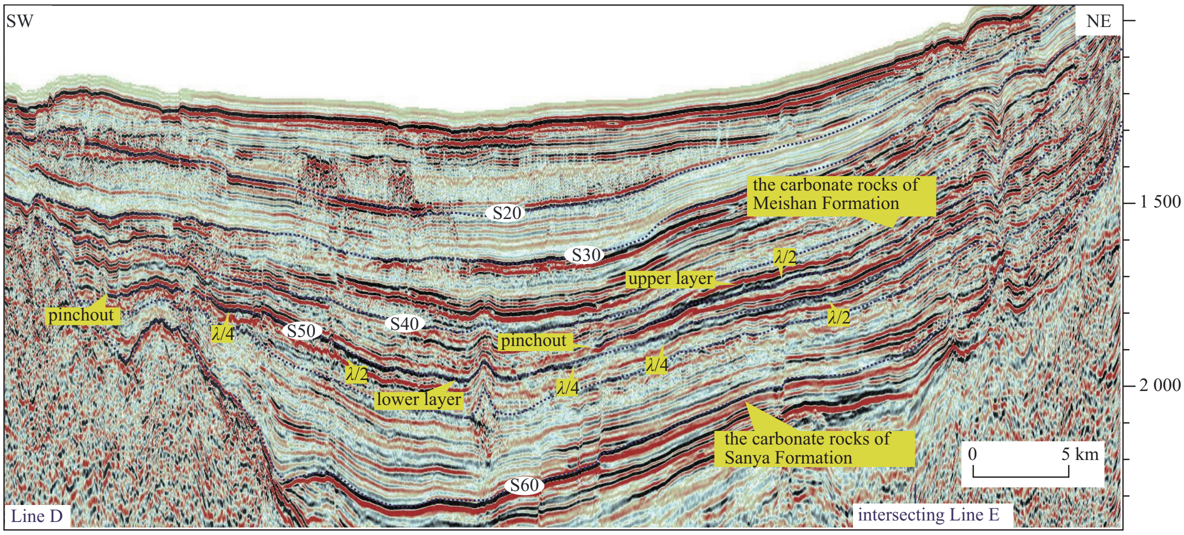

Fig. 8. Two carbonate layers of the Meishan Formation (S50–S40) and one carbonate layer at the bottom of the Sanya Formation (near S60) on the ramp platform on the southern uplift of the Qiongdongnan Basin.

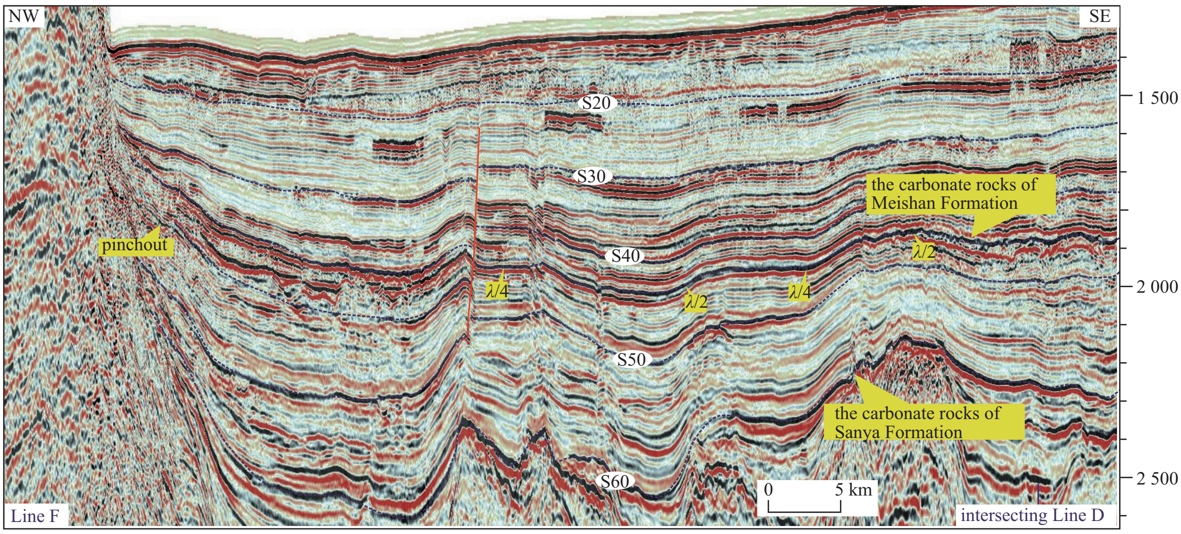

Fig. 9. Intermediate and high-amplitude reflections of the mixed deposits of the gentle ramp facies carbonate and siliciclastic rocks of the Sanya and Meishan Formations on the southern uplift of the Qiongdongnan Basin.

We identified two carbonate layers on the profile along survey Line D in the western platform on the southern uplift. The top and bottom boundaries of the upper carbonate layer have continuous high amplitudes, and the interior region has high frequencies, the carbonate layer pinched out toward the platform depression (Fig. 8). The carbonate gravity flow showed hummocky reflections in several local regions on the ramps. The lower carbonate layer is more widely distributed. It is thinnest at the platform depression and pinched out upward toward the tectonic highs on the northeast and southwest sides (Fig. 8). The two carbonate layers might be connected together on the Xisha Uplift to the southeast. They are likely mainly ramp carbonate clastic flows and low-energy micrite deposits but containing some siliciclastic deposits cannot be ruled out (Fig. 9).

The top boundary of the gravity flow on the ramps of the western block, which have a hummocky shape on the profiles, are a high-amplitude reflection, and the interior have alternating high and low amplitudes. The events showed poor continuity (Figs 10a and b). The maximum impedance inside the hummocky on the impedance-inversion profile was only 7.5×10^6 kg/m^3 × m/s, which is less than the impedance of the biogenic reefs in the Zhujiang River (Pearl River) Mouth Basin and the Qiongdongnan Basin, (8–10)×10^6 kg/m^3 × m/s (Wu et al., 2009; Zhang et al., 2011). The amplitude of the low hummock's reflection was also weaker than the amplitude of pure carbonate layers that are a few dozen meters thick. Thus, the hummocky might be a mixed deposit of carbonate and siliciclastic rocks (Fig. 10b).

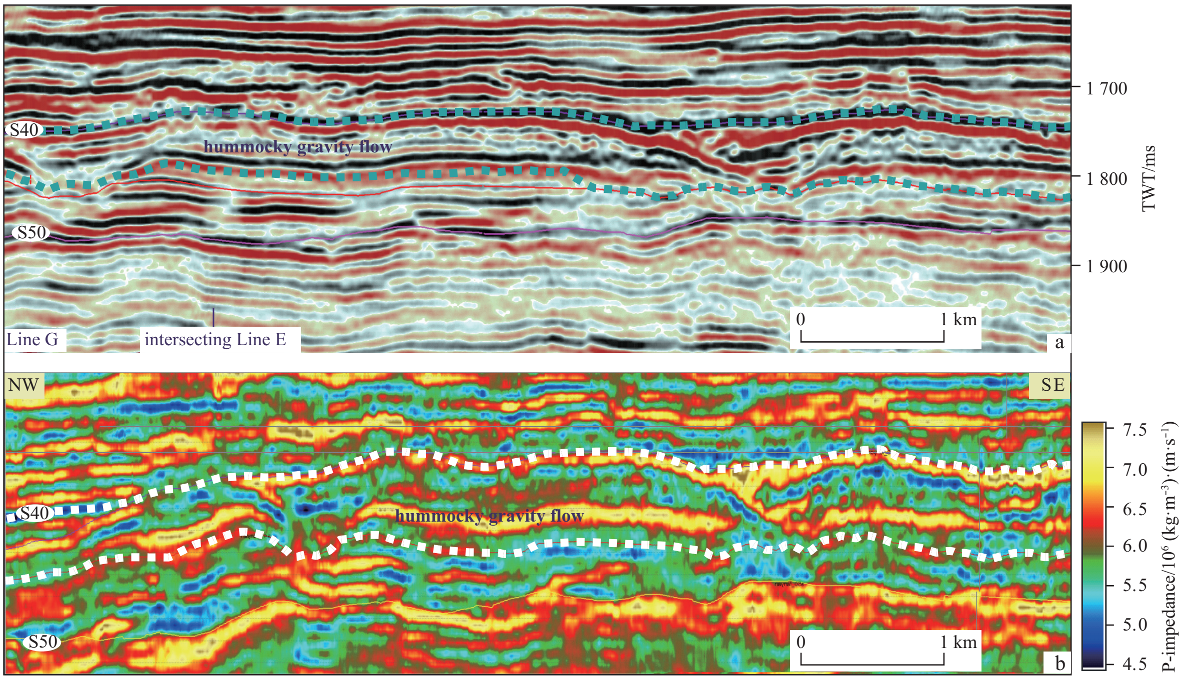

Fig. 10. Intermediate-amplitude response of the hummocky formed by a mixture of carbonate and clastic rocks of the Meishan Formation on the platform ramp profile (a) and the impedance inversion profile on the southern uplift in the Qiongdongnan Basin (b).

Mixed deposits of carbonate clasts and siliciclastics can have different seismic responses with different thickness combinations. In interbedded carbonate and siliciclastic rocks, the seismic amplitudes are high because of the large impedance difference. When carbonate and siliciclastic clasts mix and are deposited to form mixed rocks, such as calcareous mudstone or sandstone, argillaceous limestone, or silicic and calcareous mixed breccia, the impedance is similar to that of the overlying and underlying sands and shales, and the seismic amplitude will be significantly lower than that of pure carbonate interlayers. As the proportion of terrigenous clasts gradually increases from the ramps to the interior of the depression, the thickness of the carbonate interlayers and the carbonate content of the mixed deposits will both gradually decrease, and the seismic amplitude will decrease. Therefore, the hummocky intermediate-amplitude reflections on the slopes possibly reflect mixed silicic and calcareous carbonate gravity flows; and they are unlikely pure carbonate. The decrease in the amplitudes of the carbonates in the depression-ramp region may indicate both an increase in the siliciclastic content or a decrease in the carbonate content of the mixed rocks (Figs 11 and 12). In fact, the uplift of Indo-China Peninsula during the late middle Miocene caused that large amount of terrigenous clastics were transported into research area (Fyhn et al., 2013; Wang et al., 2015). Meanwhile, the rate difference of tectonic subsidence between southern uplift and surrounding sags had increased (Li et al., 2012), so that carbonate gravity flows might develop on steeper slope.

The forward model indicates that the two types of mixed rocks in the Meishan Formation can both cause the seismic amplitude to decrease. One type contains interbedded thin and pure carbonate and mudstone, and local part can show low-amplitude responses due to destructive interference (Figs 13a and b). The other type contains pure carbonate that transforms to marlstone and calcareous mudstone as the clay content increases, which also decreases the amplitude (Figs 14a and b). Therefore, the local weakening of the high amplitudes of the carbonates between S40 and S60 in the depressions may be related to the mixed deposits that were formed by the increasing supply of ter-

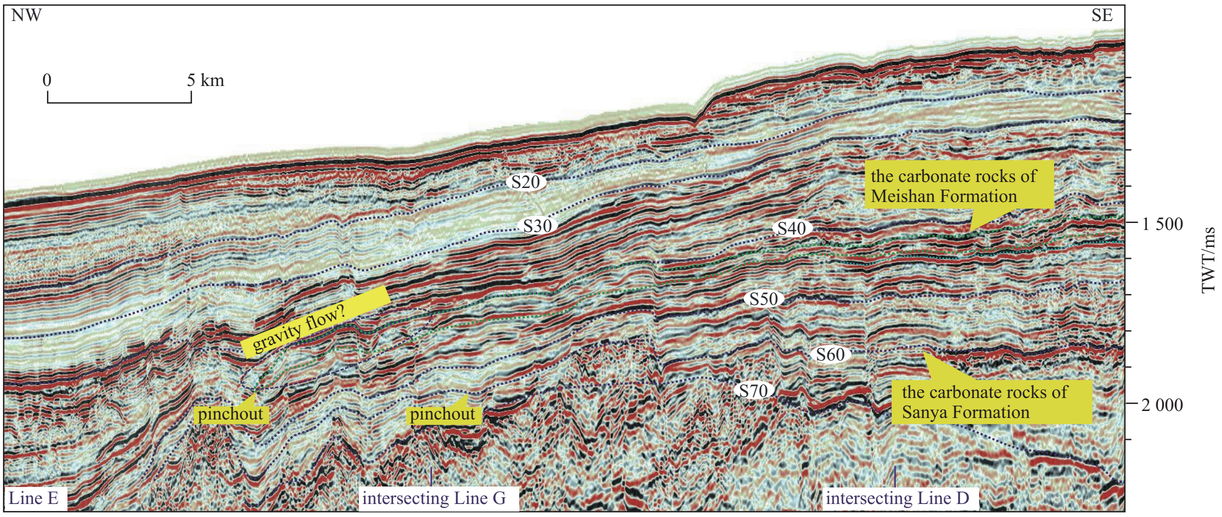

Fig. 11. Distribution and pinchout of the high amplitude carbonates of the Meishan Formation and Sanya Formation on the southern uplift in the Qiongdongnan Basin. This layer is a mixed deposit of slope carbonate and siliciclastic rocks. The change in amplitude indicates a variation in the carbonate content.

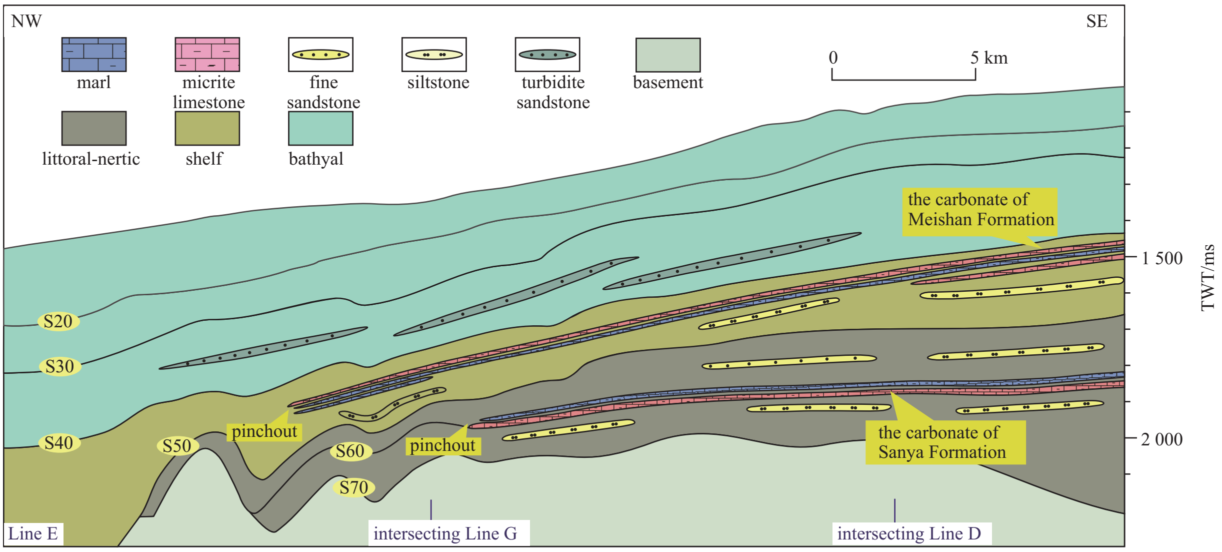

Fig. 12. Schematic geological profile of the mixed deposit of carbonate and siliciclastic rocks in the Meishan Formation and Sanya Formation on the southern uplift in the Qiongdongnan Basin.

rigenous siliciclastics and the lower energy sedimentary environment.

6 Carbonate platform and reef bank facies deposits

The platform reef on the structural high in the eastern block of the deepwater area of the southern uplift is thicker than the surrounding strata and has a high-amplitude seismic response. It is mound-shape with the interior reflections disordered and blank. The top and bottom amplitudes are strong. The both sides are overlapped by younger strata, and the amplitude decreases gradually toward the bilateral ramp (Figs 3 and 5). The reef-bank complex is approximately 10–15 km wide and 200 m thick. There are no faults or volcanic crater reflections below the mound reflection, and the top of the mound is flat. Therefore, they cannot be volcanic mounds. Their appearance looks like an isolated platform on individual profiles in certain directions.

7 Carbonate facies distribution and possible traps

Several classification methods for carbonate facies are used in China and foreign countries. The classification of the sedimentary facies of the carbonate platforms in this study followed previous classification schemes (Irwin, 1965; Friedman, 1977; Guan et al., 1980). We divided the carbonate platforms into reef core, reef flank, gentle ramp, steep ramp, and platform depression facies (Fig. 15). The carbonate gravity flows and mixed deposits that were described previously are in the ramp and platform depression facies. The reef core and reef flank facies are in the eastern carbonate block. They are typical carbonate platform deposits in high-energy environments and might form good primary pores. The slope and platform depression facies are mainly low-energy micrites, carbonate gravity flows, and mixed deposits, which were deduced to be poor reservoir. However, brecciated carbonate intergrain pore reservoirs related to gravity flows or secondary dissolution pores reservoir may exist. The steep ramp facies

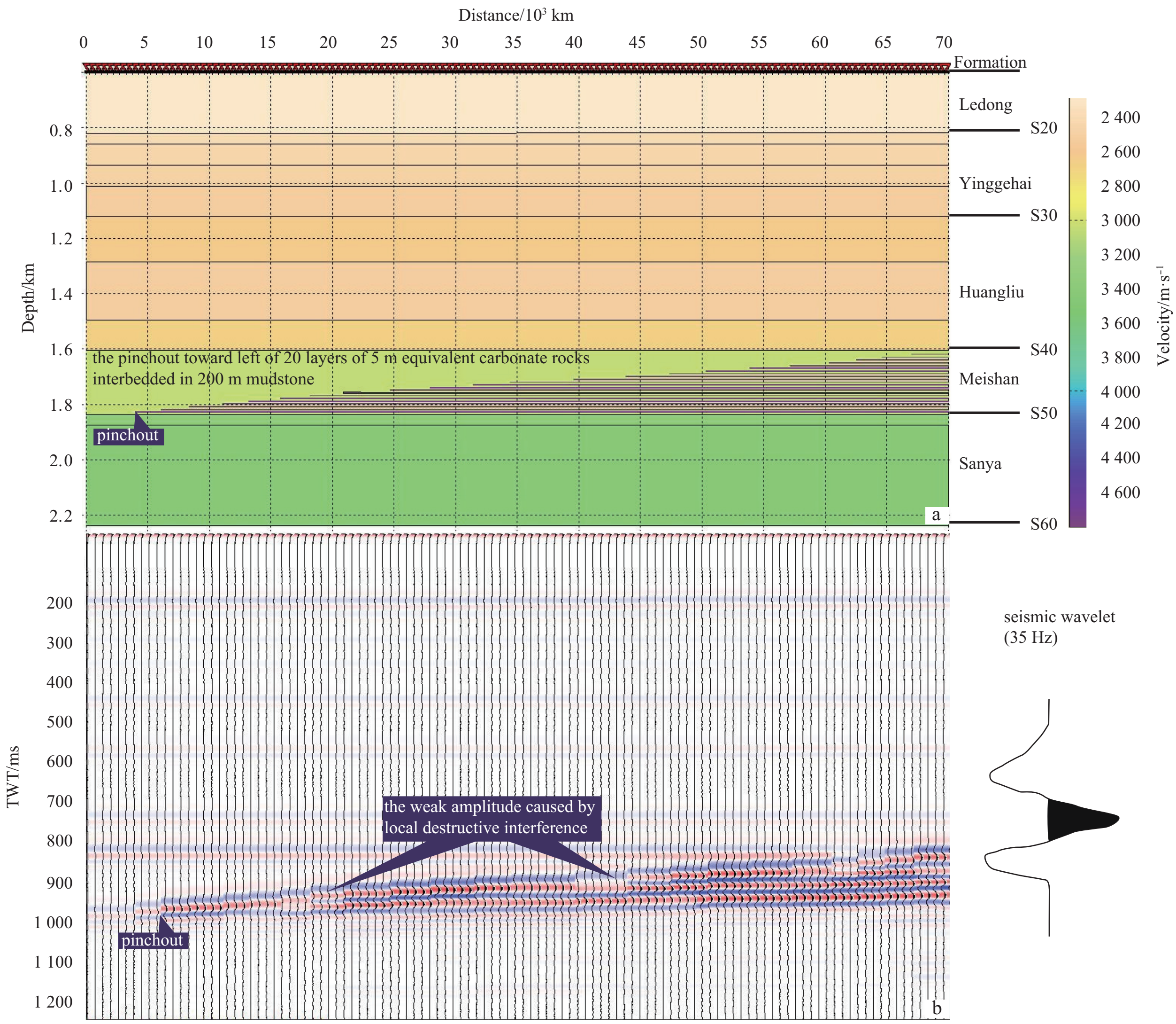

Fig. 13. Geological model showing the mudstone of the Meishan Formation interbedded with 20 layers of 5-m-equivalent carbonates that thin and pinch out (a) and the seismic response (b). The amplitudes of several local mixed rocks decrease due to destructive interference.

has high slope angles of 5° or more and is wedge shaped. The northwestern edge of the platform might contain gravity deposits. The slope angle of the gentle ramp facies is less than 5°. This facies is located in the lower regions between the isolated platforms and the Xisha platform. It is likely composed of mainly subtidal low-energy and semi-restricted lagoon deposits.

Based on the mean velocity data in the basin region and the isochronous structural map of the Miocene carbonates, we constructed a depth map of the top boundary of the carbonates (Fig. 16). The top surfaces of the two carbonate region represent a northward-dip slope background. The eastern carbonate block has a small dome structure at the location of the reef facies with a closure of approximately 30 m. The closure area is approximately 100 km^2. The southwestern part of the left carbonate block in Fig. 16 contains a 20 km×30 km nose-like structure that is inclined to the southwest. The carbonates pinch out upward to the west, which may form a stratigraphic trap or a composite trap.

8 Conclusions

Based on a forward model, the geological and seismic reflection characteristics of biogenic reefs, we determined the existence of carbonate and reef facies in the deepwater area of the southern uplift of the Qiongdongnan Basin and constructed a carbonate thickness map. The thickness map showed two peninsular carbonate platforms (eastern and western) on the southern uplift. The reef bank facies carbonates are located on ancient highs in the eastern block on the southern uplift. They are thicker than the contemporaneous non-reef facies on both sides, and the reflection amplitudes are very high.

The two Miocene carbonate platforms in the deepwater area of the southern uplift of the Qiongdongnan Basin consist of gentle ramp, steep ramp, platform depression, gravity flow, and reef facies. The carbonate platforms are generally 20–120 m thick and are thickest in the reef facies (approximately 200 m). The depressions surrounding the reefs are mixed deposits of carbonate gravity flows and clastic rocks. The Meishan Formation in the deepwater area may contain two carbonate layers.

The top surface of the eastern platform, which includes reef bank facies, has a dome structure with a closure of 30 m and a closure area of 100 km^2.

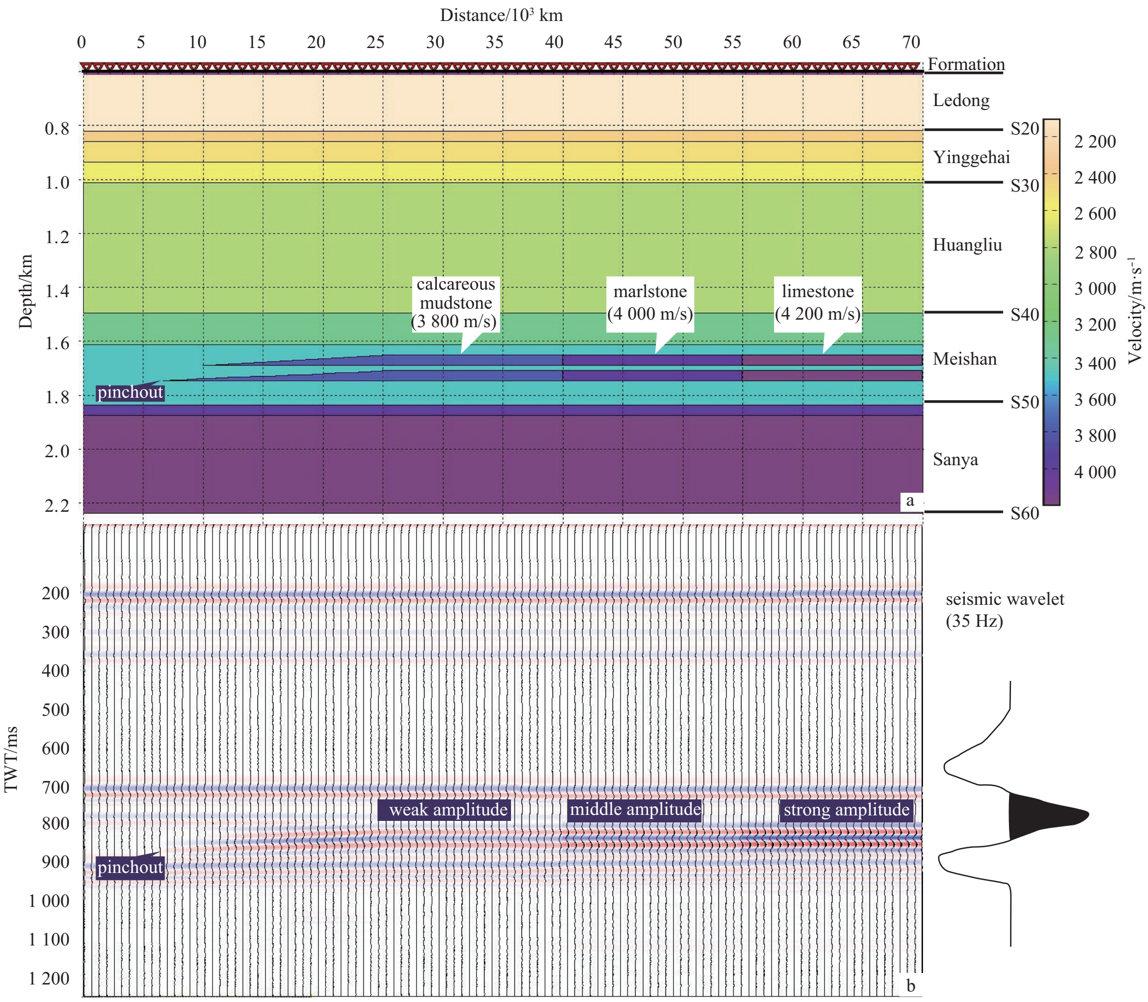

Fig. 14. Geological model showing the two carbonate layers of the Meishan Formation gradually transitioning to argillaceous limestone (a) and calcareous mudstone and the seismic response, which shows that the amplitude decreases as the pure carbonate gradually transitions to mixed deposits (b).

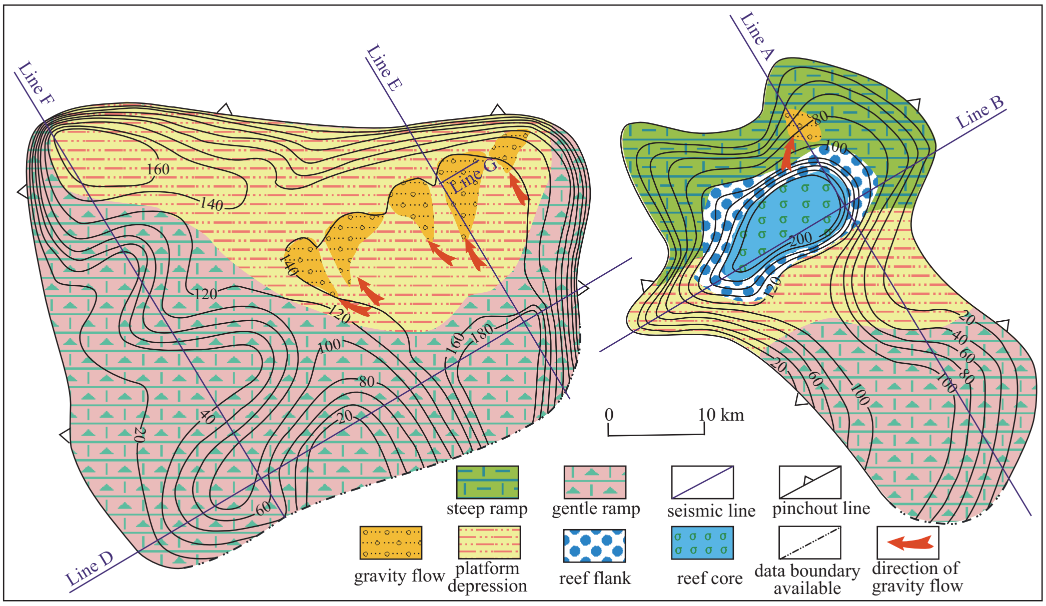

Fig. 15. Superimposed maps of the accumulated carbonate thickness (m) and facies distribution of the Miocene Sanya Formation and Meishan Formation on the southern uplift.

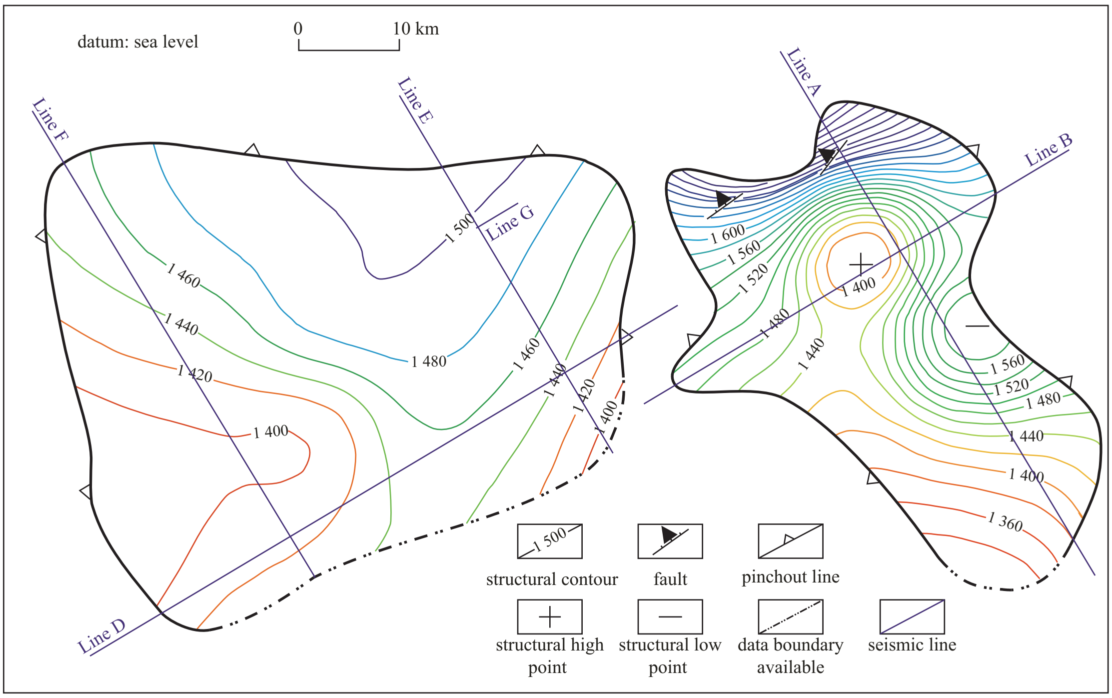

Fig. 16. Depth (m) map of the top of the Miocene carbonates on the southern uplift.

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