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RESEARCH ARTICLE

The seismic property of reef flat in the Changxing–Feixianguan Formation, Northwest Sichuan Province, China

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Abstract The development of a carbonate reservoir is dominated by its primary sedimentary environment. Generally, a good reservoir must be the oolite of a bank or bioclastics of an organic reef in a marginal mesa, which must deposit on the slope of the mesa. Therefore, the analyses of sequence stratigraphy are the key for predicting the presence of carbonate reservoirs. A typical sequence pattern can be seen in the Puguang gas field. As an independent lithological body, the mechanical property of a reef flat is very different from the surrounding rock, causing stress to concentrate. Stress centralization will, in turn, cause a lot of fractures and faults to develop, and ultimately, result in a gas chimney, which is a seismic smear zone beneath or above the reef flat. Known gas fields, such as the Puguang gas field, also possess gas chimneys. Sequence stratigraphy patterns in the marginal mesa and gas chimney near the reservoir are very obvious in all known fields in southeast and east Sichuan Province. By analyzing the seismic features of all known gas fields, a model to predict carbonate reservoirs has been set up. Using this prediction model, we have found that there is a typical reef flat of the marginal mesa in the Malubei structure of Tongnanba structural belts whose sequence stratigraphy pattern is very much like that of the Puguang gas field; and in the Cangxi–Jiulongshan structure, there is another reef flat which is symmetrical to the Malubei reef. The Cangxi reef flat possesses the largest platform edge shallow facies domestically found, and has a typical prograding sequence. Its gas chimney is very obvious too. Because the Cangxi reef flat is in the very vicinity of the hydrocarbon kitchen and the depression is much bigger than that of the Puguang gas fields, we predict that there may be a gigascopic gas field in Cangxi County. There may also be a large gas field in the Malubei structure.

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1 Introduction

In recent years, a great breakthrough has been made in the marine reservoir in the northeast of Sichuan Province. The Southwest Company of PetroChina has acquired proven reserves of up to $2\,500 \times 10^8$ m^3 from 1998 to 2005 (Wei et al., 2006), and the South Company of SINOPEC discovered the biggest domestic gas field in the Puguang structure in 2003–2005, the proven reserves of which is up to $2\,100 \times 10^8$ m^3, and the available reserves of which is up to $1\,500 \times 10^8$ m^3. The matrix primary pores of the marine carbonate rock in southeast Sichuan have almost died out; the average porosity is about 0.91% and the permeability is less than 0.001×10^{-3} μm^2 in the area where not many fractures develop. Therefore, the techniques to predict reservoirs bring vital function into play and great progress has been made (Wang et al., 1998, 2000, 2001; Wang and Xie, 2000; Liu et al., 2002; Liu and Gan, 2003a, b; Mou et al., 2004; Shun et al., 2005; Wei et al., 2006). A reef flat has been found in the Puguang gas field, the reservoir of which is corroded dolomite rock and the porosity of which is up to 15%. It is the highest grade reservoir that has been found in southeast Sichuan. However, predicting reservoirs in carbonate rocks is a hard nut to crack, and it is even so in southeast Sichuan. Before the year 2000, the prediction technique was not so reliable, and the number of abortive wells was very big. Some of the previous studies paid more attention to inversion of seismic data (Shun et al., 2005), while some attached importance to analyzing seismic facies (Wang et al., 2001). Through analyzing all the known fields, this thesis comes to a conclusion that firstly, the characteristics of sequence stratigraphy of the reef flat in southeast and east Sichuan are considerably obvious and reliable, and secondly, gas chimneys are another

feature of a gas reservoir. Many factors can affect the reservoir's properties, among which the geologic property is the most important and the most basic (Qiang, 1998). Because of this, using the sequence pattern to predict reservoirs is the most effective method. Besides, a gas chimney and depression in the neighborhood of a reef flat are also typical signs of big reservoirs. The integration of these two features is reliable and accurate for the prediction of a large-scale reservoir in a reef flat.

The region of interest is located at the front of Micang Mountain and Daba Mountain (Fig. 1). The study area contains the Tongnanba structure belts, the Jiulong anticline structure and the Puguang structure. The wells involved are Puguang 1–4 in the Puguang gas field, Heba 1 in the Tongnanba belts, and Long 4 in the Jiulong anticline.

The Tongnanba structure belt is one of the largest structures inferior to the Weiyuan structure (Petroleum Geology in China, 1989). It is the product of a multi-directional tectonic movement, and its structure is very complicated. In 2005, the well of Heba 1 obtained a testing production rate of 30×10^4 m^3/d in the Feixianguan formation. The Puguang gas field is situated in eastern Sichuan. The structure in Puguang is high and steep and very complicated. The largest domestic gas field of the reef was found between 2003 and 2005. There are a lot of wells in it, and the study is mature (Cai et al., 2005; Ma et al., 2005). The Jiulong structure is situated at the front of Micang Mountain and in the west of Tongnanba belt. However, the Jiulong structure is a little far away from Micang Mountain, Longmen Mountain and Daba Mountain. Because of this, the structure there is integral and not many faults develop. The characteristics of sedimentation are distinct and can be recognized reliably. The well of Long 4 was drilled to the Yangxin series in 1986, but with no success.

Since the eighth five-year program, a profound understanding has been acquired about the sedimentation of the Changxing–Feixianguan Formation (Wang et al., 2001; Wei et al., 2005, 2006). It has been found that the sedimentation is the key factor controlling the development of reservoirs. The study of the sedimentation of Changxing–Feixianguan has shown that there is a trough in the south front of Micang Mountain and Daba Mountain, and in the Pingchan County and Wangcang County (Fig. 1), which is called the Guang–Wang trough and Kaijiang–Liangping trough, respectively, by Wang et al. (2002). Along this trough, in the reef flat, several gas fields of large and medium sizes, which are the Puguang, Huanglongchang, Yun'an, Tiandong, Huangnitan, and Tieshan, etc., have been found. All of these fields possess considerable scale and their per well production is relatively high. The third resource assessment has shown that the total resource is about 10 102 $\times 10^8$ m^3, and the remaining resource is 9 161 114 $\times 10^8$ m^3, which means that there is great exploration potential in this area (Wei et al., 2005).

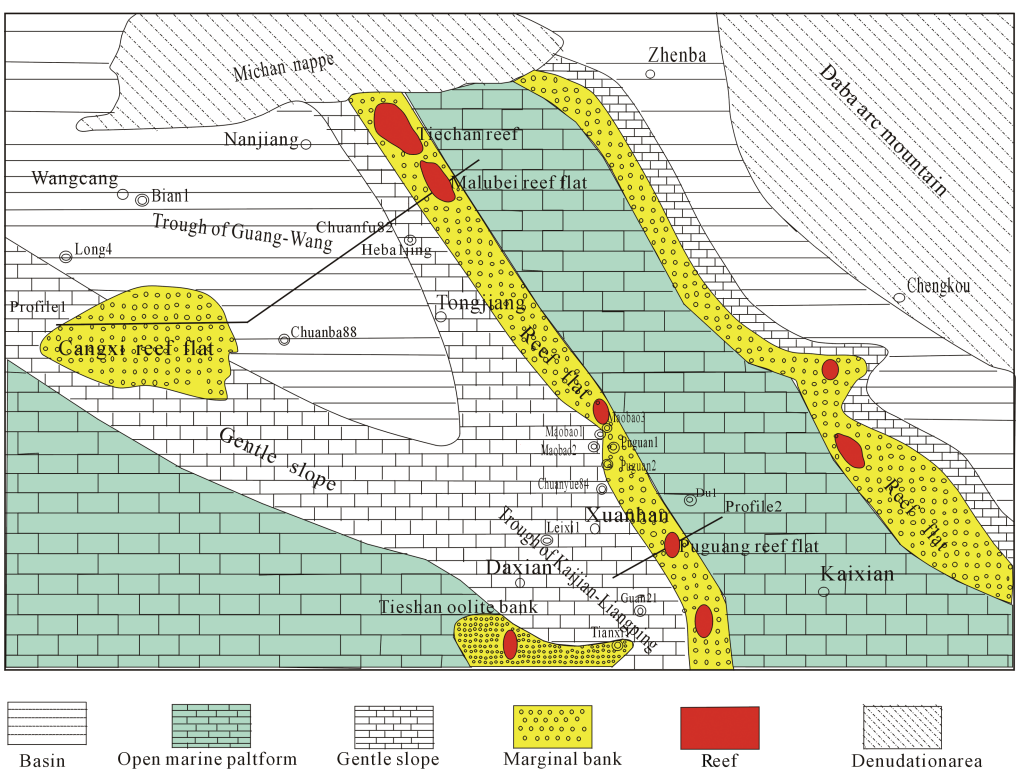

Fig. 1 The sedimentary facies of Cangxing Formation in Northeast Sichuan (compiled by Mineral Institute of Chengdu and Southeast Company)

2 The predictive methodology of reef flat of Changxing–Feixianguan Formation

2.1 The pattern of sequence stratigraphy of the reef flat on the platform edge

A beneficial primary environment is the key factor that allows carbonate formations to develop reservoirs with high porosity and high permeability. A reservoir research (Qiang, 1998) has indicated that the development of a reservoir is controlled by the whole geological history. Certain kinds of processes, such as pristine eluviation and leaching, dolomitisation, and erosion caused by hydrocarbon enrichment, dominate the constructional development of a reservoir. Generally, dolomitisation on the early stage and denudation on the later stage are factors favoring the development of a reservoir. An oolitic beach on the platform edge and reef build up most likely make up a fine reservoir (Qiang, 1998; Ma et al., 2005) (Fig. 2(a)). By analyzing the sedimentation model from Fig. 2, it can be known that because of sea level fluctuation, a high energy zone is more likely to be exposed to weather. Thus, dolomitisation and denudation on the high energy zone develops well, and porosity gets much higher. Because of this, the oolitic beach on the platform edge and the reef build up possess higher primary porosity. Though the later lithogenesis makes most of the pores die away, some of these pores can remain. Another process that benefits reservoir formation is the lithologic characteristic of these kinds of rocks, which are much purer, the grain is much bigger, and residual porosity is higher. The acidulous water coming from the generation and enrichment of hydrocarbons goes into residual pores and makes the pores of the oolitic beach get even bigger. The same oolite or reef flat of high energy, such as Pugang 2 and Po 1 in Xuanhan County, possesses an average porosity of 15% or more, which has been verified by core analysis (Ma et al., 2005).

The data obtained from the measured geological section in Nanjian County have attested to this conclusion. The lower part of Fig. 2 shows the reef geological section of Tiechan measured in 2003. The core of the reef does not possess high porosity and dolomitisation, and is also a tight formation. The crest of the reef has the highest porosity of up to 15% or more, and is not filled up by the later lithogenesis. The edge of the reef has higher porosity, which is, more or less, about 10%. The outcropping rocks of deep sea facies, or bathyal facies, which are matrix limestone, mud-bearing limestone, or shaly limestone, do not possess a porous reservoir.

Because the sedimentation environment dominates a reservoir's development, the sedimentary facies can be doped

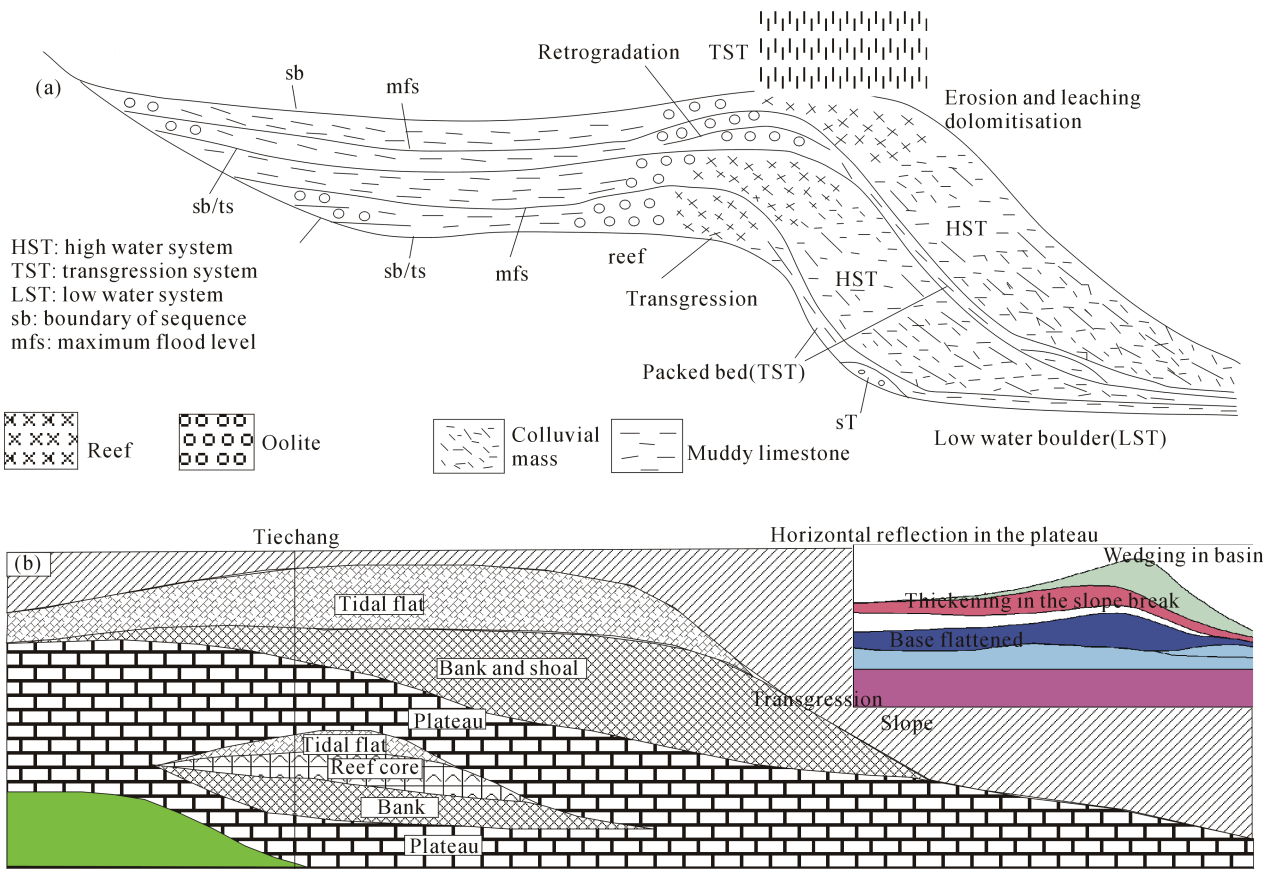

Fig. 2 (a) The sequence stratigraphy pattern of the marginal carbonate mesa (Qiang, 1998); (b) measured section in Nanjian County (the figure in the right corner is a sequence stratigraphy pattern with bottom flattened)

out by analyzing the sedimentary mode and the sequence characteristic. Furthermore, it can provide a favorable place where a good reservoir can be forecasted. The sedimentary thickness varies from the mesa to the platform edge and to the basin, and demonstrates the variation of sedimentary facies as well. Because of water level fluctuation, prograding sequences at the break of the slope come into being when water level retreats, and an onlap sequence emerges while water level moves forward. Thinning out boundaries can be recognized at the deep basin. It is very often that the onlap, downlap and topset occur. All these characteristics can be used to predict sedimentary facies accurately. By analyzing the following seismic profile, two favorable places for the development of a good reservoir with high porosity have been doped out.

2.2 Gas chimney—The seismic character of the reef flat

Wang et al. (2001) have summed up seismic features of the reef flat as follows: thickening in the Changxing Formation and reflection anomaly in the inner or on the top of the reef. The following theoretical analyses make it clear that, besides seismic facies, there is a chimney effect above or below the reef flat, and that there commonly is an accompanying depression on the bottom of the reef. Gas fields of large scale can be doped out reliably by analyzing the gas chimney, depression, and other seismic facies.

Chimney effect, which can also be called chimney structure or gas chimney, is a smear zone in the seismic profile that appears very often in offshore gas fields local and abroad (Jie et al., 1999; Caldwell, 1999; Zhang, 2001; Kommedal et al., 2002). It is a typical sign indicating that there exits a large-scale reservoir. Figures 2 and 3 show that the external shape of the organic reef flat is moundy or lentiform, while the inner is clumpy. The mechanical property of the organic reef flat is much different from its surrounding rock, which is limestone or shaly limestone. Systematic sampling of Tiechang reef was made in 2003. The sampling data show that the shear modulus of reef limestone is 33 GPa, and Young's modulus is 80 GPa. If the wall rock is of matrix limestone, the shear modulus is 26 GPa, and Young's modulus is 70 GPa. If the wall rock is of shaly limestone, the shear modulus is 13 GPa, and Young's modulus is 42 GPa. The mechanical characteristics of rock indicate that the organic reef or shoal is much harder than the wall rock, even more so when wall rock is of muddy limestone. Because of very strong tectonic movements in Northeast Sichuan, the anomalous body in the formation causes a point of force concurrence, which in turn, results in the development of many faults and fractures. As a result, a gas chimney develops. The mechanism can be described as follows:

① A lot of fractures develop inside the organic reef flat. Calculation (Zhou, 1998) and experimentation show that while the soft formation is sandwiched by rigid rocks, stress in the rigid rocks will obtain a very high concentration. The bigger the difference between the lithologic character and the volume between the rigid rocks and its wall rock, the higher and stronger the concentration is. This causes a lot of fractures to develop in the inner side of the organic reef, which in turn, contributes to the development of a seismic smear zone below the organic reef, such as in Huanglongchang (Liu et al., 2002).

② In places where sedimentation is relatively low, the wall rock of the organic reef must be of muddy limestone with high shale content. As a result, reef limestone is much harder and will move up during tectonic upwarping, and a piercing process, which is analogous to the diapir of Engale seas (Zhang, 2001), takes place. Meanwhile, fractures and faults develop also, such as in the Puguang structures. Gas chimneys can be seen very often in the upper side of the organic reef.

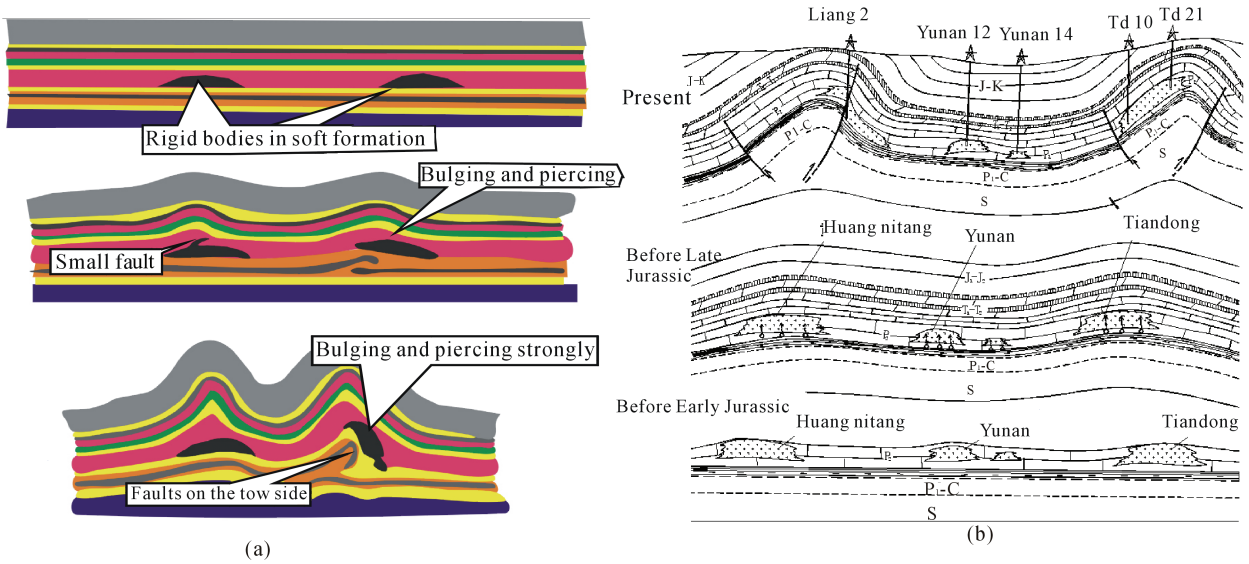

Fig. 3 Comparison of a simulation experiment with an actual structure evolvement of the reef flat (simulation is cited from Zhong, 1998, reef structure evolvement is cited from Wang et al., 2000)

③ Because mechanical properties change abruptly, the faults on the two sides of the organic reef develop a lot.

The effectiveness mentioned above can be tested by a simulation experiment (Fig. 3(a)) (Zhong, 1998). In this experiment, there is a rigid body in the soft formation. When stress is loaded on the two sides and deformation develops, a fold emerges in the vicinity of the anomalous body, faults develop, and then a bulge comes into being. When compression becomes strong enough, the deformation near the rigid body gets very obvious and a lot of faults develop, and so does the bulge above. This simulation experiment is consistent with an actual structural evolution (Fig. 3(b)). The right side of Fig. 3 is the structural evolution of an actual organic reef. Organic reefs usually exist in the high part of a structure. A lot of faults exist in the inner side of an organic reef or above it.

The laboratory findings (Huang, 2000) show that if the openness of a fracture is decreased by 7 μm, the seismic velocity will increase by 4%, and the seismic amplitude will augment by 1 274%. Thus, the more the fractures and faults develop, the smaller the amplitude, and the lower the seismic velocity. Accompanying the fracture's variation, the amplitude variation is considerably strong. In Northeast Sichuan, because the structure stress and deformation is very strong, faults and fractures near the reef cannot develop, and this will consequentially cause gas chimneys.

3 Analyses on seismic features on Puguang gas field—Sequence stratigraphy and gas chimney

In the 1980s, Chuanyue 83 and Chuanyue 84 were drilled in the high part of the Puguang structure. No reservoir, but only muddy limestone, was found in these two wells of the Feixianguan–Changxing Formation. Researchers have not found any distribution regulation of reservoirs and have since remained silent for a very long time. In recent years, a huge breakthrough has been made in the Puguang structure. Puguang 2 had a very good reservoir, the thickness of which is up to 331.1 m in the Feixianguan Formation, and 64.4 m in the Changxing Formation. The average porosity is 7.7%. A productive pool, which is the largest domestically, has been found. The sequence feature and gas chimney are very obvious (Fig. 4). By analyzing its seismic property, a model of a prospective reservoir can be set up and can easily be used.

3.1 Gas chimney (Fig. 4(a))

Instantaneous amplitude profile is used to show faults and the discontinuity of composite waves. It can be seen that depression exists below the organic reef flat, and the composite wave above is in clutter station and breaks off. The depression

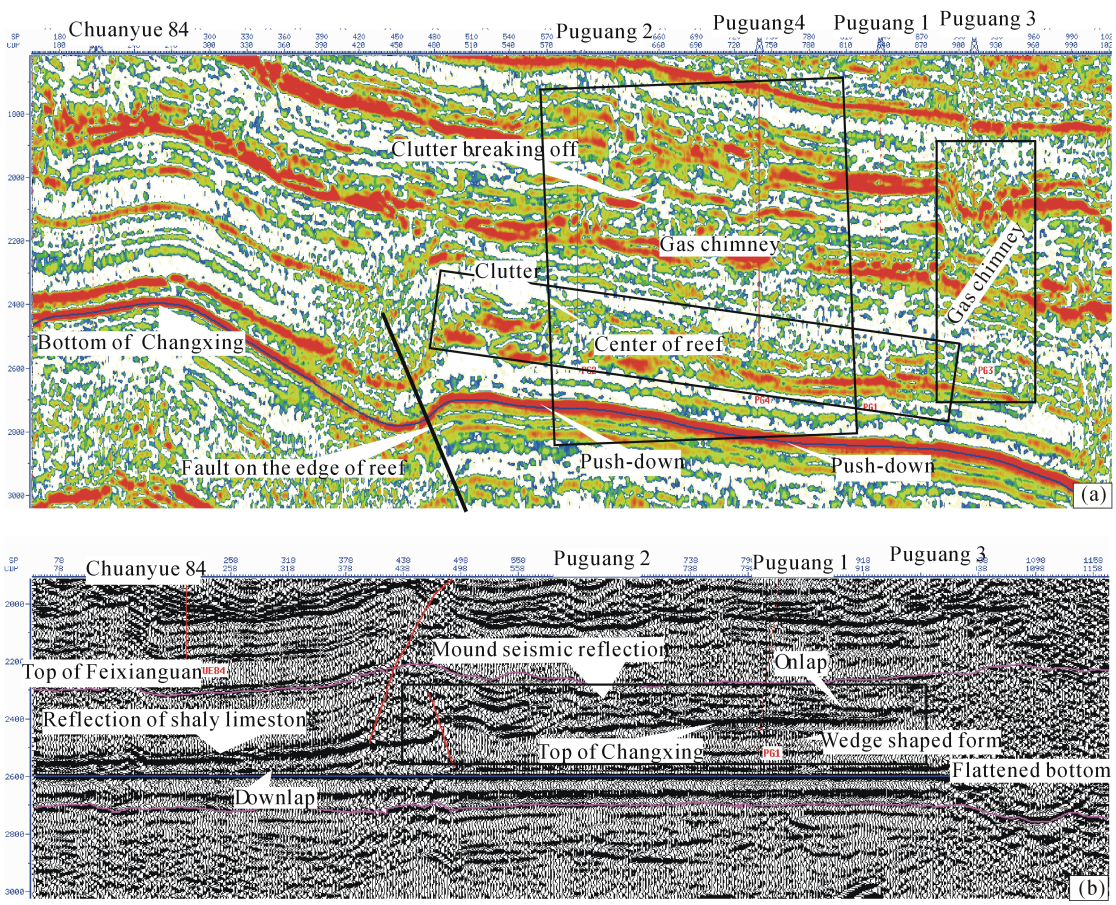

Fig. 4 (a) The gas chimney described using instantaneous profile; (b) the features of sequence stratigraphy in Puguang structure

is caused by the drop in velocity, and the discontinuity and clutter of waves is caused by faults and fractures, which are generated by the reef flat piercing upward. Because stress concentrated on the reef edge, a fault develops on the side.

There are some differences among reefs, banks and shoals. An organic reef possesses a much harder rock and has much bigger bulk than a bank or shoal, so an organic reef has a much stronger gas chimney. Gas chimneys exist in the Huanglongchang fields, Yun'an fields, Tieshan fields, and Jiannan fields (Wang et al., 2001; Liu et al., 2002; Liu and Yang, 2004). Among of all these reefs, the gas chimney features of Huanglongchang (Liu et al., 2002) and Jiannan (Liu and Yang, 2004) are most obvious.

3.2 Sequence stratigraphy (Fig. 4(b))

To describe the features of sequence stratigraphy, the bottom of Changxing is flattened. It can be seen that the top surface of Changxing is a slope, and the shape of the Changxing Formation is a wedge. There are also onlaps on the top surface. Light spots can also be recognized, which is caused by the reef cap having high porosity.

4 Application—Prediction of a large gas field using sequence features and gas chimney

The Jiulong structure is a macroscopic structure with an amplitude 1 800 m high. The structure is integrated and its preservation is also very good, so the features of sedimentation can be analyzed easily. The Long 4 well is in the highest part which was drilled in 1986. The Long 4 well encountered bioclastic rock of 12 m in the Changxing Formation. The rest of the Changxing Formation was muddy limestone but also possessed bioclasts, which indicates that the sedimentation of Long 4 well is located in a shoal area and that an organic reef or bank may exist (Fig. 1).

By analyzing sequence stratigraphy (Fig. 5), platform edge shallow facies of gigascopic scale has been found in the south of the Jiulong structure, Cangxi County. There is gas chimney above and beneath the reef flat as predicted (Fig. 6), and also there exists a striking depression. All of these features show that a giant field or even a supergiant field may exist.

Figure 5 describes the features of sequence stratigraphy clearly. Figure 5(a) is a regional seismic profile. In this profile the bottom reflection of the Changxing Formation has been flattened. A series of oblique seismic reflections clearly show that platform edge shallow facies may exist. Symmetrically, a series of oblique seismic reflections can also be seen in the Malubei, Tongnanba structure belts (Fig. 5(c)). The seismic facies pattern, shown in Fig. 5(b), equals to the theoretic sedimentation model, and the seismic features of Malubei is much like those of Puguang's. A prediction is made that there may exist an organic reef in Malubei. Currently, several wells have been proposed and are being drilled.

Figure 6 describes the gas chimney of the Cangxi reef flat. This gas chimney can also be seen in Fig. 5(b). Figure 5 is in the west-east direction, while Fig. 6 is in north-south

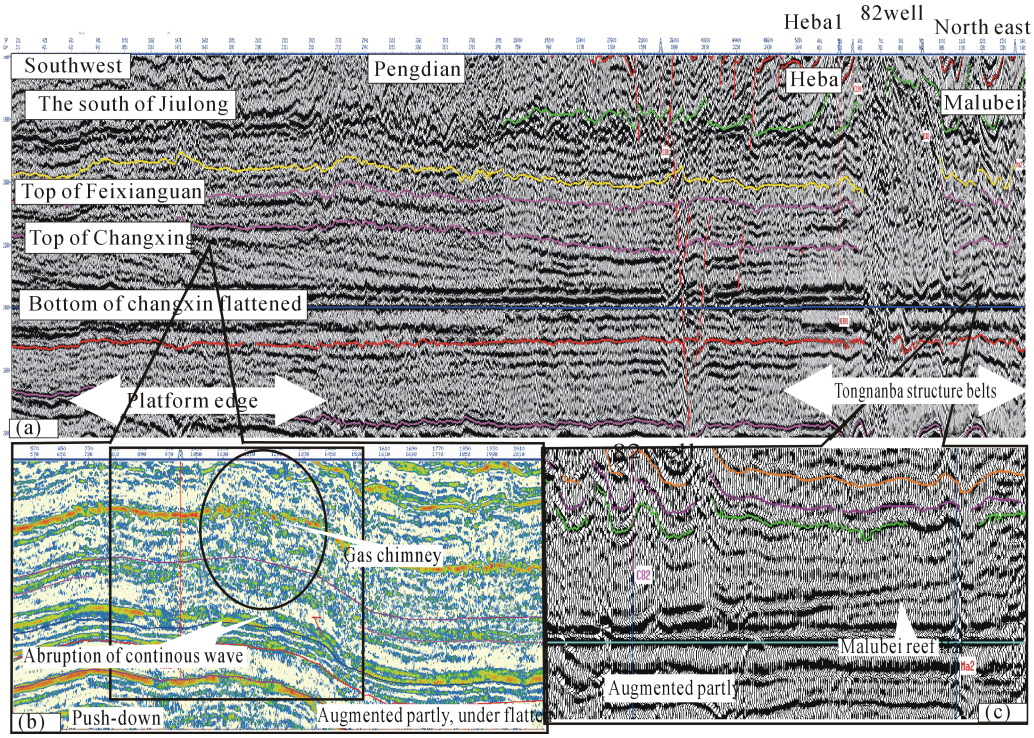

Fig. 5 (a) The sequence stratigraphy features in the south of Jiulong structure, Cangxi County; (b) gas chimney and push-down, instantaneous amplitude; (c) the sequence stratigraphy features in Tongnanba structure belt

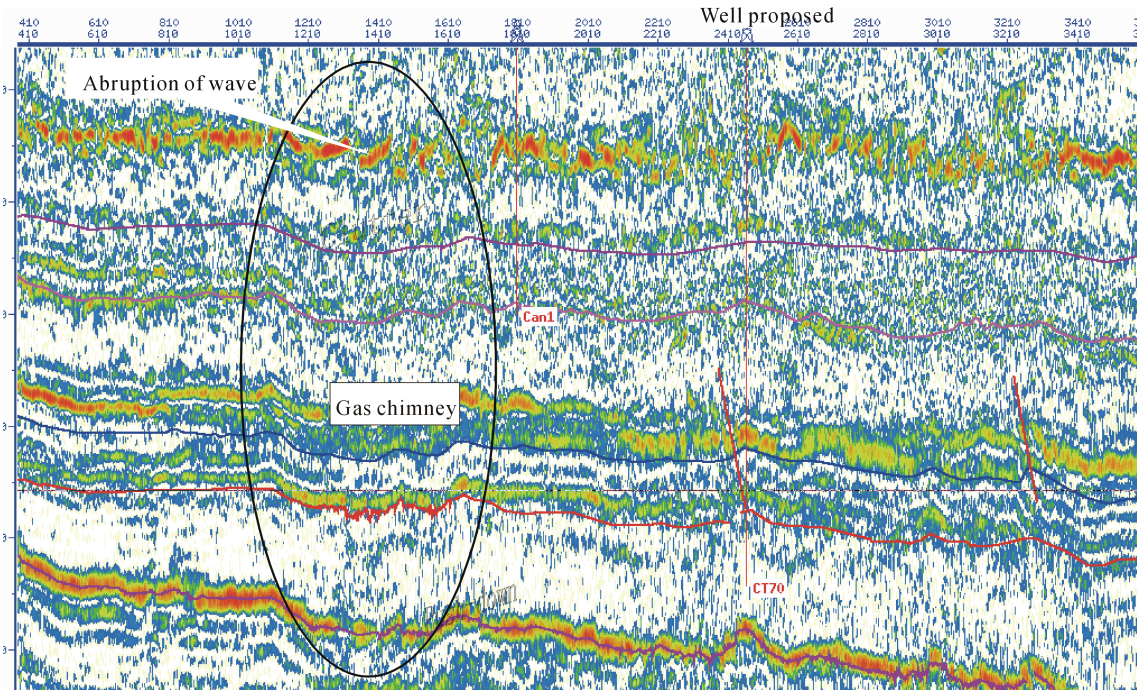

Fig. 6 Gas chimney of Cangxi reef flat (instantaneous amplitude)

direction and is enlarged partly. The gas chimney is very obvious: there is a depression, clutter reflection, abruption of wave, and so on. The most obvious feature in Fig. 6 is the depression.

Until now, the play of the Changxing–Feixianguan Formation is relatively clear (Cai et al., 2005; Ma et al., 2005). Because the structure is integrated and there are nearly no faults, the preservation is very good. The Cangxi reef flat is much closer to the hydrocarbon kitchen, and the amplitude of the structure is very high, so the hydrocarbon potential is very promising.

The anomalous area of the Chanxi reef flat is about 7–8 times than that of the Puguang gas fields, and the thickness is about twice. The size of the depression is much stronger, so a supergiant gas field can be anticipated. In fact, a very successful well near the Cangxi reef has obtained a very high commercial hydrocarbon flow, and the Yuanba 1 well will be reaching the target stratum, which will verify what we have predicted.

5 Conclusions

(1) Analyzing sequence stratigraphy is a key technique to predict the presence of a reservoir. Oblique progradation is the typical seismic pattern of a platform edge. All of the marine fields found in Northeast Sichuan possesses typical sequence feature. There are two reef flats which are symmetrical on the two sides of the Guang–Wang trough. On the east side is the Malubei reef, and on the west side is the Cangxi reef flat which is anticipated as a gigascopic gas field.

(2) The gas chimney is one of the typical seismic facies of a reef flat reservoir which may indicate the existence of a large gas field. The generation mechanism of a gas chimney is that since the mechanical strength of a reef or bank is much different from its surrounding rock, stress concentration comes into being and results in a lot of faults and fractures. The fractures and faults in the vicinity of a reef and a bank generate a seismic smear zone which is called a gas chimney.

(3) In the tectonic movement, the reef controls its structure evolution. A bulge may exist above the reef flat.

In summary, comprehensive research of the sequence feature, integrated with seismic facies, can predict a reservoir's distribution in a reef and bank reliably.

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