

Distribution of favorable reservoirs and exploration targets in the Upper Triassic of the Sichuan Basin

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Abstract: The Upper Triassic Xujiahe Formation in the Sichuan Basin is critical to reserve replacement of PetroChina Southwest Oil and Gas Field Company. Along with the developing trend of hydrocarbon exploration, the areal distribution and exploration potential of each sandbody should be appraised with the whole basin as a unit. Based on an integrated analysis of seismic, log and outcrop data, the Xujiahe Formation is divided into 4 third-order sequences and 12 system tracts. The sedimentary microfacies of the Xujiahe Formation are mapped in the whole basin with the system tracts as units. Six major delta sandbodies are identified in the Xujiahe Formation. The favorable reservoir sandbodies are mainly developed in the lowstand system tract and are mostly delta-front underwater distributary channel sands. In contrast, the small sandbodies of Lake Facies are well developed in the transgressive and highstand system tracts. The exploration potential of the Xujiahe Formation is comprehensively appraised with multiple parameters including areal distribution, hydrocarbon generation intensity, resource potential, reservoir types, exploration maturity and top burial depth of reservoirs. Several exploration targets are recognized, such as the Guangan - Yingshan and Penglai - Jinhua sandbodies in the second member of the Xujiahe Formation, the Penglai - Jinhua and Anyue - Hechuan sandbodies in the fourth member of the Xujiahe Formation, as well as the Penglai - Jinhua, Yibin - Guanyinchang and Gulan - Luzhou sandbodies in the sixth member of the Xujiahe Formation.

Key words: Sichuan Basin, Late Triassic, sandbody distribution, sequence, reservoir characteristics, hydrocarbon pooling conditions, source rock-reservoir-cap rock combination, exploration potential, Xujiahe Formation, exploration target, burial depth low-stand system tract

At present, the Upper Triassic Xujiahe Formation in the Sichuan Basin is critical to reserve replacement of PetroChina Southwest Oil and Gas Field Company. Xujiahe mainly develops the lithologic deposit and the distribution of the oil gas is mainly controlled by the sequence stratigraphic framework and the sand distribution^[1-10]. With the accumulation of the information and the changes of the exploration, it is necessary to figure out the plane distribution principles and its exploration potential of each reservoir sandstone.

1. The sequence stratigraphic framework and boundary character

According to the information of the seismic, logging, well drilling and field outcrop, Xujiahe Formation can be divided into 4 three-order sequence, each of which can further distinguish the three system tracts: LST (low system tract), TST (transgressive tract) and HST (highstand system tract). Sequence I corresponds to the first member of Xujiahe Formation, Sequence II corresponds to the second and third member, Sequence III corresponds to the fourth and fifth member and Sequence III corresponds to the sixth member (Fig.1).

The base of Sequence I is a regional plane of parallel unconformity, above which there are sediments of marine carbonate rocks while below are sediments of the transitional facies clastic rocks. The lithology and lithofacies above and below the boundary have the mutation, which is shown in the seismic as a series of reflection with strong phase and high continuity. There is truncated unconformability contact relation in the base.

The base of Sequence II is a plane of conformity, with no obvious seismic reflection character. However, the formation lithology, colors and stacking patterns above and below the boundary have the mutation.

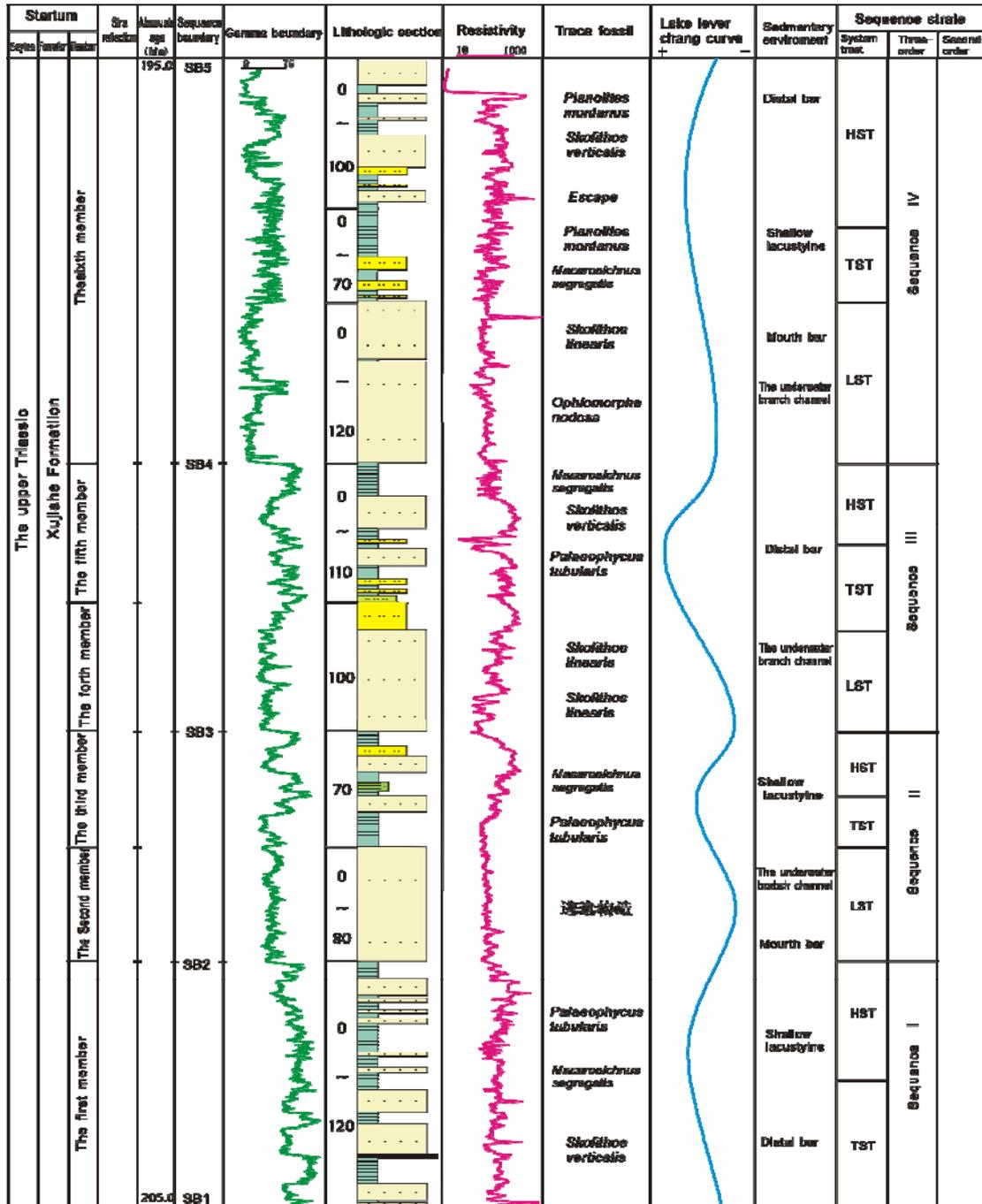


Fig.1 The stratigraphic subdivision scheme of the sequence of Xujiahe formation in Sichuan Basin

Affected by Anxian movement, the base boundary of Sequence III in the northwest of Sichuan Basin is regional angular unconformity while in other regions of Sichuan Basin, it reflects as the conformable contact, which is distinguished by the changes of the lithology, lithofacies and stacking patterns.

The base boundary of Sequence IV inside the Sichuan Basin is plane of

conformity, above and below of which the lithology, lithofacies and formation stacking patterns have mutation. Below the plane are the sediments of lacustrine facies while above are the sediments of the fluvial and delta facies. The seismic reflection in this plane presents such characters as the strong amplitude and high continuity. The top plane of Sequence IV is the interface between the Xujiahe Formation and the Upper Jurassic System, which is a plane of parallel unconformity in the whole region. The formation lithology, lithofacies and ancient climate above and below the boundary have the mutation. Below the boundary are dark grey sandstone and mudstone in the humid climate, which is rich in such fossil plants as *Neocalamites carrerei*, *N.carcinoides*, *Clathropteris meniscioides*, *Pterophyllum*, *Equisetites sarrani* while above is the amaranth sand shale, rich in the plants, spore and pollen and freshwater bivalve^[9].

2. The evaluation on the exploration potential

2.1 Favorable reservoir sandstone distribution

The Favorable reservoir sandstone of Xujiahe Formation mainly distributes in the LST in each sequence, while the TST and HST consist of the lacustrine facies, developing the pelitic and aleuritic texture sediments.

LST of Sequence II distributes along the western strip of Jiayang-Chongqing-Liangping; the six sand bodies developing inside the Basin (fig.2) respectively lie in such districts as Jiangyou-Mianzhu, Penglai-Jinhua, Guangan-Yingshan, Anyue-Hechuan, Weiyuan-Ziyang, Wuzhongshan-Qionglai. The microfacies acts as the majority of of the sand bodies in the underwater branch channels in the front edge of the delta. There are large scales of sheet sand distributing in front of the channel. In this period, the lacustrine facies only occupy a small area and the depocenter lies near the Pengji Well.

Compared with LST in Sequence II, the distribution range of LST in Sequence III expands. In this period, 6 sand bodies developed, whose distribution and spreading directions have lengthwise continuity. The scales of sand bodies in the northwest of the Basin gradually shrink on while that in the southern increases,

controlling the distribution of the oil gas resources in the large Center of Sichuan Basin. The sediments of lacustrine facies move to the south, and the depocenter lies near the oil well 1#.

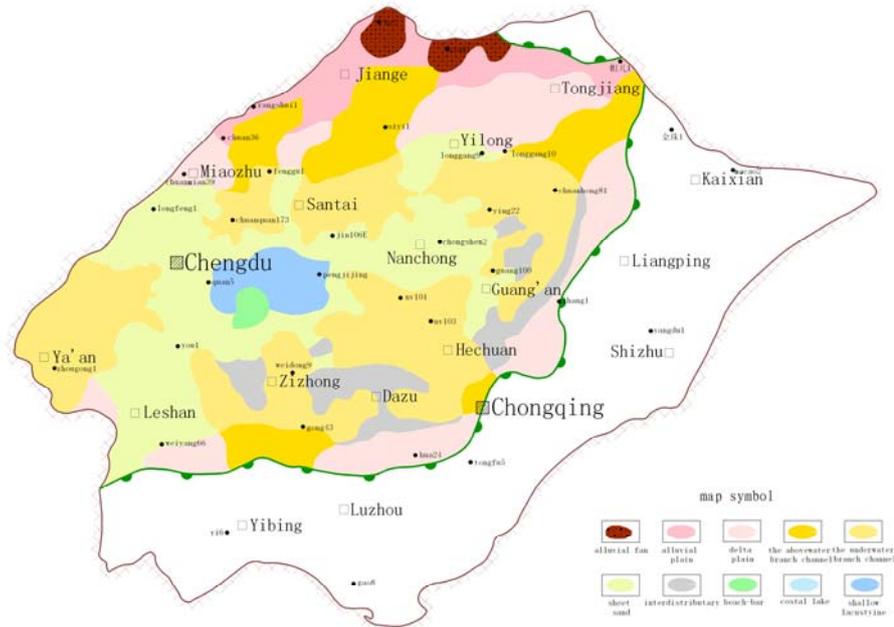


Fig. 2 The sedimentary facies diagram of the LST in the Sequence II of Xujiahe Formation in Sichuan Basin

In the development period of LST in Sequence IV, due to the extrusion from the neighboring plate tectonics, the northwest of Sichuan uplifted and suffered from the denudation. In this period, six sand bodies developed, whose distribution has lengthwise continuity. However, compared to the LST in Sequence III, the sand bodies move from the northwest to southeast. The same to the distribution of the sand bodies, the distribution of lacustrine facies further move to south.

2.2 Features and distribution of the reservoir

According to the statistics of 30,285 data points of physical property, the average porosity of Upper Triassic Xujiahe Formation reservoir is 5.5% (the minimum is 0.001 % while the maximum is 21.9 %). The average permeability of the reservoir is $4.5 \times 10^{-3} \mu\text{m}^2$ (the minimum is $0.1 \times 10^{-6} \mu\text{m}^2$ while the maximum is $15.135 \mu\text{m}^2$ when cracks develop). The porosity mainly distributes between 4 % and 8 % while the permeability distributes in $(0.01 \sim 1) \times 10^{-3} \mu\text{m}^2$. In general, the physical property of the reservoir are poor, belonging to the reservoir with the low

porosity, low permeability and ultra-low porosity and ultra-low permeability, part of which develop a few reservoirs with mesopores and low permeability.

The distribution contrast on the physical property of the reservoir in each interval of Xujiahe Formation shows that the porosity of the second member of the Xujiahe Formation is the best, followed by the fourth member, and the sixth member is the worst while the permeability of the fourth member of the Xujiahe Formation is the best, followed by the second member, and the sixth member is the worst. After the research and evaluation on the three main factors affecting the development of the reservoir (sedimentary facies, lithofacies and diagenetic facies), the ichnographies of sedimentary facies, lithofacies and diagenetic facies for three reservoir segments will be worked out and the distribution of favorable facies region will be evaluated. According to the evaluation criteria for classifying the reservoirs with low porosity and permeability, Xujiahe Formation reservoir is divided into four parts and three reservoir segments to be evaluated comprehensively. Then a conclusion is drawn that II and III reservoirs distribute mostly in the central Sichuan Basin.

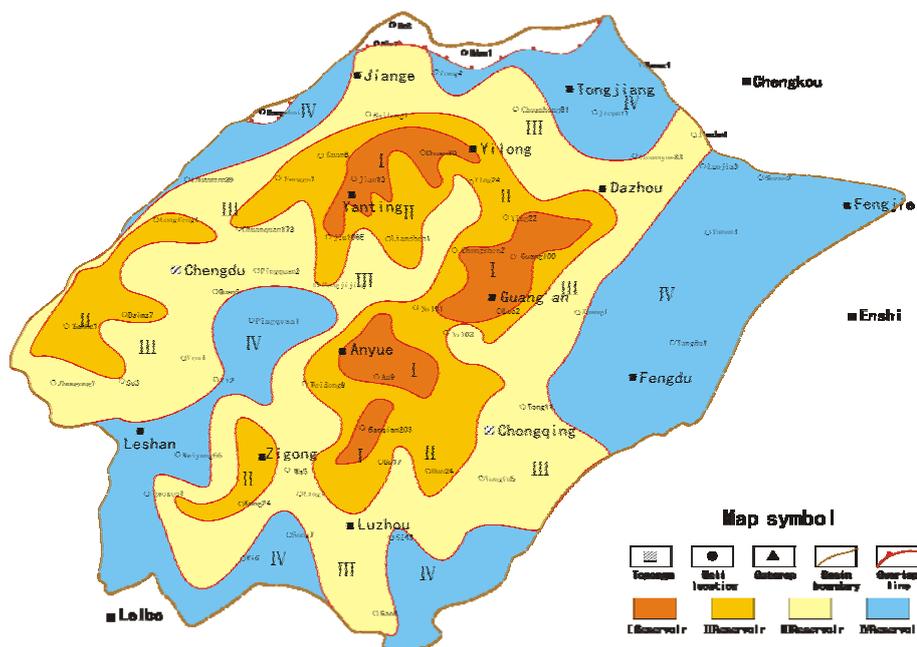


Fig. 3 The comprehensive evaluation diagram of the fourth member of Xujiahe Formation reservoir in Sichuan Basin

The second member of the Xujiahe Formation distributes mainly at II and III reservoirs. In general, the whole Sichuan Basin mainly has the reservoirs with low porosity and permeability. As a result, I reservoirs with little distribution area primarily distribute in those places where the favorable diagenetic facies, crack development zone and favorable microfacies superpose, such as Guangan, Tongnan, Bajiaochang and Hebaochang. II reservoir occupying large area mainly distributes in such districts as Chongshen, Moxi, Weidong, Tongxian, Zhongba and Southwest of Sichuan. III reservoir distributes mostly in the transition zone between Southwest of and Middle of Sichuan.

II and III reservoirs act as the majority of the fourth member of the Xujiahe Formation, while I reservoir has a less distribution. However, but it distributes wider than that of second member of the Xujiahe Formation, such as Hebaochang, Tongnan, Guangan, Bajiaochang and Pengji Districts where rock maturity is higher, matrix and soft cutting contents show a less status, diagenetic facies are chlorite binder phases and solutional phases lied at microfacies belt of delta submerged distributary channel, the porosity among plastidules saves well, at the same time feldspar contents are high because it lies at or near to hydrocarbon generation centers, erosion function are very strong. II kind of reservoir locates at Chongshen, Lianchi, Weidong, Yingshan and Southwest of Sichuan (Refer to fig. 3).

The provenance of sixth member of the Xujiahe Formation is nearer, selective table is poorer on sedimentation period, favorable zones for the development of reservoir are less than the second and fourth member of the Xujiahe Formation, majoring in II and III kinds of reservoirs, I kind of reservoirs mainly distribute at Guangan and Hebaochang with a small area, at the same time, high quality reservoirs migrate to southern gradually from the second member of the Xujiahe Formation to the sixth member of the Xujiahe Formation. II kind of reservoirs cluster at Qiongxian, Longfeng 1 well, Chongshen and Weidong District.

2.3 Source reservoir cap assemblage

Upper Triassic Xujiahe Formation reservoirs at Sichuan Basin are deposited and

typical terrestrial clastic coal measures rock sedimentations based on erosion surface of Leikoupo of Middle Triassic, which can be generally further divided into six lithologic intervals on top lateral (fig.1). First member of the Xujiuhe Formation, third member of the Xujiuhe Formation and fifth member of the Xujiuhe Formation take mudstones and shales as the main materials clipped with thin siltstones, carbonaceous shales and shed coals, which results from sedimentations on lake bog environment and formative coal-measure source rocks range widely. Second member of the Xujiuhe Formation, Fourth member of the Xujiuhe Formation and sixth member of the Xujiuhe Formation give priority to grey and fine sandstones, and medium sandstones deposited from large delta, formative ore mass of submerged distributary channel occupies a large area. Source reservoir layer interaction development constitutes good spatial dispositional relation of sandwich structure of Xujiuhe Formation (fig.4), takes advantage of large-area accumulation and improves accumulation efficiency.

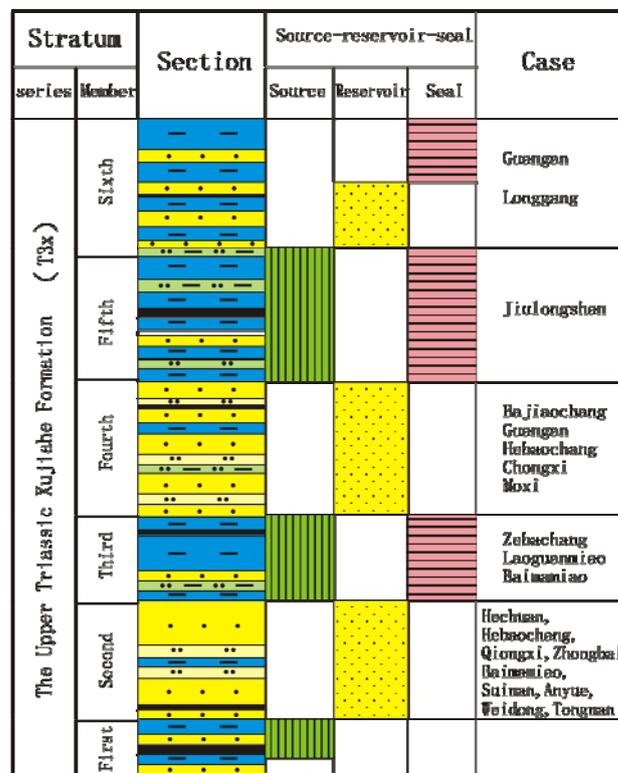


Fig. 4 The intergrated histogram of source-reservoir-seal of Xujiuhe Formation in Sichuan Basin

2.4 Exploration potential evaluation

Aiming at the distribution status of ore mass of three main reservoir intervals at Xujiache Formation, explore its potential and assess comprehensively on the basis of sand body areas, hydrocarbon production intensity, resource potential, reservoir categories and exploration actuality by layers and system, specially refer to the depth of sand bodies' top. As the research showed, Xujiache Formation reservoirs exist secondary porosity zones resulted from dissolution at the buried depth scale of 2,000 to 3,500 m, it will enter into late diagenetic age after buried depth pass beyond 3,500 m, the value of the porosity approximates the primary porosity of decline curve, reservoir conditions become bad, so we regard 3,500 m buried depth lines as a parameter of sand evaluation.

Sequence II low system tracks (the second member of Xujiache Formation): Total sand body areas are 51,440 km², sand body areas of Guangan-Yingshan, Anyue-Hechuan and Penglai-Jinhua is the largest. The buried depth of other three sand bodies is more than 3,500 m except for Jiangyou-Mianzhu, Wuzhongshan-Qionglai and Penglai-Jinhua, their reservoir kinds belong to I to II types and II to III types with good reservoir conditions. Jiangyou-Mianzhu and Wuzhongshan-Qionglai lie on hydrocarbon generation centers of Xujiache Formation with the largest hydrocarbon production intensity of (60~160) × 10⁸ m³ / km² and (20~70) × 10⁸ m³ / km² respectively. Take (1~2) × 10⁸ m³ / km² for the resource abundance and gas-bearing area between 10 % and 25 % in line with the analysis to work out resource potential of every sand bodies. Now second member of the Xujiache Formation has got nearly 5 000 × 10⁸ m³ three-level reserves, all of sand bodies are distributed by resources except for Guangan-Yingshan sand body, but earned reserves mainly focus on Wuzhongshan-Qionglai and Anyue-Hechuan., and remained resource amounts concentrate on Guangan-Yingshan and Penglai-Jinhua. Concluding above, the exploration works for sand bodies of second member of the Xujiache Formation on next step should focus on Guangan-Yingshan and Penglai-Jinhua.

The LST in Sequence III(the fourth member of Xujiache Formation): The total

areas of the sand body are 69,522 km². Nowadays, except the Guangan-Yingshan, Penglai-Jinhua and Anyue-Hechuan, others do not have found any gas reservoir. The developed gas three-level reserves are far away from that of the second member. Except that the buried depth of Wuzhongshan-Qionglai exceeds 3,500 m, other sand bodies are all less than 3,500 m. I and II reservoir are the best, including Guangan-Yingshan, Penglai-Jinhua and Anyue-Hechuan while others belong to II and III types. As for the resource potential, only Bajiaochang gas reservoir is found in the east of the Penglai-Jinhua sand body, and its main sand body in the western is close to hydrocarbon generation centers on Kawanishi with rich resources, which can be considered as the important point for next step exploration on the fourth member of Xujiache Formation. Moreover, Anyue-Hechuan sand body has larger exploration potential because of thick southern sand body and well reserve conditions.

The LST in Sequence IV (the sixth member of Xujiache Formation): its total areas of the sand body are 44,300 km². Although its buried depth all exceeds 3,500 m, reservoir conditions are poorer than the second and the fourth member. I reservoir mainly distributes in the three sand bodies: Penglai-Moxi, Anyue-Hechuan and Yibin-Guanyinchang. Because the layers of the sixth member of Xujiache Formation overlap further to the south, and suffer from the denudation in the northwest of Basin later, the distribution of the sand bodies in the sixth member of Xujiache Formation spreads further to south than the second and fourth member, and farther away from the hydrocarbon generation centers of Xujiache Formation. The hydrocarbon production intensity of all districts is generally at $(10\sim 30) \times 10^8 \text{ m}^3 / \text{km}^2$ except that of Penglai-Jinhua exceeds $20 \times 10^8 \text{ m}^3 / \text{km}^2$. Nowadays the developed reserves of the sixth member of Xujiache Formation focus on Guangan-Yingshan. In the south, the discoverable Guanyinchang gas-field in the Yibing-Guanyinchang sand body is small but stable. Moreover, the formation trap develops in the south of Basin and the later structural fracture plays a better reform role on the reservoirs. Therefore, the exploration on the sixth member of Xujiache Formation can focus on the sand bodies of Penglai-Jinhua, Yibin-Guanyinchang, Gulin-Luzhou which are with little exploration.

3. Conclusion

1) Xujiache Formation can be divided into four third-order sequences and 12 system tracts. Mainly in LST of each sequence, the reservoir sandstone is mainly the sediments in the underwater branch channels in the front edge of the delta while the TST and HST mainly consist of the sediments of lacustrine facies which are with small scale.

2) Xujiache Formation develops six sand bodies. The microfacies acts as the majority of each sand bodies in the underwater branch channels in the front edge of the delta. In early times, the scale of northern sand body was larger, and then sand body moves from the northwest to southeast because of the movement of the neighbouring plate tectonics. As a result, the scale of the southern sand body increases gradually and the depocenter moves from the northwest to southeast as well.

3) On the basis of such parameters as the distribution areas, hydrocarbon production intensity, resource potential, reservoir categories, exploration actuality and the buried depth of the six sand bodies, the next exploration emphasis in the second member of Xujiache Formation should focus on the following two sand bodies: Guangan-Yingshan and Penglai-Jinhua, Penglai-Jinhua and Anyue-Heshan for the fourth member and Penglai-Jinhua, Yibin-Guanyinchang, Gulin-Luzhou with little exploration for the sixth member.

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