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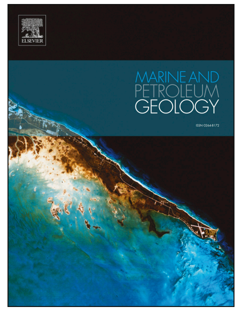

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Abstract: Sedimentary tuffs comprise important tight oil reservoirs in the Middle Permian Tiaohu Formation in the Santanghu Basin. This paper describes three research advances made on these reservoirs. (1) There are many sets of sedimentary tuff in the second member of the Tiaohu Formation and they are the “sweet section” for tight oil exploration. Vitric, crystal-vitric, and argillaceous tuffs are the main reservoir types, of which the first two are more favorable. (2) A model was established to show how the volcanic edifice controls the type and distribution of the volcanic lacustrine tuff deposition. The crystal-vitric tuff is distributed in the lacustrine deposits nearest to the volcanic crater, and the vitric tuff is distributed on both sides of the active volcanic belt a certain distance from the crater, and this is the most favorable distribution area for sedimentary tuff. Later devitrification resulted in formation of a large number of micro-pores, and this is the main reason for the presence of favorable reservoirs. (3) The sedimentary tuff reservoir has undergone successive geological processes from formation of secondary dissolution pores, then hydrocarbon charge and accumulation, to compaction. The tight oil accumulation is the result of the coupling of the diagenetic evolution of the tuff in the Tiaohu Formation and the hydrocarbon generation and charging from the shale in the Lucaogou Formation.

Key words: exploring oil inside source kitchen, tight oil, sedimentary tuff, sweet section, volcanic edifice, lacustrine facies, secondary pores, devitrification

0 Introduction

The term “tight oil” refers to the oil stored in tight reservoirs such as sandstone, carbonate rock, hybrid sedimentary rock, sedimentary tuff, mudstone/shale, and other rock types with permeability less than or equal to 0.1 mD. In addition, tight oil is an unconventional oil resource in that individual wells generally have no natural production capacity, or the natural production capacity is below the lower limit of commercial oil flow. However, economic development can be achieved through technologies such as horizontal wells and rock volume fracturing (Jia et al., 2017, 2018; Zou et al., 2013, 2019a, 2019b; Yang et al., 2019a, 2019b).

Continental tight oil is an inevitable choice for China's onshore oil exploration (Yang et al., 2019a).

In the past ten years, our research team has studied continental shale in key basins such as the Ordos, Junggar, Songliao, and Sichuan Basins. Through specific experimental analysis, geological evaluation, technological development, and strategic research focusing on the large-scale industrial development of oil in terrestrial shale, a series of original achievements have been made (Yang et al., 2015, 2016a, 2016b, 2017, 2019a, 2019b, 2019c; Zou et al., 2013, 2015, 2018, 2019a, 2019b; Wu et al., 2019a, 2019b; Zhu et al., 2019; Pan et al., 2015, 2019; Lin et al., 2019). In the processes of exploring for self-sourcing oil in continental shales in China, volcaniclastic rock has become an important reservoir worthy of attention, and the Permian strata in the Santanghu Basin are representative of this type. Based on the geological setting and the progress of tight oil exploration in the Santanghu Basin, this paper focuses on introducing our research progress on the tight reservoirs of the oil-bearing tuff in the Middle Permian Tiaohu Formation, and systematically analyzes the geological characteristics, environments, and mechanisms for forming favorable reservoir zones, and further discusses the diagenetic evolution of the tuff reservoir and the coupled relationship between hydrocarbon generation and charge within the shale series.

1 Geological background

Tight oil in China mainly exists in Mesozoic-Cenozoic shales in lacustrine basins. It is widely found in the Yanchang Formation in the Ordos Basin, the Cretaceous in the Songliao Basin, the Permian in the Junggar Basin, the Permian in the Santanghu Basin, the Shahejie Formation in the Bohai Bay Basin, the Paleogene-Neogene in the Qaidam Basin, and the Jurassic in the Sichuan Basin (Fig. 1). Target tight oil reservoir intervals include a variety of lithologies such as tight sandstone, carbonate rock, hybrid sedimentary rock, and mudstone/shale. The marginally mature lacustrine shale (with Ro between 0.5% and 1.0%) is highly heterogeneous and variable in formation pressure, fluid quality, and other properties (Zou et al., 2019b; Yang et al., 2015). In the past ten years, many in-depth comparative research studies have been carried out on the geological characteristics of, and exploration and development of oil and gas from, “unconventional” marine shales in North America (Dong et al., 2017; Hackley et al., 2016; Han et al., 2015,2017; Hao et al., 2013; Hood et al., 2012; Jarvie, 2012; Li et al., 2019). These have resulted in an ongoing evolution in both theoretical and practical technical understanding of the “horizontal well + volume fracturing” system. This has led to important progress in tight oil exploration in the Ordos, Songliao, Junggar, Santanghu, and Bohai Bay Basins (Dai et al., 2016; Jiang et al., 2016; Lyu et al., 2016; Pan et al., 2019; Ma et al., 2016a, 2016b; Tang et al., 2015; Wang et al., 2017; Zou et al., 2019b; Yang et al., 2015; Jiang et al., 2015; Hou et al., 2017; Hu et al., 2017) (Fig. 1).

The Santanghu Basin was strongly influenced by volcanism during the Permian, and the tight oil found in the Tiaohu Formation is mainly stored in the tuff therein. Because of the distinct differences in lithology from the tight oil reservoirs in other basins in China, this formation has unique mechanisms of hydrocarbon formation, distribution, and accumulation (Ma et al., 2016a, 2016b; Liang et al., 2014; Xiao et al., 2009; Liu et al., 2015). In recent years, substantial breakthroughs have been made on tight oil exploration in this formation. Many wells such as L1 and M56 have found tuff layers in the second member of the Tiaohu Formation, which is thick and has good physical properties, good oil quality, and common hydrocarbon indicators. More than thirty wells have obtained commercial oil flow, and a large-scale tight oil production zone has been constructed, suggesting that tuff is an important reservoir type worthy of exploration attention.

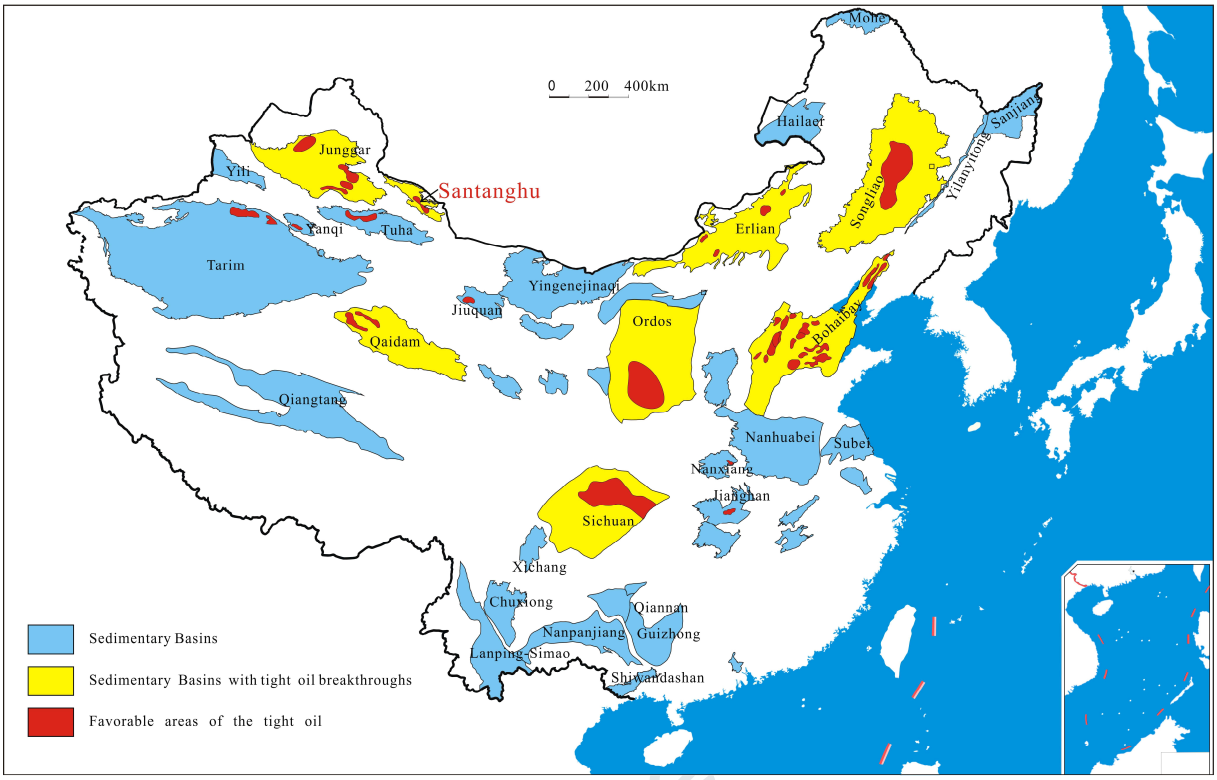

Fig. 1 Distribution of continental tight oil in China's major petroliferous basins.

The Santanghu Basin is located in the northeastern part of Xinjiang, China, and borders Mongolia to the north. It is distributed in a NW-oriented band, covering an area of approximately 2.3×10^4 km^2. Structurally, it is located on the southwestern edge of the Siberian plate. Over geologic history, the basin was an active continental marginal zone, and a multi-cycle superimposed residual basin developed on the fold basement of the late Devonian-Early Carboniferous. Currently, it is composed of three parts: the northern uplift belt, the central depression belt, and the southern thrust belt (Liang et al., 2014; Liu et al., 2015) (Fig. 2). The central depression belt, with an area of approximately 8000 km^2, is the main structural unit accumulating oil and gas in the Santanghu Basin. It is further divided into eleven secondary structural units namely Wutong sag, Kumusu salient, Hanshuiquan sag, Suhaitu salient, Tiaohu sag, Beihu salient, Tiaoshan salient, Malang sag, Weibei salient, Naomaohu sag, and Suluke sag (Ma et al., 2016a, 2016b; Liang et al., 2014) (Fig. 2). The Devonian-Carboniferous period was the most active volcanic period in the area, during which the basin was filled with thick volcanic rocks. During the Permian, the basin evolved into a fault basin within the plate. When the Lucaogou Formation was deposited, volcanic activity was relatively weak, and a set of lacustrine mudstone, marl, and sandstone sediments interbedded with volcanic rock was deposited in a semi-deep lacustrine environment. During the deposition of the Tiaohu Formation, coastal to shallow lacustrine and semi-deep lacustrine facies were developed during a period of more volcanic activity. As a result, massively thick volcanic rocks, basic intrusive rocks interbedded with mudstone, siltstones, and tuffs were deposited, and these built sedimentary formations of thick volcanic rock combined with volcaniclastic rock (Fig. 3). Since the Triassic, squeezed by the northern and southern mountain systems, depression-type sedimentation has occurred in the basin.

At present, tight oil exploration focuses on the Malang-Tiaohu sag, and the primary target layer is the Permian Tiaohu Formation, which can be divided into three members from bottom to top (Fig. 2 and Fig. 3). During the deposition of the first member, the basin was in a tensile extensional environment with frequent volcanic activities. Normal faults acted as channels for magmatic exhalation, forming many active volcanic zones, and depositing a set of medium-basic volcanic rocks in the basin. Locally, there was intrusion of diabase, which is mainly basalt or andesite, with a small amount of thin tuffaceous mudstone, and this is electrically characterized by low GR(Gamma Ray), high resistivity, and high AC(Acoustic Time Diference). The second member of the Tiaohu Formation is dominated by mudstone deposited in a period of intermittent volcanic activity along with multiple sets of sedimentary tuff deposits. There are tens of meters of vitric-clastic tuff with low GR, low resistivity, and medium AC at the base of the widespread second member. The tuff is 40-390 m thick and averages 150 m, and it is comparable and traceable regionally, making it a reservoir “sweet section” for tight oil exploration in the

Santanghu Basin (Fig. 4). The third member of the Tiaohu Formation was formed during another volcanic cycle. Almost eroded, it can only be found locally, where the lithology is similar to the first member. In general, the volcanic rock in the Santanghu Basin mainly includes basalt, andesite, and tuff, followed by diabase and rhyolite. In addition to the tuff in the second member, the volcanic rock of the overflow facies is another favorable hydrocarbon-bearing reservoir.

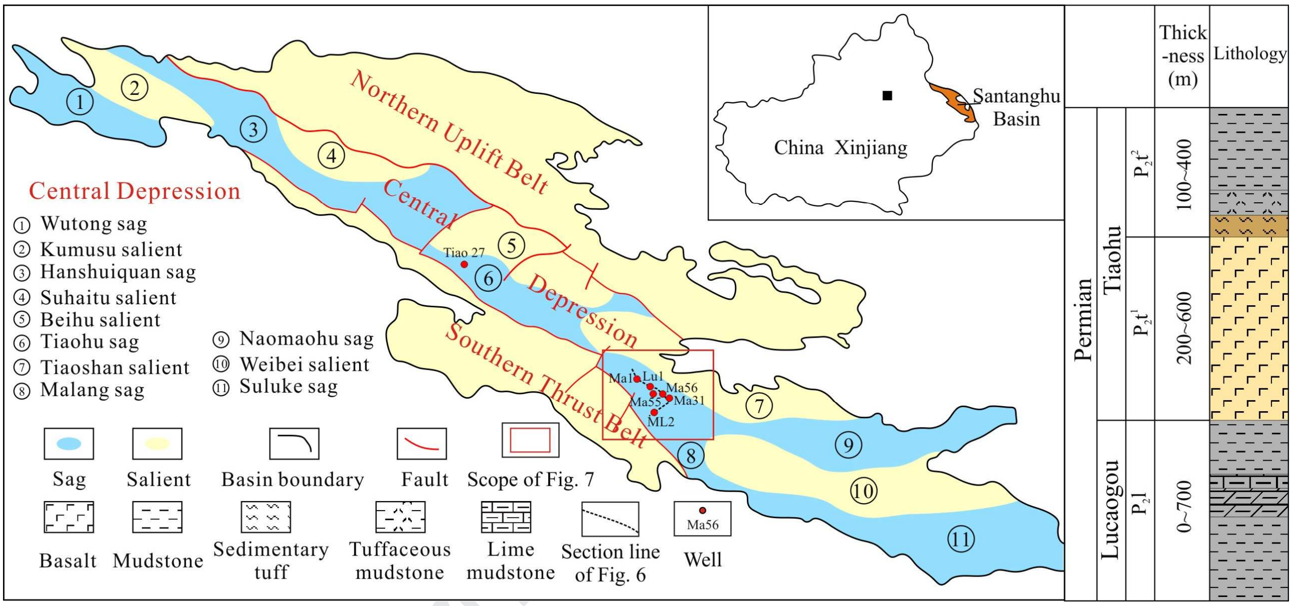

Fig. 2 Tectonic location of the Santanghu Basin and the Permian lithology column.

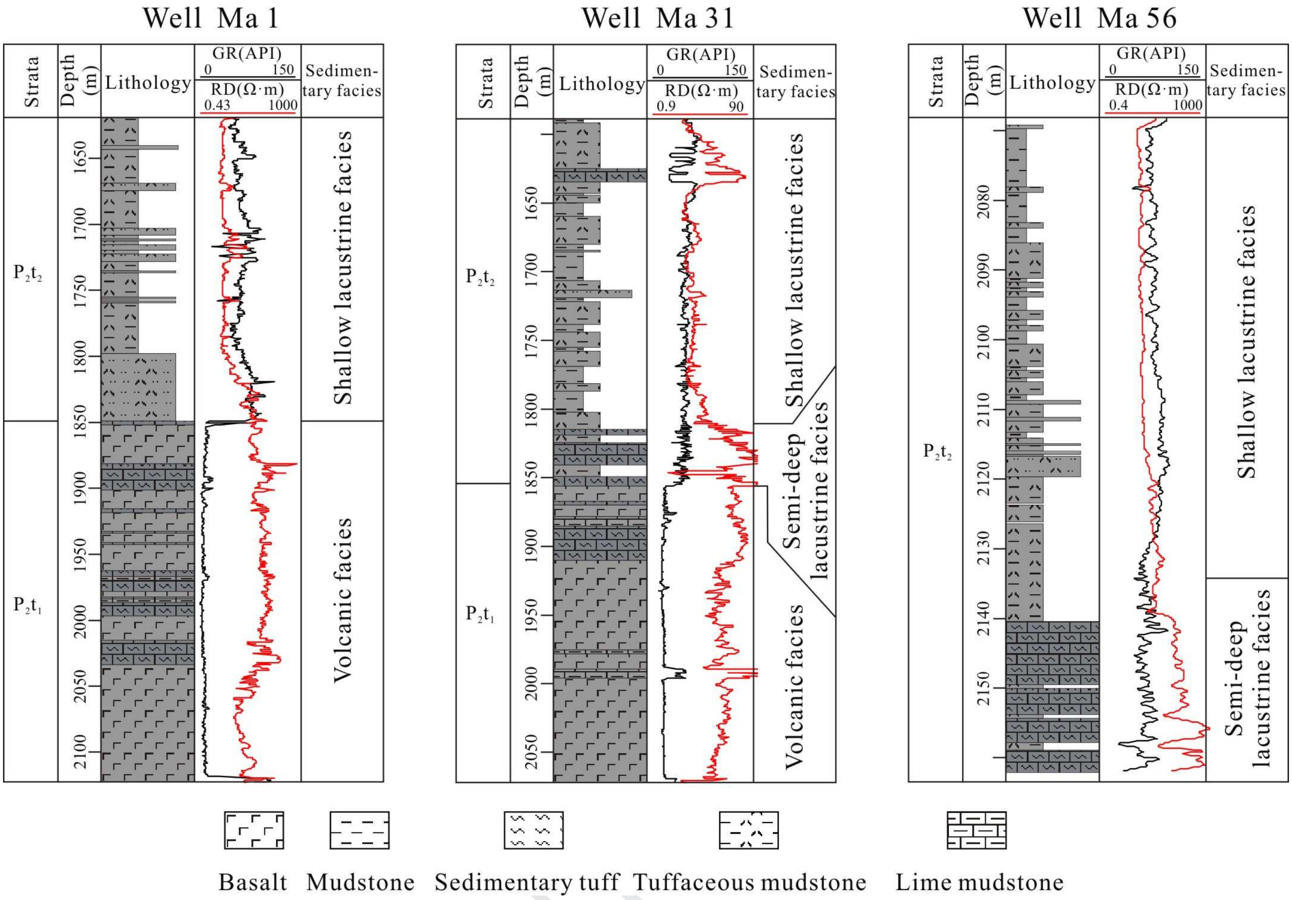

Fig. 3 Sedimentary facies of the Tiaohu Formation in individual wells in the Santanghu Basin.

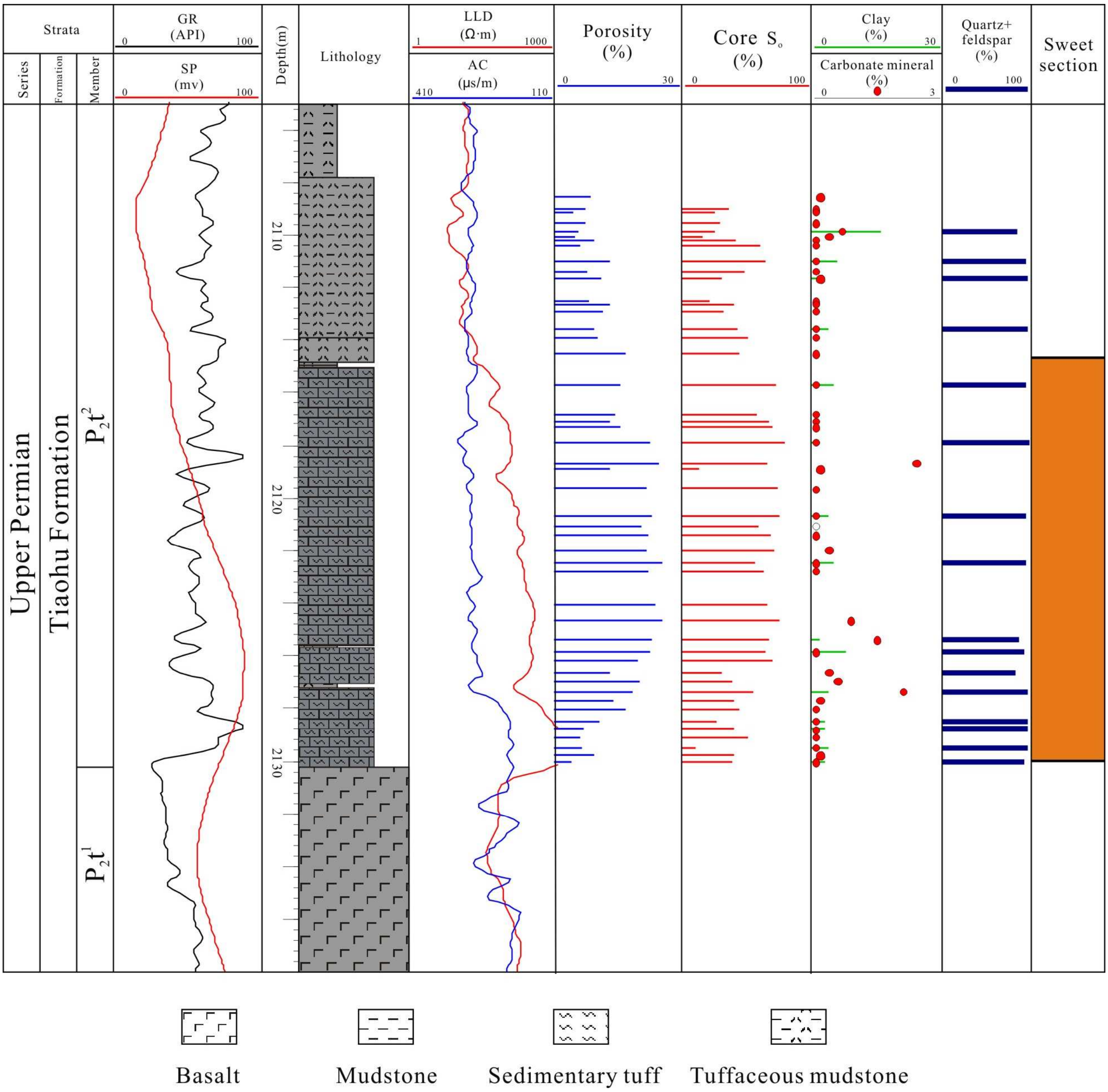

Fig. 4 Comprehensive column of Tiaohu Formation of a horizonal well adjacent to Well Ma56 in the Santanghu Basin.

2 Permian volcaniclastic reservoir description

2.1 Reservoir type and characteristic

The sedimentary tuff of the Tiaohu Formation mainly includes three rock types: vitric tuff, crystal-vitric tuff, and argillaceous tuff (Fig. 5).

Vitric tuff: The original volcanic ash is mainly composed of vitric clastic components, with a content greater than 50%. The particle size is small, quartz and feldspar are the primary minerals, and clay content is low (Fig. 5-A, B). Volcanic vitreous devitrification is the main factor leading to high porosity and low permeability of the reservoir; the primary pore type is formed by devitrification. This type of lithology is distributed in the middle of the tuff interval (Fig. 3). It has high porosity, numerous pores with fine uniformly distributed pore throats, good sorting, and relatively coarse flexure. It is a high-quality reservoir in the study area.

Crystal-vitric tuff: The original volcanic ash is mainly composed of vitric clastic components, with a content greater than 50%. Compared with vitric tuff, it has more crystal clastic components, larger grain size, and higher clay content (Fig. 5-C, D). Clay minerals infill the pores, which complicates the pore structure and results in lower porosity and narrower pore throats. As in the vitric tuff, the primary pores are devitrified. This type of lithology is distributed in the middle of the tuff interval (Fig. 3) and as interlayers between the slab tuff. The reservoir can be characterized as having high porosity, medium sorting, and relatively fine flexure. It is another good reservoir with petroleum storage capacity.

Argillaceous tuff: The original volcanic ash is mainly composed of vitric clastic components, with a content greater than 50%, and with a small amount of fine-grained crystal clastics. The terrestrial argillaceous content is higher than in the other rock types, reaching over 20% (Fig. 5-E, F). The rock is highly compacted, and the introduction of argillaceous debris creates a poor quality reservoir with high clay content (generally greater than 15%) and less devitrified porosity. This type of lithology is distributed at the top of the tuff interval (Fig. 3) and is the product of introducing terrestrial mud material. It has low porosity, fine particle size, good sorting, and fine flexure. It is a reservoir without storage capacity.

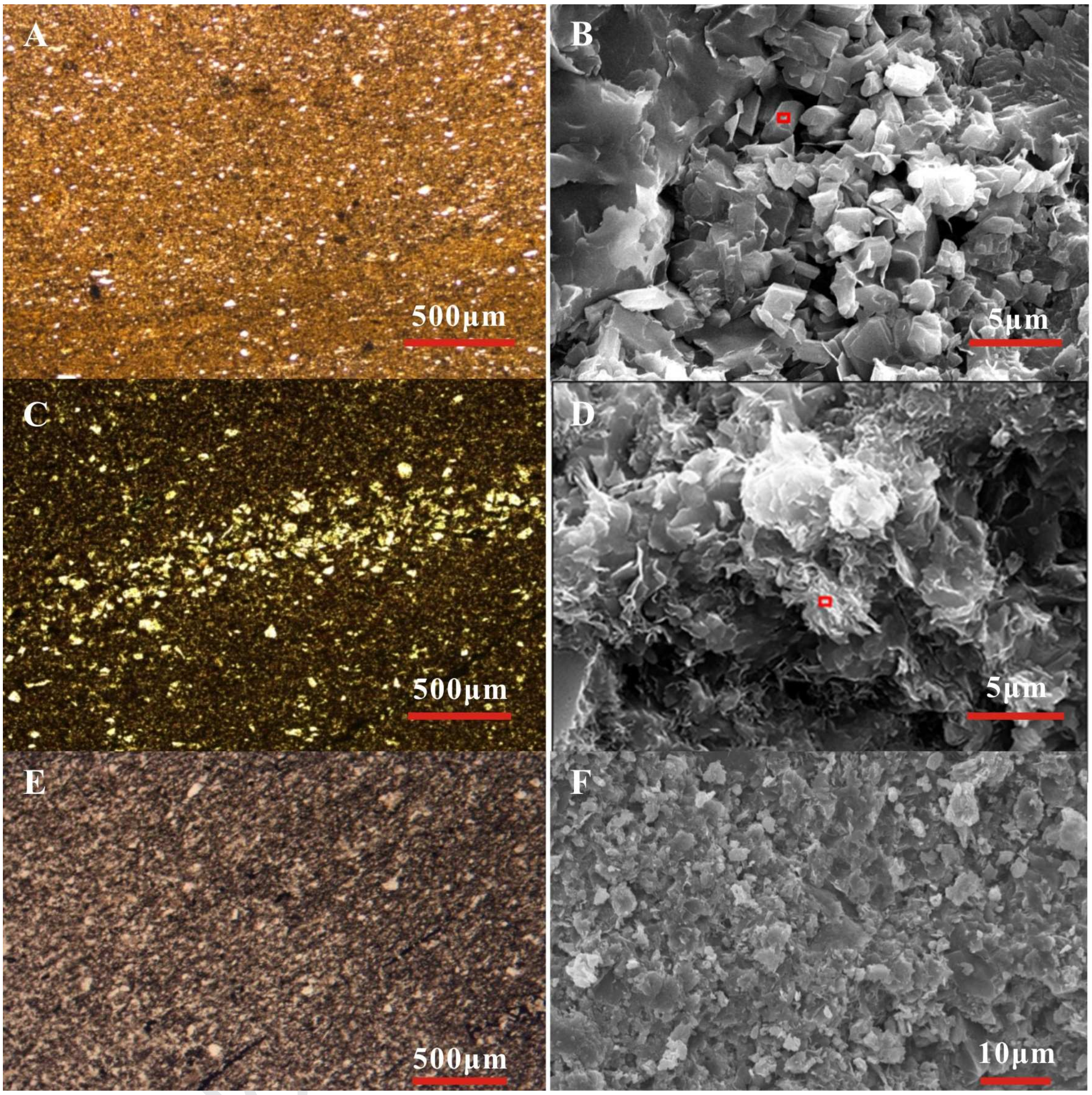

Fig. 5 SEM photographs of the three types of tuff in the Tiaohu Formation.

A. Vitric tuff, 2nd member of Tiaohu Formation,2850 m, Well Tiao 27, plane-polarized light; B. Vitric tuff, 2nd member of Tiaohu Formation, 2121.09 m, a horizonal well adjacent to Well Ma56, SEC; C. Crystal- vitric tuff, 2nd member of Tiaohu Formation, 2252.34 m, a horizonal well adjacent to Well Ma56, plane-polarized light; D. Crystal-vitric tuff, 2nd member of Tiaohu Formation, 2248 m, a horizonal well adjacent to Well Ma56, SEC; E. Argillaceous tuff, 2nd member of Tiaohu Formation, 2110.2 m, a horizonal well adjacent to Well Ma56, plane-polarized light; F. Argillaceous tuff, 2nd member of Tiaohu Formation, 2110.3 m, a horizonal well adjacent to Well Ma56, SEC.

2.2 Reservoir forming environment

There are large differences in the interval velocities of the volcanic lava and the volcanic clastic rock erupted in the volcanically active periods, and the clastic rock deposited during the inactive periods. The interval velocity of the basalt-andesite in the Tiaohu Formation is 4,200-4,500 m/s, that of the overlying tuff is 3,100-3,300 m/s, and that of the top mudstone is low, less than 3,000 m/s (Liang et al., 2014). The physical properties of the volcanic edifice and its surrounding rock are also quite different. A strong seismic amplitude reflector at the interface is an important basis for studying the volcanic facies. The velocities of the volcanic edifice, the internal structure, and the surrounding rock are very different, and they show up as different mound-shaped seismic responses (Fig. 5). At the top of the volcanic edifice, there is strong reflection. Inside the volcanic edifice, there is weak reflection, with chaotic, low frequency, and intermittent reflection features. After the volcanic eruption, due to the effect of cold contraction of the rock, the top of the mound-shaped reflector on seismic sections shows a graben-shaped depression. On seismic sections, the events at the top of the volcanic crater appear to be pulled down. In addition, the seismic section is chaotic or contains steep events. Chaotic seismic reflection or steep events can be found near the volcanic channel on the seismic section because the surrounding rock has been damaged by magma intrusion. It is common that overlap and draping phenomena show strong, continuous, stable events, and are found in the wings of a volcano edifice.

Based on the fault distribution, seismic reflection, drilling data, and Permian sedimentary environment, active volcanic zones were identified on seismic sections, and the model for how volcanic edifices controlled the type and distribution of the volcanic lacustrine tuff was established (Fig. 6, Fig. 7). In the Malang sag, crystal-vitric tuff in the Permian Tiaohu Formation was distributed closest to the volcanic crater in a lacustrine environment where the Ma 7 block is located. Vitric tuff was distributed on both sides of the active volcanic belt a certain distance from the crater where there was a volcanic barrier lake, and where Block Ma 56 is located. Argillaceous tuff was mainly distributed in the deep water of the lake basin, which was a lacustrine environment far from the volcanic crater, and comprises the area south of Well Ma 7.

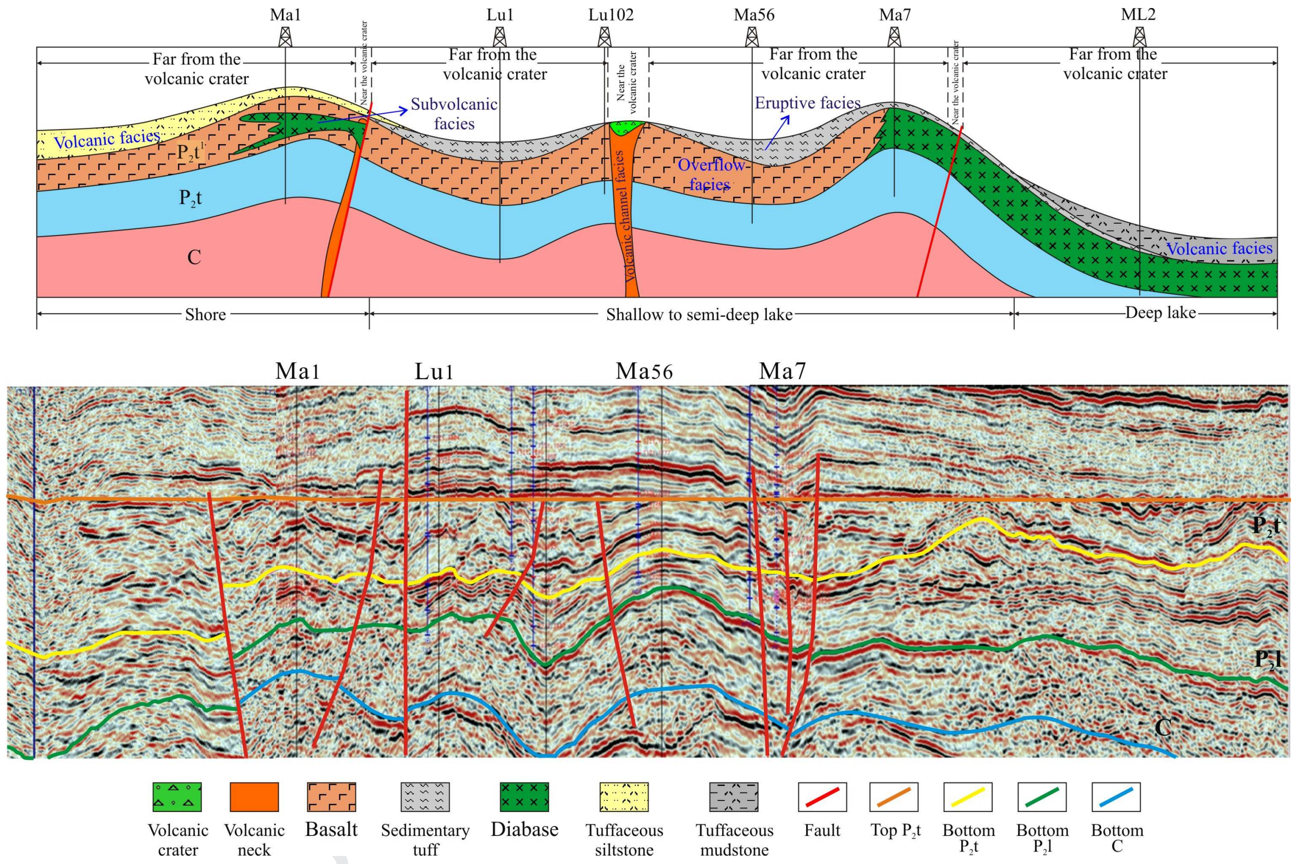

Fig. 6 Lithofacies profile controlled by the volcanic edifice of the Tiaohu Formation in the Santanghu Basin. The upper one is the geological interpretation and the lower one is the seismic interpretation, and these two maps are corresponding to the same cross-section.

In the Permian period, the Santanghu Basin was mainly a stable shallow lacustrine to semi-deep lacustrine environment with low supply of terrigenous clastic materials. During the deposition of the Permian Tiaohu Formation, the Malang sag experienced three stages of sedimentary evolution, namely volcanic eruption, volcanic ash, terrigenous clastic deposition, and inactive volcano dormancy. A complete volcanic activity cycle successively went through volcanic eruption period, volcanic effusion period, deposition of tuff period and inactive period. Volcanic eruptions followed volcanic channels in the main deposition. During the deposition of the first member of the Tiaohu Formation, volcanism was active and was dominated by volcanic lava and volcanic clastic rock, which were interbedded with thin layers of lacustrine mudstone deposited during the short inactive volcanic periods. Afterwards, due to the weakening of the volcanic eruption, the formation entered a longer volcanic eruption period (Fig. 7). During the deposition of the second member, early-erupted tuffs and late tuff mudstones or mudstones were developed, which are typical of intermittent volcanic eruption periods (Fig. 7). During the deposition of the third member, volcanic activity intensified again, and volcanic lava and volcanic clastic rock were deposited with less sub-volcanic rock and thin mudstone interbeds. Afterwards, the sag entered a long period of structural uplift and erosion. As a result, the third member of the Tiaohu Formation is locally present only in the western and eastern sag.

The sedimentary tuff of the Tiaohu Formation is the product of volcanic ash directly falling into the lacustrine basin, and volcanic eruptions of different scales led to different volcanic lacustrine facies (Fig. 6 and Fig. 7). Low-energy eruptions coupled with low levels of faulting usually resulted in a crater lake. High-energy eruptions coupled with high levels of faulting resulted in volcanic lava blocking and dividing the shallow lakes, resulting in volcanic barrier lakes. Larger crystal particles in volcanic ash fell close, and rapidly accumulated belt-like or fan-shaped sediments in the crater and surrounding areas. Therefore, with increasing distance from the crater, the type of tuff regularly changed, and the proximal area received predominantly crystal-vitric tuff sediments. Within a certain range, farther away from the crater, vitric clastic content was higher. Vitric tuff deposited in volcanic barrier lakes, thus vitric tuff is mainly areally distributed medium to long distances from the crater. When the distance from the crater was too great, volcanic supply was limited, and the argillaceous content increased. In this case, argillaceous tuff was deposited in a shallow to semi-deep distal lacustrine environment. In summary, due to the differences in i) intensity of volcanic eruption, ii) levels of fracture channels, iii) magma energy attenuation, iv) distance, and v) volcanic ash supply, different types of volcanic lacustrine facies were formed, which controlled the formation of different types of tuffs.

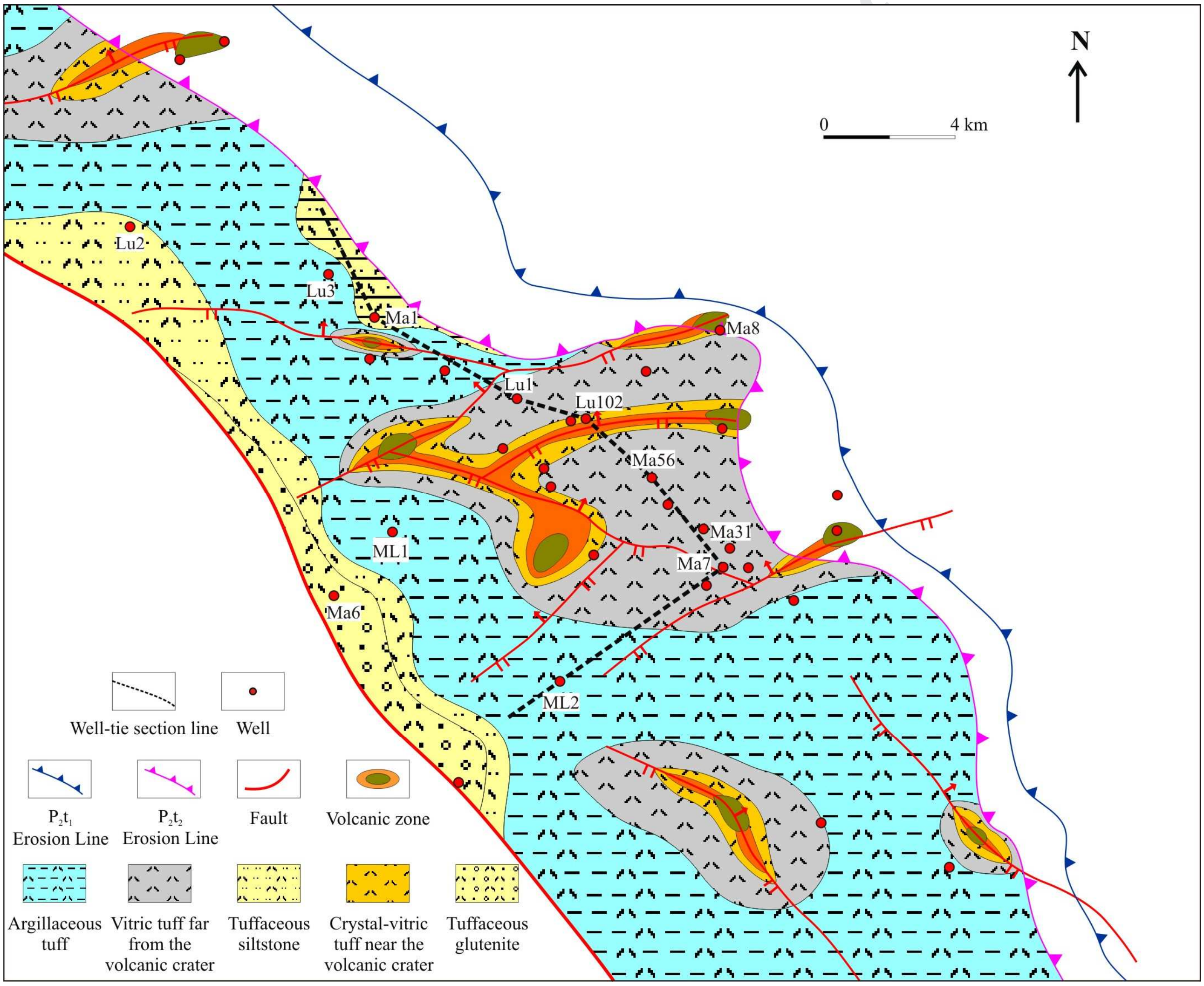

Fig. 7 Volcanic facies controlled by volcanic edifices of the Tiaohu Formation in the Santanghu Basin.

2.3 Reservoir "sweet section"

The reservoir properties of the sedimentary tuff in the second member of the Tiaohu Formation are mainly controlled by the sedimentary conditions, mineral composition, the extent of mixing of terrigenous argillaceous materials, intensity of devitrification, and diagenesis. The porosity is largely not dependent on particle size, and reservoir properties are greatly affected by the sedimentary environment. Through wind transportation, extremely fine volcanic ash and dust slowly rained down and settled on the bottom of the distal lake and covered the bottom-dwelling microorganisms, forming sedimentary tuff. Though intergranular pores were largely destroyed during compaction, the sedimentary tuff reservoir has high porosity today due to tuff devitrification. After the devitrification process, the particles of sedimentary tuff were closely arranged to produce devitrified pores. These pores are small, but their large quantity results in overall high porosity (Fig. 8). Most of the clastic component of the sedimentary tuff in the study area is vitric-clastic, that is mainly composed of vitreous materials. Because the vitreous materials are in a thermodynamically unstable state, the volcanic glass tends to transform into crystals. There are three factors controlling devitrification. First, the devitrification of acid tuff can form more and larger micro-crystals, which tends to produce devitrified pores and better reservoirs. Second, the higher the vitreous content, the larger the porosity formed by devitrification. The higher the vitreous content in the tuff, the greater the devitrification potential. Third, the devitrifying rate is controlled by the organic acid content. A certain amount of organic matter exists in the sedimentary tuff of the Tiaohu Formation, which generates an organic acid during burial that can effectively promote the devitrification process. The higher the organic matter content, the more organic acid is produced, the lower the pH value, the higher the dissolution rate of the vitreous materials, and the more favorable the conditions for devitrification. In general, the stable coastal-shallow lake environment lacking a regular supply of terrigenous clastic materials is the key element to the formation of tight tuff reservoirs in the slope area, and the deposition area of volcanic ash slowly settling after volcanic eruptions constrains their distribution. In addition, tectonic activities can enable the formation of a natural fracture system within the tuff reservoir, which further enhances the storage capacity of the reservoir.

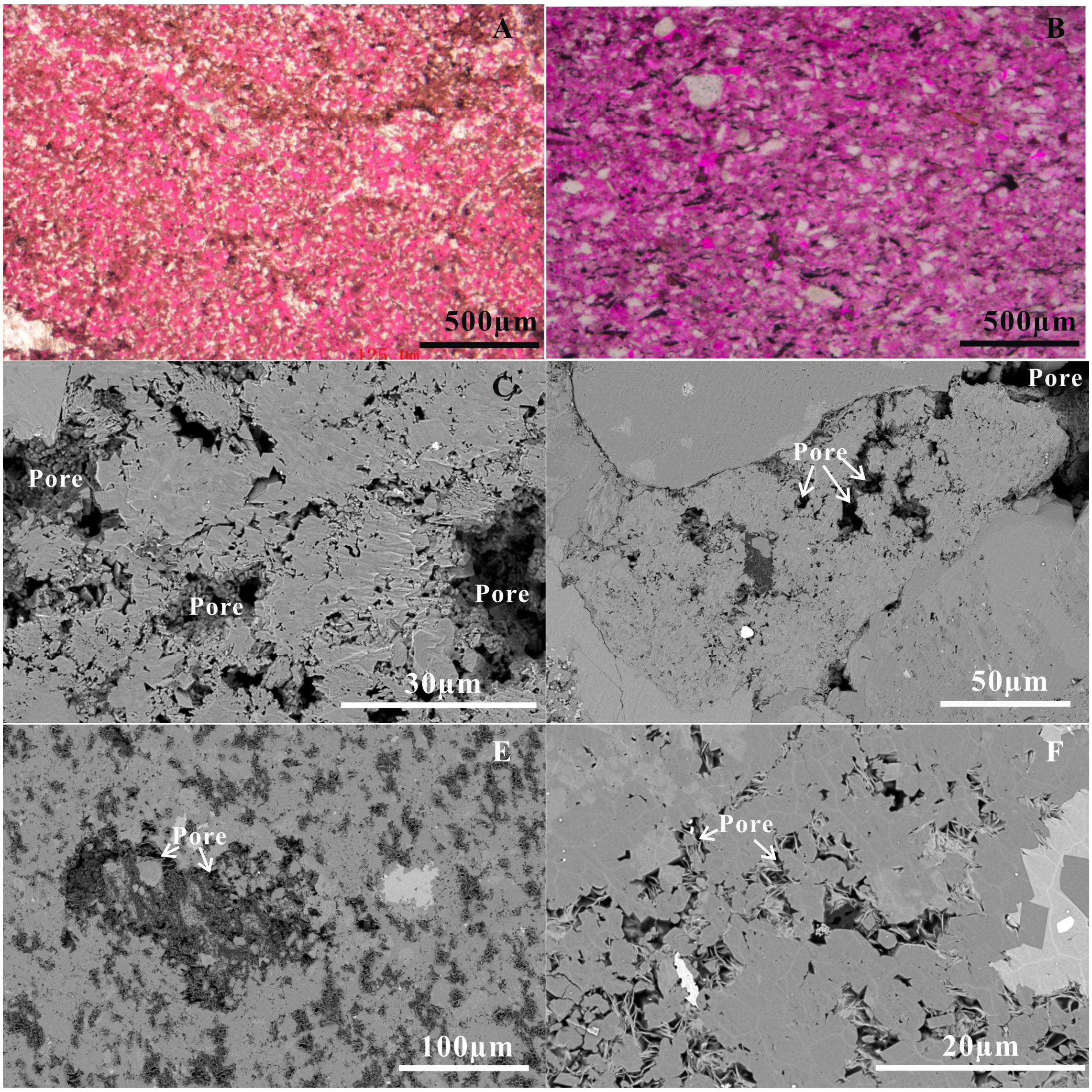

Fig. 8 SEM photographs of microscopic pores of the sedimentary tuff in the Tiaohu Formation.

A. Dissolved pores in vitric tuff, the pores are the parts filled by Alizarin RED, 2nd member of Tiaohu Formation, 2245 m, a horizonal well adjacent to Well Ma56, cast thin section, plane-polarized light; B. Micropores in fine powdery vitric-crystal tuff, feldspar crystal pyroclast obviously dissolved, the pores are the parts filled by Alizarin RED, 2nd member of Tiaohu Formation, 2476.16 m, Well Ma 55, cast thin section, plane-polarized light; C. Dissolved pores in vitric tuff, 2nd member of Tiaohu Formation, 2269.5 m, Well Ma 55, argon ion polishing SEM; D. Dissolved pores in vitric tuff, 2nd member of Tiaohu Formation, 2269.5 m, Well Ma 55, argon ion polishing SEM; E. Dissolved pores in vitric tuff, 2nd member of Tiaohu Formation, 2142.6 m, Well Ma 56, argon ion polishing SEM; F. Crystal-vitric tuff, 2nd member of Tiaohu Formation, 2142.6 m, Well Ma 56, argon ion polishing SEM.

3 Discussion of the relationship between reservoir formation and hydrocarbon accumulation

The porosity, permeability, and oil content of the volcanic clastic reservoirs are significantly controlled by lithology. At present, most of the wells delivering commercial oil flow contain vitric-crystal clastic sedimentary tuff (Fig. 9), and the burial depth of the prospective oil-bearing section is mainly between 1800 and 2500 m (Fig. 10).

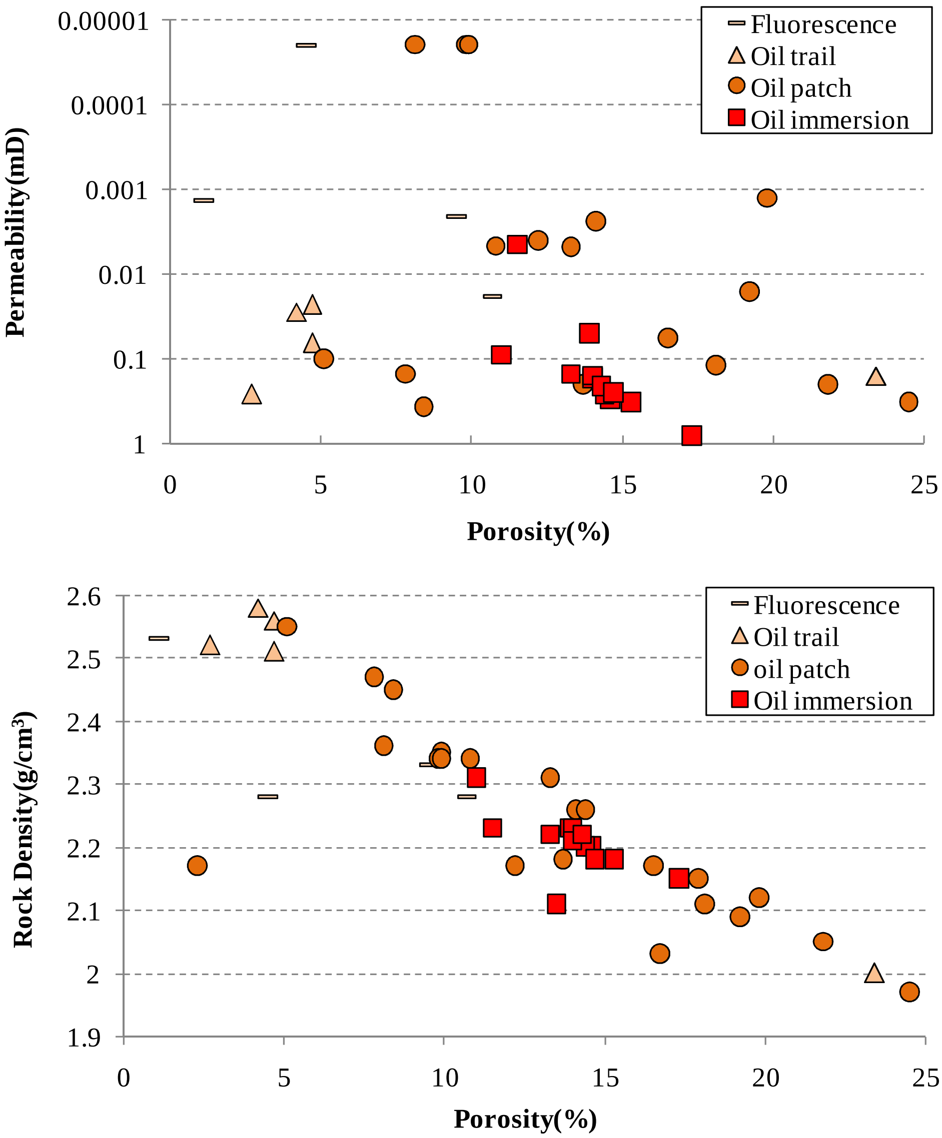

Fig. 9 Physical properties and hydrocarbon shows of tuff reservoirs in the Tiaohu Formation.

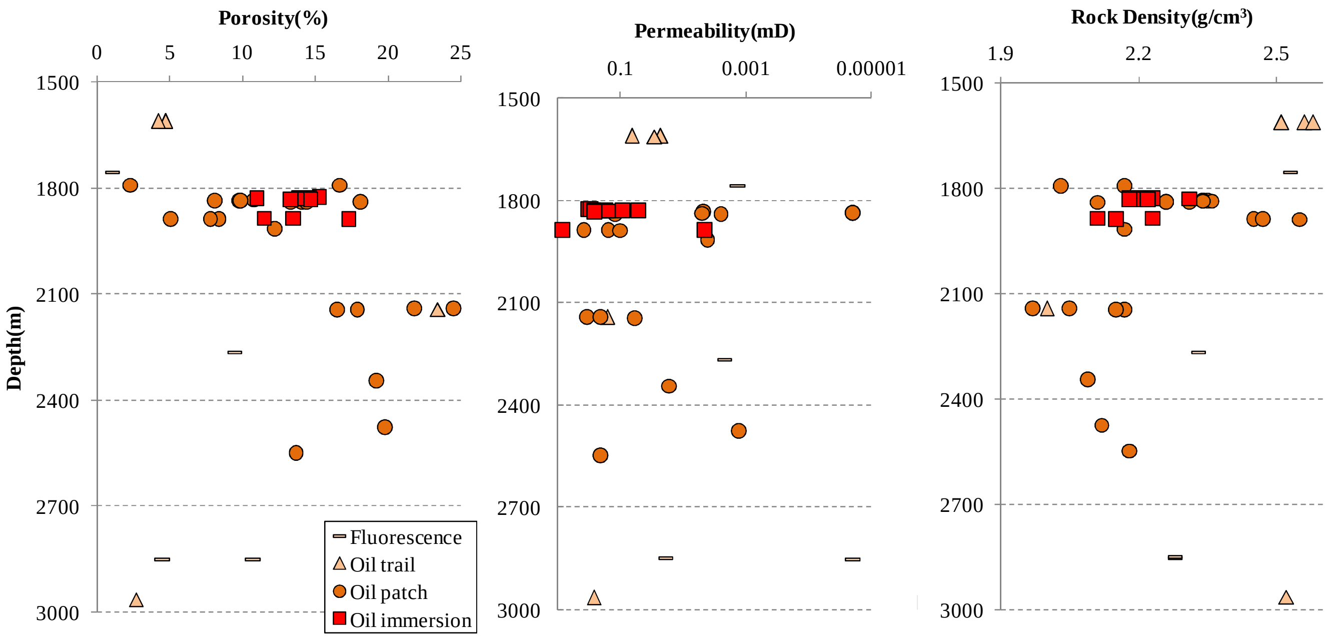

Fig. 10 Physical properties and hydrocarbon shows of tuff reservoirs at different depths of the Tiaohu Formation.

Both the diagenetic evolution of the sedimentary tuff in the Tiaohu Formation and the oil charge from the shale in the Lucaogou Formation have played an important role in the process of tight oil accumulation in the Tiaohu Formation (Fig. 11), thus, the oil accumulation is a result of the coupling of these two processes. At the onset of the early diagenetic stage of the Tiaohu Formation, the reservoir was weakly to semi-consolidated, and the clastic particles were matrix-supported so the reservoirs mainly developed primary intergranular pores. In the early diagenetic stage (depth<1000 meters), diagenesis was dominated by mechanical compaction, and the cementation was mainly carbonate and clay cementation, which enhanced pore filling, decreasing porosity rapidly. At the late stage of early diagenesis (approximately 1000 m deep), the organic matter in the Tiaohu Formation began to thermally degrade, removing oxygen-containing functional groups, forming organic acid, and then eroding feldspar and crystal clastics to form secondary dissolution pores. Early in the middle diagenesis stage (between 1000 and 2200 m, R_o between 0.5% and 0.7%), the organic matter in the shale of the Lucaogou Formation entered the oil-generation window, during which a large amount of CO_2 and organic acids and a small amount of hydrocarbons were produced. Consequently, dissolution and devitrification occurred on a large scale, and large quantities of secondary dissolution pores appeared, significantly increasing the porosity. Late in the middle diagenesis stage (depth > 2200 m, R_o greater than 0.7%), the decarboxylation of organic matter in the source rocks of the Lucaogou Formation was basically completed, the production of organic acids was low, and the organic matter gradually reached the peak of oil generation. At that time, a large amount of liquid hydrocarbon was generated by the Lucaogou source rocks, which migrated upward through the faults and the weathering crust to the tuff reservoir of the Tiaohu Formation. The regional mudstone at the top of the Tiaohu Formation was an effective seal. After oil and gas accumulated, tectonic movement in the Santanghu Basin has been relatively weak, the fractures have closed, and the tuff reservoirs gradually became tight and less permeable. Since then, the reservoir has not undergone extensive alteration.

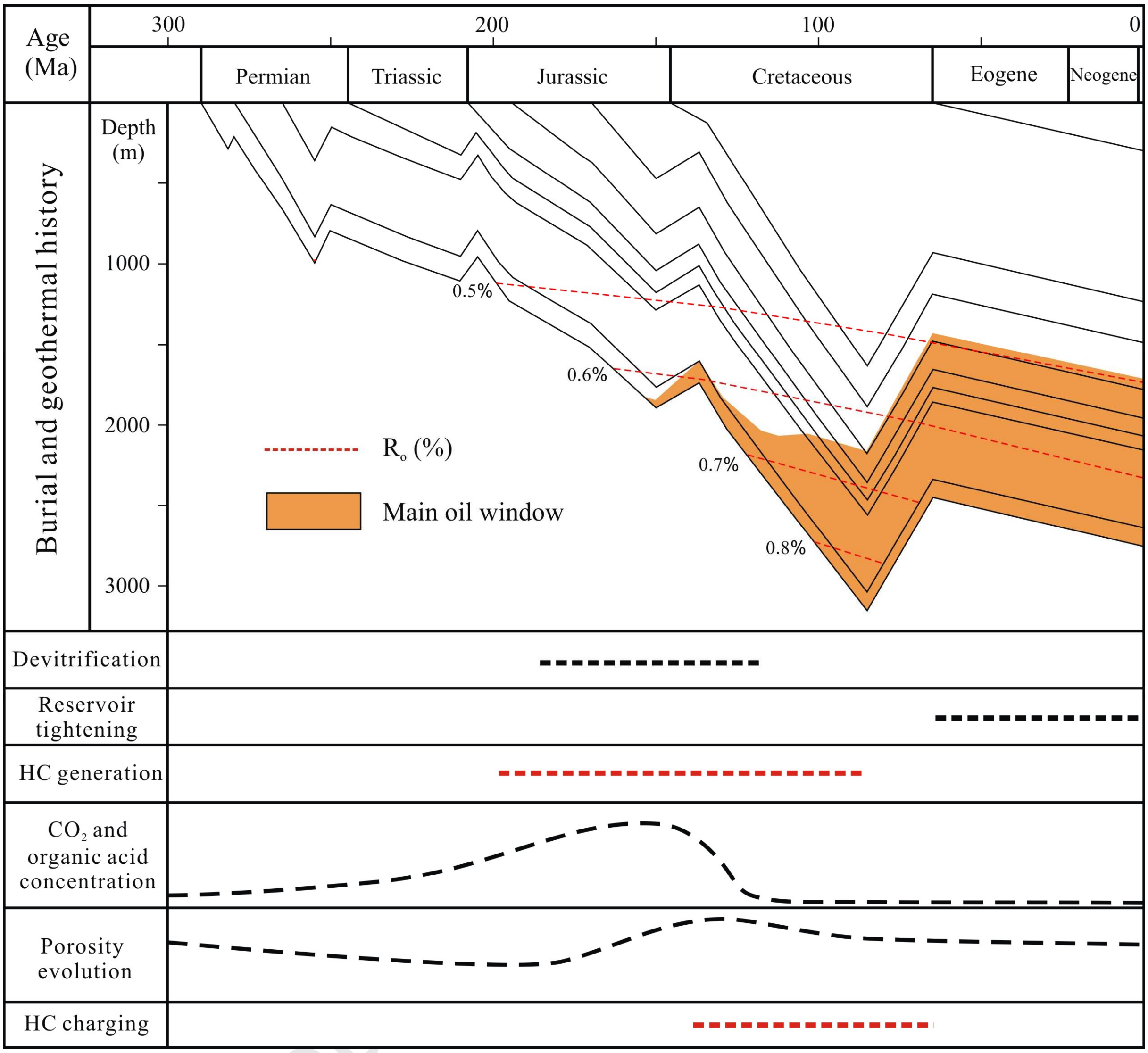

Fig. 11 Diagenetic evolution and hydrocarbon accumulation of the tuff reservoir in the Tiaohu Formation of the Santanghu Basin

4 Conclusions

(1) The second member of the Tiaohu Formation is a “sweet section” for tight oil exploration. There are many sets of sedimentary tuffs in this member and they include two types of favorable reservoirs: vitric tuff and crystal-vitric tuff. The vitric tuff is distributed in the lows on both sides of the active volcanic belt a certain distance from the crater and the crystal-vitric tuff is distributed in the lacustrine deposits nearest to the volcanic crater. Later devitrification that resulted in a large number of

micro-pores is the main reason for the formation of the favorable reservoir.

(2) The sedimentary tuff reservoir has undergone successive geological processes including formation of secondary dissolution pores, hydrocarbon charge and accumulation, and ultimately reservoir compaction. Tight oil accumulation is the result of the coupling effect of the diagenetic evolution of the tuff in the Tiaohu Formation and the hydrocarbon generation and charge from the shale in the Lucaogou Formation.

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Highlights

1. The most typical and famous sedimentary tuff tight oil reservoir in China.

2. A model showing how volcanic edifice controlling the type and distribution of the volcanic lacustrine tuff deposition.

3. The coupling effect of the diagenetic evolution of the tuff and the hydrocarbon generation and charging from the shale.

4. Vitric tuff and crystal-vitric tuff are two types of favorable reservoirs.

Declaration of interests

√The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

√The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled, "Permian sedimentary tuff reservoirs in the Santanghu Basin, NW China".
The Authors
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