PS Heterogeneity of Zhangjiatan Lacustrine Shale and its Implications, Ordos Basin, China*

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Abstract

The Upper Triassic Zhangjiatan shale in the 7th Member of Yanchang Formation, Ordos Basin, China, was deposited in a fresh-brackish, sublittoral to profundal lacustrine environment (Yang and Zhang, 2005; W. Z. Zhang et al., 2008). It is 30-130 m thick and contains types I and II_1 organic matter with a TOC (total organic carbon) of 0.45-13.73%. The free liquid hydrocarbons values (S1) range between 0.47 and10.7 mg/g. The oil saturation index (OSI, S_1×100/TOC) generally varies from 18 to 276 mg/g TOC. The vitrinite reflectance (R_o) ranges from 0.7% to 1.3%. The Zhangjiatan shale is one of the most prolific hydrocarbon source rocks and an exploration target for shale oil and gas in the Ordos Basin.

Recent research shows that the sedimentary environment, including climate, bathymetry, salinity, oxidation-reduction states and productivity, of Zhangjiatan shale changing periodicity (Zheng et al., 2015). The variations of sedimentary environment contribute to noticeably macroscopic heterogeneity. Four lithofacies, including black organic-rich shale, grey black organic-rich shale, siltstone and sandstone, were recognized and among which the thickness, fabric, mineral composition, organic matter content are different. Compaction, cementation, and dissolution, combined with the generation of hydrocarbons result in the difference in pore type and pore structure. The macro and micro heterogeneity lead to the different amount of free, dissolved, adsorbed oil and gas in different lithofacies. Millimeter scale silty laminae were observed in organic-rich shale and they are interlaminated with clayey layers. The thickness of silty laminae generally ranges from 0.5 to 10mm. In comparison to the clayey layer, the amount of quartz, feldspar and carbonate, porosity and permeability are higher, and clay minerals, pyrite, TOC, and S_1 are less.

Mineral composition,TOC,S1,pore type and pore structure of silty laminae differ from those of clayey layers. The former has 22-43% clay minerals, average 34%, average 55% of quartz and feldspar, 0.45-3.45% of TOC, 0.45-3.45% of S1. On the other hand, clayey layers contain average 55% of clay minerals, average 37% of quartz and feldspar, average 6.4% of TOC, average 5.8% of S_1. Pores in silty laminae are mainly interparticle pore, dissolution pore, intercrystalline pore, and organic pores are rare. Mesopores (2~50 nm in diameter) and macropores (50 nm~1 μm) are common, whereas micropores (< 2 nm) are rare. The porosity of silty laminae varies from 1.10% to 8.37%. However, besides the interparticle and dissolution pores, organic pores are also very common in organic-rich clayey layers. The pore diameters in silty laminae are larger than those in the adjacent clayey layers. The porosity of

clayey layers generally ranges from 0.71 to 6.20% and the pore volume of micropores is about 35 percent on average of the total.

The differences in mineral composition, TOC, pore structure etc. lead to the different amount of free, solution, adsorbed oil and gas and the total volume between silty laminae and organic-rich clayey layers. The total volume of shale gas in the organic-rich clayey layers is larger than that in silty laminae. The adsorbed gas, free gas and solution gas are 48%, 39% and 13% of the total in clayey layers respectively, while which in the silty laminae are 17%, 72% and 11%, respectively. Although the clayey layers have higher TOC and S_1, the oil saturation index is lower, which ranges from 18 to 190 mg/g TOC, with 94 mg/g TOC on average. While the OSI of silty laminae varies from 63 to 208mg/g TOC, average 143 mg/g TOC. It indicates that quite a few amounts of absorpted oil were stored in the high clay, low feldspar and quartz contents, organic-rich clayey layers and movable oil content is lower because of the adsorption of clay and kerogen. In spite of lower oil contents, the organic-lean, high porosity and high permeability silty laminae may have much higher free oil contents due to the much lower sorptive capacity.

The clay content and TOC decreases and the quartz, feldspar, and brittleness increase with the increasing proportion of silty laminae in the organic-rich shales. Furthermore, subparallel fractures occur at the interface between silty and clayey layers and the number of the fractures increases with the abundance of silty laminae. Therefore, the shale with abundant silty laminae could be more favorable to hydraulic fracturing. The amount of movable oil and free gas increases with the increasing abundance of silty laminae due to the decreasing clay content and TOC and the increasing meso and macro pore volume. And that in the siltstone and sandstone interlayers would be higher. Thus, the shales with abundant silty laminae, siltstone and sandstone interlayers would be the shale oil and gas “sweet spot”.

The porosity and permeability of silty laminae are higher than that of the clayey layers, and bedding-parallel fractures commonly occur in clayey adjacent to silty laminae, and some partially in the silty laminae, which contributes to higher porosity and permeability of shale with abundant silty laminae. These silty laminae and the kerogen network, together with the bedding-parallel fractures and joints nearly perpendicular to the bedding plane, form pathways of primary hydrocarbon migration. The oil and gas generated by the kerogen in the organic-rich clayey layers were firstly expelled into the low clay content and organic lean silty laminae and then migrated to siltstone and sandstone interlayers through silty laminae and fractures. Silty laminae, siltstone and sandstone interlaminated or intercalated with clayey shale, commonly formed a sandwich structure is favorable to oil and gas generated from organic-rich shale expelling to the overlying, underlying sandstone reservoirs and enhance the hydrocarbon expulsion efficiency. The silty laminae, siltstone and sandstone interlayers, together with fractures, provide the storage and primary migration pathways for shale oil and gas, and have higher movable oil and free gas content. Understanding the heterogeneous distribution of silty laminae, siltstone, sandstone, consequently different mineral composition, pore structure and the amount of shale oil and gas, is important to shale oil and gas “sweet spot” optimization and analysis the mechanism of petroleum primary migration.

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Abstract

The Upper Triassic lacustrine Zhangjiatan shale is an exploration target for shale oil and gas in Ordos Basin, China. The heterogeneity lead to different amount of free, solution, adsorbed oil and gas in different lithofacies. Especially, millimeter scale silty laminae, interlaminated with clayey layers, were observed in organic-rich shale. In comparison to the clayey layer, the amount of quartz, feldspar and carbonate, porosity and permeability are higher and pore diameters are larger, while clay minerals, pyrite, TOC, and S1 are less. These differences lead to the different amount of free, solution, adsorbed oil and gas and the total volume between silty laminae and clayey layers. Quite a few absorpted oil were stored in clayey layers and movable oil content is lower because of the adsorption of clay and kerogen. Furthermore, subparallel fractures occur at the interface between silty and clayey layers, the shale with abundant silty laminae could be more favorable to hydraulic fracturing. The amount of movable oil and free gas increases with the increasing abundance of silty laminae. Thus, the shales with abundant silty laminae, siltstone and sandstone interlayers would be "sweet spot". Silty laminae, siltstone and sandstone interlaminated or intercalated with clayey interlayer formed a sandwich structure, is favorable to primary migration. The silty laminae, siltstone and sandstone interlayers, together with fractures, provide the storage and migration pathways for oil and gas, and have higher movable oil and free gas content. Understanding the heterogeneity of Zhangjiatan shale is important to "sweet spot" optimization and analyzing the mechanism of primary migration.

Introduction

The upper Triassic Zhangjiatan shale in the 7th Member of Yanchang Formation, Ordos Basin, China， was deposited in a fresh-brackish, sublittoral to profundal lacustrine environment (Yang and Zhang, 2013; W. Z. Zhang et al., 2015). The Zhangjiatan shale is one of the most prolific hydrocarbon source rocks and an exploration target for shale oil and gas in the Ordos Basin. Recent research shows that the sedimentary environment, including climate, bathymetry, salinity, oxidation-reduction states and productivity, of Zhangjiatan shale changing periodicity (Zheng et al., 2015). The variations of sedimentary environment contribute to noticeably macroscopic heterogeneity. Four lithofacies, including black organic rich shale, grey black organic rich shale, silt and sandstone, were recognized and among which the thickness, fabric, mineral composition, organic matter content are different. Compaction, cementation, and dissolution, combined with the generation of hydrocarbons result in the difference in pore type and pore structure. The macro and micro heterogeneity leads to different amount of free, dissolved, adsorbed oil and gas in different lithofacies.

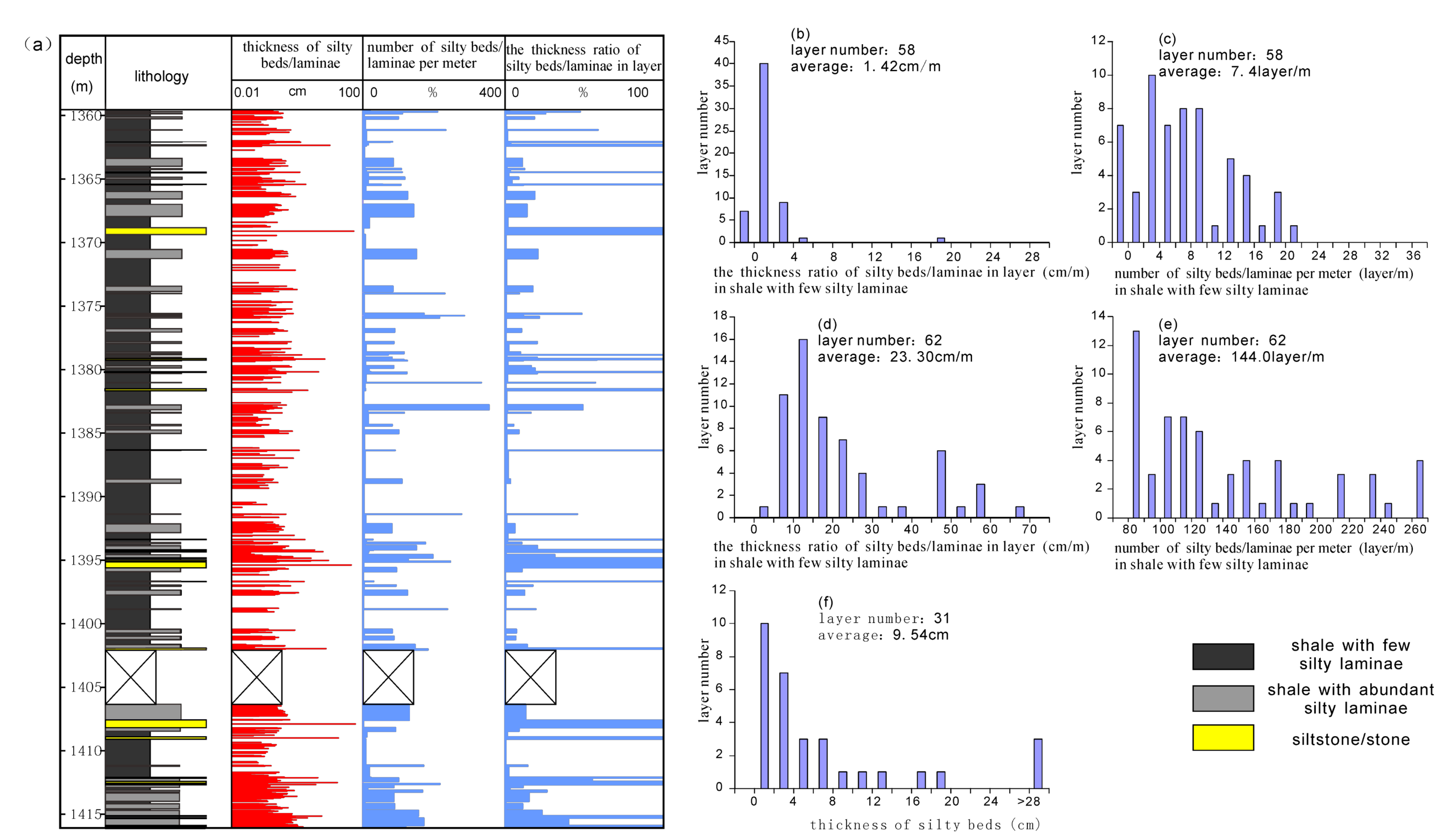


Fig. 2. Vertical distribution of silty beds/laminae in Well 1 and histograms of their thickness and density.

Heterogeneity of Zhangjiatan shale

Lithology

Millimeter scale silty laminae were observed in organic rich shale and they are interlaminated with clayey layers(Fig.1). The thickness of silty laminae generally ranges from 0.5 to 10mm(Fig.2).

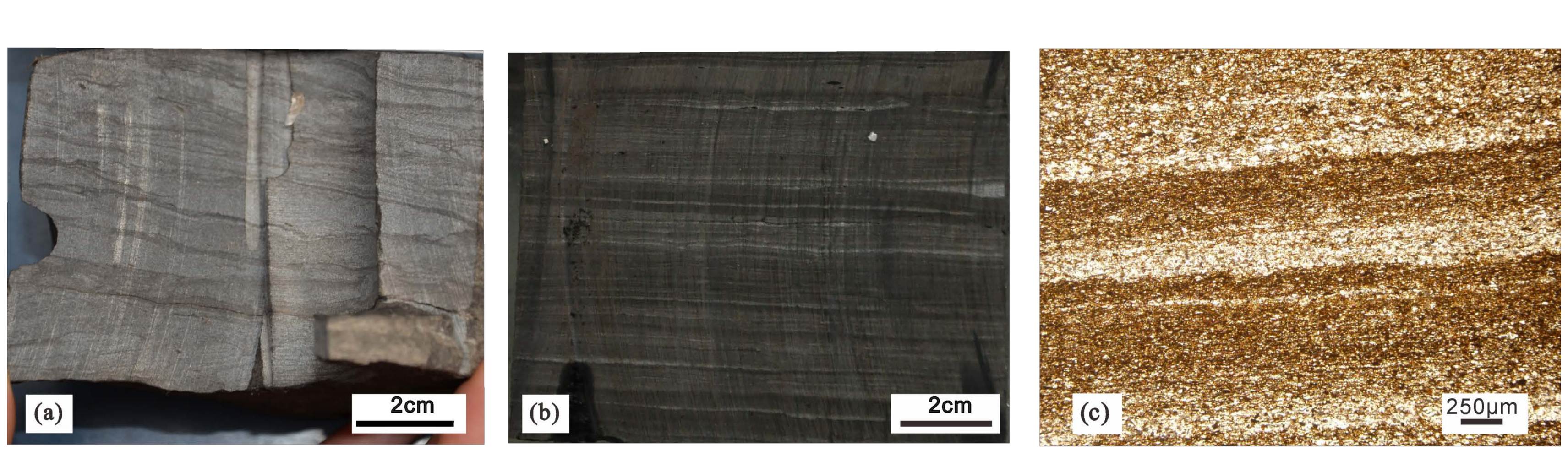


Fig. 1. Different scales of silty beds/laminae in Zhangjiatan shale.

Mineral composition

Silty laminae has 22-43% clay minerals, average 34%, average 55% of quartz and feldspar. On the other hand, clayey laminae contains average 55% of clay minerals, average 37% of quartz and feldspar,

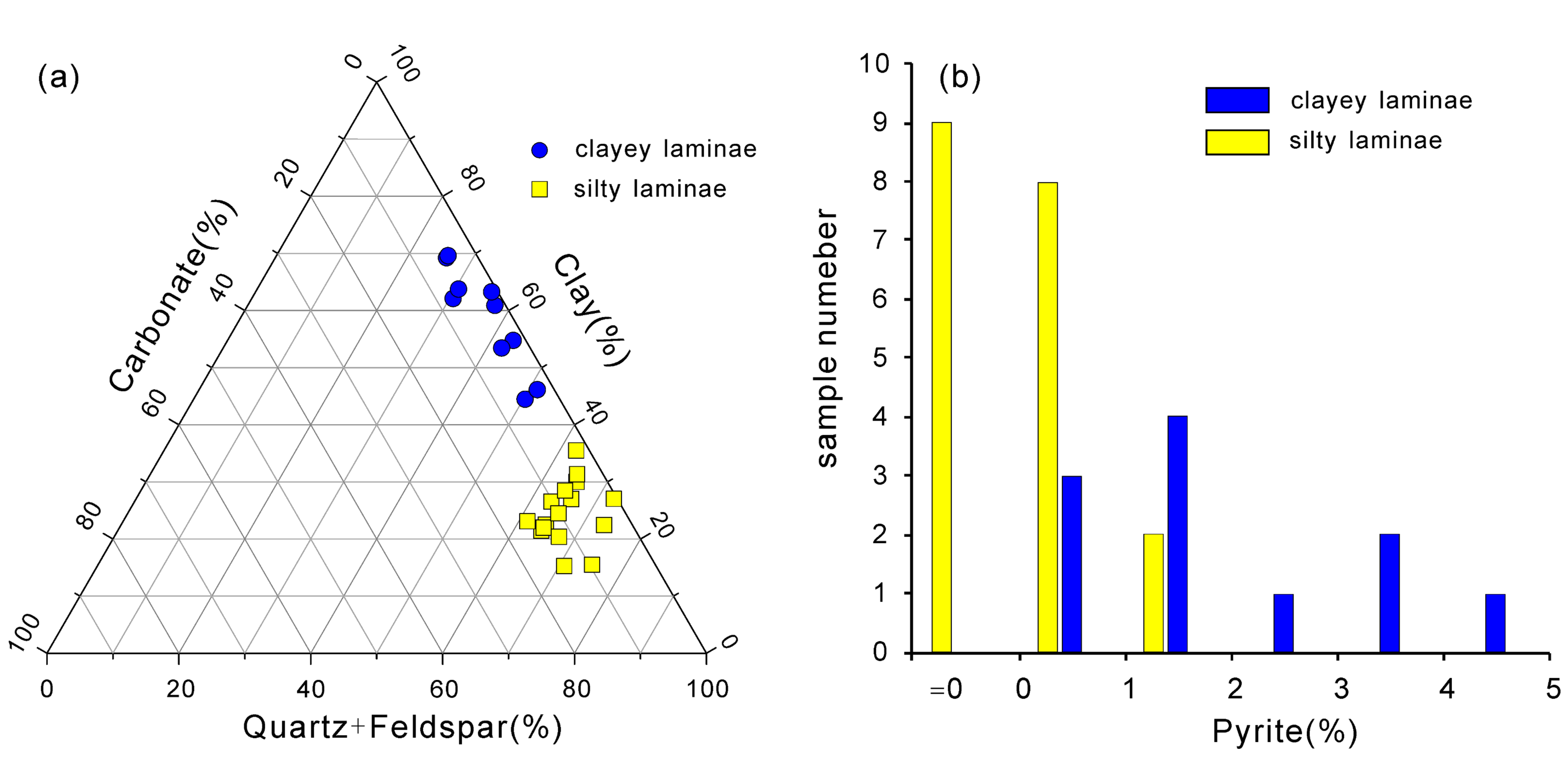


Fig. 3. Differences in mineral composition between clayey laminae and silty laminae.

Geochemistry characteristic

The sity laminae has 0.45-3.45% of TOC, 0.45-3.45mg/g of S1, 0~0.33% chloroform bitumen ‘A’ . On the other hand, clayey laminae contains average 6.4% of TOC, average 5.8 mg/g of S1 and 0.92% chloroform bitumen ‘A’ . However, average of OSI(S1×100/TOC) is not quite different in silty laminae and clayey laminae .

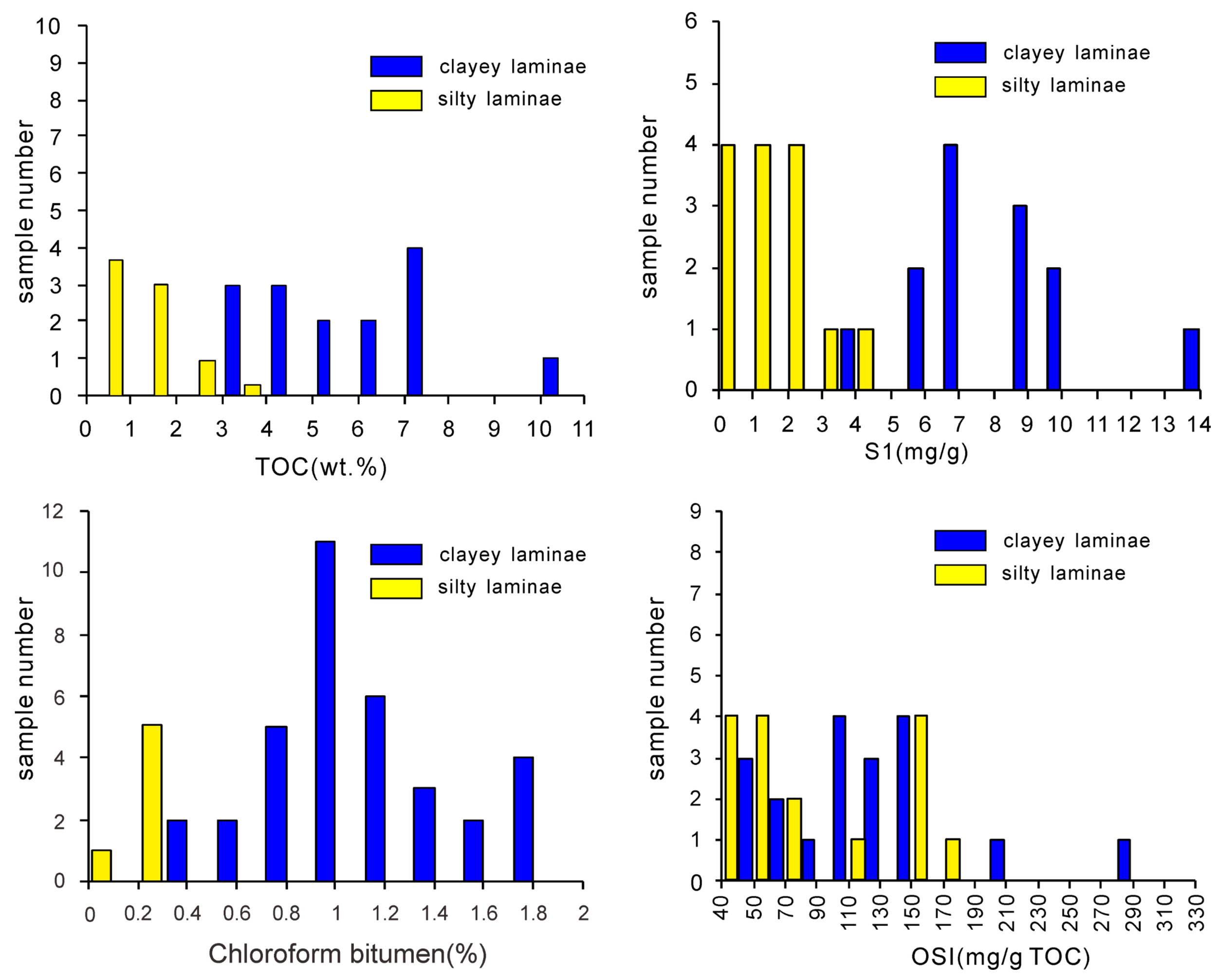


Fig. 4. Statistical data of TOC, S1, Chlorogorm bitumen ‘A’ and OSI (saturation index, S1×100/TOC) in clayey and silty laminae.

Pore type and pore size distribution

Pores in silty laminae are interparticle, dissolutional, intercrystalline, and microfracture, organic pores are rare. Mesopores (2~50 nm in diameter) and macropores (50 nm~1 mm) are common, whereas micropores (< 2 nm) are rare. However, besides the interparticle, dissolutional pores, organic pores are also very common in organic rich clayey laminae. The pore diameters in silty laminae are larger than those in the adjacent clayey laminae.

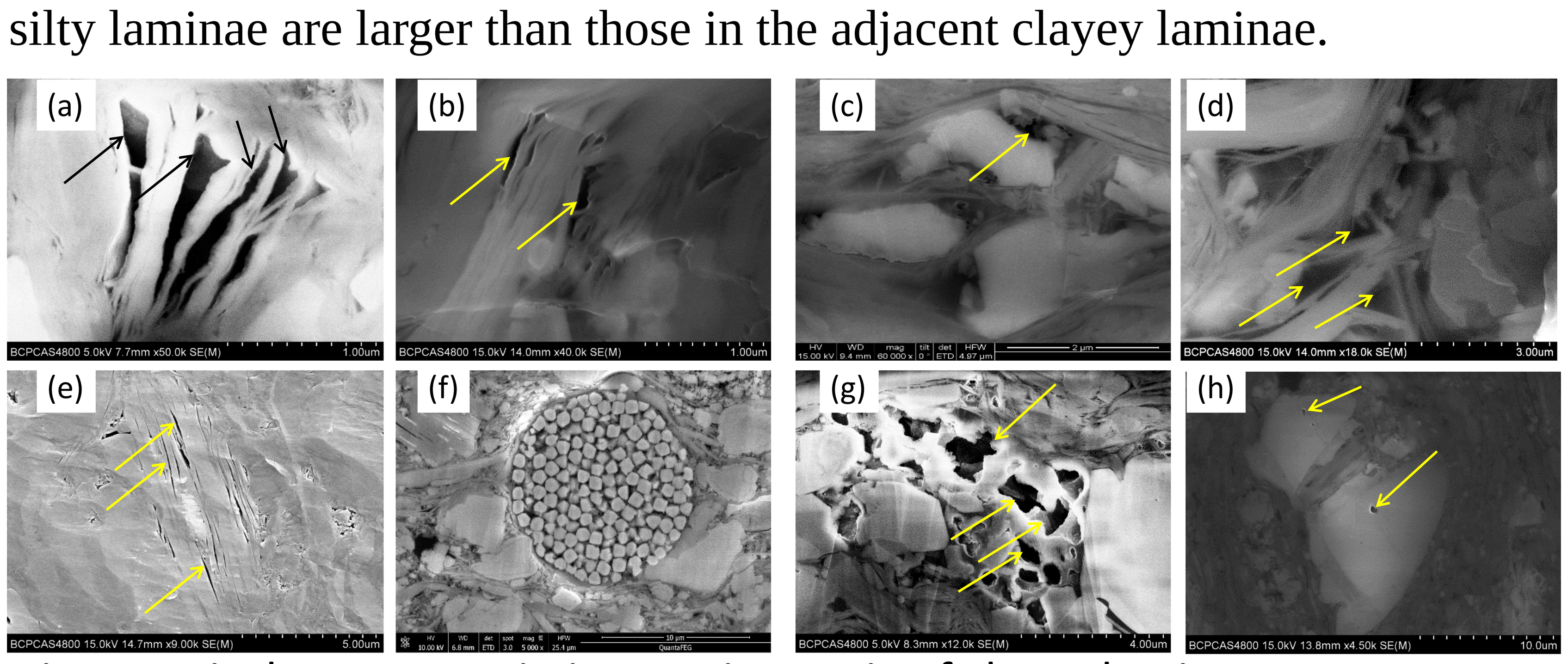


Fig. 5 Typical pore types in inorganic matrix of clayey laminae.
(a)~(d): interparticle pores;(e)~(f) : intragranular pores;(g)~(h) dissolution pores

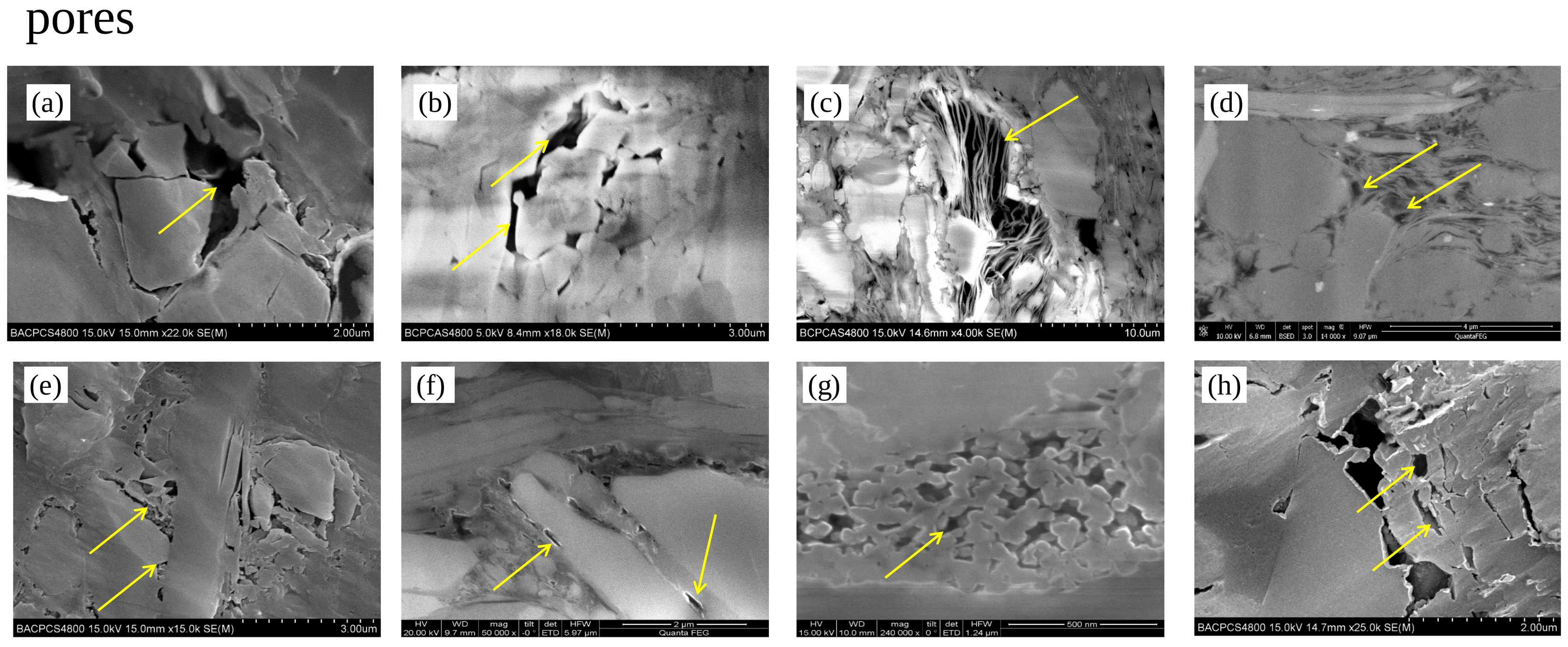


Fig. 6 Typical pore type in inorganic matrix of silty laminae.
(a)~(d): interpartical pores; (e) and (h): dissolutional pores; (f)~(g): intragranular pores

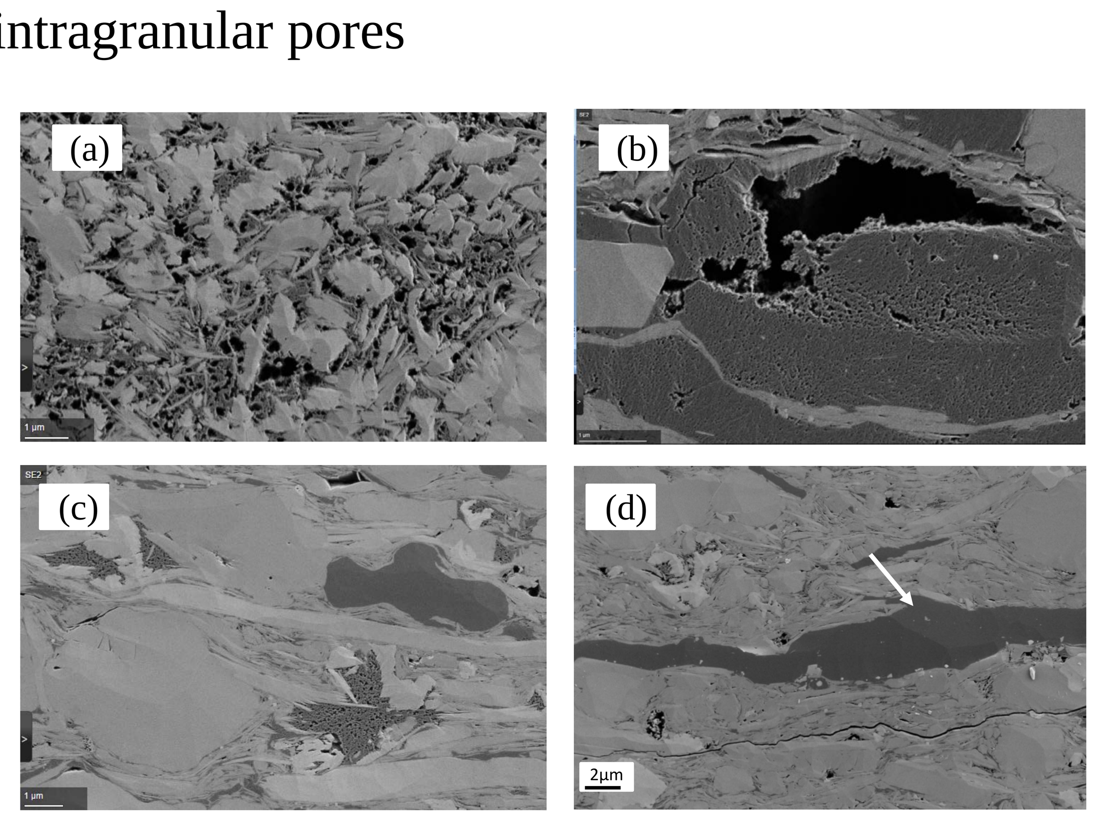


Fig. 7 Heterogeneity in organic pores in clayey laminae.

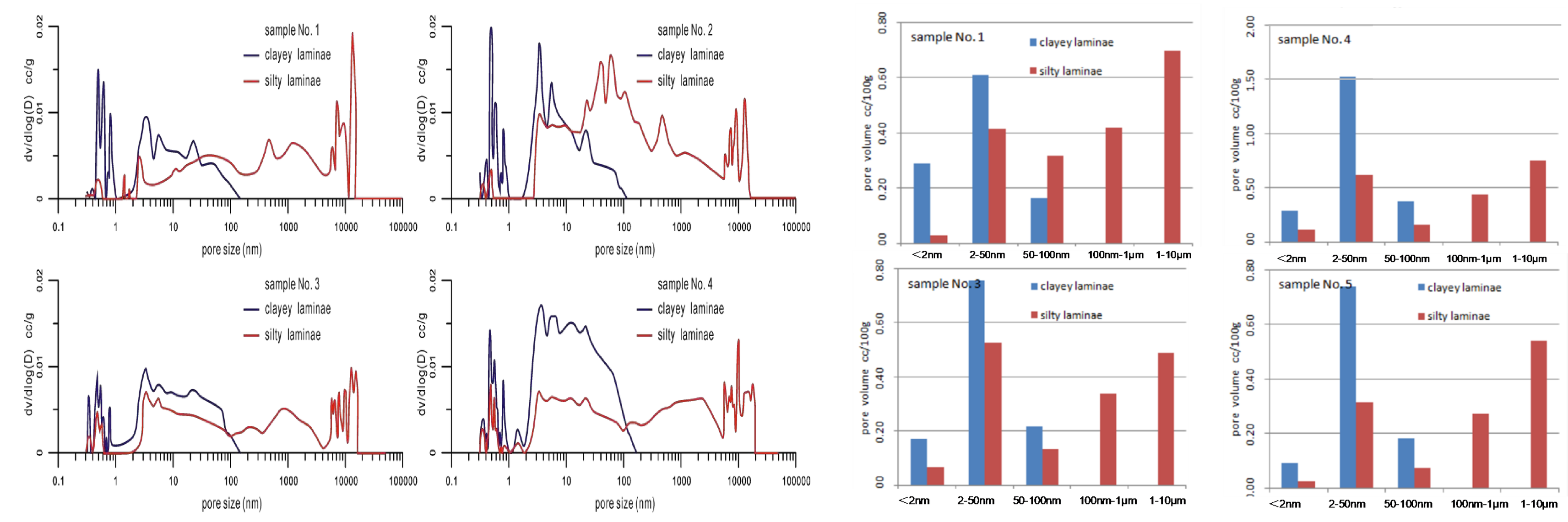


Fig. 8. pore size distribution and pore volume of silty laminae and clayey laminae.
Left: pore size distribution; right: pore volume of different pore size range.

Significance of silty laminae for Shale oil and gas accumulation

The total volume of shale gas in the organic rich clayey liaminae is larger than that of silty laiminae. The adsorbed gas, free gas and solution gas are 48%, 39%, 13% of the total in clayey laminae respectively, while which in the silty laiminae is 17%,72%,11%, respectively.

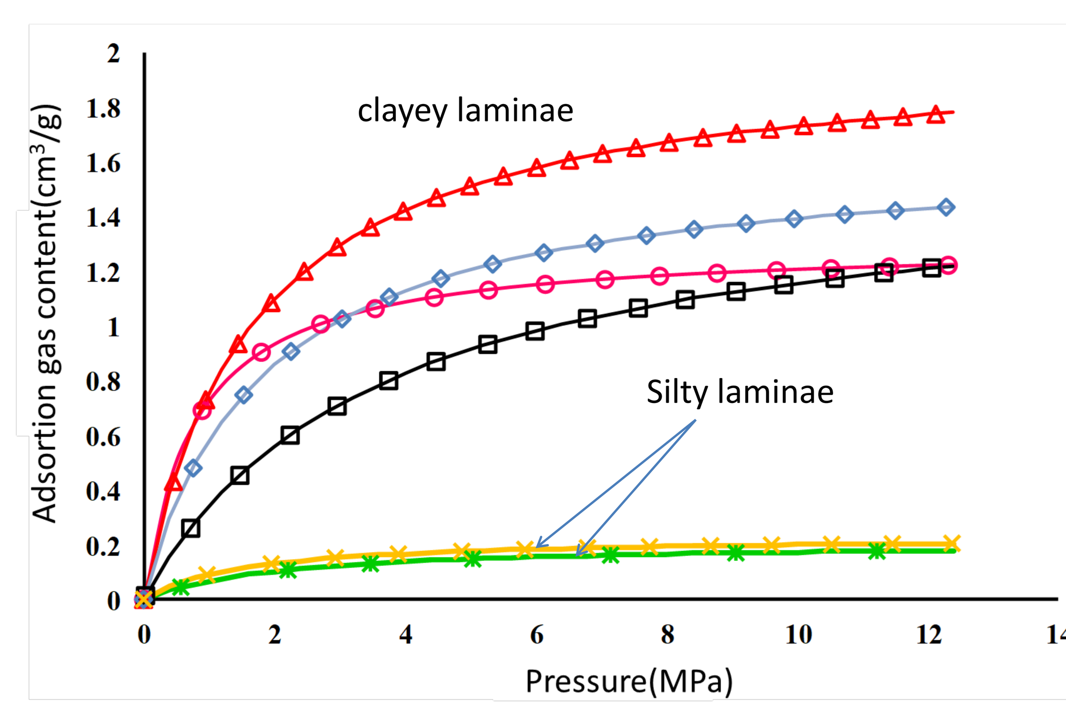


Fig. 9. Methane sorption isotherms for clayey and silty laminae.

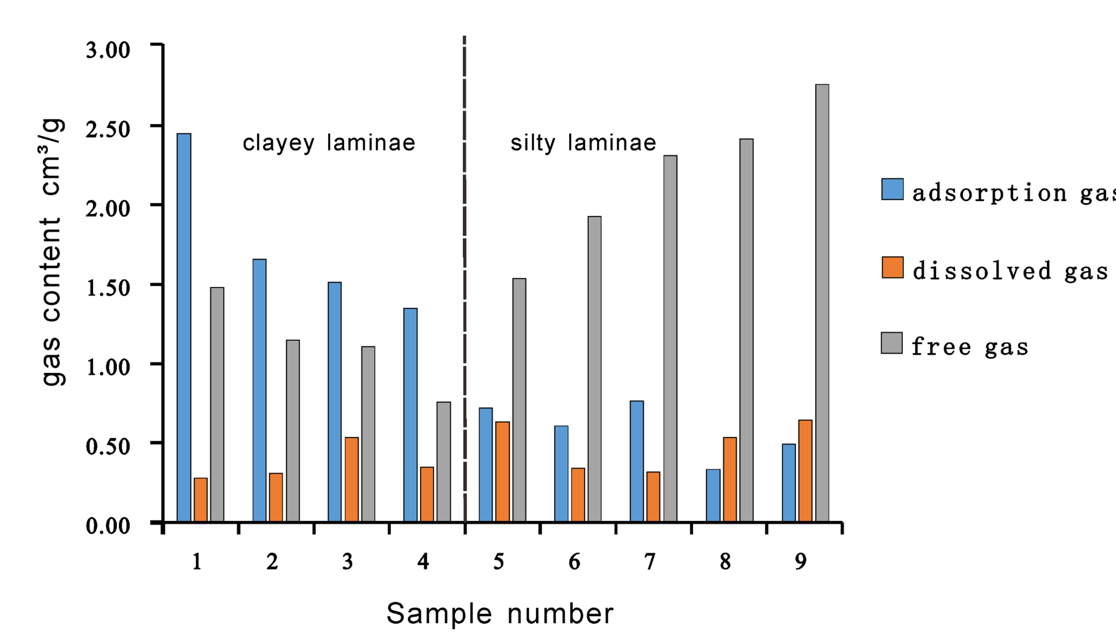


Fig. 10 The estimated amount of adsorbed gas, dissoved gas and free gas of clayey and silty laminae in Zhangjiatan shale.

The shales with abundant silty laminae, siltstone and sandstone interlayers would be the shale oil and gas “sweet spot”.

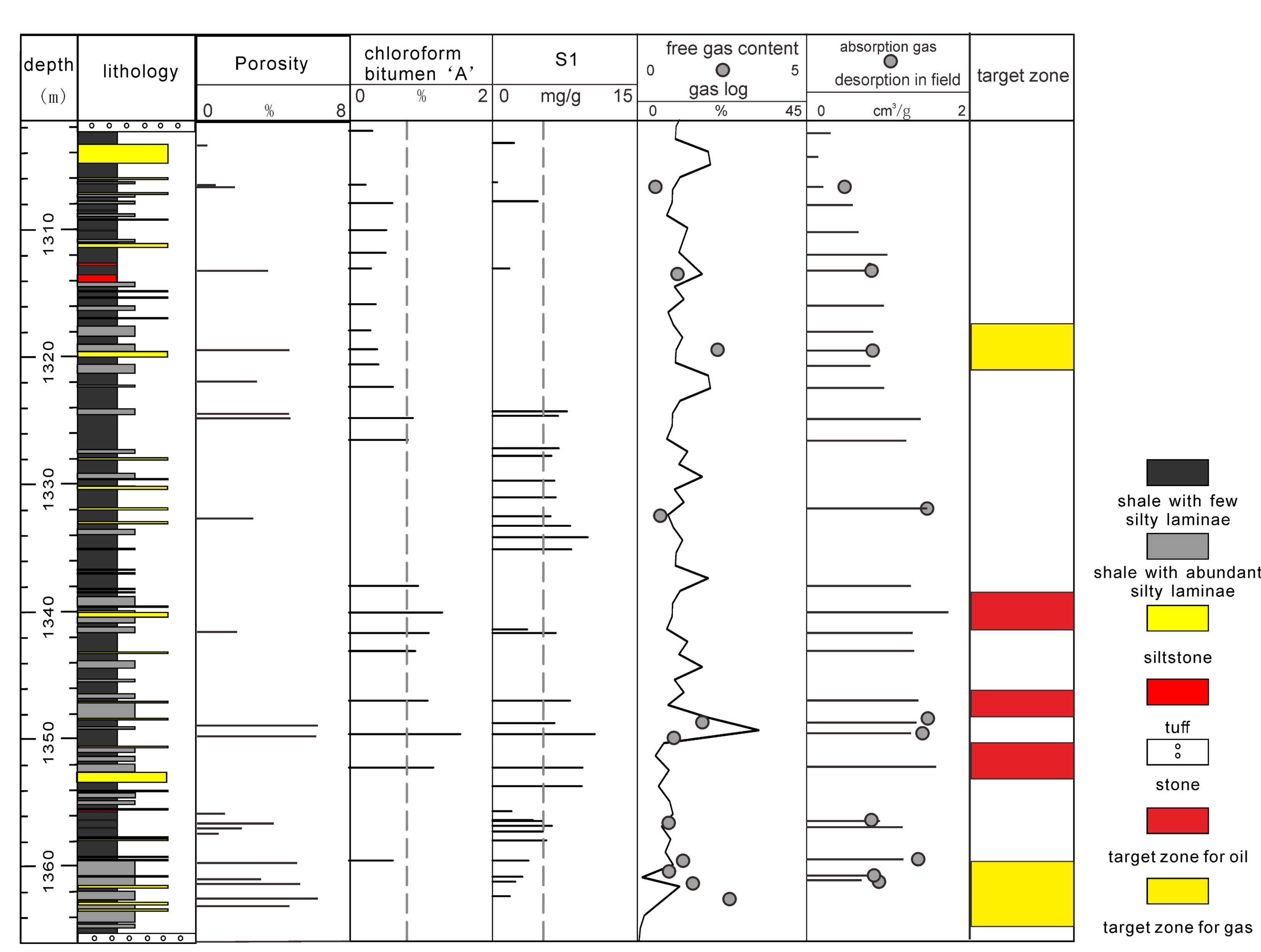


Fig. 11 Distribution of porosity and geochemical parameters of silty laminae and clayey laminae and its relationship with gas content.

Primary migration pathways for shale oil and gas

These silty laminae and the kerogen network, together with the bedding-parallel fractures and joints nearly perpendicular to the bedding plane, form pathways of primary hydrocarbon migration.

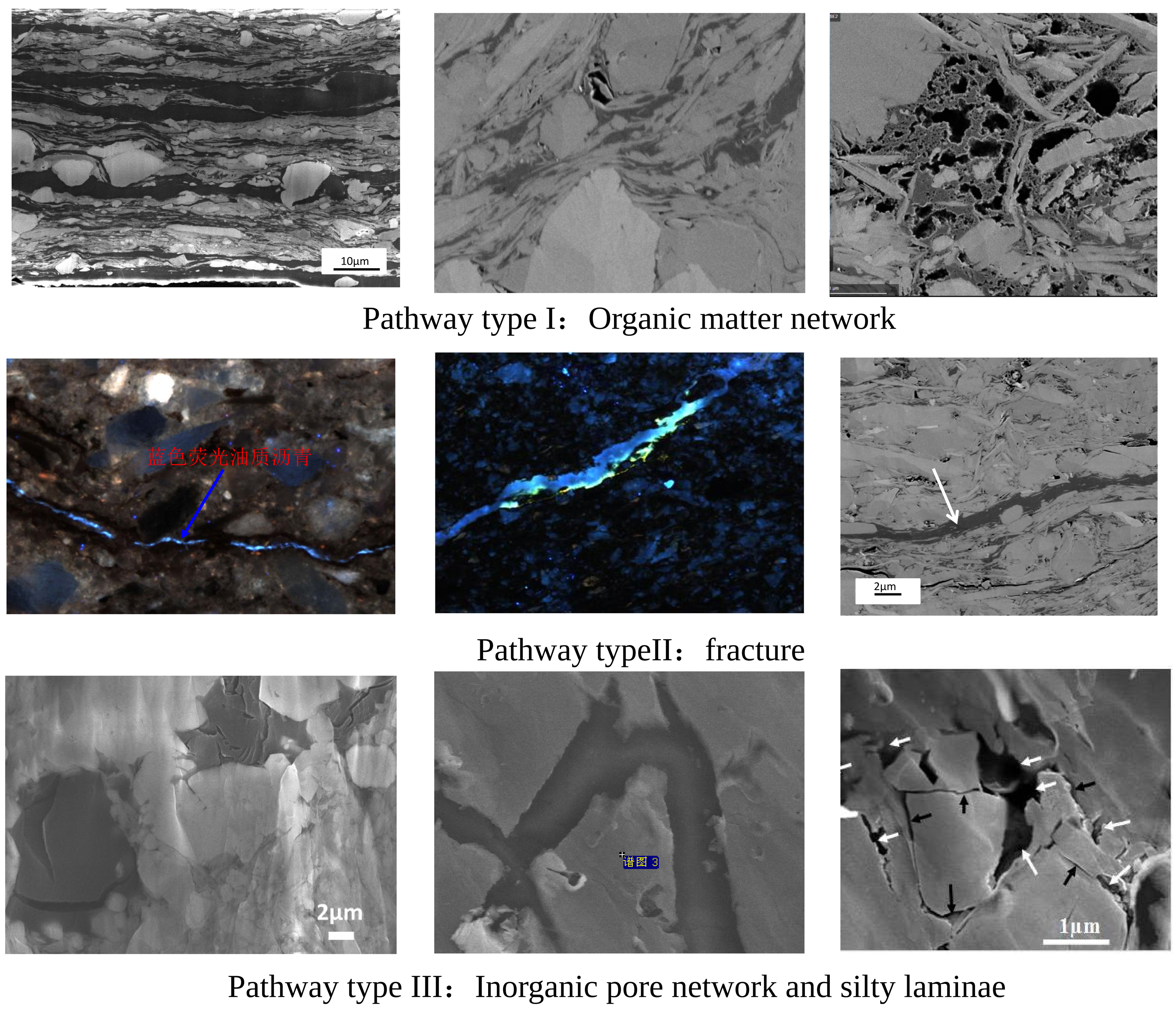


Fig.12 Types of primary migration pathway in Zhangjiatan shale.

The silty laminae, siltstone and sandstone interlayers, together with fractures, provide the storage and primary migration pathways for shale oil and gas.

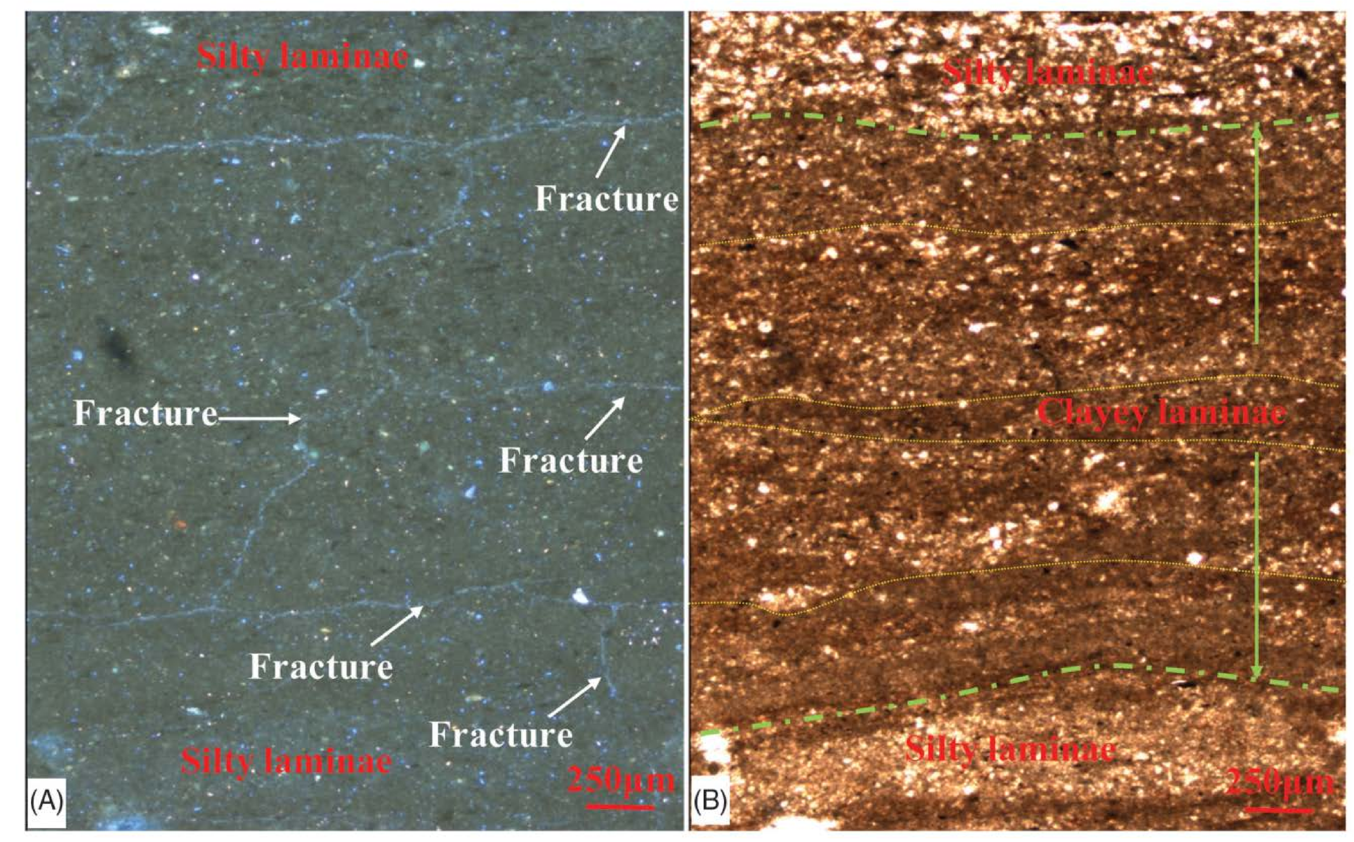


Fig.13 Network fractures in silty and clayey laminae of Zhangjiatan Shale (A) under fluorescent light and (B) plane light under microscope.

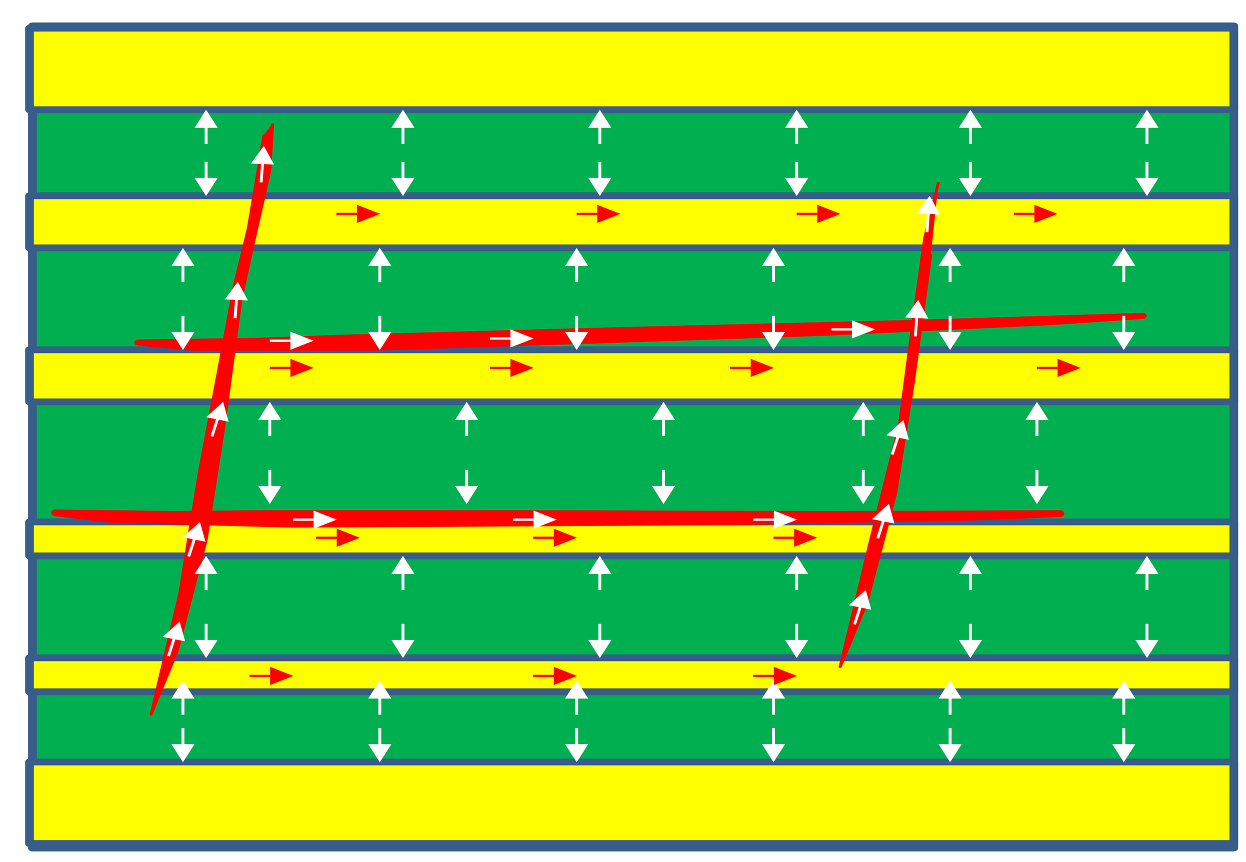
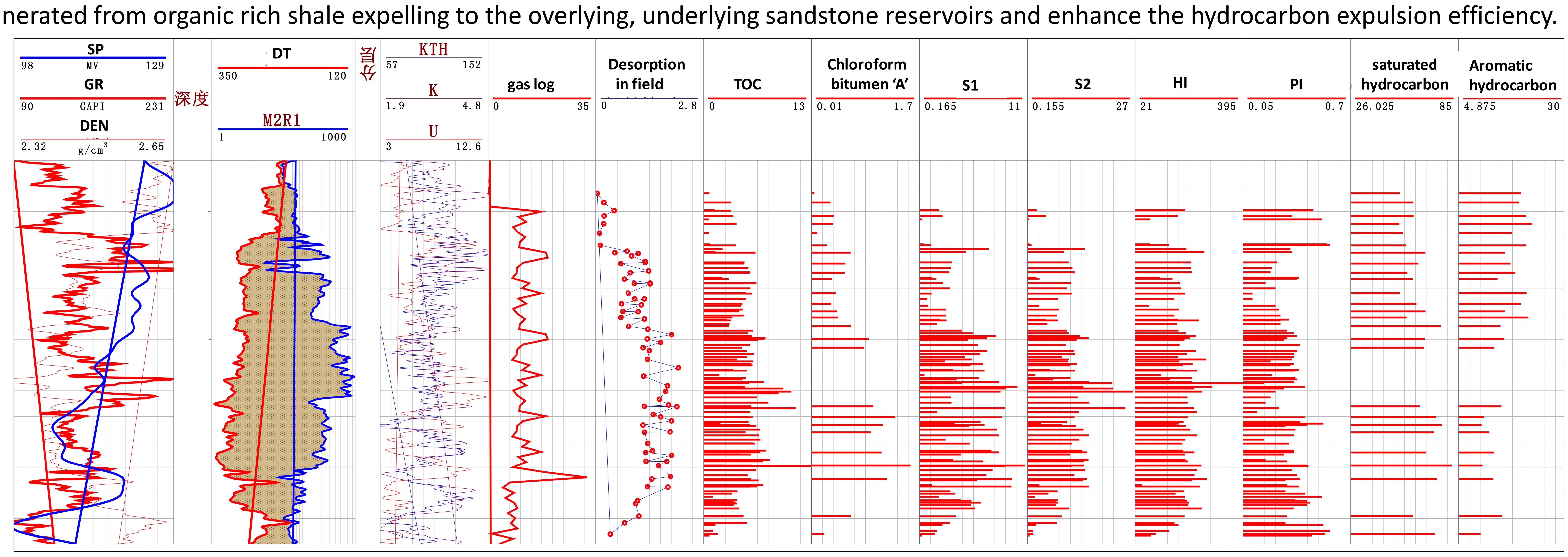


Fig.14 Pattern of primary migration in Zhangjiatn shale.

Silty laminae, siltstone and sandstone interlaminated or intercalated with clayey shale, commonly formed a sandwich structure, is favorable to oil and gas generated from organic rich shale expelling to the overlying, underlying sandstone reservoirs and enhance the hydrocarbon expulsion efficiency.



Conclusions

1.Millimeter scale silty laminae are interlaminated with clayey layers in Zhangjiatan shale. In comparison to clayey layer, the amount of quart, feldspar and carbonate, porosity and permeability are more higher, and clay minerals, pyrite, TOC, and S1 are less.
2. In spite of lower oil contents, organic-lean, high porosity and permeability silty laminae may have much higher free oil contents due to the much lower sorptive capacity. Thus, the shales with abundant silty laminae, siltstone and sandstone interlayers would be the shale oil and gas “sweet spot”.
3. The silty laminae, siltstone and sandstone interlayers, together with fractures, provide the storage and primary migration pathways for shale oil and gas.

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