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Mineralogy and fracture development characteristics of marine shale-gas reservoirs: A case study of Lower Silurian strata in southeastern margin of Sichuan Basin, China

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Abstract: Mineral contents and fractures of shale from well Yuye-1 and outcrops were examined mainly based on systematic description of the cores and outcrops, and data from experimental analyses. The data enabled us to thoroughly explore the mineralogy and developmental features of shale of the Lower Silurian Longmaxi Formation in the study area. The results show that, the Lower Silurian Longmaxi Shale (SLS) in the southeastern margin of Sichuan Basin, China, is primarily characterized by a high content of brittle minerals and a relatively low content of clay minerals. The total content of brittle minerals is approximately 57%, including 27% quartz, 12.2% feldspar, 11.2% carbonate and 2.4% pyrite. The total content of clay minerals reaches 41.6%, composed of illite (23.8%), mixed-layer of illite and smectite (I/S) (10.8%) and chlorite (7.0%). The SLS accommodates the widespread development of various types of fractures, including tectonic fractures, diagenetic fractures, inter-layer fractures and slip fractures. The developmental level of the fracture in the SLS is mainly influenced by faults, lithology, mineral contents and total organic carbon content (TOC) in study area.

Key words: shale fracture; mineralogy; gas shale; Lower Silurian; margin of Sichuan Basin

1 Introduction

Shale is commonly treated as a source rock or cap rock in traditional petroleum geology and is rarely considered as a reservoir. However, in practical exploration and development, more and more commercial gas flows have been found in shales recently, indicating that shale can act as a reservoir [1−2]. Fractures play a vital role in the production of shale gas reservoirs with low porosity and permeability [3]. Gas shale with low porosity and permeability can form effective natural gas reservoirs if this shale has developed sufficient natural fractures, microfractures, and nanometer scale pores and fractures within rocks or if fracturing treatments can generate a fracture system that features a large number of fractures. The development of natural fracture systems not only directly controls the fluid flow property of shale gas reservoirs but also determines the quality and production levels of these reservoirs [4−5].

The southeastern margin of Sichuan Basin is the pilot experimental area in China for the key strategic investigations of shale gas. Well Yuye-1, the first well strategically investigated for shale gas in China, was drilled in this experimental area in 2009. This well revealed the existence of high-quality shale in the region, namely, the Lower Silurian Longmaxi Shale (SLS). The SLS, which has industrial gas production, is the most important and target shale gas reservoir in southeastern margin of Sichuan Basin. Researchers have performed the studies on the forming environment, the origin of fractures and their distribution in the SLS [6−8]. However, mineralogy and fracture development characteristics of the SLS need further study. In this work, mineral contents and fracture development characteristics of the SLS in southeastern margin of Sichuan basin are comprehensively investigated, mainly based on outcrops and core observations, combined with data from experimental analyses. The dominant factors affecting fracture formation in shale gas reservoirs are studied, to provide guidance for the exploration and development of shale gas in this area.

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2 Geologic settings

The study area is located in the southeastern margin of the Sichuan Basin (Fig. 1(a)), i.e., at the intersection of Dalou Mountain and Wuling Mountain [9]. The Sichuan Basin is a foreland basin formed during the Late Triassic [10]. With respect to tectonics, this region is part of a depression tectonic unit in the Upper Yangtze platform of the Yangtze paraplatform, which includes three fourth-order tectonic units, i.e., the Qiyao Mountain uplift fold belt, the Qianjiang depression fold belt and the Xiushan uplift fold belt, and constitutes an important portion of the Upper Yangtze plate [7]. The southeastern margin of Sichuan Basin features relatively high uplift rates with strong tectonic compression, and then the tectonic stresses of folds formed in the Cretaceous undergo relaxation or release in the Cenozoic, leading to the creation of a series of large-scale NNE-trending faults along anticlinal axes and wings that consist of horst and graben fault systems, and these processes ultimately create the modern tectonic landscape of the study area (Fig. 1(b) and Fig. 2).

Palaeozoic strata comprise almost the entire sedimentary filling of the basin [11]. The SLS was deposited in the Early Silurian Longmaxi stage. Deposition occurred in a foreland basin that had generally a restricted circulation with the open ocean, and detrital materials came chiefly from the Chuandian Uplift located in the southeastern part of the study area [8]. The SLS is 250 m in thickness in the northern part of the study area and 15 m in its southern part. The SLS overlies the Ordovician Wufeng shale and is covered by Mid-Silurian gray shale and light gray to yellow siltstone (Fig. 3).

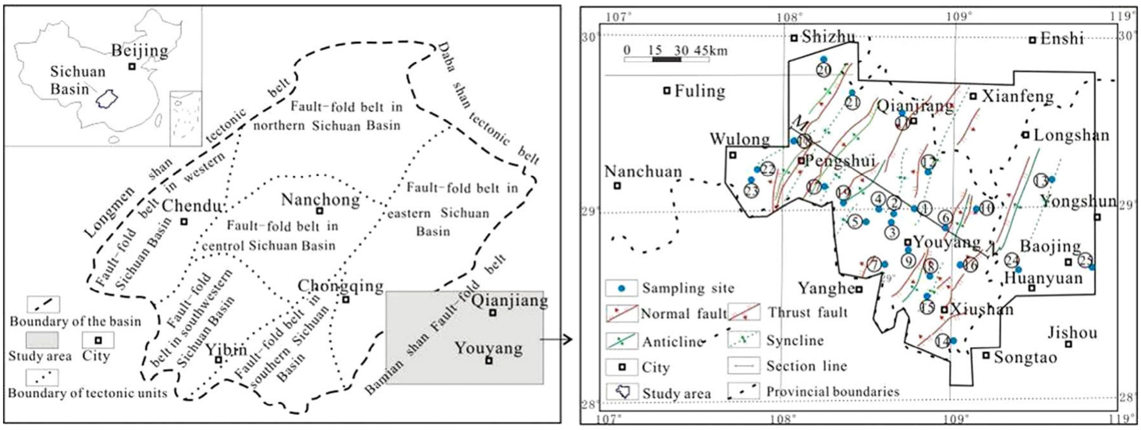
3 Samples and methods

In this work, mineral contents and fracture development characteristics for the shale are obtained from the well Yuye-1 and some outcrops which uniformly distribute in the southeastern margin of Sichuan Basin (Fig. 1(b)). The X-ray diffraction and clay mineral analyses were accomplished with a D8 DISCOVER X-ray diffractometer, at a temperature of 24 °C and a relative humidity of 35%. The organic carbon contents were measured with a CS−200 carbon and sulfur analyzer, and the measurement was conducted at a temperature of 25 °C and a relative humidity of 60%. All the tests were completed at the Research Institute of Petroleum Exploration and Development in North China.

4 Results analysis

4.1 Petrology and mineralogy of SLS

The SLS developed in early Silurian Longmaxi stage is predominantly black and dark gray in color and is relatively pure, brittle and stiff [8, 12]. The detailed



(a) (b)

Fig. 1 Location and tectonic map of study area (a) and sampling site distribution in study area (b) (1−Heishui; 2−Taihe; 3−Cangling; 4−Miaoxi; 5−Liangzheng; 6−Houxi; 7−Guanqing; 8−Jiangfeng; 9−Zhongduo; 10−Daxi; 11−Shihui; 12−Mala; 13−Hongyanxi; 14−Meijiang; 15−Rongxi; 16−Daxi; 17−Lujiao; 18−Gaogu; 19−Shangan; 20−Qiliao; 21−Well Yuye-1; 22−Jiangkou; 23−Shiqiao; 24−Maogou; 25−Shuangxi)

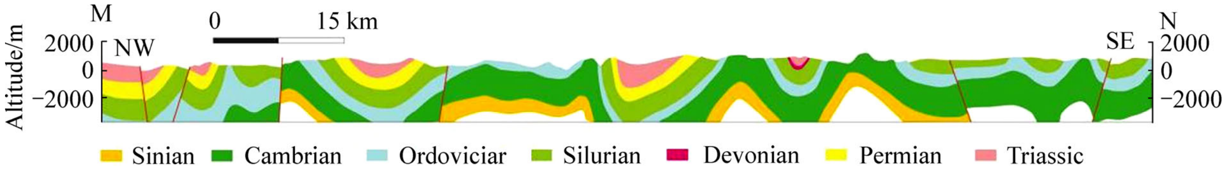


Fig. 2 Tectonic cross-section (position as shown in Fig. 1(b)) in southeastern margin of Sichuan Basin

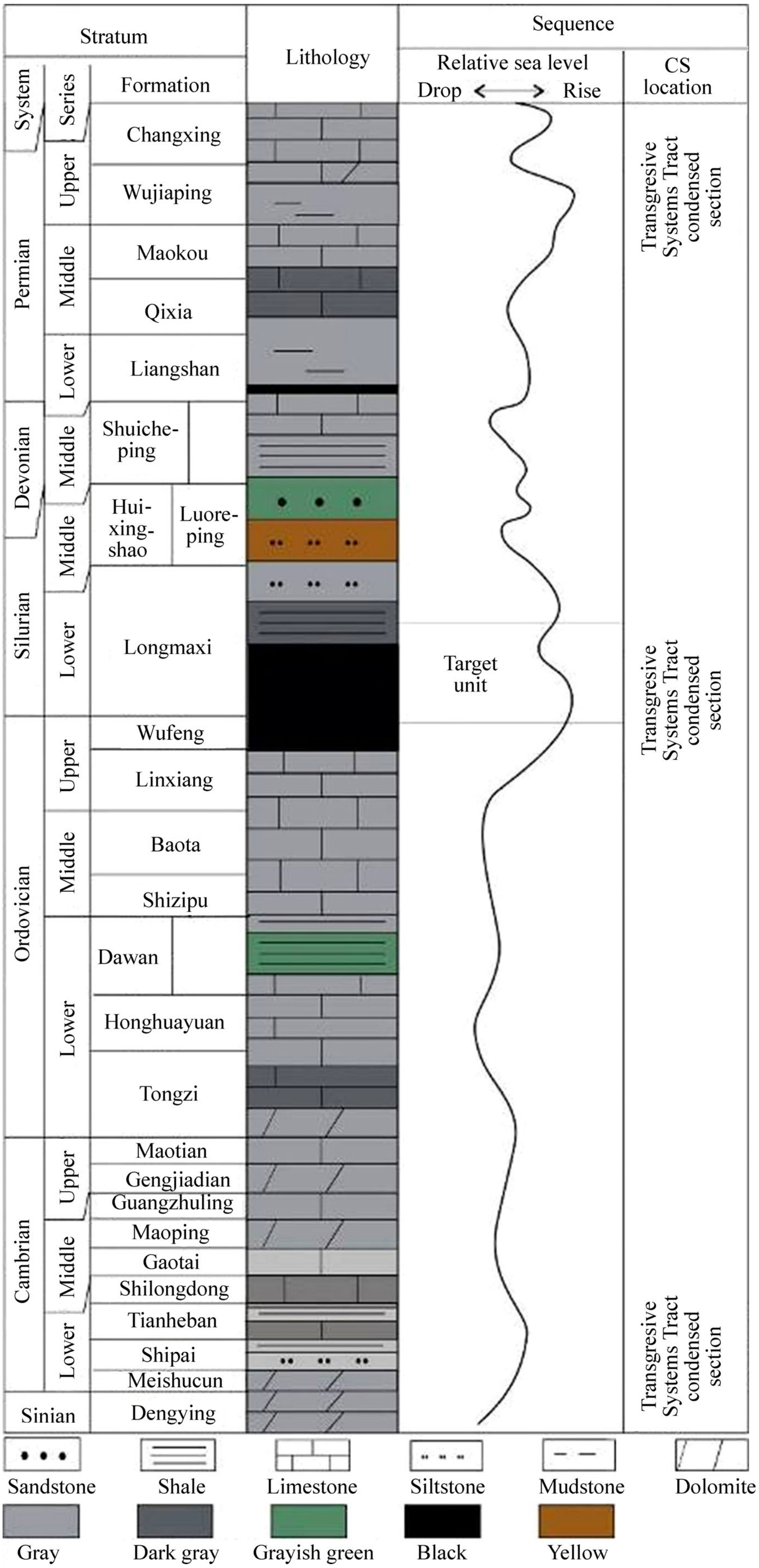


Fig. 3 Comprehensive stratigraphic column of study area

description of slabbed cores and outcrops, comparison with spectral core gamma logs, analysis of 54 thin sections and analysis of mineral data from 72 samples allow us to subdivide the SLS into the following six lithofacies: 1) clayey shale, 2) siliceous calcareous shale, 3) siliceous dolomitic shale, 4) silty-clayey interlaminated shale, 5) muddy siltstone, and 6) graptolite shale (Fig. 4). X-ray diffraction data of 72 specimens (Table 1) reveal that the major mineral components of the SLS are quartz and clay minerals, accounting for 39.2% and 41.6%, respectively (Fig. 5). Clay mineral is composed of chlorite, illite and mixed-layer I/S, with average contents of 7.0%, 23.8% and 10.8%, respectively. The following minerals are plagioclase (average content of 8.9%), dolomite (average content of 5.7%), calcite (average content of 5.5%), potash feldspar (average content of 3.4%) and pyrite (average content of 2.4%).

4.2 Fracture types

The SLS in southeastern margin of Sichuan Basin displays various types of fractures, including tectonic fractures, diagenetic fractures and complex fractures. Tectonic fractures can be divided into three kinds, including tensile fractures, shear fractures and compression fractures. Complex fractures can be divided into the following kinds, i.e., tectonic diagenetic fractures, inter-layer fractures and slip fractures. Among them, tectonic fractures and complex fractures are the most developed.

4.2.1 Tectonic fractures

This type of structure refers to fractures resulting from regional or local tectonic stress which are mainly controlled by ground stress and are closely associated with fractured tectonic deformation [13]. Based on the fracture occurrence, fracture-areal features and ground stress in the study area, the tectonic fractures of the SLS

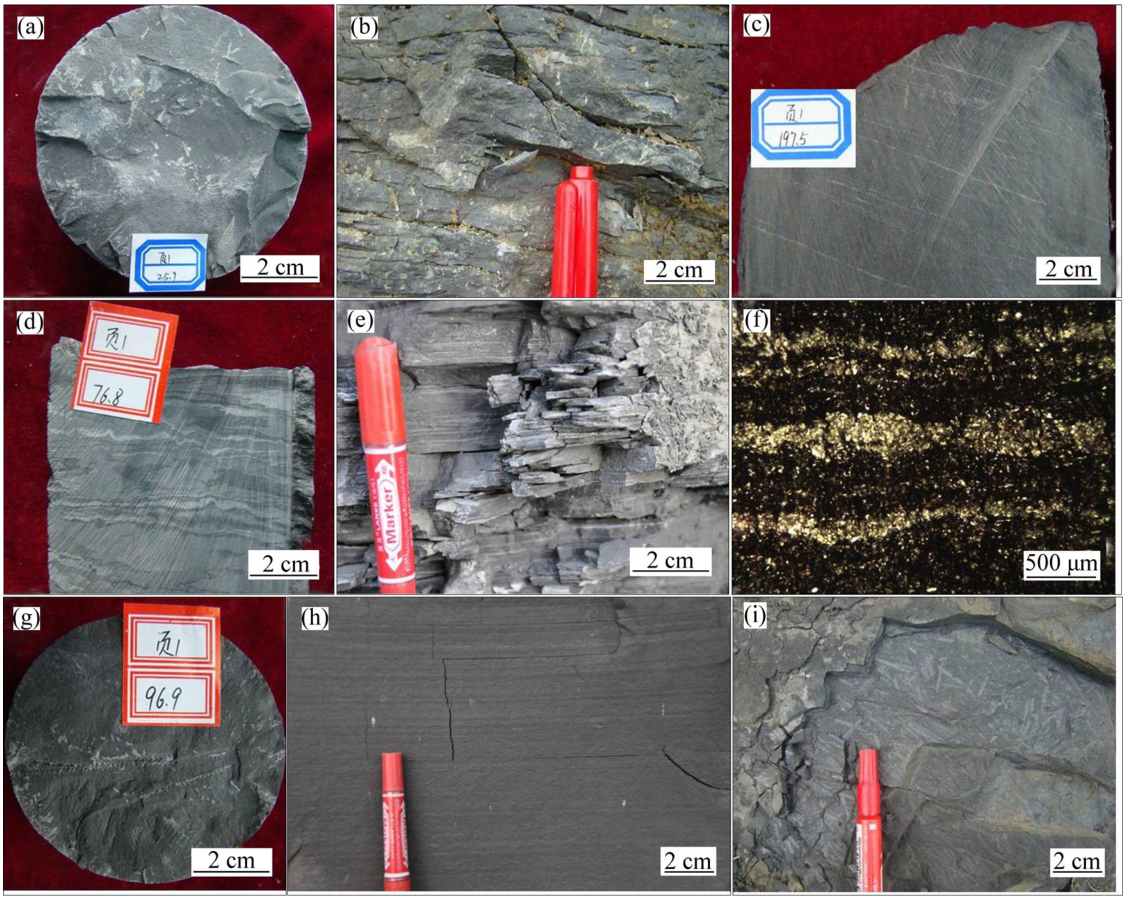


Fig. 4 Pictures of representative lithofacies of SLS in study area: (a) Gray clay shale with massive bedding indicating relatively lower energy and rapid deposition condition, well Yuye-1, at depth of 25.9 m; (b) Dark gray siliceous calcareous shale, outcrops of Longmaxi shale, Jiangkou Town, Wulong County; (c) Black siliceous dolomitic shale with horizontal bedding, well Yuye-1, at depth of 197.5 m; (d) Dark gray muddy siltstone with microwave bedding, well Yuye-1, at depth of 76.8 m; (e) Silty-shaly interlaminated shale comprised of gray siltstone and dark gray shale, outcrop in Dingshi Town, Youyang County; (f) Thin section of silty-shaly interlaminated shale showing silty layer (bright part) and shale layer (dark part), outcrop in Lujiao Town, Pengshui County; (g) Black graptolite shale with graptolite in surface of shale layer, well Yuye-1, at depth of 96.9 m; (h) Dark gray muddy siltstone characterized by thin light siltstone and horizontal bedding, outcrop in Lujiao Town, Pengshui County; (i) Black graptolite shale with abundant of graptolite in interlayer of shale, outcrop in Lujiao Town, Pengshui County

Table 1 Mineral compositions of selected samples from SLS in study area (mass fraction, %)

Sample No.	Ch	I	I/S	TC	Q	Pf	Pl	C	D	P
TH1	3.9	21.0	10.2	35.0	45.0	4.0	12.0	4.0	—	—
SH2	0.8	16.7	9.5	27.0	62.0	5.0	4.0	2.0	—	—
QL3	0.8	24.6	15.6	41.0	47.0	3.0	9.0	—	—	—
HS5	12.4	28.6	13.0	54.0	37.0	2.0	7.0	—	—	—
CL6	0.6	3.3	26.1	30.0	10.0	—	6.0	54.0	—	—
SG7	9.3	28.9	10.8	49.0	34.0	2.0	7.0	5.0	3.0	—
GT8	6.3	18.9	9.8	35.0	41.0	6.0	13.0	5.0	—	—
MX9	11.6	33.6	9.9	55.0	37.0	1.0	7.0	—	—	—
HX10	3.9	17.1	7.0	28.0	43.0	5.0	20.0	4.0	—	—
YL11	11.4	31.7	8.8	52.0	33.0	1.0	7.0	7.0	—	—
ML12	8.6	31.9	13.5	54.0	32.0	3.0	6.0	5.0	—	—
GQ13	4.5	27.9	8.6	41.0	41.0	2.0	5.0	3.0	8.0	—
JF14	4.5	16.8	6.7	28.0	40.0	10.0	15.0	7.0	—	—
ZD15	10.5	32.2	19.2	62.0	25.0	3.0	9.0	1.0	—	—
DX16	6.5	18.9	17.6	43.0	45.0	4.0	1.0	7.0	—	—
JK1	11.7	26.0	13.3	51.0	36.0	2.0	7.0	4.0	—	—
JK2	13.5	28.0	8.5	50.0	41.0	1.0	6.0	2.0	—	—
JK3	12.2	27.6	13.3	53.0	37.0	1.0	5.0	4.0	—	—
JK4	13.3	33.2	4.6	51.0	41.0	1.0	4.0	3.0	—	—
JK5	14.3	29.7	11.0	55.0	36.0	1.0	6.0	2.0	—	—
JK6	11.2	29.6	10.2	51.0	35.0	1.0	7.0	6.0	—	—
JK7	10.1	23.1	8.8	42.0	32.0	1.0	7.0	18.0	—	—
JK8	10.2	29.1	11.7	51.0	38.0	2.0	6.0	3.0	—	—
SQ1	2.8	31.2	6.0	40.0	39.0	1.0	8.0	4.0	5.0	3.0
SQ2	5.5	27.6	12.9	46.0	41.0	1.0	5.0	2.0	4.0	1.0
SQ3	6.0	24.4	9.6	40.0	22.0	—	3.0	—	34.0	1.0
SQ4	8.0	29.0	13.0	50.0	37.0	—	6.0	2.0	4.0	1.0
SQ5	10.2	30.1	10.7	51.0	31.0	—	4.0	3.0	10.0	1.0
SQ6	2.0	25.5	6.5	34.0	43.0	2.0	6.0	3.0	8.0	4.0
DY21	6.5	27.0	16.5	50.0	33.0	—	4.0	8.0	4.0	1.0
YQ22	4.6	18.9	11.6	35.0	42.0	—	11.0	6.0	4.0	2.0
GG23	15.1	30.8	10.1	56.0	37.0	—	6.0	—	—	1.0
RX1	2.4	19.4	12.2	34.0	46.0	4.0	10.0	3.0	—	3.0
RX2	1.8	11.5	9.7	23.0	37.0	6.0	14.0	11.0	8.0	1.0
RX3	0.7	8.0	5.3	14.0	51.0	6.0	19.0	10.0	—	—
RX4	6.5	20.6	15.9	43.0	39.0	5.0	9.0	4.0	—	—
RX5	7.8	22.1	16.1	46.0	36.0	4.0	8.0	5.0	—	1.0
RX6	4.5	15.4	12.2	32.0	44.0	10.0	14.0	—	—	—
RX7	6.8	19.6	13.6	40.0	39.0	3.0	10.0	7.0	—	1.0
RX8	7.2	23.1	24.8	55.0	41.0	—	4.0	—	—	—
DX1	3.2	19.2	17.6	40.0	44.0	6.0	10.0	—	—	—
DX2	4.1	16.7	13.3	34.0	47.0	5.0	14.0	—	—	—

to be continued

continued

Sample No.	Ch	I	I/S	TC	Q	Pf	Pl	C	D	P
DX3	0.3	17.0	9.7	27.0	49.0	7.0	17.0	—	—	—
DX4	1.1	11.0	9.9	22.0	47.0	10.0	15.0	6.0	—	—
DX5	0.4	22.4	17.2	40.0	50.0	5.0	5.0	—	—	—
LJ1	6.1	17.1	14.8	38.0	42.0	5.0	15.0	—	—	—
LJ2	5.1	15.3	9.6	30.0	46.0	4.0	12.0	4.0	3.0	1.0
LJ3	4.4	16.0	13.6	34.0	40.0	6.0	11.0	4.0	3.0	2.0
LJ4	5.1	17.9	16.0	39.0	39.0	3.0	10.0	5.0	2.0	2.0
LJ5	6.3	19.7	16.0	42.0	39.0	3.0	8.0	5.0	2.0	1.0
LJ6	5.0	17.3	13.7	36.0	41.0	3.0	7.0	6.0	4.0	3.0
LJ7	5.6	20.0	14.4	40.0	41.0	3.0	9.0	4.0	—	3.0
LJ8	2.5	11.8	13.7	28.0	44.0	2.0	5.0	11.0	3.0	6.0
LJ9	1.8	10.0	13.3	25.0	43.0	3.0	8.0	6.0	8.0	6.0
HYX1	11.5	23.5	15.0	50.0	41.0	1.0	7.0	—	—	1.0
HYX2	13.0	26.5	14.6	54.0	37.0	—	7.0	—	—	2.0
HYX3	13.0	27.0	12.0	52.0	38.0	—	8.0	—	—	2.0
HYX4	9.7	27.5	16.7	54.0	35.0	—	7.0	—	—	4.0
HYX5	5.6	27.3	14.1	47.0	42.0	2.0	6.0	—	—	3.0
HYX6	5.1	23.0	17.9	46.0	35.0	4.0	9.0	—	3.0	3.0
HYX7	2.4	16.5	8.1	27.0	51.0	5.0	17.0	—	—	—
HYX8	3.5	21.4	12.6	35.0	44.0	3.0	11.0	—	3.0	3.0
YY1	16.2	41.5	0.0	57.7	30.0	—	8.1	—	2.7	1.5
YY2	8.0	39.3	0.0	47.3	36.4	0.6	9.0	1.2	3.0	2.5
YY3	6.1	37.5	0.0	43.6	33.7	0.9	12.8	2.1	2.7	4.2
YY4	5.4	39.5	0.0	44.9	33.2	1.4	10.9	2.4	3.9	3.3
YY5	8.2	34.7	0.0	42.9	35.8	1.8	12.4	1.2	3.7	2.2
YY6	5.3	35.8	0.0	41.1	37.5	1.8	8.7	2.1	3.9	4.9
YY7	5.6	34.5	0.0	40.1	36.9	1.8	11.4	1.6	5.5	2.7
YY8	7.9	31.7	0.0	39.6	39.0	2.1	13.0	1.0	3.3	2.0
YY9	5.1	29.1	0.0	34.2	36.0	1.3	9.1	0.4	16.8	2.2
YY10	32.6	6.7	0.0	39.3	39.8	1.0	9.8	3.4	3.1	3.6

Ch−Chlorite; I−Illite; I/S−Mixed-layer of illite and smectite; TC−Total clay mineral; Q−Quartz; Pf−Potash feldspar; Pl−Plagioclase; C−Calcite; D−Dolomite; P−Pyrite.

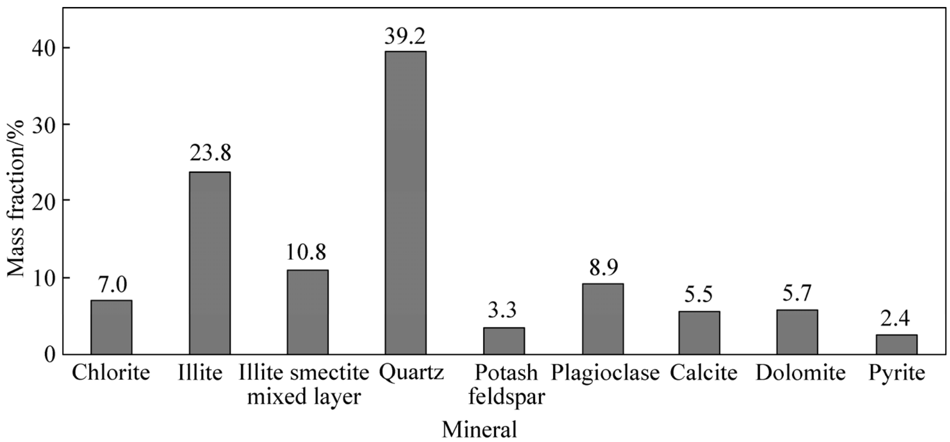


Fig. 5 Average mineral contents of SLS in study area

are divided into tensile fractures (Fig. 6(a)), shear fractures (Fig. 6(b)) and compression fractures (Fig. 6(c)).

1) Tensile fractures

Under the action of horizontal stretching stress and pressure solution, tectonic tensile fractures may be formed which are perpendicular or nearly perpendicular to the bedding surfaces [13]. Tensile fractures are the dominantly tectonic fractures not only in cores but also in outcrops (Figs. 6(a), (b) and (c)) in the study area. The length of the tensile fractures in cores is generally less than 90 cm and mainly between 8 and 15 cm; the fracture apertures are mainly between 2 and 20 mm. The majority of the fractures in cores are half-filled and fully filled fractures. The filling materials are mainly quartz and calcite (Figs. 6(a) and (b)). The length of the tensile fractures in outcrops is generally less than 150 cm and mainly between 50 and 110 cm; the fracture apertures are mainly between 2 and 30 mm. Importantly, the majority of the fractures are unfilled and they can preferably serve as migration channels and reservoir space for shale gas (Fig. 6(c)).

2) Shear fractures

Shear fractures refer to the fractures where the relative displacement is parallel to the fracture plane, and they are mainly formed under the action of shear stress or tensile-shear stress, and have the following main characteristics. Their occurrence is relatively consistent, with strong grouping, and they are closed and the filling materials are predominantly quartz minerals in cores (Fig. 6(d)). In addition, the shear fractures are characterized by small opening angle and relatively long extension, especially in the outcrops (Fig. 6(e)).

3) Compression fractures

Compression fractures refer to fractures formed under compressional tectonic stress, and have the following two characteristics. Firstly, their occurrence is relatively consistent, with strong grouping and multiple attitudes. Secondly, compression fractures often develop accompanied by compressional anticline (Fig.6(f)).

4.2.2 Diagenetic fractures

Diagenetic fractures refer to expansion or tensile fractures accompanied by a diminished total volume of rocks. In addition, diagenetic fractures are formed in the

Fig. 6 Pictures of SLS representative of different tectonic fracture types from cores and outcrops in study area: (a) Black shale filled with quartz showing high-angle (75°−85°) tensile fractures, well Yuye-1, at depth of 275 m; (b) Black shale filled with quartz showing relatively high-angle (60°−75°) tensile fractures, well Yuye-1, at depth of 307.7 m; (c) Dark gray shale showing relatively high-angle (75°−90°) tensile fractures, outcrop in Zhonghe Town, Xiushan County; (d) Black shale filled with quartz showing shear fractures, well Yuye-1, at depth of 269.7 m; (e) Dark gray shale showing shear fractures, outcrop in Maogou Town, Baojing County; (f) Dark gray shale showing compression fractures developed in minitype compressional anticline, outcrop in Shuangxi Town, Guzhang County

process of compaction and diagenesis, and they grow slowly by chemically aided processes under long-term loading in corrosive or liquid-saturated environments, above some minimum stress intensity but below material fracture toughness [14]. During early diagenetic stages, shale rocks might undergo contraction due to the dehydration of clay minerals or phase transition, which promotes rectangular or mesh-like cracks [15]. Our examination reveals that diagenetic fracture is a common fracture type in the SLS in the study area, and it dominantly develops in the interface of shale and muddy siltstone. Diagenetic fractures developed in the SLS are characterized by small scale and small open angle (Figs. 7(a) and (b)).

4.2.3 Complex fractures

Complex fractures refer to fractures formed under complex geological process, such as tectonic stress, sedimentary process and diagenesis. Based on the fracture occurrence and fracture-areal features in the study area, the complex fractures of the SLS are divided into tectonic diagenetic fractures (Figs. 7(c), (d) and (i)), inter-layer fractures (Figs. 7(e), (f), (j) and (k)) and slip fractures (Figs. 7(g) and (h)).

1) Tectonic diagenetic fractures

Tectonic diagenetic fractures refer to fractures formed under complex geological process, and they

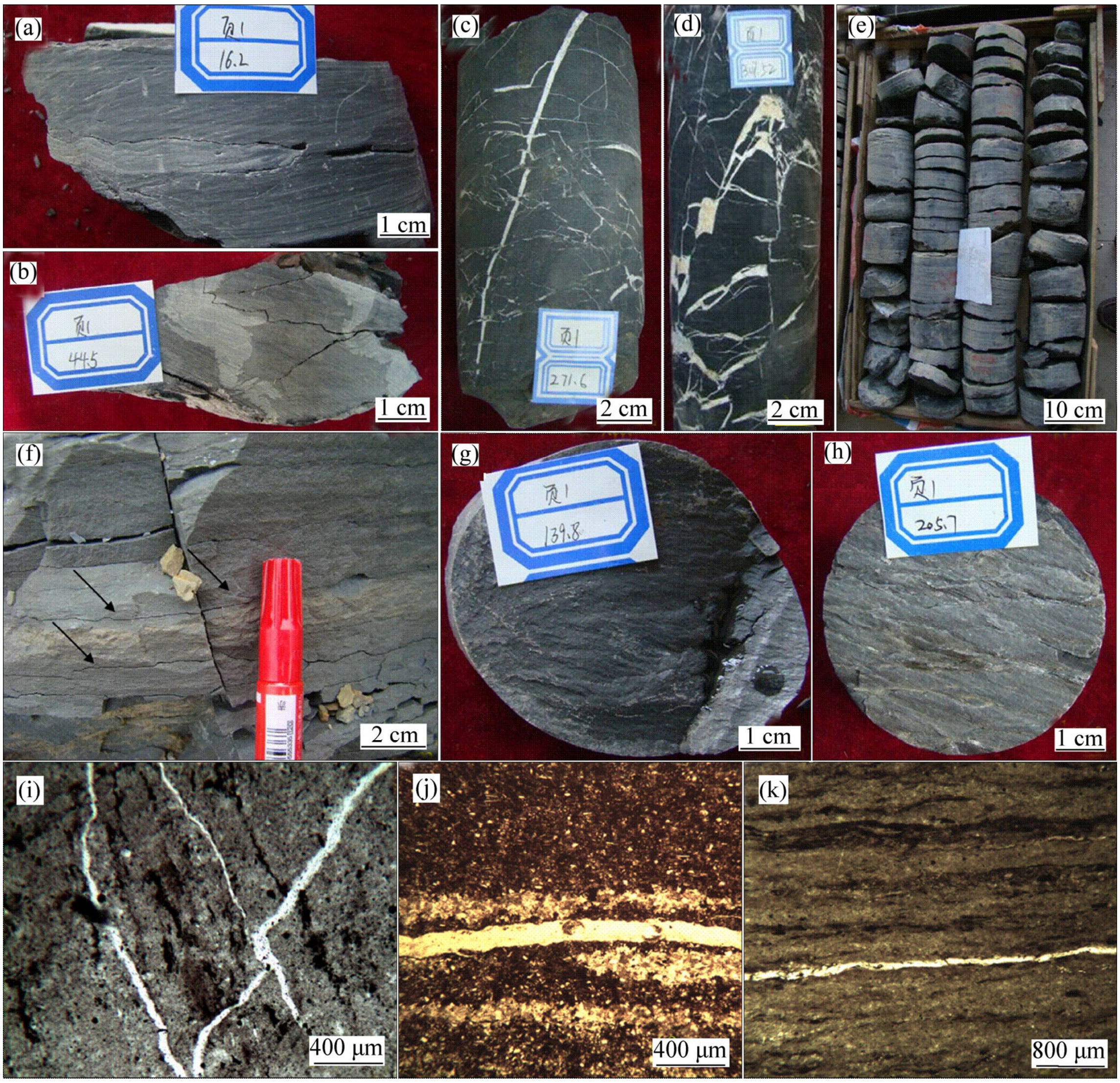


Fig. 7 Pictures of SLS representative of different diagenetic and complex fracture types from cores and outcrops in study area: (a) Black shale interbedded with thin siltstone showing diagenetic fractures, well Yuye-1, at depth of 16.2 m; (b) Dark gray muddy siltstone showing diagenetic fractures, well Yuye-1, at depth of 44.5 m; (c) and (d) Black shale showing complex fractures (tensile and diagenetic fractures) filled with quartz, well Yuye-1, at depth of 271.6 m and 307.3 m; (e) Black shale showing many inter-layer fractures, well Yuye-1; (f) Dark gray silty-clayey interlaminated shale showing inter-layer and tensile fractures, Jiangkou Town, Wulong County; (g) and (h) Black shale showing slip fractures, well Yuye-1, at depth of 139.8 m and 205.7 m, respectively; (i), (j) and (k) Slices of shale showing diagenetic and complex fractures filled or partly filled with quartz, well Yuye-1, at depth of 55 m, 54 m and 27 m, respectively

include tectonic stress and diagenetic fractures. OLSEN et al [14] have proposed that diagenetic fractures are often linked processes especially in deformed rock. Based on the fracture occurrence, fracture-areal features, ground stress and filling characteristics, the tectonic digenetic fractures of the SLS are divided into tensile-diagenetic fractures (Fig. 7(c)) and shear-digenetic fractures (Fig. 7(d)). Our examination reveals that this type of fractures displays araneose appearance and is mainly filled with quartz which decreases reservoir space (Figs. 7(c), (d) and (i)).

2) Inter-layer fractures

This type of fractures refers to fractures along sedimentary bedding that result from various geological forces, and this type of fractures is commonly found in the SLS (Figs. 7(e) and (f)). Interface of laminations in shale displays relatively feeble mechanical property and they are easily peeled off, and then inter-layer fractures are easily developed in this area. JIANG et al [8] proposed that fine grained sedimentary rock is mainly developed in relatively deep water and thin sedimentary layer often forms. Thin layer of shale develops very well in the SLS as shown in thin section photo in Fig. 4(f), and bedding cracks often appear in the intersection surface of the shale and display flat and smooth fracture planes. In addition, siltstone and organic-rich shale frequently appear in the adjoining part of inter-layer fractures (Figs. 4(f), Figs. 7(e), (f), (j) and (k)). Importantly, most of the fractures are not filled and have excellent effectiveness. HE et al [16] proposed that bedding cracks, i.e., inter-layer fractures not only provide excellent reservoir space but also serve as a major seepage channel for the shale reservoir fluid, and thus, they can effectively improve reservoir permeability.

3) Slip fractures

Slip fracture is a common fracture type in the SLS, especially in cores, and it often has a smooth surface and displays mirror features or some scratches (Figs. 7(g) and (h)). Organic-rich clayey shale or calcite often appears in the surface of slip fractures, which might be the weak mechanics belt of the shale. DING et al [17] proposed that the emergence of the slip fractures is related to the following several factors, i.e., compression, differential gravity load of the overlaying stratum, and relative plasticity of shale. In addition, the slip fractures are mainly resulted from bedding detachment and subsequent shear stress due to tectonic extension or compression [3]. Drilling attempts in industrial shale gas producing basins in North America have indicated that slip fractures and other relevant extension and compression fracture belts often develop in black shale that contains rich organic matter [18].

4.3 Dominating controls on fracture formation

The formation of fractures in shale is affected by many factors, such as faults, diagenesis, geological stress, lithology, mineral composition, and total organic carbon content [19−21], and the fracture formation in the study area is mainly affected by faults, lithology, mineral composition and total organic carbon content.

4.3.1 Faults

The southeastern margin of Sichuan Basin features relatively high uplift rates with strong tectonic compression, and then the tectonic stresses of folds formed in the Cretaceous undergo relaxation or release in the Cenozoic, leading to the creation of a series of large-scale NNE-trending faults along anticlinal axes and wings that consist of horst and graben fault systems (Fig. 1(b) and Fig. 2). The development of tectonic fractures is mainly controlled by faults. For instance, fractures developed in outcrops show a relatively good relationship between faults and fractures (Fig. 7(f)).

The controlling effects of faults on fracture development in research area are: 1) intensity of the faults, 2) the distance from the fault, and 3) the variation at different parts of the faults. New data have been obtained to prove the fracture frequency as a function of distance from the fault core and a pronounced difference on fracture densities and apertures between fault damage zones and the host rocks for carbonates has also been proved [22]. JIU et al [23] proposed that stronger fault activity corresponds to a greater likelihood for the formation of a fracture, and in other words, fractures are more developed when being closer to the fault.

However, it should be noted that the relationship between fault and fracture formation is complicated, which is indicated by the fact that different parts of faults have different impacts on the degree of fracture development. Fractures are generally developed in areas such as the turning ends of faults and intersections of different faults, which are also the areas where the shale reservoirs are developed [23]. Fractures are not well developed near every fault, and there is fracture, such as digenetic fractures, and development in regions without fault development, indicating that fracture formation is subjected to the influence of other factors.

4.3.2 Lithology and mineral composition

Shale lithology and mineral composition are the main intrinsic factors controlling fracture development in shale [13]. Shale as a general lithologic terminology in study area includes clayey shale, siliceous calcareous shale, siliceous dolomitic shale, silty-clayey interlaminated shale, muddy siltstone, and graptolite shale. Statistical results show that fractures develop relatively well in graptolite shale in bathyal plain environment, as shown in Fig. 8.

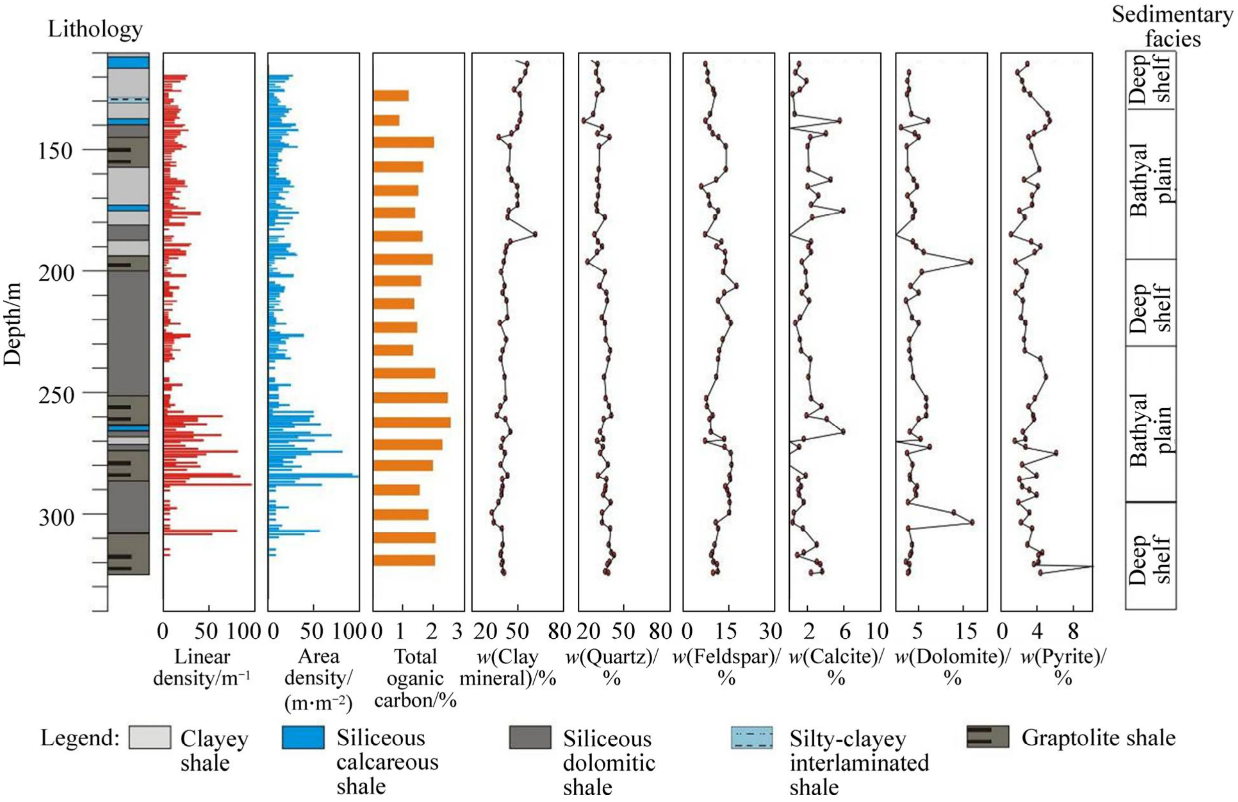


Fig. 8 Relationship between fracture development and total organic carbon content and mineral content in SLS for well Yuye-1 (Values for fracture characters are from Ref. [7])

Mineral composition and content in organic-rich shale can not only impact the mechanical properties of the rocks but also directly modulate fracture development [17]. It is generally accepted that higher levels of brittle minerals, such as quartz, feldspar, carbonate and pyrite, promote fracture development. For example, the Paleozoic marine shale in the United States, generally contains high levels of brittle minerals (over 60% on average) and low levels of clay minerals (less than 40% on average), leading to well-developed fractures in these areas. Specifically, the total content of brittle minerals in research area, including quartz, feldspar, carbonate and pyrite, is approximately 57%; the levels of the quartz, feldspar (potash feldspar and plagioclase), carbonate and pyrite are 39.2%, 12.2%, 11.2% and 2.4%, respectively, and the total content of clay minerals is only 41.6 %.

It has been proved that organic-rich shale rich in quartz is brittle, leading to better development of fractures compared to the more “plastic” shale rich in clay mineral [13]. Feldspar and dolomite also increase the brittleness of dark shale. If shale has less swelling clay minerals but more silica, carbonate and feldspar, the rock is highly brittle and likely to be fractured. Fractures develop relatively well in the section with lower content of clay mineral, but higher content of brittle mineral, i.e., quartz, feldspar and pyrite in the SLS from well Yuye-1(Fig. 8). It is generally accepted that the deeper the sedimentary water, the finer the grain size of sedimentary rock. ZENG et al [24] proposed that in shales with identical mineral compositions, the finer the grain size is, the more conducive the fracture development is, and vice versa. Statistical result shows that fractures develop well in relatively deep water, i.e., bathyal plain in well Yuye-1, as shown in Fig. 8.

4.3.3 Total organic carbon content (TOC)

Under identical geodynamic conditions, TOC is one of the most important factors affecting fracture development in shale [25]. Shale with high contents of organic matter and quartz is more brittle, has less tensile strength, and is prone to produce natural and induced fractures under external forces [13]. JARVIE et al [18] experimentally demonstrated that during its hydrocarbon evolution, the consumption of 35% organic carbon by shale may increase its porosity by 4.9%, and in other words, a high content of organic carbon correlates with more microfractures during hydrocarbon generation. Based on the relationship between TOC and fracture development in shale under exploitation for shale gas, the higher the TOC in shale, the greater the total gas accumulation, corresponding to a higher volume of free gas and better development of fractures [13]. The relationship between TOC and fracture development in the study area can be divided into three levels: 1) TOC<1.0%, poor fracture development; 2) TOC= 1.0%−2.0%, moderate fracture development; 3) TOC> 2.0%, good fracture development (Fig. 8). Overall, there is a positive correlation between the linear density/area density and organic carbon content in the SLS in southeastern margin of Sichuan Basin.

5 Conclusions

1) The SLS is dominantly composed of clayey shale, siliceous calcareous shale, siliceous dolomitic shale, silty-clayey interlaminated shale, muddy siltstone, and graptolite shale formed in marine-continental transgression period. The minerals are mainly composed of quartz and clay minerals, accounting for 39.2% and 41.6%, respectively. The following minerals are plagioclase (average content of 8.9%), dolomite (average content of 5.7%), calcite (average content of 5.5%), potash feldspar (average content of 3.4%) and pyrite (average content of 2.4%).

2) The SLS exhibits widespread development of various types of fractures including tectonic fractures, diagenitic fractures and complex fractures. Tectonic fractures are characterized by high to medium angle and frequently filled with quartz and calcite. Complex fractures including tectonic diagenitic fractures, inter-layer fractures and slip fractures also develop well. These fracture types not only provide reservoir space, but also effectively improve reservoir permeability for shale gas.

3) Faults, lithology, mineral composition and TOC are the main factors that influence the fracture development in the SLS. The greatest impact on fracture development is provided by faults, followed by the mineral composition and content of the shale. Within the same tectonic setting, the quantity of brittle minerals such as quartz, feldspar, carbonate, and pyrite in shale governs the fracture development of that shale. Specifically, the analysis demonstrates that increased fracture development is associated with TOC, within the same tectonic setting and similar composition of minerals.

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