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Tight sandstone diageneses, evolution, and controls on high-graded reservoirs in slope zones of foreland basins: A case study of the fourth Member of Xujiahe Formation, Tianfu gas field, Sichuan Basin

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A B S T R A C T

The Triassic Xujiahe Formation in the slope zone of the Sichuan foreland basin is a new field of continental tight gas exploration in recent years. The fourth member of the Xujiahe Formation (Xu4 Member), the major interval in the Jianyang Block of the Tianfu gas field in the basin, is characterized by considerable buried depth, tight reservoirs, and strong heterogeneity. By using cast thin section, X-ray diffraction (XRD), scanning electron microscopy (SEM), fluid inclusion thermometry, and core analysis, the reservoir rock types, dominant diageneses, diagenetic history, and controls on high-graded reservoirs were investigated. It is found that the Xu4 Member in Jianyang mainly consists of lithic feldspar sandstones and feldspar lithic sandstones, followed by lithic quartz sandstones. High-energy hydrodynamic conditions in the microfacies of underwater distributary channels and mouth bars are beneficial to the preservation of primary pores and the occurrence of secondary pores, and there are no significant differences in petrophysical properties between these two microfacies. Compaction and calcareous cementation are the dominant controls on reservoir porosity decrease in the Xujiahe Formation; corrosion is the major contributor to porosity increase by generating secondary dissolved pores, e.g. intragranular dissolved pores and intergranular dissolved pores, as major reservoir space in the study area. Fracture zones around the faults inside the Xujiahe Formation (fourth–order faults) are favorable for proximal tight gas accumulation, preservation, and production. The research findings have been successfully applied to explore the Xujiahe Formation in the slope zone of the Sichuan foreland basin. They can be referential for other similar tight sandstone gas accumulations.

1. Introduction

The formation of foreland basin is closely related to orogenic belt, which generally has rich oil and gas resources, and many large and super-large oil and gas fields have been found in foreland basins, so the study is of great significance (Jia CZ et al., 2005; Li JZ et al, 2012). A foreland basin can be divided into four tectonic units: Foreland fold-thrust belt, foredeep depression belt, slope belt, and foredeep uplift belt (Jordan TE, 1995; Schwab FL, 1986). There are apparent differences in trap types, formation time, development degree and preservation conditions of source rocks, and burial depth of favorable reservoirs among different tectonic zones, which control the distribution of oil and gas in foreland basins. As a large superimposed petroliferous basin, the Sichuan Basin was a typical foreland basin at the depositional stage of the Late Triassic Xujiahe Formation (Luo ZL, 1998; Li W et al., 2022; Liu JL, 2015). The Xujiahe Formation gas exploration in the basin began in the 1950s. It went through the process from structural traps to lithologic traps, from single structures to pervasive gas accumulations, and from western Sichuan to central Sichuan (Wu XF et al., 2014; Li GH et al., 2012;

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Zhang DW and Yang Y, 2022; Jin H et al., 2018). The Xujiahe Formation tight gas exploration once faced challenges because pervasive lithologic tight gas reservoirs discovered in the foreland uplifted zone of central Sichuan Basin are far away from source centers, where gas saturation is low and gas-water differentiation is not remarkable (Chen JX et al., 2019; Xie ZY et al., 2021). According to the new idea of prospecting more intervals and areas around the source centers in the Xujiahe Formation, western Sichuan Basin, since 2018, Well YQ1, a preliminary prospecting well, was deployed and yielded gas flow of 312.6×10^3 m^3/d from the Xu4 Member (the Xu4 Member refers to T_3X^4, the same below), which marked the discovery of proximal tight gas accumulations within the Xu4 Member, Jianyang Block of Tianfu gas field in the foreland slope zone of Sichuan basin.

The current exploration results show that Xu4 gas reservoirs in the Jianyang Block feature small distances to sources, no water, gas accumulation in the whole interval, large reservoir thickness, and large potential resources according to preceding exploration. The disadvantages are large buried depth and tight reservoir properties. Preceding studies showed that tight reservoir properties are related to sedimentation, diagenesis, and buried depth (Taylor TR et al., 2010; Ehrenberg SN et al., 2008; Bjørlykke K, 2014; Zhu RK et al.,2009; Zhao DF et al., 2021; Lu YQ et al., 2020; Shi LZ et al., 2023), but the deliverability of low-permeability reservoirs is dominated by diagenesis (Tobin RC et al., 2010; Stroker FL et al., 2013). Many studies of reservoirs and diageneses in the Xujiahe Formation mainly focused on tight water-bearing sandstone reservoirs with moderate porosities and permeabilities in the depressed zone or uplifted zone of the foreland basin (Yu Y et al., 2019; Lin LB et al., 2022). There are no published reports about tight water-free sandstone reservoirs with low porosities and permeabilities discovered for the first time in the slope zone of the foreland basin. Fractures function as important pathways for gas flow in tight sandstone gas recovery; thus, it is significant to assess the relationships between gas deliverability/diagenesis and natural fractures (Wüstefeld P et al., 2017; Yin S et al., 2020; Gong L et al., 2019). There is no clear understanding of the relationship between reservoir quality, fractures, and natural gas deliverability, which hinders gas exploration and development in this study area. Therefore, a variety of test and analysis techniques will be adopted in this study of the Xu4 Member of PetroChina Jianyang Block, carrying out detailed analysis of reservoir characteristics to clear the mechanism of favorable tight sandstone reservoir and its influence on gas production capacity in the foreland slope zone of Sichuan basin. This study is expected to provide a theoretical basis for the follow-up oil and gas geological exploration and well deployment and reference for other tight sandstone formations with similar characteristics.

2. Geologic setting

The Sichuan Basin in the northwestern Yangtze Craton is among the most important gas basins in China (Huang S et al., 2014; Zhao DF et al., 2022). The Tianfu gas field is adjacent to Yanting County in Mianyang City on the north, Jianyang District in Chengdu City on the south, the Longquanshan Mountain on the west, and Shehong County in Suining City on the east. The field structurally lies in the slope zone of the foreland basin (Fig. 1). The Sichuan Basin was deposited with marine strata, consisting mainly of carbonate rocks in and below the Middle Triassic, and continental strata, consisting mainly of sandstones and mudstones, from the Upper Triassic to the Tertiary. Among several tectonic movements in the Caledonian, Hercynian, Indosinian, Yanshanian, and Himalayan, the last three movements had the greatest impact on the Triassic Xujiahe Formation (Zheng Y et al., 2018; Yang CQ et al., 2008). In the early stage of the Late Triassic, thin deposits of neritic and transitional facies only occurred locally in the western Sichuan Basin. Owing to the influence of paleotethys closure in the middle and late stages of the Late Triassic, the Ganzi-Aba area was uplifted, intensely folded, extruded and thrusted toward the east to form the Longmenshan nappe structural zone, on the east of which the Upper Triassic foreland basin came into being. In the subsequent Indosinian, Yanshanian, and Himalayan movements, the Xujiahe Formation in the basin subjected to the constraint of the stable basement in the central Sichuan Basin went through small tectonic deformation by regional stress in the east-west direction; a series of low-relief gentle structures began to occur in the Yanshanian and finally shaped in the Himalayan. Subjected to the constraint of the ferromagnetic rigid basement in the central Sichuan Basin, the Xujiahe Formation in the Jianyang Block is structurally gentle owing to small tectonic deformation and folding.

The fourth member of the Xujiahe Formation (Xu4 Member) in the Jianyang Block of the Tianfu gas field is lithologically composed of light grey to grey medium-grained and medium- to fine-grained feldspar lithic sandstones and lithic feldspar sandstones intercalated with some thin greyish black mudstones. Xu4 top is in conformable contact with overlying greyish black shales at the bottom of Xu5, and there is a distinct boundary between Xu4 bottom and underlying black shales at the top of Xu3. The top of Xu4 in the study area is buried at 2260–3650 m (sea-level elevation from −1670 m to −3100 m). The thickness consistently ranges 80–130 m.

In the transition zone from central to western Sichuan Basin, the Xujiahe Formation is structurally gentle owing to the constraint of the ferromagnetic rigid basement in central Sichuan Basin. The sedimentary system with braided-river deltas was deposited persistently. Due to tectonic-depositional differentiation, the Xu4 Member was extensively settled with deltaic deposits originating from eastern and southern sedimentary sources. The cumulative thickness of sands, mainly multi-phase pervasive superimposed underwater distributary channel sands and mouth bar sands, generally ranges 80–100 m and may be over 140 m. Sandstone-formation thickness ratio is mostly more significant than 80%.

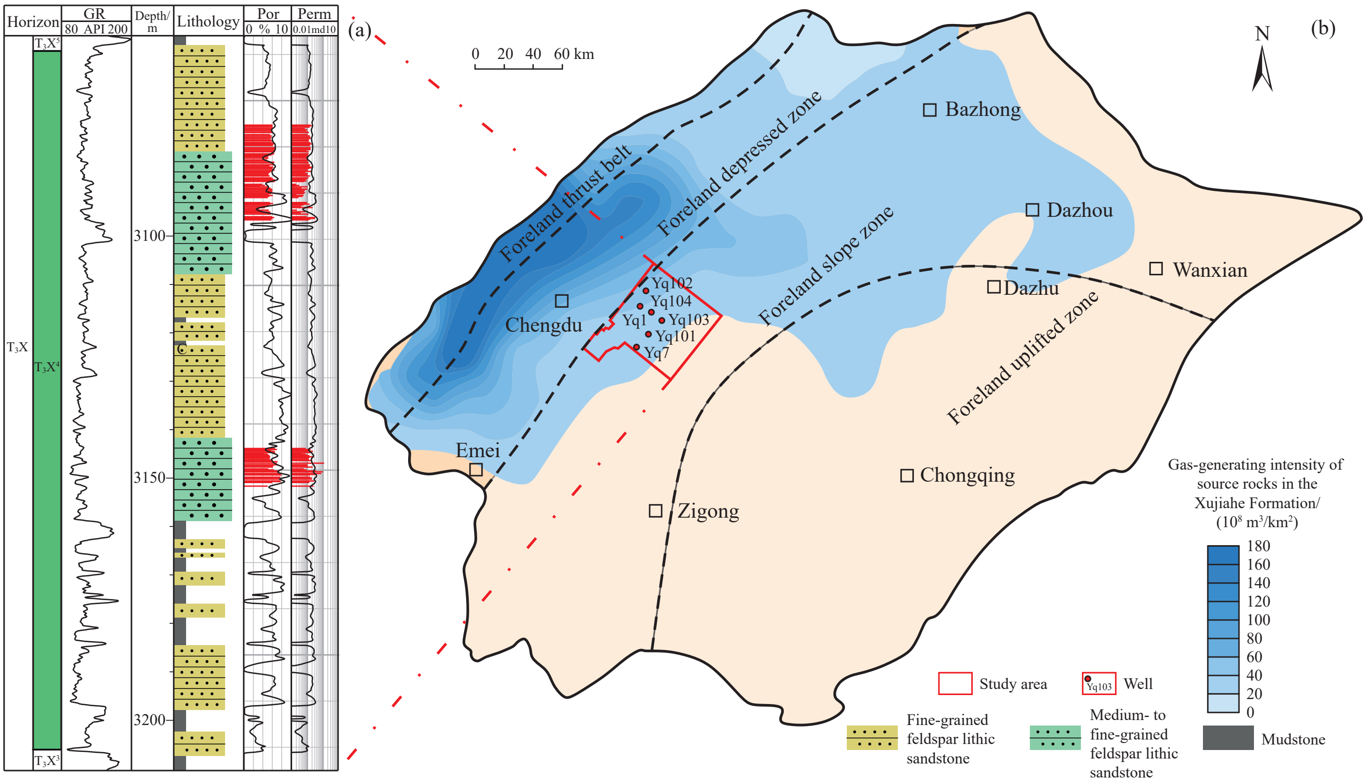

Fig. 1. Geological setting of Jianyang Block, Tianfu gas field. a–Lithologic column of Well YQ104; b–tectonic provinces in the foreland basin overlaid with hydrocarbon-generating intensity of source rocks in the Xujiahe Formation.

3. Data and methodology

All the research findings of Xu4 reservoirs in the Jianyang Block were mainly based on the analytic data of 5 wells (YQ1, YQ7, YQ101, YQ102, and YQ104). The Xu4 cores of 119.23 m long cumulatively acquired from the study area were used for core observation, dyed cast thin section analysis, whole-rock XRD, clay-mineral XRD, temperature measurement of inclusions, SEM, and petrophysical property analysis. Thin sections were stained with alizarin red to distinguish the calcareous components in the sandstone. The physical properties of the drilled core plunger were analyzed using the alcohol method. The whole-rock XRD was carried out by BRUKER D8 Discover X-ray diffractometer, with continuous scanning at 2θ Angle of 5°–45°, scanning speed of 2°/min, and step width of 0.02°, under the condition of Cu for the anode target material of the optical tube, 40 kV voltage and 40 mA current. Analysis methods were referred to “Analysis method for clay minerals and ordinary non–clay minerals in sedimentary rocks by the X-ray diffraction” (SY/T 5163–2018). SEM analysis was carried out by FEI-QUANTA FEG 250 field emission scanning electron microscope (with OXFORD X-MaxN EDS spectrometer), under the conditions of 0.2–30 kV acceleration voltage, 200 nA maximum beam current, 10 mm working distance, 60×10^{-3} Pa for high vacuum mode, 10–130 Pa for low vacuum mode, and 10–4000 Pa for ambient vacuum mode. The analytical method is referred to as “Analysis method of rock sample by scanning electron microscope” (SY/T 5162–2021). The above experiments were completed in the Key Laboratory of Carbonate Reservoir of China National Petroleum Corporation.

Rock types were determined based on debris and core observation, microscopic thin section identification, and whole-rock XRD, which focused on average grain size, mineral composition, particle contact, sorting and rounding features, and quantitative analysis of rock composition. Pore space types and geometries were established based on microstructure analysis of cast thin sections using scanning electron microscope, which focused on pore space type, porosity, diagenesis type and phase, and clay mineral occurrence. A total of 220 debris thin sections, 119 thin sections, and cast thin sections, six samples for temperature measurement of inclusions, 25 sections for SEM, and 355 petrophysical property data of plug samples were used for analysis.

4. Results

4.1. Petrologic features

The Xu4 Member in the study area mainly consists of light grey medium-grained and fine- to medium-grained sandstones intercalated with thin (<1 m) greyish-black mud shales. As per the statistical data of 5 wells, the cumulative sandstone thickness of each well accounts for 79.8%–99.6% of Xu4 Member thickness; the thickness of argillaceous rocks generally accounts for less than 5% of member thickness.

According to debris and core observation and microscopic thin section identification, the Xu4 Member mainly comprises lithic feldspar sandstones and feldspar lithic sandstones, followed by lithic quartz sandstones (Fig. 2a).

The intergranular fillings are mainly clay minerals, and the cements are mainly calcite and secondary-overgrowth quartz (Fig. 2b). The sandstones feature medium to fine grain size in the majority and coarse to medium grain size in the minority, good to moderate sorting, sub-angular to sub-rounded geometries, line to concavo-convex contact (Figs. 2c–f), moderate compositional maturity, and maturity index (quartz/feldspar + debris) of 0.6–1.5. Debris mainly include quartzite debris, which belong to metamorphic rock debris, followed by mudstone and sandstone debris, which belong to sedimentary rock debris. According to whole-rock XRD, average quartz content is 59.4%; average plagioclase, clay, potash feldspar, and carbonate contents are 15%, 13.7%, 9%, and 2.7%, respectively.

4.2. Reservoir properties

According to 355 petrophysical property data (Figs. 3a,

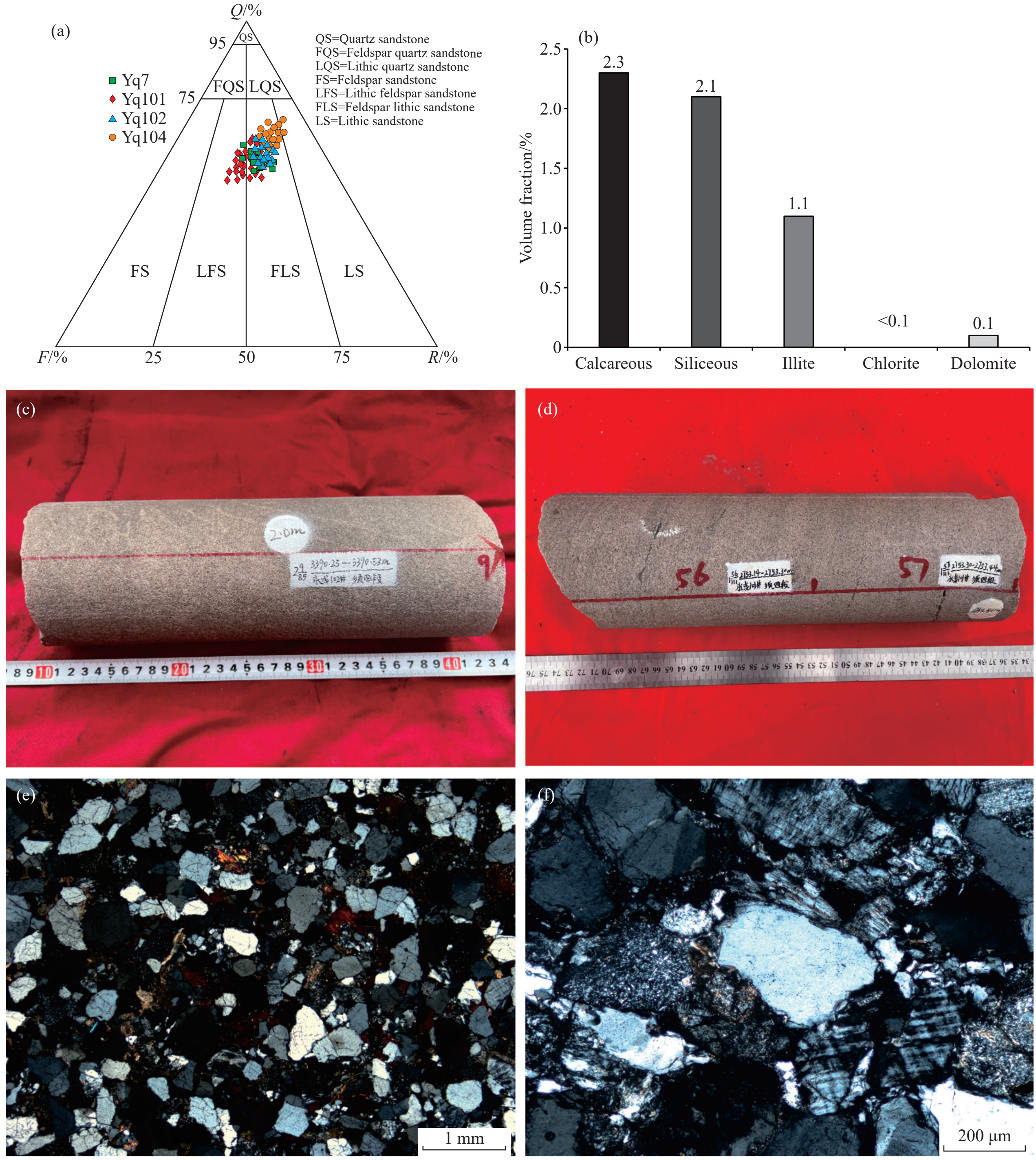

Fig. 2. a–Classification triangle of Xu4 sandstone in the Jianyang Block; b–cement content histogram; c–d–light grey medium-grained and fine- to medium-grained blocky sandstones; e–feldspar lithic sandstones, Well YQ102, Xu4 Member, 3181.87 m, cross-polarized light; f–feldspar lithic sandstones, Well YQ101, Xu4 Member, 2744.6 m, cross-polarized light.

b), the porosity of tight sandstone reservoirs in the Xu4 Member mainly ranges from 6%–8% with an average of 6.02%; the samples with porosity <7% account for 78.25%. The permeability ranges from 0.05–0.3 mD with an average of 0.33 md; the samples with a permeability <0.1 md account for 43.94%. The cross plot of porosity and permeability (Fig. 3c) shows that the Xu4 sandstone reservoirs in the study area are mainly porous and fractured-porous reservoirs; porous-fractured reservoirs are uncommon.

4.3. Diageneses and features

4.3.1. Compaction and pressolution

The Xu4 sandstones in the study area experienced intense mechanical compaction in the process of burial, leading to rapid pore water drainage and rock particle rearrangement and deformation (Figs. 4a, b). The signs of compaction and pressolution include plastic deformation, flexural deformation, rupture, and undulating extinction of sheet-like minerals, e.g. mica (Fig. 4b). The framework grains of Xu4 sandstones are usually highly compacted (mechanically and chemically), which could be observed as flattened strip-like plastic particles and concave-convex contact of rock particles (Fig. 4b).

4.3.2. Cementation

The most common cements in the Xu4 Member in the study area are carbonate, siliceous, and clay minerals (Fig. 4c, e); calcareous cements are in the majority in Xujiahe reservoirs. Calcareous cement in Xu4 sandstone reservoirs occurs in two forms: Crystal stock and pore-space-filling, and the latter are more common (Fig. 4c, d). Siliceous cement (authigenic quartzes), occurring in the forms of secondary enlargement border of quartzes and pore-space-filling (Fig. 4e), may originate from the dissolution of minerals, e.g., feldspar, resolution of quartz particles, and transformation of clay minerals (Xie XM et al., 2021). Pressolution is generally supposed to be the dominant origin of siliceous cements in diagenetic evolution, particularly in deep-buried sandstones; pressolution causes material redistribution and secondary enlargement of quartz. As per thin section observation and clay mineral XRD, clay cement in Xu4 sandstones include illites, chlorites, mixed-layer illites/smectites, and kaolinites. Smectites rich in sodium and potassium react with potash feldspar to produce illites, and mixed-layer illites/smectites (I/S) are the intermediate product of smectites' transformation into illites. As buried depth increases, smectites in mixed-layer illites/smectites continuously transform into illites. Feldspar is corroded to form kaolinites, which may become unstable when the temperature exceeds 110°C. In a closed diagenetic system, kaolinites react with neighboring K^+ ions to produce illites and quartzes (Bjørlykke K, 2010; Yuan GH et al., 2013). That is why kaolinite content is low in clay minerals in Xu4 sandstone reservoirs nowadays in the study area. Illite cements in Xu4 sandstone reservoirs occurring in the form of threads in pores usually originated from smectite transformation and feldspar dissolution (Luo L et al., 2015).

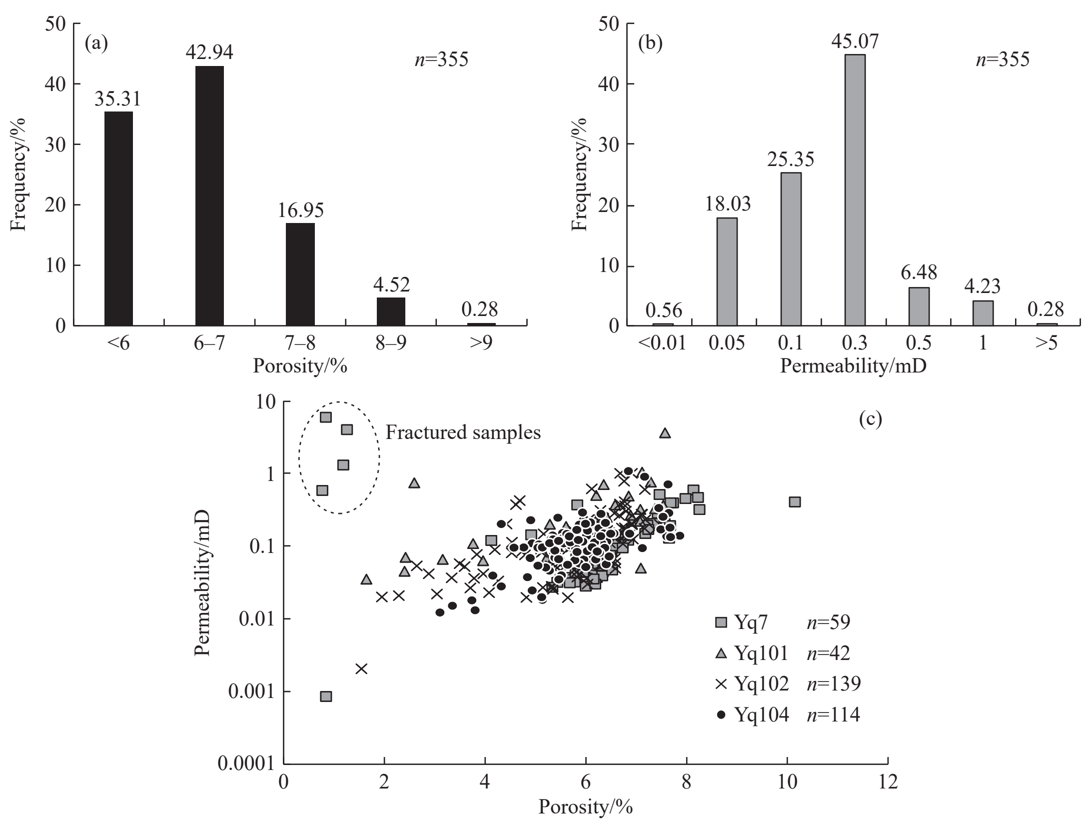

Fig. 3. Reservoir properties in the Xu4 Member, Jianyang Block. a–porosity histogram; b–permeability histogram; c–crossplot of porosity and permeability.

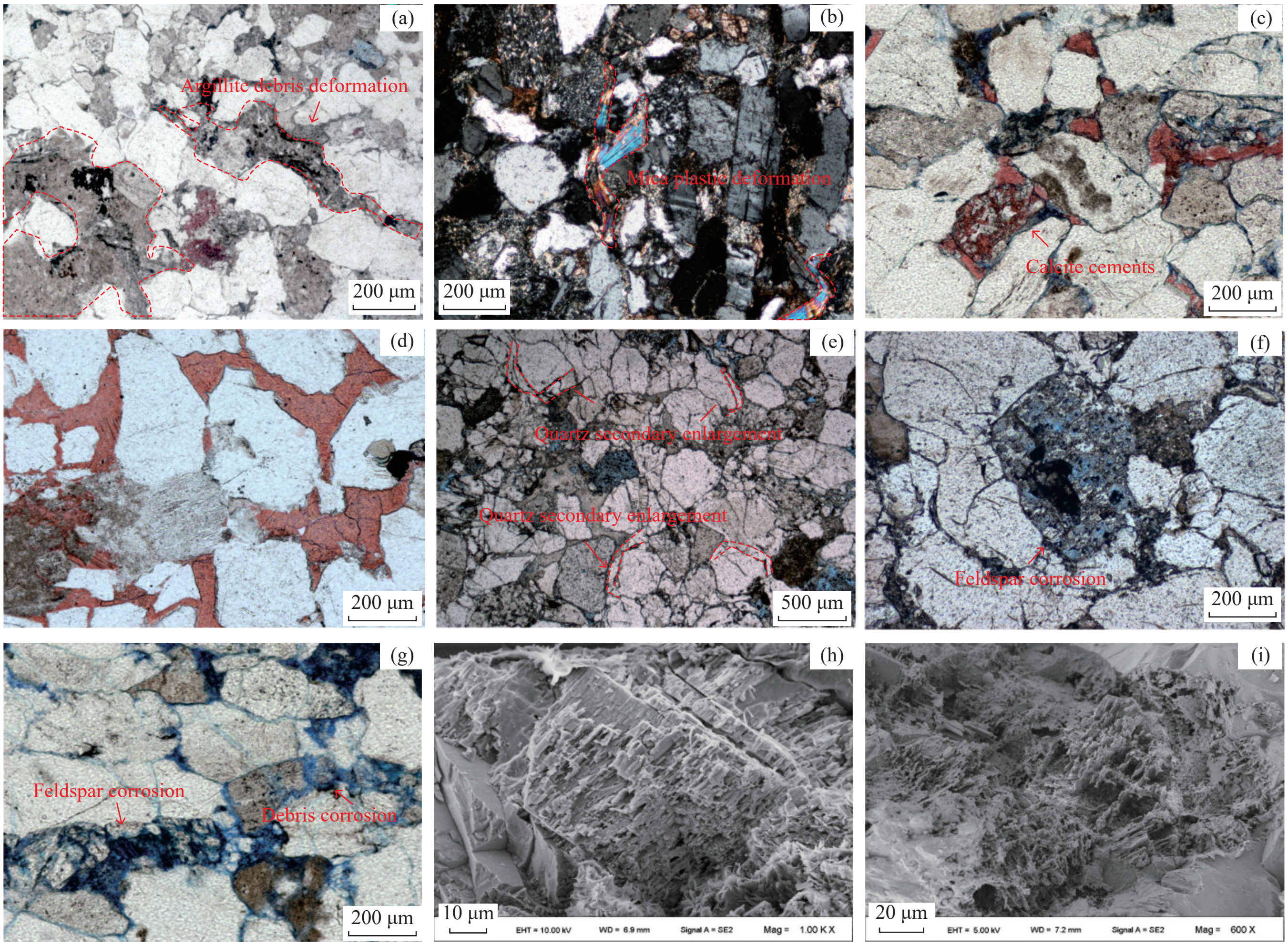

Fig. 4. Diagenetic features in the Xu4 Member, Jianyang Block. a–compressional deformation of plastic debris, e.g. slate and mudstone debris, Well YQ104, Xu4 Member, 3201.5 m, linearly polarized light; b–mica plastic deformation caused by compaction, Well YQ7, 2915.75 m, cross–polarized light; c–intergranular dissolved pores partially filled with calcareous cements, Well YQ101, Xu4 Member, 2744.6 m, linearly polarized light; d–calcareous crystal stock cementation, Well YQ101, Xu4 Member, 2753.61 m, linearly polarized light; e–well-developed siliceous cements, Well YQ7, Xu4 Member, 2716.76 m, linearly polarized light; f–intragranular dissolved pores inside feldspar, Well YQ102, Xu4 Member, 3388.4 m, linearly polarized light; g–intragranular dissolved pores inside feldspar and debris, developed fractures at grain boundary, Well YQ101, Xu4 Member, 2757.15 m, linearly polarized light; h–dissolved pores and microcracks in potash feldspar, Well YQ101, Xu4 Member, 2757.15 m, SEM; i–corroded porous potash feldspar which is transforming into clay minerals, Well YQ101, Xu4 Member, 2763.2 m, SEM.

4.3.3. Corrosion

Corrosion is the major diagenetic process to increase porosity (constructive diagenesis) in the Xujiahe Formation, particularly in the Tianfu gas field, where secondary dissolved pores constitute the dominant reservoir space. In Xu4 sandstone reservoirs in the study area, reservoir space is mainly composed of secondary intragranular dissolved pores and intergranular dissolved pores, around which there are harbor-like corrosion borders (Fig. 4f, g). The Xu4 sandstone reservoirs are usually intercalated in source rocks, from which organic acids generated by mature organic matter may flow into sandstone reservoirs to cause corrosion. Corrosion often occurs in aluminate and silicate minerals, e.g. feldspar, in igneous rocks (Fig. 4h) and is occasionally accompanied with dissolution of quartzes and interstitial materials. Dissolved aluminate and silicate minerals are an additional important origin of siliceous cements in reservoirs (Fig. 4i). Feldspar is usually dissolved into crystalline grains along cleavages, with associated intragranular dissolved pores. If corrosion is strong enough, moldic pores may be produced.

4.4. Fluid inclusion features

According to petrographic analysis and microscopic observation, there are two types of fluid inclusions in Xu4 sandstone reservoirs in the study area: One occurring irregularly inside quartz particles and the other occurring linearly along fissures inside quartz particles (Fig. 5). For Type-I (Figs. 5a, b), CO_2 inclusions rich in gas phase at room temperature, liquid phase can be observed at the edge. They are associated with aqueous inclusions, with no fluorescence reactions, irregular and strip-like geometries of 3–18 μm in diameter, gas-liquid ratio of 6%–9%, homogenization temperature of 71°C–165°C (avg. 104.89°C), freezing temperature from −5.1°C to −1°C (avg. −2.4°C), and salinity of 1.73%–8% (avg. 3.99%). For Type-II (Fig. 5c, d), also

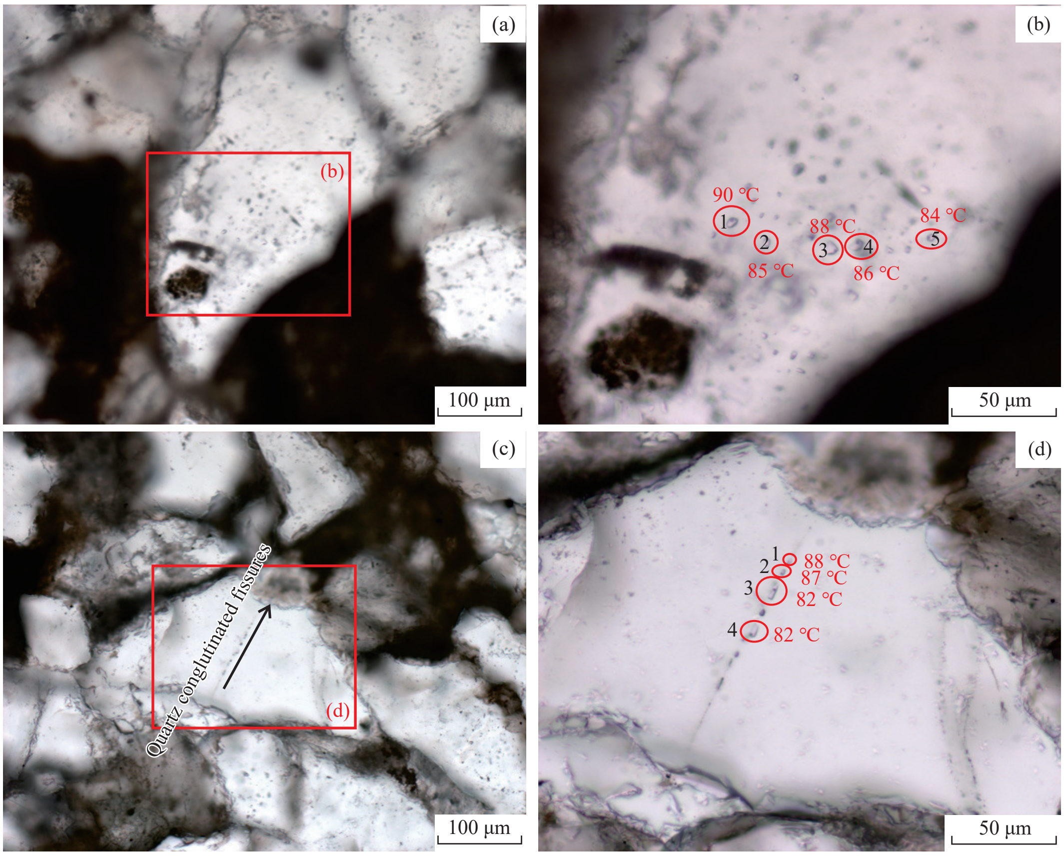

Fig. 5. Petrographic features of fluid inclusions in the Xu4 Member in the study area.

two-phase gas-liquid inclusions composed of CO_2, with elliptic, irregular, and strip-like geometries of 3–15 μm in diameter, gas-liquid ratio of 5%–10%, homogenization temperature of 82°C –126°C (avg. 100.34°C), freezing temperature from −3.4°C to −1°C (avg. −2.1°C), and salinity of 1.73%–5.55% (avg. 3.52%).

4.5. Diagenetic evolutionary sequence

According to XRD analysis, the volume fraction of clay minerals in the Xu4 Member in the study area ranges 4.7%–17.8% (avg. 9%). The volume fraction of illites in clay minerals ranges 35%–60% (avg. 50%). The volume fraction of chlorites ranges 36%–60% (avg. 46%). The volume fraction of I/S ranges 3%–5% (avg. 4%). As per the relative content of clay minerals, it is inferred that samples are mainly at the mesogenetic stage. Core observation and thin section identification show point-line contact and line contact of rock particles in the period from the eogenetic-B stage to the mesogenetic-B stage in the Xu4 Member. Dominant pore types of dissolved pores and microcracks indicate the period from the eogenetic-B stage to the mesogenetic-B stage. According to the homogenization temperatures of siliceous inclusions in sandstones, the samples at the eogenetic-B stage (60°C –90°C) account for 25%; the samples at the mesogenetic-A stage (90°C –140°C) account for 70%; the samples at the mesogenetic-B stage (140°C–170°C) account for 5% (Fig. 6).

According to the standards stipulated in the Division of Diagenetic Stages in Clastic Rocks (ST/5477-2003), the diagenetic evolutionary sequence in the Xu4 Member in the study area was reconstructed based on paleo-heat flow values and corresponding boundary parameters of the Sichuan Basin (Fig. 7). From the initial phase of burial to the eogenetic-A stage, Xu4 rocks mainly with primary intergranular pores were weakly consolidated to semi-consolidated. As burden pressure increased in the process of burial, the porosity decreased quickly owing to mechanical compaction. There were no distinct fluid-rock reactions at the eogenetic-A stage due to rapid compaction; authigenic minerals are underdeveloped, and some thin calcite and chlorite films could be observed locally. From the eogenetic-B stage to the mesogenetic-A stage, clastic particles with some secondary pores were in point-line contact. Quartz enlargement occurred at the end of the eogenetic-B stage, when the most drastic fluid-rock-hydrocarbon reactions took place and hydrocarbon generation and expulsion gave rise to secondary pores and cement precipitation. At the mesogenetic-B stage, when illites and chlorites were in the majority in clay minerals, the diagenetic system became closed, and some cements settled. As a result, the porosity decreased slowly; effective pore space was mainly composed of fractures.

5. Discussion

5.1. Controls on high-graded reservoirs

5.1.1. Sedimentation

In an environment with high water energy, coarse-grained

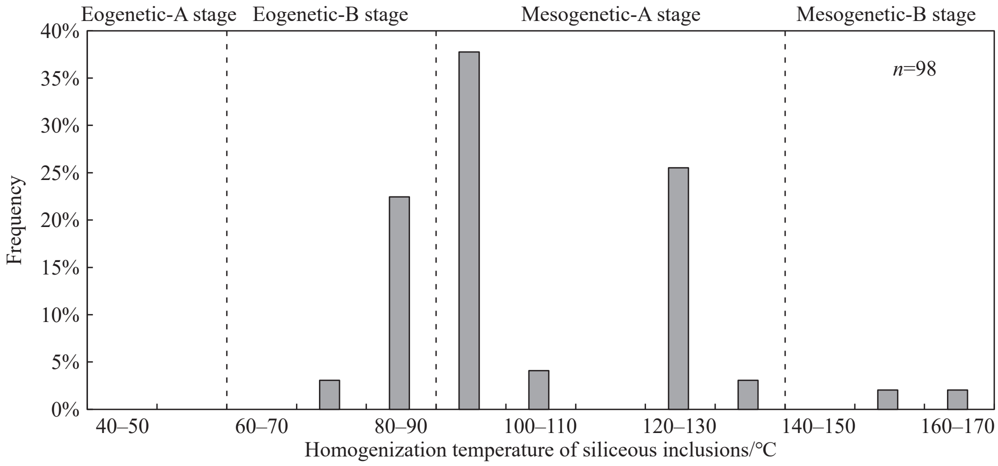

Fig. 6. Homogenization temperature histogram of Xu4 siliceous inclusions in Jianyang Block.

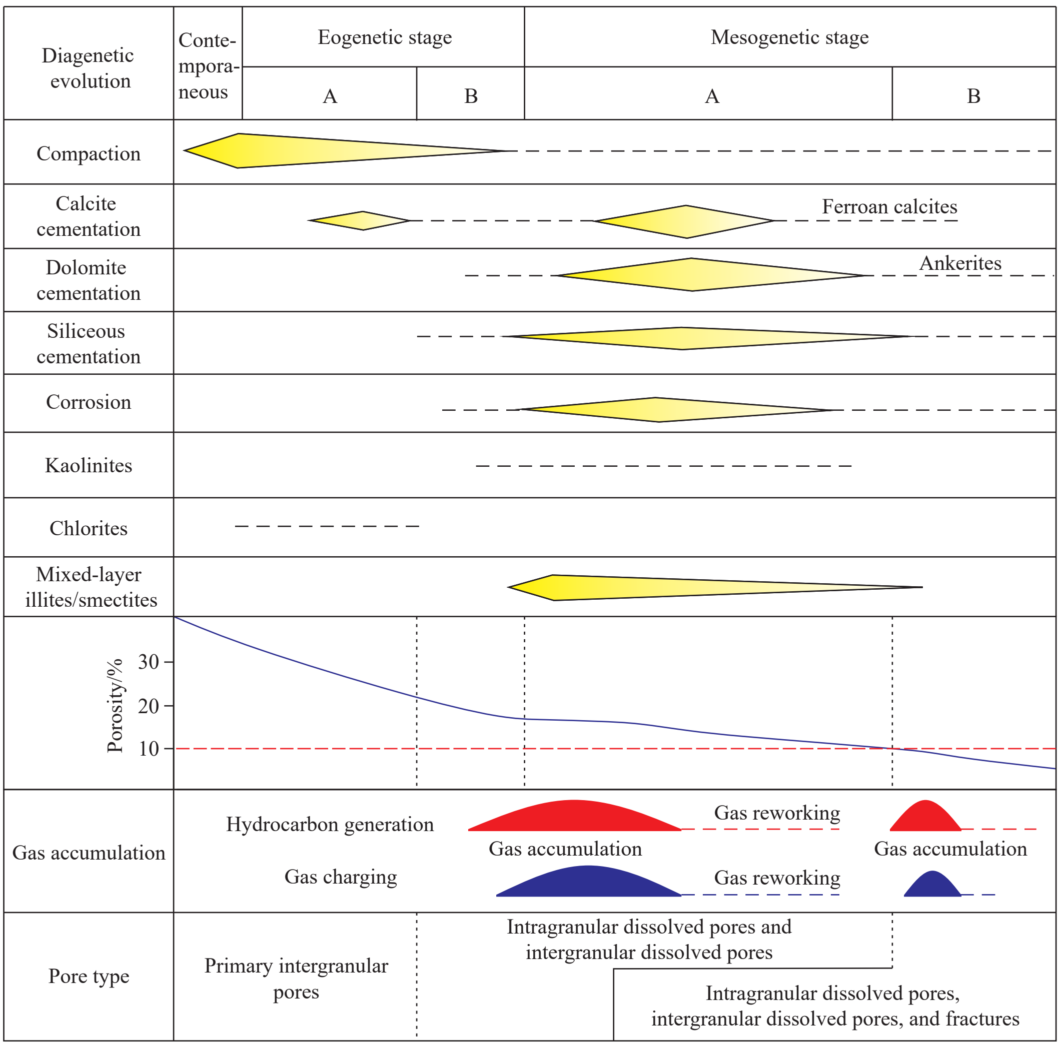

Fig. 7. Schematic diagenetic evolutionary sequence, accumulation history, and porosity evolution in the Xu4 Member, Jianyang Block.

sediments tend to be better sorted and rounded, and primary pores (e.g. intergranular pores) may be well developed (Zhao DF et al., 2023; Zhong Y et al., 2018). The intensity of compaction is closely related to the percentage of fine-grained rock particles in sandstones. Compared with a low-energy environment, coarse- grained sediments are more compaction-resistant. Primary pores preserved may function as the migration pathways for later acidic fluids and thus be subject to corrosion by acidic fluids running through to form secondary dissolved pores and small dissolved caverns. This means that original predominant depositional fabrics are the prerequisite to high-graded reservoirs. As per the analysis, high-graded reservoirs in the Xu4 Member, Jianyang Block, are mouth bar sands and underwater distributary channel sands, which were deposited in an environment with high water power. Interdistributary bays composed of fine-grained thin mudstones or mudstones intercalated with siltstones were deposited in a low-energy environment where reservoirs are underdeveloped. In terms of petrophysical properties (Table 1), the average porosity of Xu4 mouth bar sands is 6.81% and the average permeability is 0.043 mD; the average porosity of underwater distributary channel sands is 6.77% and the permeability is 0.039 mD. There are no significant differences in petrophysical properties between these two high–energy microfacies; the petrophysical properties of mouth bars are slightly better than of underwater distributary channels.

5.1.2. Diageneses

Sandstone reservoir quality is also dependent on diageneses in the process of burial in addition to original sedimentary environments (Moore and Druckman, 1981; Li MY et al., 2019). Common diageneses include compaction, pressolution, cementation, and corrosion. For most reservoirs in the Xujiahe Formation, compaction is a major control on reservoir porosity decrease. Calcareous cementation is another contributor, for example, at Well JH2 in the Qiulin area. Quartz content is low in Xu4 sandstones in the study area. High-content plastic debris were compacted and deformed intensely in the diagenetic process and thus blocked intergranular pores; this is an important cause of why intragranular pores preserved are in the majority nowadays in the study area. As per cast thin section analysis, there is a negative correlation between intergranular porosity and plastic debris (including mudstone, argillite, schist, and siltstone debris) content (Figs. 8a, b), indicating a severe impact of compaction on Xu4 reservoirs in the study area. In general, low cement content may be related to strong compaction in the area. Calcareous cementation, as the predominant type in Xu4 reservoirs (Fig. 2b), is the major cementation to cause reservoir porosity decrease. High-content calcareous cement occurring in the form of crystal stock may lead to calcareous tight zones (Fig. 4d), and late low-content calcareous cement filling in residual intergranular pores and intragranular dissolved pores will further decrease reservoir porosity to form tight reservoirs. Siliceous cement (authigenic quartzes) and clay cements also have a negative impact on reservoir properties; the former occurs in the forms of secondary enlargement border of quartzes and pore-space filling, and the latter may be filled in pores in the forms of

Table 1. Petrophysical properties of sedimentary microfacies in the Xu4 Member, Jianyang Block.

Physical property	Number of samples	Mouth bar			Underwater distributary channel		
		Max.	Min.	Avg.	Max.	Min.	Avg.
Porosity /%	355	7.65	6.22	6.81	7.7	5.52	6.77
Permeability /mD	355	0.097	0.018	0.043	0.248	0.013	0.039

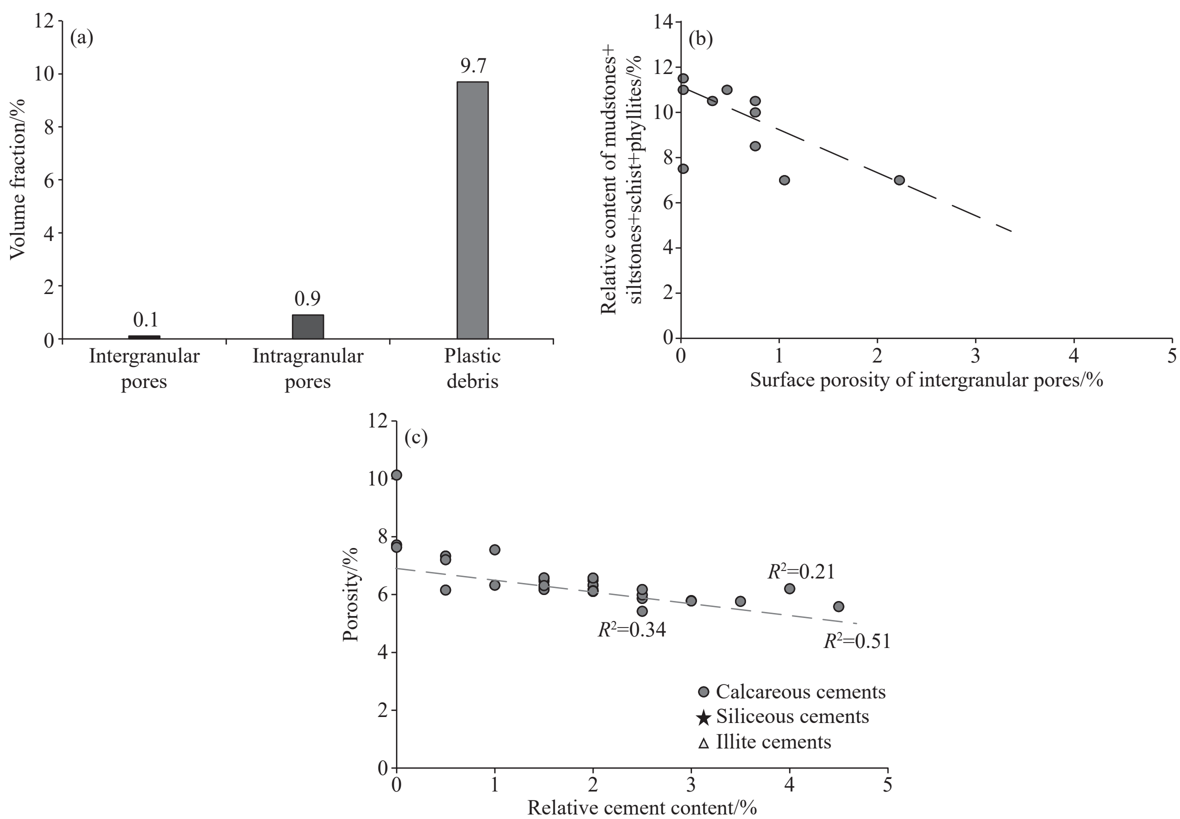

Fig. 8. Correlations between diageneses and physical properties in the Xu4 Member, Jianyang Block. a–volume fraction histogram of intergranular pores, intragranular pores, and plastic debris; b–correlation between surface porosity of intergranular pores and relative content of plastic debris; c–correlations between cement content and porosity.

illites and/or mixed-layer illites/smectites. There are poor correlations between these two factors and reservoir properties (Fig. 8c), which may be related to the open or closed diagenetic system. On the contrary, the content of chlorite cements, with compaction resistance to preserve intergranular pores, is low in the area (Zhao CJ et al., 2022). Corrosion is the major diagenesis to increase porosity (constructive diagenesis) in the Xujiahe Formation, particularly in the study area where secondary dissolved pores constitute dominant reservoir space (Fig. 4f, 4i).

5.1.3. Fractures

Fractures, as hydrocarbon migration pathways, are crucial to hydrocarbon enrichment in tight low-permeability porous sandstones and tight reservoir stimulation (Zhang JC et al., 2020; Yue DL et al., 2018; Li H et al., 2019). Fractures can be classified as structural fractures, diagenetic fractures, and overpressure fractures in terms of geologic origin. Most fractures in the Xu4 Member in the study area are structural fractures. According to core and imaging log data, high-angle structural fractures generally open in the tectonic process tend to be filled with cements (e.g. quartz crystals and calcites) at the late stage. These fractures show as dark infilling images on well logs (Fig. 9a). Drilling cores may be broken if fracture density is high (Fig. 9b). Low-angle structural fractures run nearly parallel to small-dip bedding planes and may not be filled with cements at the late stage; but such fractures are mostly small in size and only several to dozens of centimeters in length.

Fractures usually coexist with faults. According to core and log data, fracture density increases with decreasing fracture-fault distance in the Xujiahe Formation (Lai J et al., 2017). As per oil testing, large porosity (>9%) and large fractures are usually unfavorable for proximal tight gas accumulation and preservation in the Xujiahe Formation; there are risks of producing water. On the contrary, the wells close to the faults inside the Xujiahe Formation may be drilled with more fractures and higher-graded reservoirs, and there are almost no water production risks. Most reservoirs in the Xu4 Member in the area are porous reservoirs, but high production tends to be obtained from fractured-porous reservoirs because tectogenetic microcracks could penetrate rock particles and connect pores to form map fractures, which will be converted into map-dissolved fractures by corrosion (Fig. 9c, d). Fault-associated fractures significantly improved petroleum deliverability. According to the study, fractures have a few impact on porosity and a great impact on permeability, which may be improved by 10 and even more times (Fig. 3).

5.2. Effects of reservoir quality on gas deliverability

Gas deliverability from the Xujiahe Formation is related to reservoir quality (Li Y et al., 2019), which is dominated by

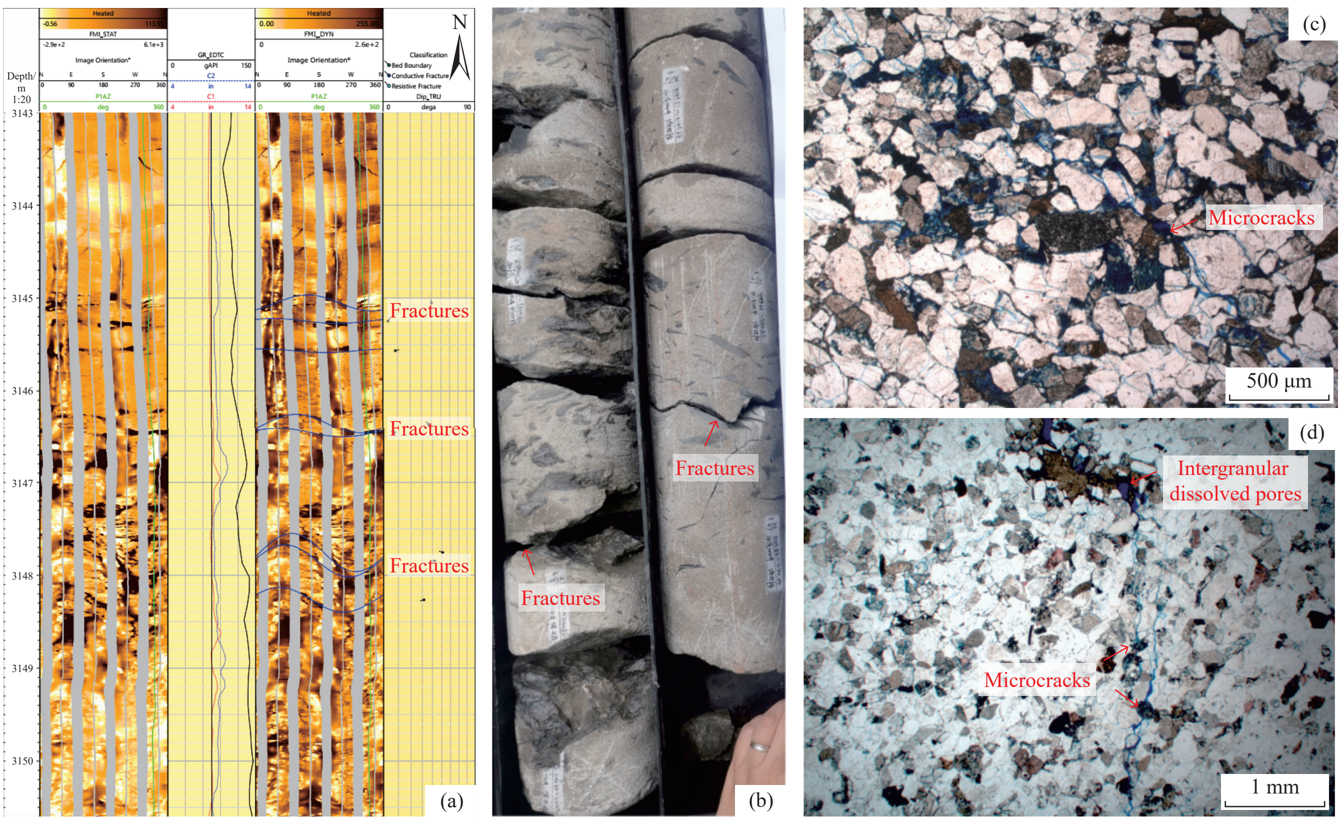

Fig. 9. Macroscopic and microscopic features of fractures in Jianyang Block. a–electric imaging of the Xu4 Member at Well YQ104, developed dark net-shaped semi-filled fractures, 3143–4151 m; b–cores with fractures from Well YQ104, 3143.51–3144.75 m (cores repositioned by +2 m); c–medium- to fine-grained feldspar lithic sandstones, with intergranular dissolved pores, intragranular dissolved pores, and map dissolved fractures, φ=6.04%, 3135.4 m, YQ104; d–Medium- to fine-grained feldspar lithic sandstones with microcracks, φ=5.68%, 3145.5 m, YQ104.

diagenetic intensity and fractures.

Porosity is a key parameter to characterize reservoir quality. All the wells with economic gas production from the Xu4 Member in the Jianyang Block show porosity >6%, indicating good reservoir quality. According to microscopic observation of cast thin sections, reservoir space at gas wells is mainly composed of intergranular dissolved pores and intragranular dissolved pores which went through intense corrosion. Fracture density is relatively large at the wells with high production (Fig. 9b), and microscopic images show map fracture–cavity system connected by microcracks (Fig. 9c, d). In the context of similar reservoir thickness and porosity, gas production is usually low at wells with no fractures, such as YQ7 (Fig. 10); this means that natural fractures are the dominant control of gas production.

The occurrence of natural fractures is closely related to faults, flexures, and low-relief structures, and a common practice is locating fractures at 1.5 km away from a fault. The extrusion stress field caused by the Longmenshan Mountains gave rise to reverse faults extending in a northeast direction in the Jianyang Block. In terms of penetration, reverse faults are classified into 4 orders (Fig. 11). The first-, second- and third-order faults, which are large in size, usually penetrate the whole Xujiahe Formation and may be connected with water zones. For example, the first- and second-order faults at Well PQ2 penetrate the Permian and Triassic formations, and the interval of Xu5–Xu6 was tested to produce water of 22.13 m^3/d. A third-order fault at Well YQ205 penetrates the Leikoupo Formation, and lower Xu3 was tested to produce water of 250 m^3/d. In contrast, the fourth-order faults are internal faults inside the Xujiahe Formation and most developed in the Jianyang Block. The wells with economic gas flow and no water output were mostly drilled close to the fourth-order faults. For example, Well YQ1 penetrating a fourth-order fault obtained gas yield of 312.6×10^3 m^3/d from the Xu4 Member in the testing (Fig. 11).

6. Conclusions

(i) The Xu4 sandstone reservoirs in the Jianyang Block of Tianfu gas field are generally at the mesogenetic-B stage nowadays. Tight reservoir properties are mainly attributed to calcareous cementation and compaction. Potash feldspar and debris corrosion gave birth to secondary pores, which improved sandstone reservoir quality.

(ii) Tight Xu4 sandstone reservoir properties were initially dominated by sedimentary environments and then by intense diageneses and tectonic movements. High-energy hydrodynamic conditions in the microfacies of underwater distributary channel and mouth bar are beneficial to porosity preservation and occurrence of secondary pores. High-graded reservoirs were generally reworked by corrosion, and structural fractures connect isolated pore space in tight sandstones to significantly improve reservoir permeability.

(iii) Tight sandstone reservoir properties are the prerequisite to gas deliverability. Gas production is usually low at the wells with no fractures. The wells in the Jianyang Block drilled close to the fourth-order faults mostly obtained high gas production from the Xu4 Member, whereas the wells deployed around larger faults risk water production.

CRediT authorship contribution statement

Zhi-min Jin, Ji-rong Xie, Zheng-lin Cao, Yu-chao Qiu conceived of the presented idea. Chao Zheng, Liang-biao Lin, Yu Yu carried out the experiment. All authors discussed the results and contributed to the final manuscript.

Declaration of competing interest

The authors declare no conflicts of interest.

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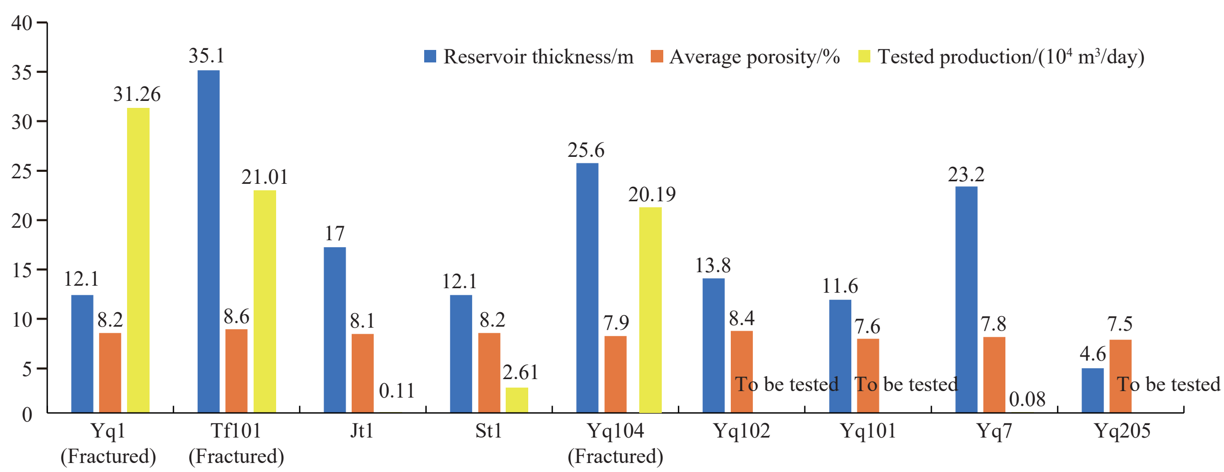

Fig. 10. Deliverability, average porosity, and reservoir thickness histogram for Jianyang Block.

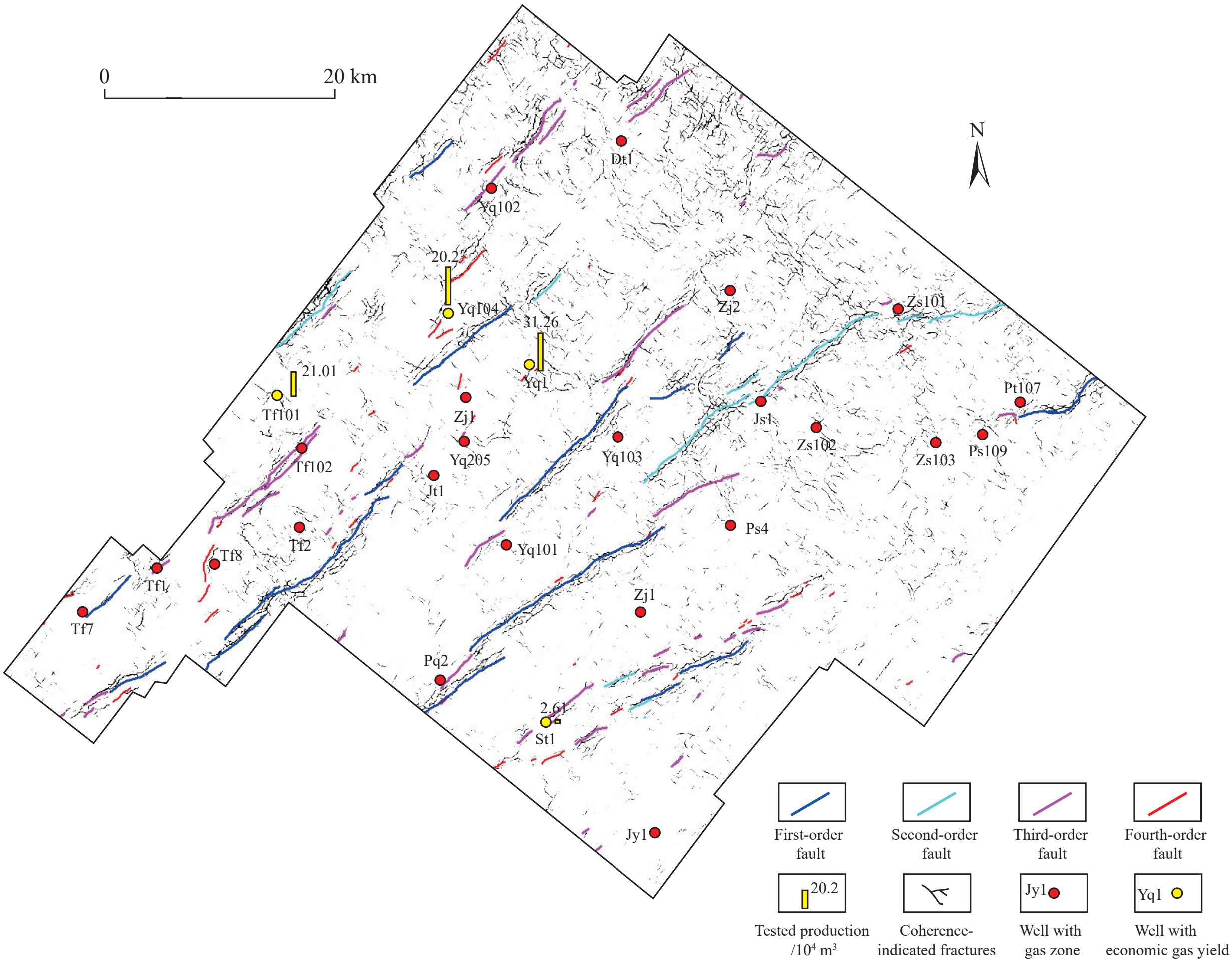

Fig. 11. Coherence map of multi-order faults in Jianyang Block.

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