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ORIGINAL ARTICLE

Impact of depositional environment and diagenesis on the Upper Triassic Xujiahe tight-sand reservoir in Guang'an area, Central Sichuan Basin, SW China

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Abstract The Upper Triassic Xujiahe tight-sand reservoir is characterized by low porosity and ultra-low permeability as well as intense heterogeneity. Investigation on depositional facies and their impact on reservoir quality has been proven to be a powerful tool to predict high-quality reservoirs. This study attempted to explain impacts of depositional environment and diagenesis on Xujiahe tight-sand reservoir quality in Guang'an area by: (1) identifying petrofacies and wireline logs patterns and analyzing the spatial variation of sedimentary facies, (2) determining diagenesis through detrital components, rock properties and their spatially variation as well. The results suggest that (1) T_3x^2, T_3x^4 and T_3x^6 were mainly deposited in delta system, including braided river in delta plain, delta distributary channels, underwater distributary channel, and mouth bar, etc., (2) the Upper Triassic Xujiahe Formation in the Guang'an area is typical tight-sand reservoir with porosity of 0.68–15.94% and permeability of 0.001–274 mD. Poor reservoir quality is attributed to intense compaction and dissolution during middle diagenetic stage A2, which are dominated by feldspathic litharenite and lithic sandstone. (3) Potential high-quality reservoirs in T_3x^2, T_3x^4 and T_3x^6 are associated with delta plain distributary channel, delta front underwater distributary channel and mouth bar, since high-energy delta channel microfacies typically resulted in a large number of primary pores in sand body. Considerable secondary pores were resulted from organic acid derived from source rocks during middle diagenetic stage, improving reservoir quality significantly.

Keywords Sedimentary facies · Diagenesis · Reservoir quality · Upper Triassic · Xujiahe formation · Sichuan basin

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Introduction

As increasing demand for natural gas intensifies, identifying and producing reserves from tight-sand gas reservoirs have gained considerable exploration interest and activities (Higgs et al. 2007; Zou et al. 2012). Currently, the Upper Triassic Xujiahe Formation in the Sichuan Basin, with proven gas reserves of more than 1000×10^8 m^3, has been regarded as an important target for tight-sand gas exploration in China (Ma et al. 2010; Dai et al. 2014).

The reservoir quality of tight-sand reservoir has been reported in many previous studies. Higgs et al. (2007), Zou et al. (2012), Ozkan et al. (2011) proposed that tight gas reservoirs were typically characterized by poor petrophysical properties with strong heterogeneities as a function of initial sediment composition and subsequent diagenetic modification. Also, many studies have provided insight into the characteristics of mineralogical composition, porosity evolution, diagenetic history reconstruction, and diagenetic facies classification as well (Zou et al. 2009; Chen et al. 2012; Lai et al. 2014). For example, in terms of tight-sand reservoir in Sichuan basin, diagenetic reactions are sensitive to climate in an early diagenetic stage, which controls the flow of meteoric water and may result in a geochemically open system. However, sediments are geochemically closed and mass transport is also limited in

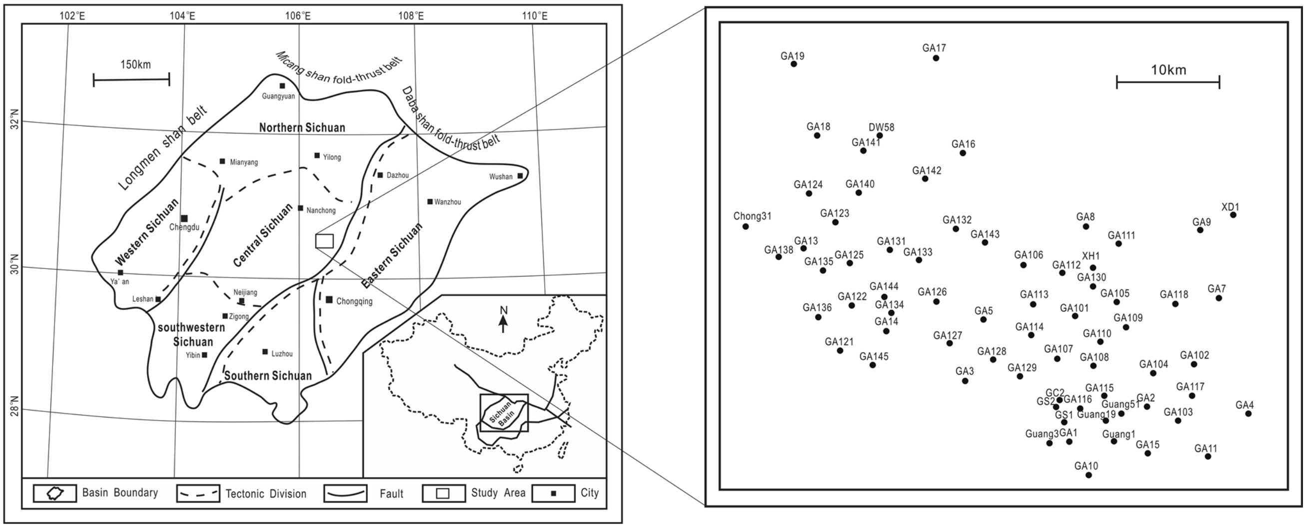

Fig. 1 The tectonic divisions of Sichuan basin and the wells location in Guang'an area

closed diagenetic environments, (Taylor et al. 2010; Bjørlykke and Jahren 2012). Also, sedimentation plays an important role in reservoir quality through determining original mineral composition of the sediments (Bjørlykke and Jahren 2012). Thus, sedimentation and diagenesis typically work together to determine reservoir quality through governing mineralogical composition, sand body thickness, reservoir scale, pore types, etc.

The Upper Triassic Xujiahe Formation in the Sichuan Basin generally has low porosity and ultra-low permeability, high water saturation and strong heterogeneity (Gao et al. 2005; Zhu et al. 2009; Li et al. 2010). However, many sedimentological descriptions of the Upper Triassic Xujiahe Formation are limited by mineral compositions, sedimentary facies of different scale. Thus, it is of great importance to systemically study the impact of sedimentation and diagenesis on tight-sand reservoir in Guang'an area (Zhu et al. 2008; Dai et al. 2011; Bjørlykke 2014) with a series of available data, including cores, thin section, mineral compositions, well log, etc. Firstly, we identified sedimentary facies symbol and wire logs patterns, and restored the spatial variation of sedimentary facies of the Upper Triassic Xujiahe formation. Secondary, diagenesis was determined with detrital components and rock properties. Finally, the impact of sedimentation and diagenesis on the Upper Triassic Xujiahe tight-sand reservoir was discussed based on analysis above.

Geological setting

Tectonic history

The Sichuan Basin in southwestern China, which cover an area of 180,000 km^2, is a rhomboid-shaped sedimentary basin on top of pre-Cambrian metamorphic rocks on the Yangtze platform. It is situated west of west Sichuan depression, central gently folded region, northern fold-and-thrust belt, east steep structures, southwest uplift, and a southern area with gentle folds (Xie et al. 2006; Dai et al. 2011; Li et al. 2014) (Fig. 1). Guang'an is located in the intersection of Huayingshan fold belt, Leshan–Longnusi paleo-uplift and Dabashan fold belt in northeast of central gently folded region, central Sichuan basin (Chen et al. 1994) (Fig. 1). As an integral part of the Sichuan Basin, Guang'an area experienced multiple tectonic movements, including Caledon, Hercynian, Indosinian, Yanshan and Himalayan tectonic movements.

Stratigraphy

Generally, the sedimentation can be subdivided into two main stages: (1) a succession of carbonate-dominated marine strata from the Sinian to the Middle-Lower Triassic; (2) sand- and shale-dominated continental strata from Upper Triassic to Tertiary (Qu et al. 2009a, b; Tao et al. 2014; Lai et al. 2015) (Fig. 2).

The Upper Triassic, a set of typical terrigenous coal-type deposits, is dominated by sandstones and mudstones and remarked by an unconformable contact with underlying Middle Triassic. In general, it can be divided into six members vertically from bottom to top (Deng et al. 2012). The first, third and fifth members (T_3x^1, T_3x^3 and T_3x^5) are regarded as main source rocks in Sichuan basin, which are dominated by black shale and mudstone with thin shaly siltstone, coal seam. The second, fourth and sixth members (T_3x^2, T_3x^4 and T_3x^6) are considered as typical tight-sand reservoirs, which consists mainly of gray fine–medium sandstone laminated by argillaceous siltstone, mudstone and coal line (Fig. 2). Thus, large

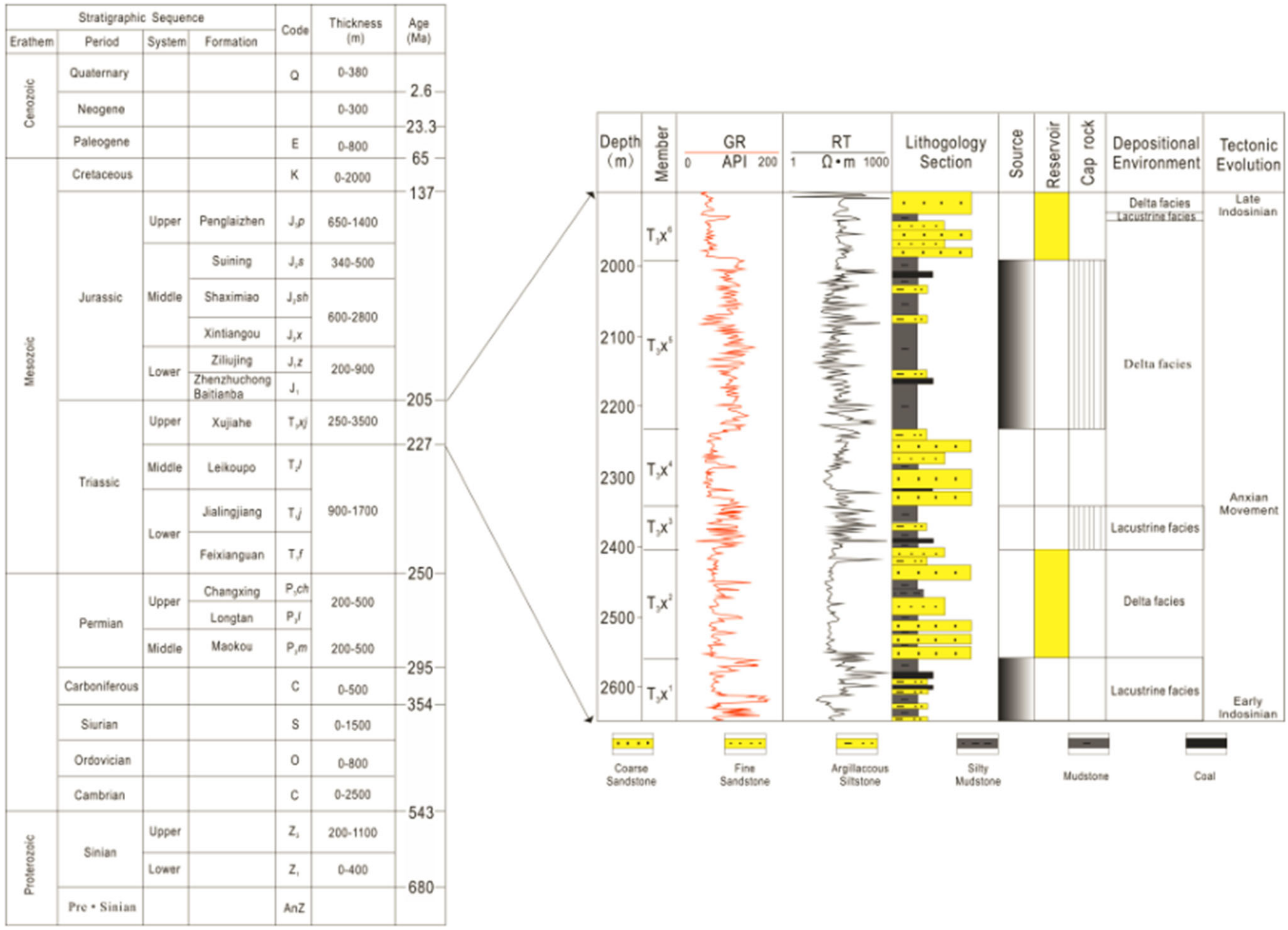

Fig. 2 Generalized stratigraphy of the central paleo-uplift in the Sichuan Basin

fluvial delta sand bodies and pervasive coal-type source rocks were superimposed vertically as a function of lake level fluctuating to form a favorable source-reservoir-seal assemblage in Guang'an area.

Methods

The general distribution of depositional environments associations in T_3x^2, T_3x^4 and T_3x^6 were identified based on (1) 125 cores from 22 wells (well locations in Fig. 1); (2) microfacies derived from log response from 69 wells (well locations in Fig. 1), which cover most parts of the study area. Detrital compositions (%) for all samples from T_3x^2, T_3x^4 and T_3x^6 are studied following classification scheme of siliciclastics from Pettijohn et al. (2012). Furthermore, diagenetic history was determined with detrital components, rock properties. Finally, we discussed the impact of depositional environment and diagenesis on the Upper Triassic Xujiahe tight-sand reservoir in Guang'an area based on the evidence mentioned above.

Sedimentary characteristics

Sedimentary facies symbol

The Xujiahe sandstone are commonly grey and light grey mudstone, and black shale and coal line, indicating humid climate and weak oxidation—reduction environment. Specifically, black mudstone contains considerable plant debris or fossilized stems under weak hydrodynamic conditions, such as flood plain, deltaic swamp plain, inter-distributary channel, etc. And black carbonaceous shale, coal line and coal seam are typically developed in swamp.

The primary sedimentary structures of Xujieha Formation in studying area, an indicator of the depositional environment and hydrodynamic conditions (Boggs 2006; Zahid et al. 2016), are dominated by bedding plane and bedding structure.

Scouring surface, mold on mudstone surface are primary bedding plane in studying area. Specifically, scouring surface associated with unexpected increase of

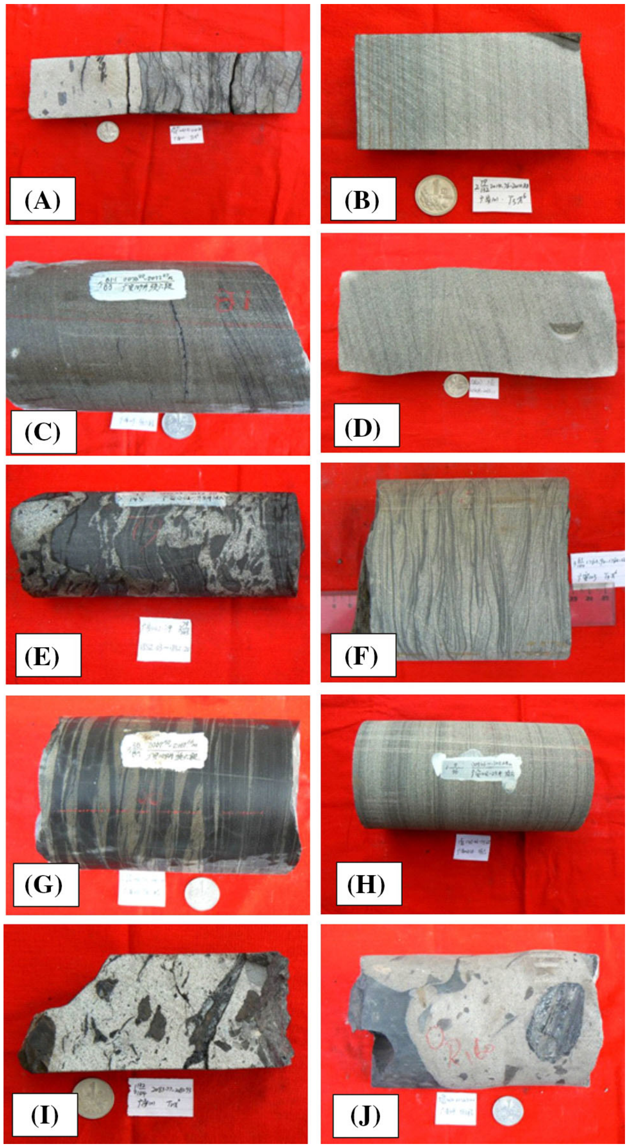

Fig. 3 Cores photographs showing sedimentary facies in Xujiahe Formation. **a** Guang'an 101 well, T_3x^6, 2062.59 m, *gray* fine-grained sandstone, irregular stripe rich in carbonized plant debris, a scour surface between it and upper standstone. **b** Guang'an 101 well, T_3x^6, 2014.88 m, *light-gray* siltstone–fine sandstones, parallel bedding, brown oxidized texture. **c** Guang'an 109 well, T_3x^6, 2077.27 m, *light-gray* fine sandstones, tabular cross bedding, parallel bedding. **d** Guang'an 107 well, T_3x^6, 2055.11 m, light-gray fine sandstones, wedge cross bedding. **e** Guang'an 002, T_3x^6, 1852.20 m, mud pebbles of different size. **f** Guang'an 103 well, T_3x^6, 1764.02 m, *gray* siltstone- fine sandstones, ripple bedding. **g** Guang'an 109 well, T_3x^6, 2067.66 m, thin interbed of *light-gray* argillaceous siltstone and black silty mudstone, wavy bedding with calcareous sand wave. **h** Guang'an 002 well, T_3x^6, 1705.65 m, *gray* siltstone, horizontal bedding. **i** Guang'an 101 well, T_3x^6, 2083.83 m, *light-gray*, *gray* pebbled fine sandstones, carbonized plant debris. **j** Guang'an 109 well, T_3x^6, 2070.35 m, *light-gray* pebbled sandstone, carbonized plant debris

hydrodynamic normally marks sharp contact (Fig. 3a), while rock above the surface is dominated by larger grain size or some mud pebbles from underlying block. Thus, scouring surface indicates deposition in channels with frequent alternation of hydrodynamic.

In general, parallel bedding, massive bedding, cross bedding, horizontal bedding, ripple bedding, etc., are commonly observed in Xujieha Formation.

Parallel bedding: coarse sandstone with parallel bedding are generally deposited in channels with shallow water (Boggs 2006). It is well developed in medium- and fine-grained sandstones with large thickness in the study area (Fig. 3b), reflecting a high-energy depositional environment (Li et al. 2014).

Cross bedding: an unit is characterized by oblique intersections (Boggs 2006). Wedge cross bedding and planar cross bedding can be observed in T_3x^6 in studying area with some local trough cross bedding (Zhang et al. 2016).

Tabular cross bedding: an unit resulted from the migration of ripple with flat and straight ridge, which mainly develops in high-energy environment, such as braided river delta, delta distributary channel, etc. It can be found in medium sandstone with a thickness of 30–40 cm (Fig. 3c).

Wedge cross bedding: an unit comprises of two groups or more intersected thin layers with low angle, while the lower group are commonly washed and cut by the upper one with frequent variation of water direction (Boggs 2006). It has been considered as the most remarkable signal of braided river delta deposition (Fig. 3d).

Massive bedding: an indicator of high-energy and repaid-depositing environment. It generally develops in medium-coarse sandstone (thickness over 1 m) with small proportions of mudstone in the study area. Normal graded bed sequence with medium-coarse sandstone can be identified in thick sand body, indicating a typical braided river delta deposit. And a large erosional basal surface occurs at bottom with considerable poor-sorted and poor-rounded mud pebble in grey medium-coarse sandstone. Different from that, mudstone conglomerate distributes locally in studying area. It is usually developed by bank failure or the break of original mudstone due to strong water erosion, which is regarded as syngeneic channel-lag deposit (Fig. 3e).

Ripple bedding: a small crossing bedding developing in siltstone with a thickness <3 cm (Boggs 2006). It is commonly formed by silty sediments under low-energy environment with continuous or discontinuous wave-shape (Fig. 3f).

Lenticular bedding: an unit commonly resulted from overbank deposits from flood plain, abandoned channel and crevasse splay. Banding bedding and lenticular bedding can be observed in studying area (Fig. 3g).

Horizontal bedding: an unit of suspended sediments depositing slowly in low-energy environment, such as sediments filling the upper parts of an abandoned channel under humid conditions, flood plain, swamp, etc. (Boggs 2006). It is primarily developed in silty mudstone and siltstone, which has no obvious scour in interbedded dark mudstone of the studying area (Fig. 3h).

In a summary, parallel bedding, massive bedding, cross bedding are typical indictors of high-energy depositional environments such as channel and delta plain/channel delta of the study area. Horizontal bedding and ripple bedding commonly suggest low-energy sedimentary environments such as flood plain and swamp, etc.

Also, evidence of abundant charcoal, some fossils, including plant stems and leave molds found in mudstone, suggests that the Xujiahe coal-bearing strata in the study area were deposited under humid conditions (Fig. 3i). Local enrichment of fossil plant formed coal line or coal seam, with incomplete-carbonized plant stems in sandstone (Fig. 3j).

Well-log patterns

Five classic gamma ray (GR) well-log patterns were identified in Upper Triassic deposits:

1. Bell-shaped GR curve in Fig. 4a reflects decreasing energy of depositional environment. The corresponding sediments are dominated by normal graded bedding with a sharp contact with overlaying mudstone and a gradual contact with upper mudstone. This pattern suggests a fining-upward cycle in channels.
2. Funnel-shape GR curve in Fig. 4b suggests a variation of deposition energy from week to strong. Deposits in this section are characterized by reverse graded bedding with a sharp contact at top and a gradual contact at bottom.
3. Finger-shape GR curve in Fig. 4c indicates a sedimentary environment of low energy with few sources. This section is dominated by fine sandstone and siltstone with sharp contacts at both top and bottom.
4. Box-shape GR curves in Fig. 4d illustrates abundant source supply and strong deposition energy. Jugged-box shape can be explained by the combination of multiple normal graded beddings and reverse graded beddings formed with frequent alternation of hydrodynamic. The deposits in corresponding section are characterized by sharp contacts both at top and bottom.

Depositional environments from wells

Depositional systems of T_3x^4 in Guang'an 101 well and T_3x^6 in Guang'an 102 well were identified based on well logs and cores (Hammer et al. 2010), which can be described as following.

The main sedimentary microfacies of T_3x^4 in Guang'an 101 well comprise braided channels in delta plain, delta distributary channels, underwater distributary channel, and mouth bar (Fig. 5a). The channel sand at bottom is interpreted as delta plain deposits with following evidences: (1) frequent incision of channels and erosion surface; (2) considerable gravel with some mud pebble and plant debris; (3) occurrence of massive beddings. The middle section is considered to be transitional sediments from delta plain

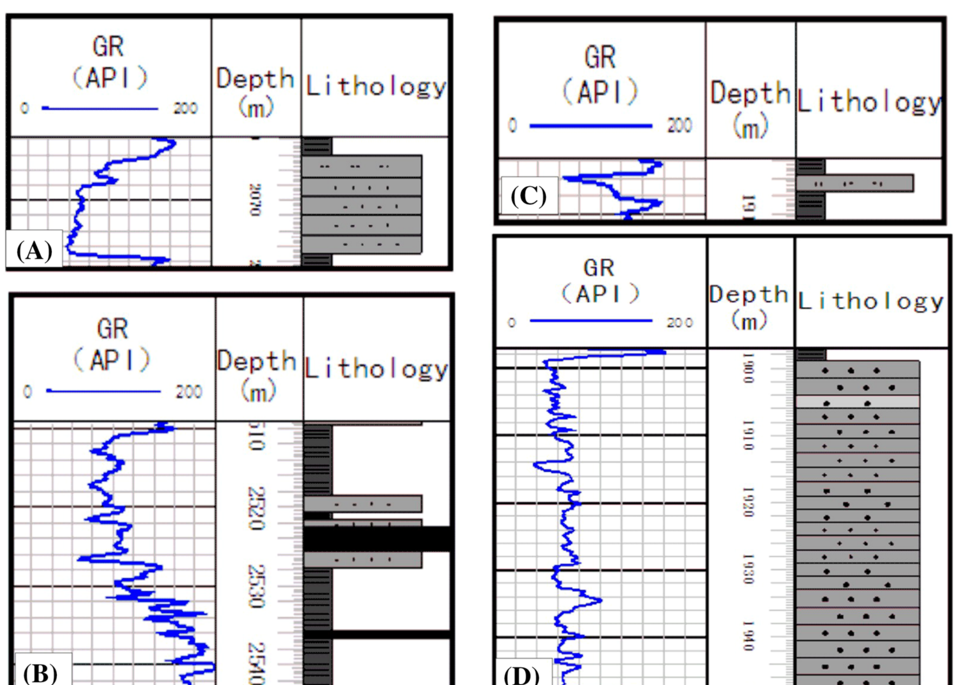

Fig. 4 Typical GR responses for the Upper Xujiahe sequence in the study area

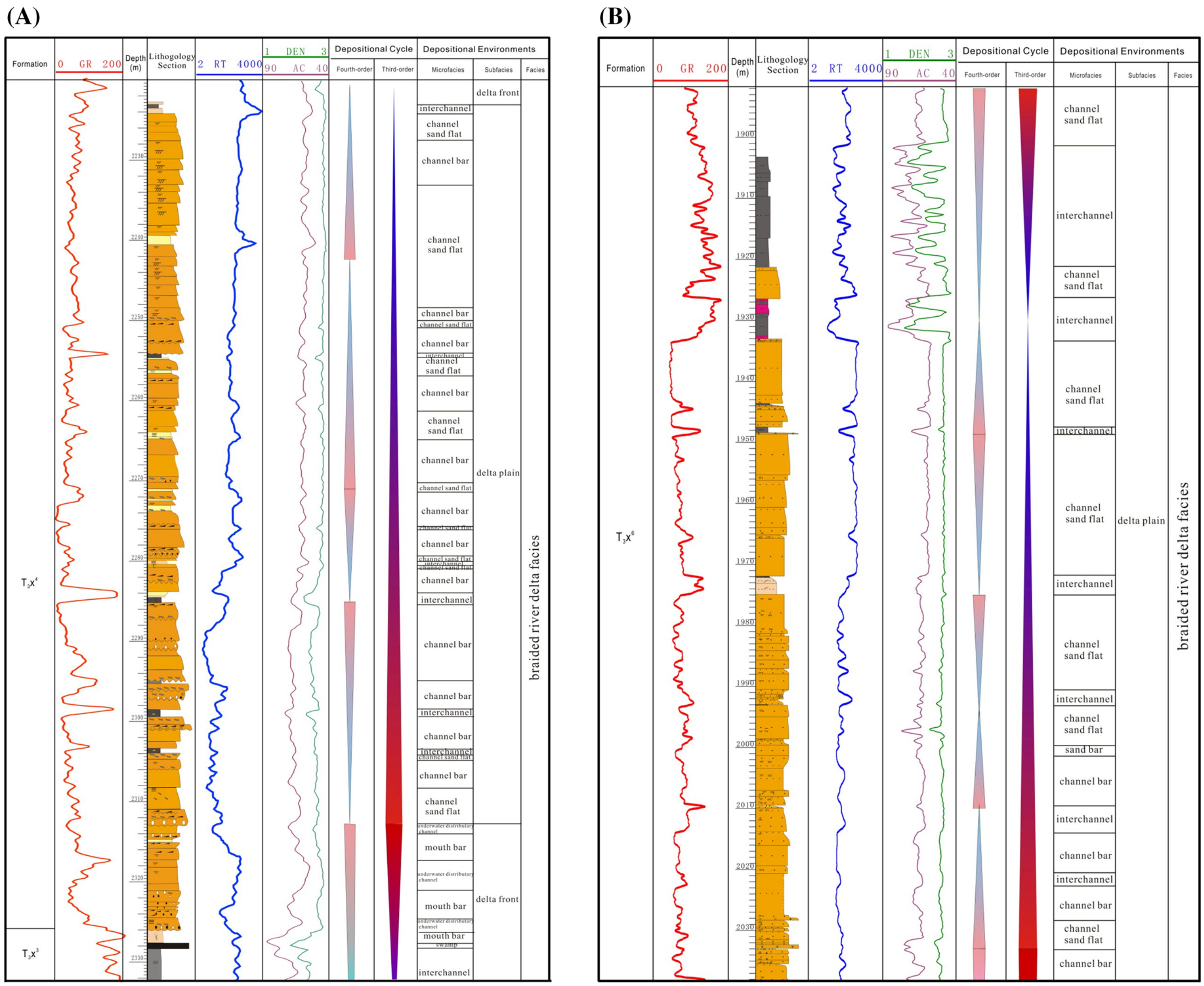

Fig. 5 Single well sequence stratigraphy and reservoir characteristics of T_3x^4 in Guang'an 101 well (**a**) and T_3x^6 in Guang'an 102 well (**b**)

to delta front, because of (1) frequent incision of channels; (2) lag deposit dominated by mud pebble and plant debris; (3) massive beddings with some cross beddings. The upper section is delta inner front deposit with well-developed parallel bedding and cross bedding. In general, the sand body was deposited by flood fast-filling to water transformation from bottom to top, which is characterized by bell- and box-shaped GR curve.

The T_3x^6 in Guang'an 102 well is a typical delta front and delta plain system, which can be subdivided into 3 sections (Fig. 5b). Specifically, the medium-coarse sandstones in lower section are channel bar and distributary channel deposits, inferred from (1) plant debris, mud pebble and chert, and (2) massive beddings, cross beddings and oblique bedding. The medium to fine-grained sandstone with cross bedding and parallel bedding in middle section are delta front distributary channel and mouth bar deposits. The interbed of dark gray mudstone, silty-fine sandstone and coal in upper section is deposited in delta outer front, while ripple cross lamination can be observed in silty sandstone.

Distribution of depositional environments

The main sedimentary microfacies of T_3x^2 in studying area are meandering channels in delta plain, inner front and outer front (Fig. 6a) with sediment sourced from the north and south. The sedimentary microfacies of T_3x^4 include delta outer front, delta plain and delta inner front (Fig. 6b), while microfacies of T_3x^6 are shallow lake-prodelta, delta plain with delta outer/inner front in studying area (Fig. 6c).

Previous studies suggested that the deposition and subsidence center during Xujiahe period was located in the western Sichuan, which gradually shifted to the north at later stage because of the subduction of Dabashan and Micangshan in the north and uplift and erosion event in the

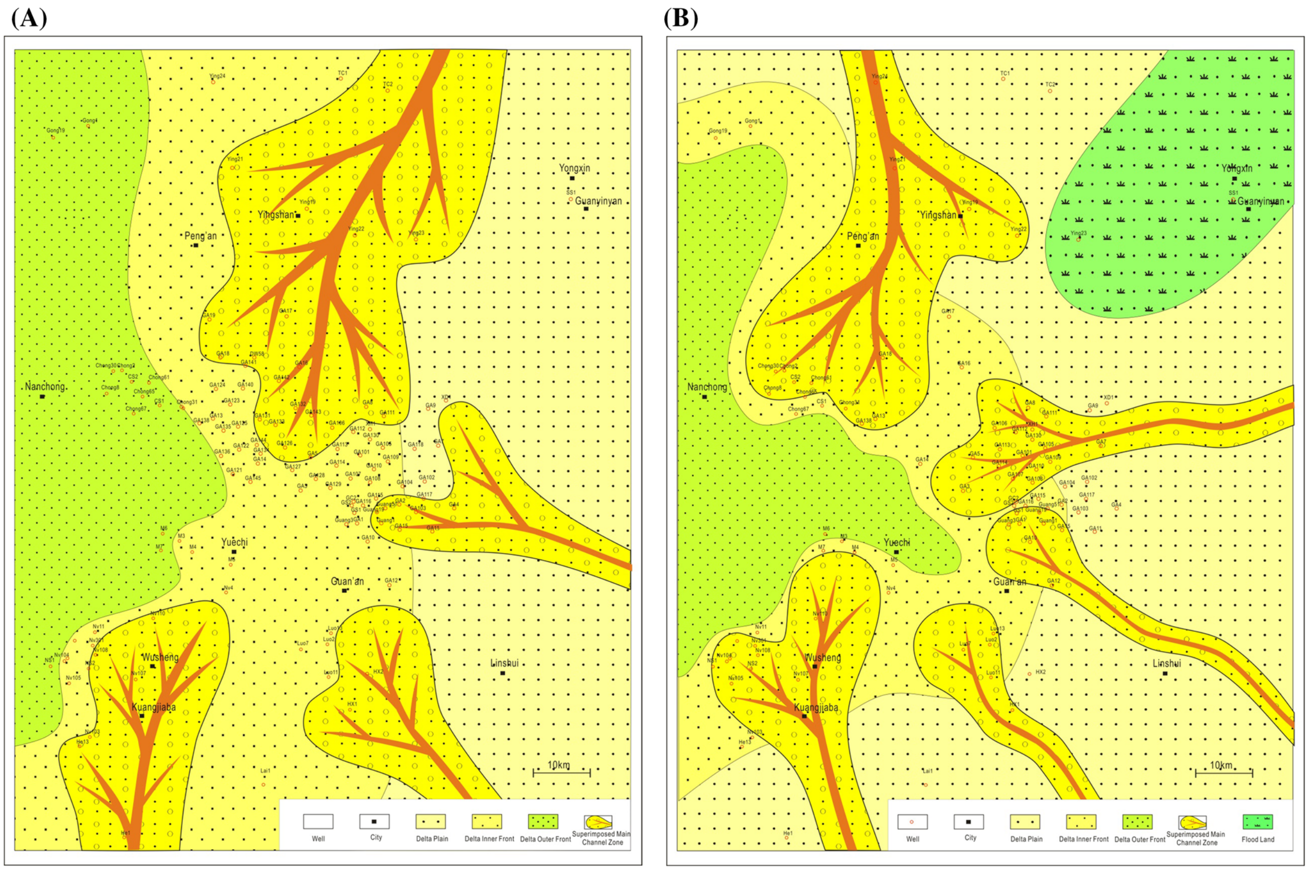

Fig. 6 Plain facies map showing depositional pattern during different periods. **a** T_3x^2, **b** T_3x^4 and **c** T_3x^6, respectively

west (Luo et al. 2013; Tao et al. 2014). However, being located in the stable Yangtze block, the central Sichuan was regarded as optical deposition location (Deng et al. 2012). During dry season, sufficient sediments due to intense structure movements formed large scale braided river delta system in shallow lake and swung to develop extensive sand body (Xie et al. 2006; Tao et al. 2014), which can be evidenced by depositional environments from wells analyzed above.

Digenetic evolution

Detrital components

The T_3x^2 sandstones are dominated by feldspathic litharenite. Specifically, the quartz concentration is relatively high with content ranging from 58 to 68%, and feldspars content ranges from 8 to 18%. Lithics content is averaged of 22.1% with a range of 18–28%.

The T_3x^4 sandstones are predominantly feldspar litharenite and litharenite. Quartz is also the most abundant detrital mineral, ranging from 37 to 73%. Feldspar content ranges from 25 to 45%, and lithic fragments content varies from 19 to 62.5%.

The T_3x^6 sandstones are rich in litharenite. Specifically, quartz content of T_3x^6 sandstones is about 24–64%, and lithic fragments content varies from 32 to 75.2%, whereas feldspar content is relatively low with a range of 0.5–11%.

Thus, the difference in detrital components in T_3x^2, T_3x^4, and T_3x^6 intervals indicates a significant variation of sedimentation and diagenesis in Xujiahe Formation (Fig. 7).

Porosity and permeability

As exhibited in Fig. 8a, over 96% of porosity in T_3x^2, T_3x^4 and T_3x^6 is less than 12%, with an averaged value of 4.73, 5.69 and 5.28%, respectively. On the other hand, samples with permeability <1 mD can be up to 95% (Fig. 8b), while permeability varies significantly among different members, e.g., the permeability range is 0.00003–5.89, 0.0001–21.6 and 0.00002–20.9 mD, respectively.

Displayed in Fig. 9 are the spatial variations of porosity in T_3x^2, T_3x^4 and T_3x^6 of Guang'an area. In general, porosity in T_3x^2 increases from the west from the east, with

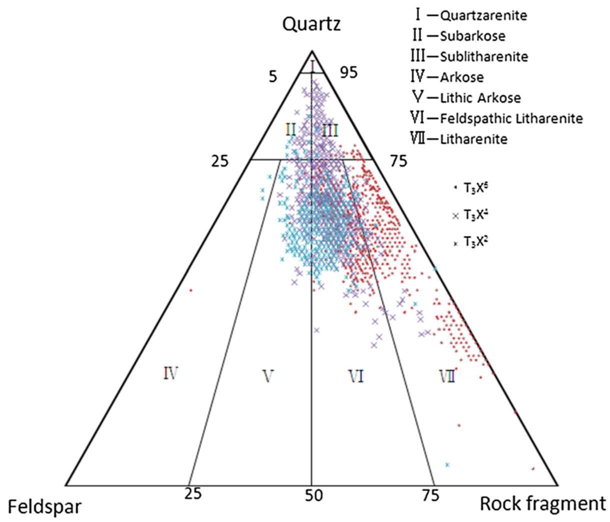

Fig. 7 Ternary diagram illustrating the composition of the Xujiahe sandstones in Guang'an area (According to Pettijohn et al. 2012)

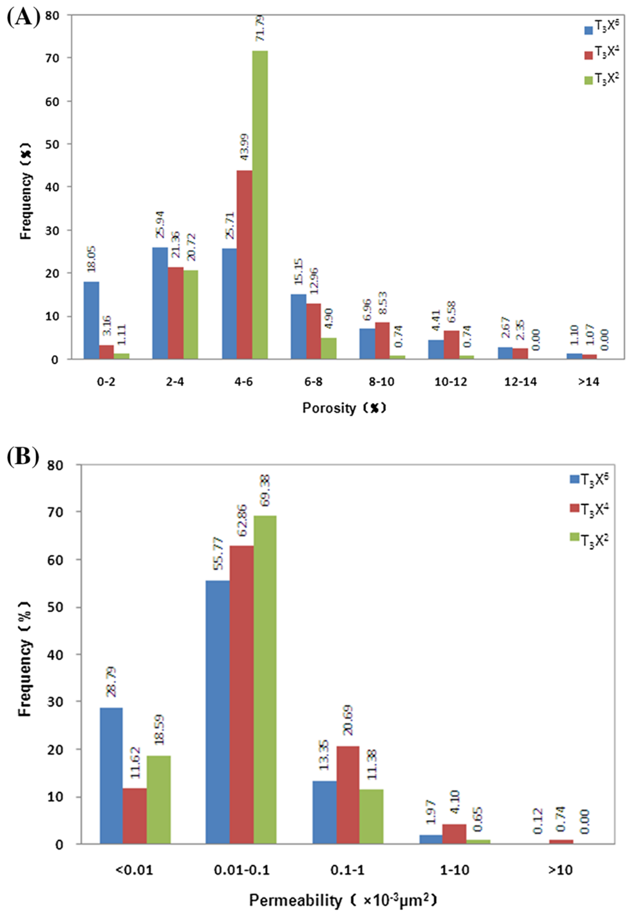

Fig. 8 Porosity (**a**) and permeability (**b**) of Xujiahe reservoir, Guang'an area

most value less than 12% (Fig. 9a). Different from T_3x^2, porosity of T_3x^4 varies from 8 to 12%, with mostly less than 10% in the central Guang'an (Fig. 9b). It is in a range of 9–13% in T_3x^6, which has a potential zone with porosity larger than 12% in Guang'an area (Fig. 9c).

Diagenesis

As shown in Fig. 10a, b, quartz overgrowth rims are commonly line- and concavo-convex contact, with broken mica and microstylolite contact between local soft particles. Thus, mechanical compaction can be considered as one of the most important diagenetic events in the study area. Cementation in the studying area is weak with interstitial material content of 5–6%, and primary cements are quartz overgrowth, authigenic quartz, and carbonate cement (Fig. 10c, d). In contrast, dissolution plays a significant role in constructive diagenesis process, with intergranular- and intragranular-dissolved pores in both edge and interior of feldspar and typical debris particles (Fig. 10e, f).

The average temperature of fluid inclusions in Xujiahe tight-sand reservoir is approximately 90–120 °C, with measured vitrinite reflectance (Ro) of 0.92–1.29% (Dai et al. 2011). According to the Chinese Oil and Gas Industry Standard—the division of diagenstic stages of clastic rocks (SY/T5477-2003), two diagenetic stages were identified in Xujiahe reservoir: early diagenetic stage and middle diagenetic stage.

Early diagenesis stage A: burial depth of reservoir in this stage is commonly less than 1000 m, corresponding temperature and vitrinite reflectance (Ro) less than 50 °C and 0.35%, respectively. Illite infilling and carbonate can be observed in intergranular pores, where is favorable to quartz overgrowth, pyrite, siderite, chlorite, etc. The primary porosity can decrease from 40% to 20–25% in this stage.

Early diagenesis stage B: burial depth in this stage is approximately 1000–2000 m, corresponding temperature between 50 and 80 °C. Most of the organic materials in source rocks are immature with vitrinite reflectance (Ro) typically less than 0.5%. The formation water in reservoir is alkaline or weak alkaline. With metasomatism and minerals transformation (such as transformation of biotite to chlorite) in this stage, the typical minerals are smectite and disordered mixed-layer minerals with small proportions of authigenic kaolinite and calcite. Furthermore, stage-II quartz overgrowth can be observed from Fig. 10d, while point-to-line contact and loss of considerable intergranular pores in Fig. 10d, e are indictor of intense mechanical compaction at early diagenetic stage, which may dramatically decrease primary porosity. Previous studies proposed that chlorite in Xujiehe tight-sand reservoir typically formed at this stage, corresponding temperature less than 60 °C, while the chlorite rim improved stress-resistant capacity of rock and inhibited quartz

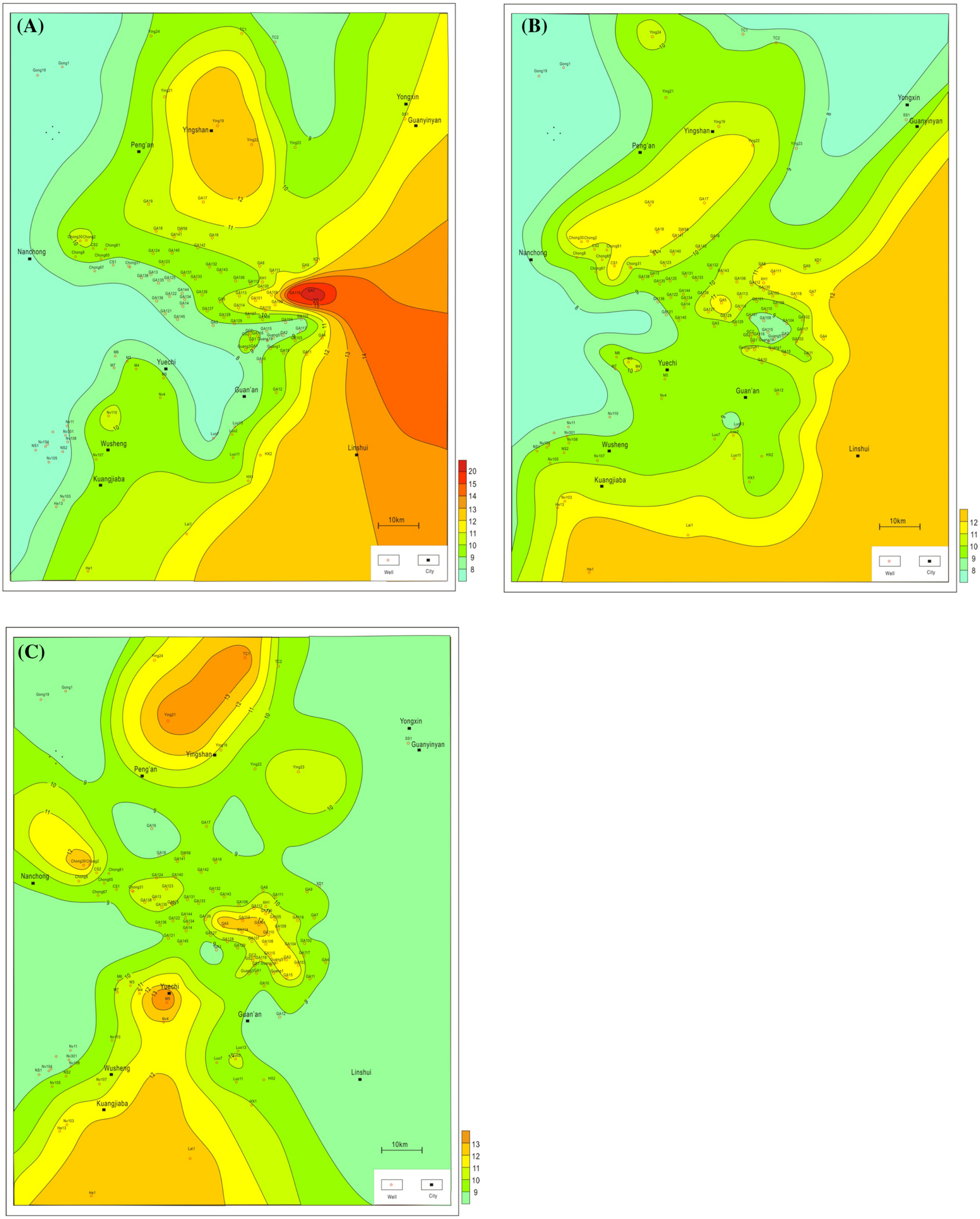

Fig. 9 Porosity distribution of the Xujiahe Formation showing the variation of reservoir quality in **a** T_3x^2, **b** T_3x^4 and **c** T_3x^6, respectively

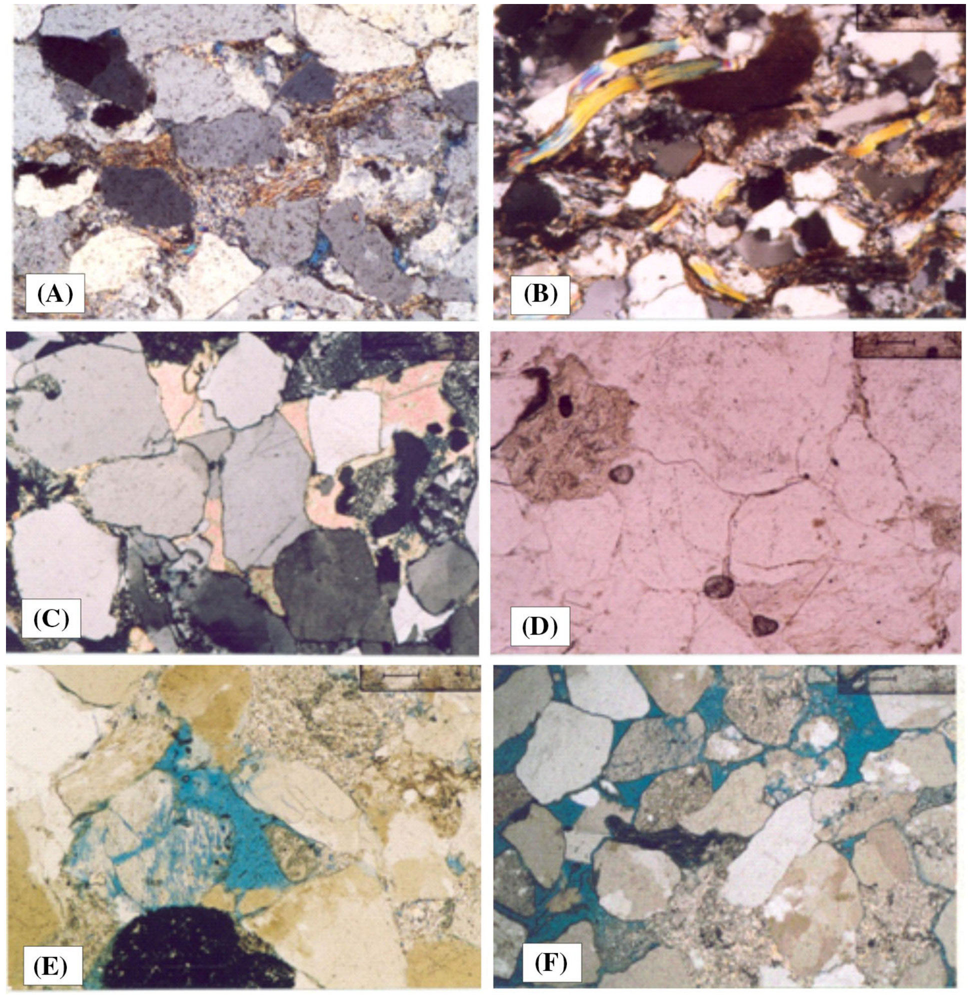

Fig. 10 Thin sections revealing distinctive diagenetic features in Upper Xujiahe reservoir (T_3x^6) in Guang'an 101 well. **a** 2055.3 m, false matrices caused by plastic debris deformation, lineal to concavo-convex grain contacts. **b** 2014.8 m, intensely deformed mica. **c** 2055.3 m, poikilitic cementation of calcite, lineal to concavo-convex grain contacts. **d** 2034.74 m, quartz secondary outgrowth rims. **e** 2034.74 m, intergranular-dissolved pores and intragranular dissolved pores, coarse sandstone with strong compaction. **f** 2080.1 m, point to lineal grain contacts, dissolved intergranular pores and residual intergranular pore

overgrowth, which can preserve primary pores (Xiao et al. 2010; Zhang et al. 2016).

Middle diagenetic stage A1: burial depth in this stage is commonly over 2000 m, with corresponding temperature and vitrinite reflectance (Ro) of 85–100 °C and 0.5–0.7%, respectively. Co_2 and organic acids derived from kerogen decarboxylation result in acidic environment. Pyrite can be generated as a function of hysterogenic reduction in this stage, with increasing illite and I/M mixed-layer minerals content and decreasing chlorite content. Also, stage-II quartz overgrowth is widespread with authigenic quartz growing toward pores; meanwhile, metasomatism and recrystallization occur with dissolution of calcite cement. As a result, dissolution pores, such as intragranular pores, intergranular pores and moldic pores, are well developed in this stage, contributing 5–6% of secondary porosity (Surdam et al. 1989).

Middle diagenetic stage A2: burial depth in this stage is about 2500–4000, corresponding temperature and vitrinite reflectance (Ro) of 100–150 °C and 0.7–1.5%, respectively. Stage-III quartz overgrowth occurs with grain mosaic- or concavo-convex contact because of the depletion of organic acid. The further compaction and cementation decrease porosity significantly, remaining only 6–8% porosity. However, porosity could be in a range of 8–10% because of the growth of intragranular pore and intergranular pore.

Based on these analyses, the porosity evolution was generally restored, with reservoir being tight (porosity less than 12%) at middle diagenetic stage A1. Currently, the Xujiahe reservoir is in the middle diagenetic stage A2 (Fig. 11).

Impact of depositional environment and diagenesis on reservoir quality

As exhibited in Fig. 12a, b, the reservoir zone which developed in delta plain distributary channel, delta front underwater distributary channel and mouth bar are

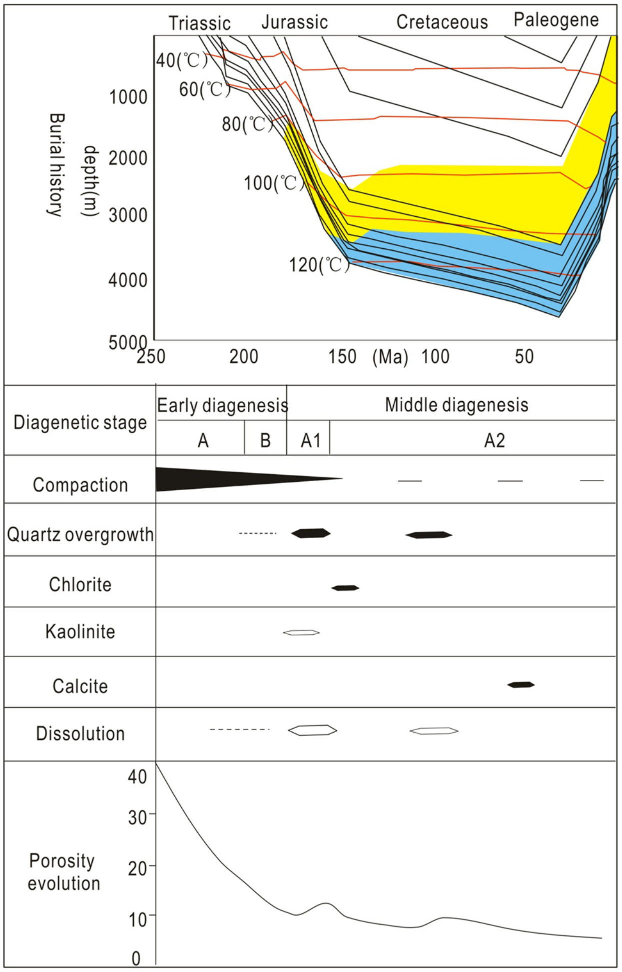

Fig. 11 Paragenetic sequence of the main diagenetic features observed in Xujiahe sandstones

characterized by a relatively high porosity and permeability, e.g., the porosity and permeability ranges between 6 and 12% and 0.5 mD, respectively. In contrast, the quality of pay zones which deposited in the distal bar, sand sheet and mixed flat is poor with porosity and permeability less than 6% and 0.05 mD, respectively, e.g., porosity of sheet sands is about 3–8%. Therefore, high reservoir quality in Xujiahe Formation is associated with delta plain distributary channel, delta front underwater distributary channel and mouth bar. Also, comparison of porosities from different samples exhibits a relatively high porosity in medium-coarse sandstone (8.66%) and relatively low porosity in fine-grained sandstone (less than 5%) (Fig. 12c). This can be explained by strong hydrodynamic conditions in the delta plain distributary channels superimposed in delta. Main channels can result in mid-fine-grained sandstone with good sorting and high compositional maturity and textural maturity, which can protect primary porosity from intense compaction in later stage (Zhang et al. 2016).

Also, previous studies from Zhang et al. (2016) suggested that sedimentary facies of Xujiahe formation was of great importance to reservoir quality, because litharenite and feldspathic litharenite in Upper Triassic Xujiahe tight-sand reservoir, especially T_3x^2 and T_3x^4 sandstones, had potential to act as effective hydrocarbon reservoir. Digenetic history analysis indicates that anomalously low porosity in Xujiahe sandstones is attributed to the high compaction, quartz overgrowth. Zhang et al. (2016) held that pore volumes in Xujiahe sandstones in Sichuan Basin were significantly decreased due to high matrix content and rock fragments, especially carbonate rock fragments and their compaction and cementation. However, the intensity compression- and pre-solution-resistance capacity of coarse particles preserves a large amount of primary pores and allows acidic fluids to enter reservoir and dissolve unstable particles and cement, resulting in a large amount of secondary pores. In general, organic acid generated by T_3x^1, T_3x^3 and T_3x^5 source rocks at early diagenesis stage A in Chuanzhong area migrated upward to corresponding reservoir in T_3x^2, T_3x^4 and T_3x^6 (Dai et al. 2007; Tao et al. 2014). High-energy sand body deposited in delta distributary channel and fractures acted as significantly migration paths (Liu et al. 2014). The dissolution of feldspar and debris in intergranular pores generates considerable secondary pores in reservoirs and improves reservoir quality (Taylor 1978).

Conclusions

1. Delta-dominated sedimentary systems are identified in T_3x^2, T_3x^4 and T_3x^6 with multiple microfacies, including braided rivers in delta plain, delta distributary channels, underwater distributary channel and mouth bar, etc.
2. The Upper Triassic Xujiahe Formation is a typical tight-sand reservoir with low porosity and permeability. Porosity in Xujiahe tight-sand reservoir ranges from 0.68 to 15.94%, while permeability is in a range of 0.001–274 mD. It is dominated by feldspathic litharenite and lithic sandstone in the middle diagenetic stage A2.
3. Potential high-quality reservoirs in Xujiahe Formation mainly distribute in the middle-lower section of T_3x^2, T_3x^4 and T_3x^6, which are associated with delta plain distributary channel, delta front underwater distributary channel and mouth bar. Also, dissolution due to organic acid during middle diagenetic stage developed considerable secondary pores, contributing greatly to the high-quality reservoir.

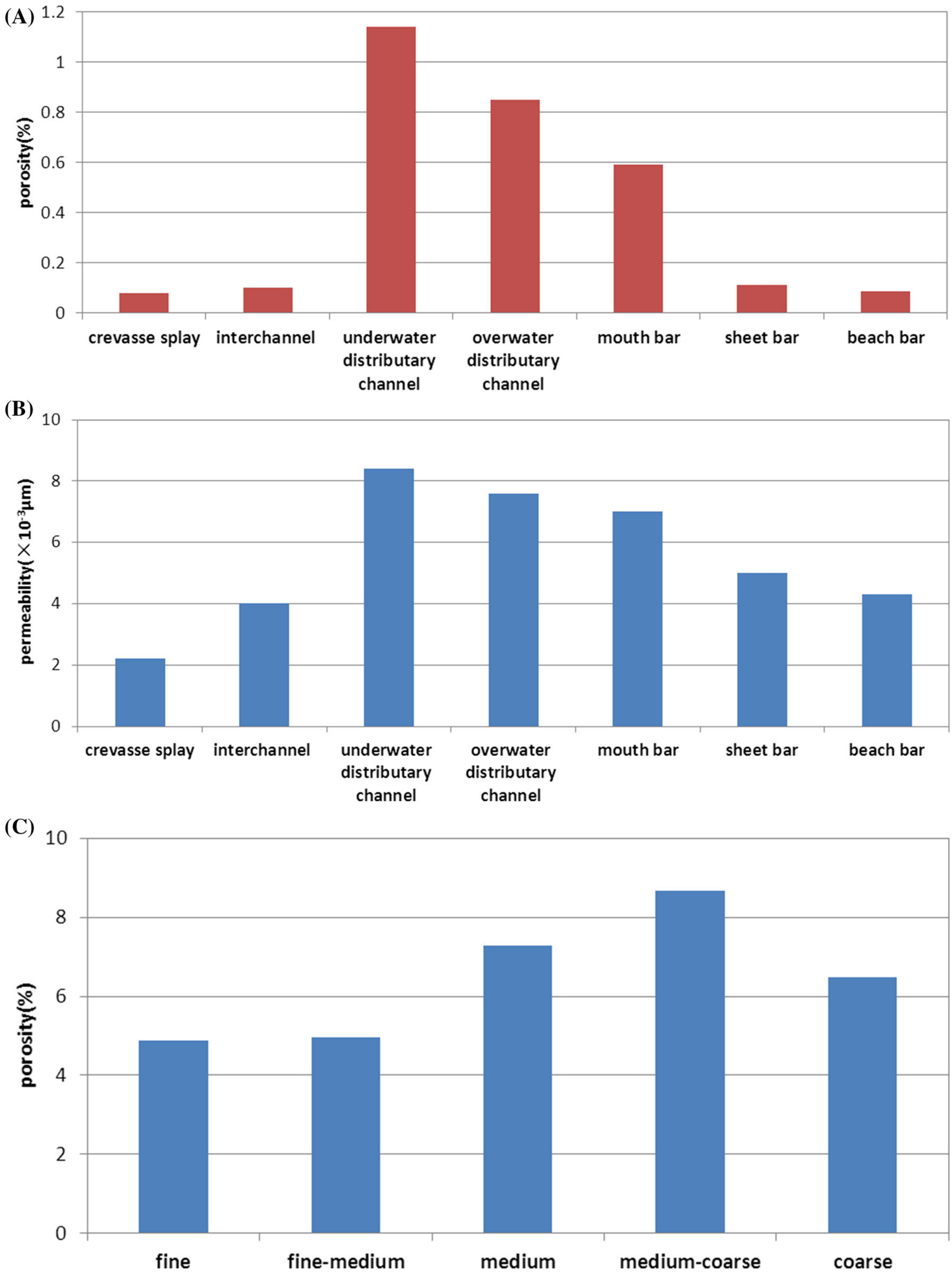

Fig. 12 Cross plot of rock properties and sedimentation. Porosity (**a**) and permeability (**b**) vs micro-facies, and porosity vs particle size (**c**)

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