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Journal of Natural Gas Geoscience 1 (2016) 335–352

http://www.keaipublishing.com/jnggs

Original research paper

Coupling relationship between reservoir diagenesis and gas accumulation in Xujiahe Formation of Yuanba–Tongnanba area, Sichuan Basin, China☆

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Received 15 September 2016; revised 12 October 2016
Available online 10 November 2016

Abstract

The relationship between reservoir tightening time and gas charge period are the key subjects that have not been well solved considering the studies on the tight sand gas accumulation mechanism and enrichment regularity. The diagenetic evolution history, interaction sequence of organic–inorganic in aquiferous rock, gas charge history, the tightening mechanism of tight sandstone reservoir and the relationship between reservoir tightening time and gas accumulation period of the Xujiahe Formation have been analyzed in the Yuanba–Tongnanba area of the Sichuan Basin. It has been confirmed that the main reason for the tight sandstone reservoir formation is the intensive mechanical compaction which has dramatically reduced the sandstone reservoir quality, and it resulted to a semi-closed to a closed diagenetic fluid system formation at the early diagenetic stage. In the semi-closed to a closed diagenetic fluid system, at the later part of the diagenetic stage, the fluid circulation is not smooth, and the migration of the dissolution products are blocked, hence, the dissolution products mainly undergo the in situ precipitation and cementation. Such dissolution products block the dissolution pores and the residual primary pores; and the stronger the dissolution is, the higher the cement content is, which makes the reservoir further tightened. The hydrocarbon generation and expulsion history of source rocks and reservoir fluid inclusion characteristics in the Xujiahe Formation show that the charge of natural gas occurs in the Middle Jurassic–Early Cretaceous (mainly Early Cretaceous). A comprehensive analysis of the reservoir tightening history, gas charge history, and interaction sequence of organic–inorganic aquiferous in rock indicate that the sandstone reservoir experienced a tightening process when gas charging took place in the Xujiahe Formation in the Yuanba–Tongnanba area of the Sichuan Basin.

Keywords: Xujiahe Formation; Diagenesis; Tighting process; Charge history; Coupling relationship between diagenesis and accumulation; Yuanba–Tongnanba area of Sichuan Basin

1. Introduction

In reality, tight sandstone gas is a relative concept, and there are different definitions from different scholars and research institutes. It is usually defined as the gas produced from reservoirs with formation permeability that is less than 0.1 mD as well as a porosity that is less than 10%. In the recent years, it has been difficult to make a major breakthrough in conventional gas exploration, and the global tight sandstone gas reserves and production have continued to grow, thus, the

☆ This is English translational work of an article originally published in *Natural Gas Geoscience* (in Chinese).The original article can be found at:10.11764/j.issn.1672-1926.2016.07.1164.

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Peer review under responsibility of Editorial office of *Journal of Natural Gas Geoscience*.

http://dx.doi.org/10.1016/j.jnggs.2016.11.003

exploration progressed and the accumulation studies on tight sandstone gas has captured the extensive attention and financial support of all sectors of society such as the government departments, academic circles, and oilfield company. Nevertheless, the understanding of the relationship between the tight period of sandstone gas reservoir and gas accumulation period, accumulation mode and enrichment regularity remains controversial. Most scholars believe that the preferential formation of tight sandstone reservoir is the precondition for the formation of tight sandstone gas, thus, the gas cannot overcome the up dip of the migration direction of capillary pressure by only depending on the buoyancy force. The residual pressure difference of source reservoir is the main driving force for gas migration [1–5], "water resistance effect" [1], "dynamic occlusion" [6], diagenetic sealing [7], etc. are its main sealing mechanism. Based on these, three theories are proposed, namely, the deep basin gas/basin-centered gas theory of tight sand gas reservoir [1,5,8], continuous gas reservoir theory [9,10], and quasi-continuous gas reservoir theory [11–13].

However, in the past 10 years, along with the increase of exploration and development degree of tight sand gas, some scholars proposed that the gas reservoir is a deep basin gas or basin-centered gas only to find out that it's not true. In reality, they are conventional gas reservoirs similar to the Greater Green River Basin in the Rocky Mountains [14] and San Juan Basin [15], where both of the unconventional gas accumulations like the basin-centered gas and the conventionally trapped gas accumulation exist in most of the basins in the Rocky Mountains [16]. Recently, Cant [17] pointed that two classic "basin-centered gas" production zones (Falher Member and Cadomin conglomerate) featured the characteristics of a conventional trap, with their gas zones and water zones were separated. All of the basin-centered gas accumulation, including many basins in the USA such as the Uinta-Piceance Basin and San Juan Basin of Northwest of Wyoming, are categorized as conventional trap type. For the tight sandstone gas of conventional trap, it is possible that the reservoir compaction occurs before, concurrently with, or after the gas accumulation. Actually, it is more important that the gas accumulation occurs before the reservoir compaction if the conventional gas accumulation of through gas–water separation with a clear gas accumulation boundary, distinct gas–water contact, and evident edge and bottom water forms [13,14,18].

As one of the richest basins in a tight sand gas resource of China, the Sichuan Basin also has the controversial problem of understanding its own gas model, specifically, the gas is the deep basin gas or the conventional tight gas [19–25]. Some scholars once thought that the gas reservoir in the Triassic Xujiahe Formation in the Western Sichuan Depression was a deep basin gas [19]. Meanwhile, Ye [20,21], Yang et al. [22,23], and Chen [24] thought that the gas in the Xujiahe Formation in this depression was a conventional gas reservoir rather than a deep basin gas. In the Yuanba–Tongnanba area of the Sichuan Basin, there is a new block by Sinopec that explores tight sand gas in the latest years. There are numerous works on the origin and source rock of gas and gas enrichment regularity [26–28], but the relationship between the reservoir tightening time and gas charge period has not been well determined. The tight sand gasses formed by different diagenetic-accumulation relationships have significant differences in the accumulation mechanism and enrichment regularity, hence, the reservoir tightening mechanism, tight period, and its relationship with the gas charge period directly relate to further exploration deployment and decision. This study aims to perform a systematic study on the coupling relationship between the tightening process of a tight sand reservoir and gas accumulation by the charge in the Xujiahe Formation through the analysis of the diagenetic evolution of tight sandstone reservoir and gas charge history in the Xujiahe Formation within the Northeast Sichuan Basin. Therefore, a great foundation can be laid to understand the gas accumulation process, main factors controlling gas accumulation, and provide a basis for the next exploration deployment.

2. Geological setting

The Yuanba–Tongnanba area is located in the northeast of the Sichuan Basin and is surrounded by the Micangshan uplift as well as the Dabashan fold belt (Fig. 1). The Yuanba area presented itself as a rolling fold belt, the Tongnanba area as the NE-NEE anticlinal zone, and the thrust fault belt for the intensive tectonic compression by the Micangshan uplift, Dabashan fold belt, and Longmenshan fold belt. The evolution history of the peripheral orogenic belt of the Sichuan Basin indicated that the tectonic deformation in the Yuanba–Tongnanba area occurred at the beginning of the middle–late Jurassic, and it ended with the Himalayan orogenic movement [29–31].

The oil–gas exploration blocks in the area are mainly Sinopec's Yuanba Block and Tongnanba Block. The main oil–gas–bearing layer systems include carbonating gas-bearing layer system of the Upper Permian (P_2c)-Lower Triassic Feihsienkuan Formation (T_1f) and the tight sand gas-bearing layer system is predominated by the Upper Triassic Xujiahe Formation (T_3x). The Upper Triassic Xujiahe Formation is a set of continental sedimentation bearing coal clastic rock, and it is divided from top-down into six lithologic members: the 1st member (T_3x^1) up to the 6th member (T_3x^6) of the Xujiahe Formation. The 2nd member of the Xujiahe Formation is divided into the upper sub-member and lower sub-member via a sandstone member (Yaodaizi Mudstone) commonly developed in the middle part of the formation, and the 6th member of the Xujiahe Formation is generally absent (Fig. 2). In the area, the two gas fields of the Yuanba and Tongnanba Gas Field are currently discovered in the Xujiahe Formation. In the principal producing formation of the 2nd and 4th member of the Xujiahe Formation, the porosity is less than 10%, permeability is less than 0.1 mD, and the natural production capacity is very low when fracture acidizing did not take place, therefore, the gas belongs to the typical tight sand gas.

As for the tight sandstone gas bearing layer system in the Xujiahe Formation, Sichuan Basin, the 1st, 3rd, and 5th

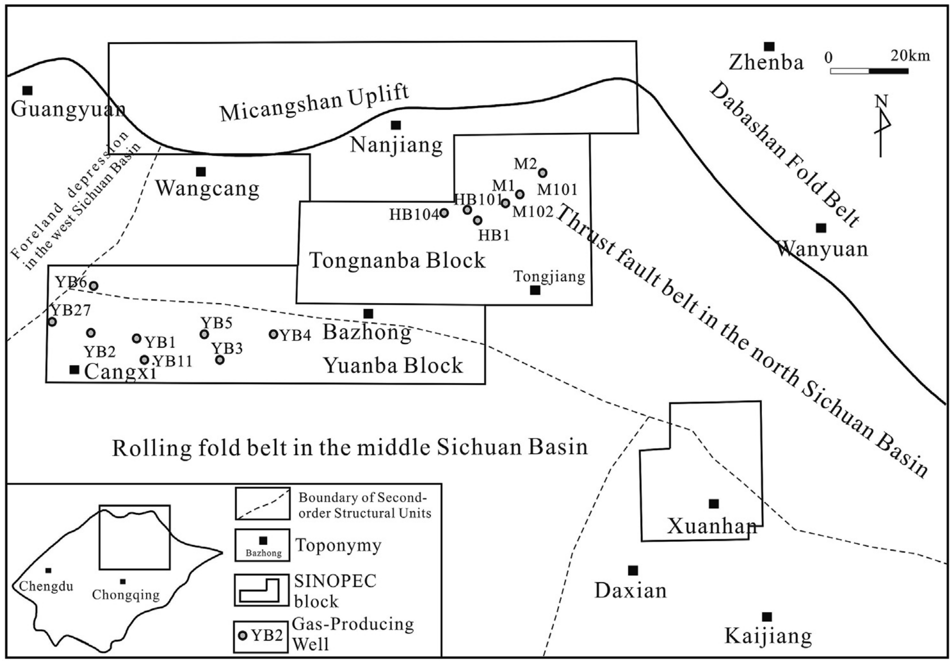

Fig. 1. The structural location of the Yuanba–Tongnanba area.

members of Xujiahe Formation are hydrocarbon source rocks. The hydrocarbon source rocks are not developed in the 1st and 6th members in the study area. The tight sandstone gas in the 2nd and 4th members is mainly from the coal-measure source rocks in the lower sub-member of the 2nd and 3rd member of the Xujiahe Formation. The reservoirs in the 2nd and 4th members of the Xujiahe Formation mainly have fine-medium lithic sandstone and are supplemented by quartz sandstone, feldspar, and lithic sandstone. The rock fragments are mainly composed of metamorphic rock fragments and igneous rock fragments, with a less content of sedimentary rock fragments. The reservoir has a medium-good sorting and is mainly supported by particles, with a sub-angular – sub-rounded psephicity. Interstitial materials mainly include argillaceous matrix and cement, and the content of the argillaceous matrix is less than 5%; that constitutes around about 35% of the cement (mainly within 5%–20%), and the key components include quartz, calcite (ferrocalcite). clay minerals, etc.

3. Typical diagenesis characteristics and origin of tight sandstone reservoir

Through the maximum buried depth of 6000 m [32], the reservoir in the Xujiahe Formation, Yuanba–Tongnanba area of the Sichuan Basin underwent a superimposed reformation multi-stage tectonic movement since the Late Triassic Epoch. Thus, its diagenetic process is extremely complex and the diagenetic phenomena are very rich. According to the analysis results of reservoir thin section, scanning electron microscope, total rock X-ray diffraction, cathodoluminescence, fluid inclusion, etc., the diagenesis which is closely related to the reservoir tightening mainly includes: compaction, dissolution, quartz overgrowth, carbonate cementation, and clay minerals.

3.1. Compaction and its effect of pore reducing

The reservoir in the Xujiahe Formation, Northeast Sichuan Basin undergoes intense compaction and dissolution. In the thin section, it is mainly characterized by point to lineal and lineal to sutured grain contacts of clastic particles, elongated deformation of plastic rock fragments such as phyllite, mudstone, and schist, as well as the bending and fracture of mica (Fig. 3). Lithologically, the higher the content of rock fragments is, the stronger the compaction is. Nonetheless, the compaction in lithic sandstone is the strongest, and the quartz sandstone is strongly characterized by the pre-solution and quartz overgrowth.

The intense compaction undoubtedly has an important impact on the formation of a tight reservoir in the study area. Houseknecht [33] proposed using the diagram of intergranular pore volume versus cement content to quantitatively assess the contribution of compaction and cementation to the reduction of reservoir porosity. In Fig. 4, we can see the relationship between the compaction and cementation of the reservoir in the Xujiahe Formation's study area as well as the reduction of reservoir porosity. By means of a few calcarenaceous sandstones with a particularly high content of calcareous cement, reservoirs in all members of the Xujiahe Formation are in the porosity reduction area predominated by compaction; hence, the compaction is undoubtedly the factor with the greatest contribution to the reduction of reservoir porosity. The reduction rate of porosity by compaction of a reservoir in the lower sub-member of the 2nd member of Xujiahe Formation is mainly within 75%–95%, and that in the upper sub-member of the 2nd and the 4th member of the Xujiahe Formation are mainly within 65%–90% (Fig. 4). If the initial sedimentary porosity is calculated by 40%, 10%–12% remains after the

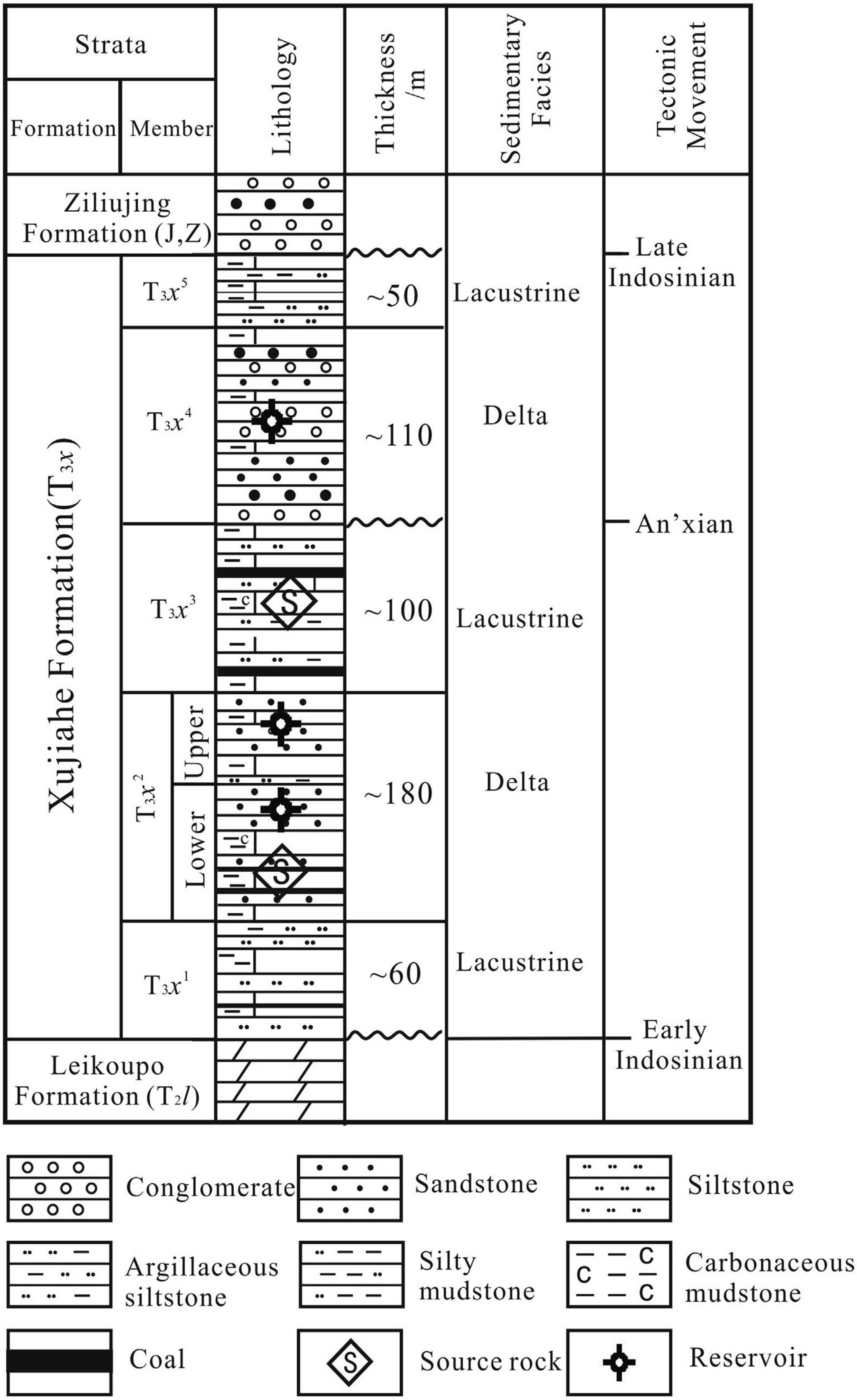

Fig. 2. Generalized stratigraphy of the Upper Triassic Formation (T_3x) in the northeastern Sichuan Basin. Source rock and reservoir intervals are marked. FOR. = Formation, MEM. = Member.

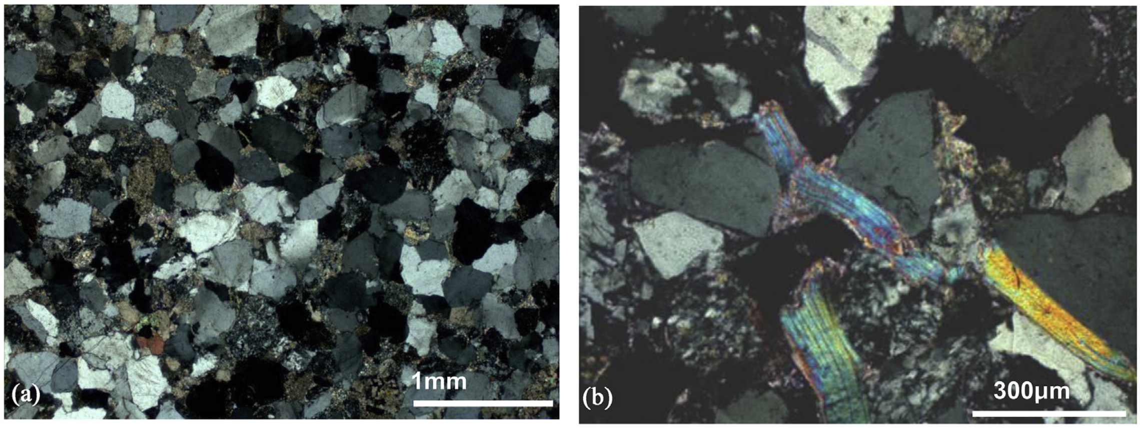

Fig. 3. Thin-section photomicrographs for the chemical compaction in the Xujiahe Formation in the Yuanba−Tongnanba area. (a) Optical micrograph (crossed polarizers) from the Well Yuanba, 2, 4563 m from the showing point to lineal and lineal contacts for intense compaction; (b) Optical micrograph (crossed polarizers) from the Well Yuanba, 6, 4574 m from the showing point to lineal, lineal contacts, and disconnected micas for intense compaction.

main compaction period of the reservoir in lower sub-member of the 2nd member of the Xujiahe Formation. The average reservoir porosity is within 10%−15% after the main compaction period of reservoirs in the upper sub-member of the 2nd member of the Xujiahe Formation and the 4th member of Xujiahe Formation.

The results of numerical [34] and physical simulation experiment [35] during the compaction process of clastic rock reservoir show that the compaction takes place at the stage when the reservoir buried depth nearly reaches the paleo-temperature of 80 °C or equivalently the period from the syndiagenetic stage at the initial sedimentation to the early diagenetic stage. The reduction of porosity after the buried depth reaches 2000−3000 m is mainly caused by the cementation. Therefore, the reduction of porosity of most reservoirs in the Xujiahe Formation, Yuanba−Tongnanba area of the Sichuan Basin has actually completed at the early diagenetic stage. Some primary pores leave the reservoir after the early diagenetic stage, but the compaction has made the grain of reservoir appear as a point-point-line contact. Most of the left primary pores are at the isolated state and have a poor connectivity, and the reservoir has been basically compact.

In summary, compaction is the primary factor with the greatest contribution to the reduction of reservoir porosity in the Xujiahe Formation. After the main compaction period, the reservoir still has a certain type of pore space, but the skeleton particles of debris have no close contact and have poor pore connectivity. Therefore, the compaction forms the geologic setting of low porosity and permeability of the reservoir in the Xujiahe Formation, and the dissolution and cementation characteristics at the later stage provides further proof on that.

3.2. Distribution of dissolution products

The lithology evidence of secondary pores generated by the distribution of feldspar, aluminum-rich silicate rock fragment, and carbonate cement have been generally observed and recorded in a vast amount of studies. Surdam and his co-workers [36−38] pointed out that the short-chain carboxylic acid generated by the maturation of kerogen within the hydrocarbon source rocks provides chemical driving for the occurrence of dissolution and formation of secondary pores in sandstone. A certain scale of secondary pores formed by the dissolution of feldspar and aluminum-rich silicate rock fragment in the sandstone reservoir requires an open diagenetic fluid environment which can both allow the injection of acidic dissolution fluid and a considerable discharge of dissolution products. However, in the closed and semi-closed diagenetic environment, the discharge of dissolution products (especially K^+) is blocked; the process of secondary pores formed by feldspar and rock fragments will be inhibited [6,39]. For example, the Fulmar reservoir in the center graben of the UK North Sea forms 10% of secondary pores in the overpressured fluid discharge area formed by the "denudation window" due to the dissolution of feldspar, and the isolated turbidite sandstone reservoir in its deep part forms few secondary pores due to the dissolution of feldspar [40]. Similarly, a large number of dissolved pore generate in the main discharge channel of the overpressured fluid in the Kela 2 thrust belt of the Tarim Basin in China [41].

According to the identification results of rock thin section and scanning electron microscope, the dissolution in reservoirs of all members of the Xujiahe Formation is mainly characterized by the dissolution of rock fragments and feldspar (Fig. 5a−d). However, unlike the secondary pore space formed by migration of a considerable amount of dissolution products in the open fluid system, the dissolution of the reservoir in the Xujiahe Formation in the study area is characterized by a closed − semi-closed fluidic system.

On one hand, the dissolution phenomenon in the Xujiahe Formation reservoir is common, but the dissolution intensity is quite weak and most of the dissolution products don't migrate. The reservoir in the Xujiahe Formation is chiefly composed of cement formed by precipitation in situ and is characterized by that idea that the more developed the dissolution is, the higher the content of quartz cement. The reservoirs of all members of the Xujiahe Formation have varying degrees of dissolution. Over 80% of nearly 200 observed samples underwent a

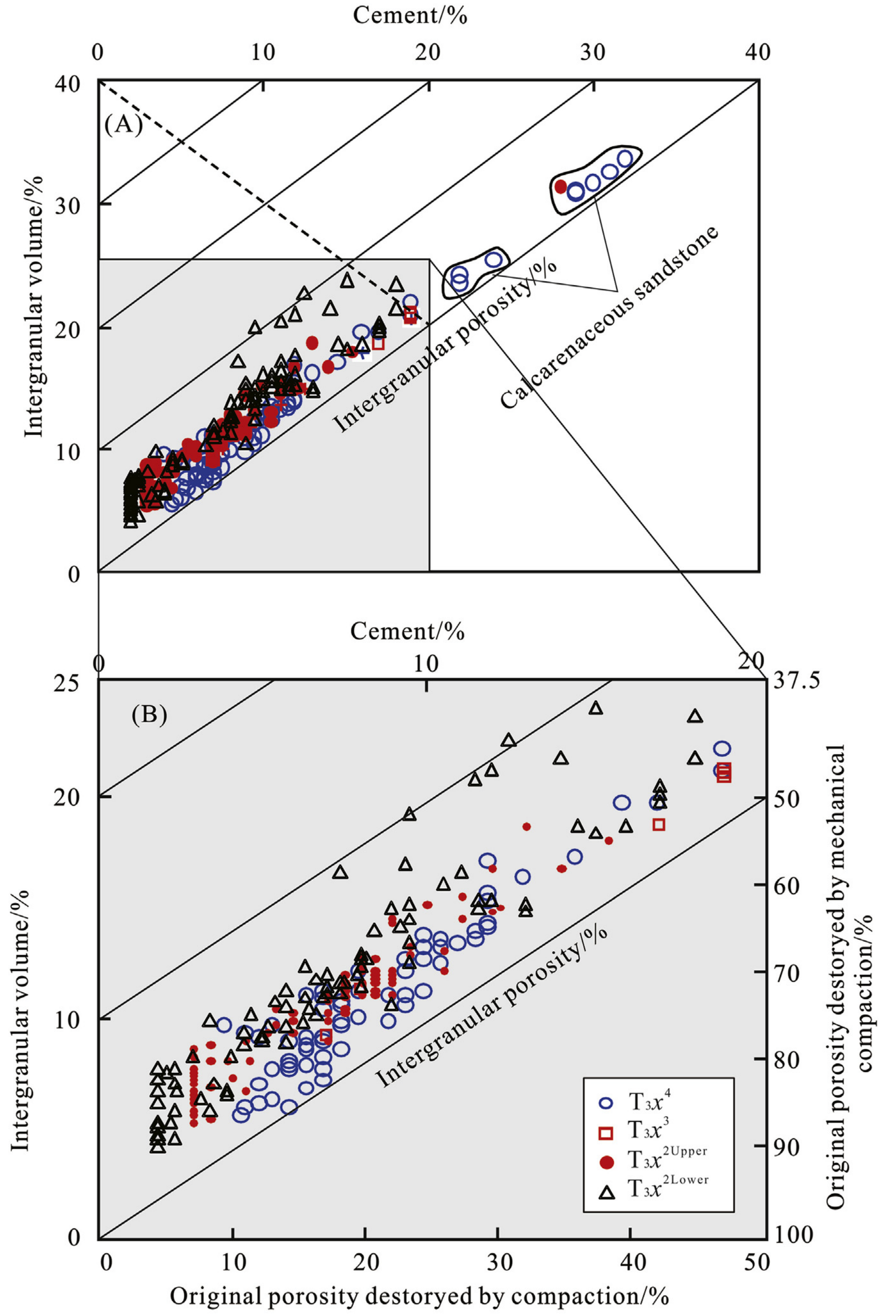

Fig. 4. Diagram for evaluating the relative importance of the compaction processes and cementation to porosity development in the Xujiahe Formation of the Yuanba–Tongnanba area of the Sichuan Basin.

dissolution phenomenon, but the dissolution plane porosity is mainly within 0–3%, and that within 0–1% accounts for 30%–40%. Meanwhile, under the polarizing microscope and scanning electron microscope, the dissolution of rock fragments and feldspar mainly occurs along with the particle edge and cleavage; all forms of dissolved pores are rare (Fig. 5a–d). Moreover, a considerable amount of quartz cement is symbolic to dissolution pores (Fig. 5c,d). Along with the intensity of dissolution, the content of quartz cement rises, for example, with the Profiles of the Well Yuanba 16 – Well Yuanba 123 – Well Yuanlu 1 – Well Yuanlu 6 – Well Yuanba 6, the content of the dissolved matrix feldspar decreases, the dissolution plane porosity increases, and that of dissolution products (quartz cement) also increases (Fig. 6). A similar situation is in the reservoirs for the 2nd member of the Xujiahe Formation (Fig. 7).

On the other hand, the intensity of dissolution in the reservoir in the Xujiahe Formation is closely related to the quality of hydrocarbon source rocks and the quality of coal-measure source rocks; these control not only the source of the acidic fluid but also the migration pathway of the acidic fluid. Vertically, among all members of the Xujiahe Formation, the source rocks in the lower sub-member of the 2nd member and the 3rd member of the Xujiahe Formation have the best quality and are

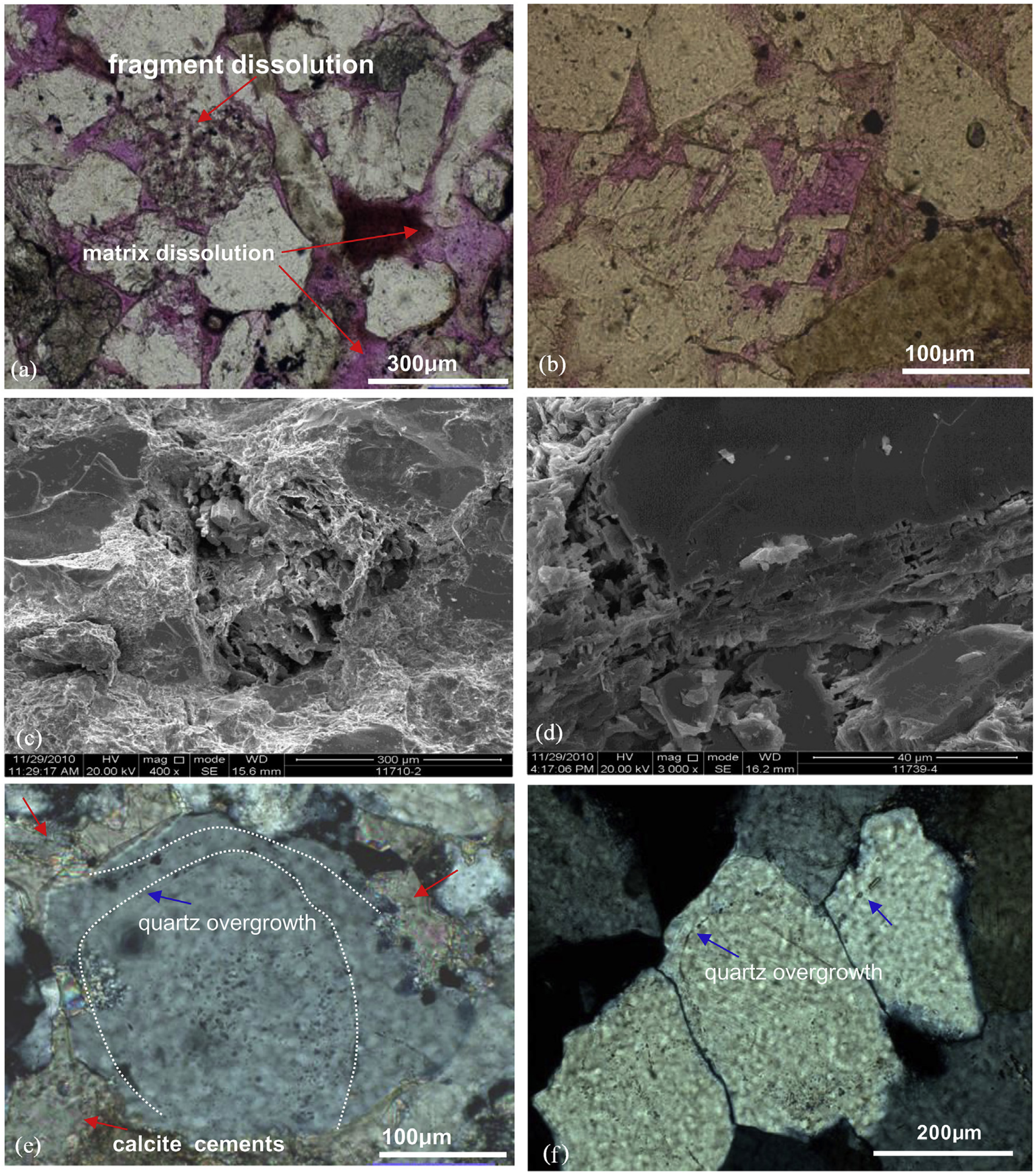

Fig. 5. Thin-section photomicrographs for dissolution and cementation in the Xujiahe Formation in the Yuanba–Tongnanba area. (a) Optical micrograph (plane-polarized light) from the Well Yuanba 22, 4478 m showing point of the dissolution of rock fragments and matrix; (b) Optical micrograph (plane-polarized light) from the Well Yuanba 6, 4574 m showing point of dissolution of feldspar; (c) Scanning electron microscope (SEM) image from the Well Yuanba 16, at 4624.72 m, a residual feldspar can be seen, pore-filling quartz, and illite cement for dissolution of feldspar in the semi-closed to a closed diagenetic system; (d) Scanning electron microscope (SEM) image from the Well Yuanba 16, 4634.33 m showing point of feldspar boundary dissolution; (e) Optical micrograph (crossed polarizers) from the Well Yuanba 104, 4271.09 m showing point of the multiphase quartz overgrowth and calcite cement. Note that quartz's overgrowth precedes calcite cement; (f) Optical micrograph (crossed polarizers) from the Well Yuanba 204, 4550.879 m showing point of the multiphase quartz overgrowth.

the main gas source rocks for the gas in the Xujiahe Formation. The dissolution in reservoirs of the lower sub-member of the 2nd member of the Xujiahe Formation with the interbedded development, as well as the 4th member of the Xujiahe Formation for having a large contact area with the source rocks in the 3rd member of the Xujiahe Formation is the strongest. Horizontally, the acidic fluid required by dissolution in the reservoir of the 4th member of the Xujiahe Formation in the Yuanba area is mainly from the rocks generated in the 3rd member of the Xujiahe Formation. The thickness of generating rocks in the 3rd member of the Xujiahe Formation for the Well Yuanba 16, Well Yuanba 123, Well Yuanlu 1, Well Yuanlu 6, Well Yuanba 6 has little difference. Along with the direction of TOC reduction, the content of dissolution plane porosity, and dissolution products (quartz cement) in the reservoir in the 4th member of Xujiahe Formation both decreases (Fig. 6). Similarly, the intensity of dissolution development in the reservoir of the lower sub-member of the 2nd member of Xujiahe

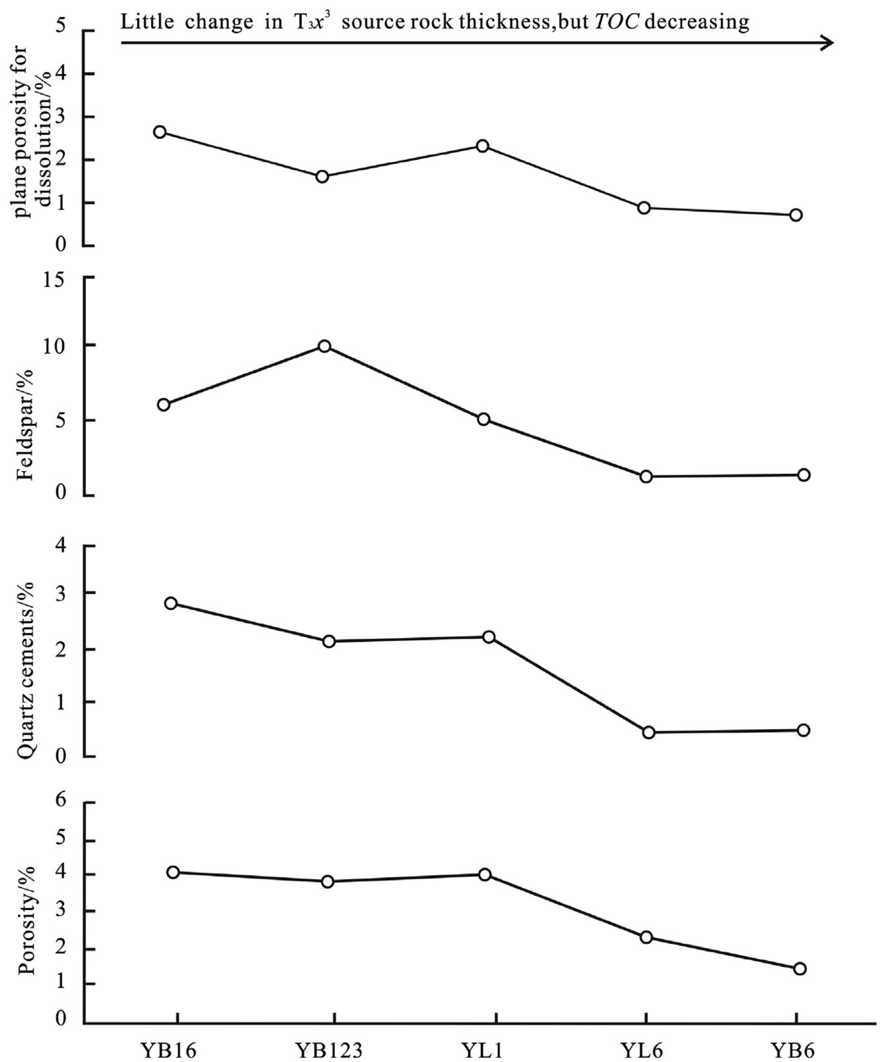

Fig. 6. The relationship between the dissolution intensity in the fourth member and the source rock thickness in the third member of the Xujiahe Formation, Yuanba–Tongnanba area of the Sichuan Basin YB = Yuanba, YL = Yuanlu.

Formation and the thickness of generating rocks share the same relationship, i.e. along with the direction of thickness reduction of generating rocks, the dissolution plane porosity, the reduction content of quartz cement, and the content of feldspar increases overall (Fig. 7).

Under normal conditions, the development of dissolution in the reservoir is mainly controlled by three factors: the content of soluble substances, the source of acidic fluid, and migration pathway of acidic fluid. When the macro depositional setting controls the space distribution soluble substances such as feldspar, the intensity of dissolution is mainly controlled by the source of acidic fluid and migration pathway of acidic fluid. Source rocks in Xujiahe Formation are coal-measure source rocks and may generate a lot of organic acid during the low maturity – maturity evolution stage. If the reservoir is in the open fluidic system, the migration pathway of acidic fluid and discharge channel of dissolution products are unblocked. The source of acidic fluid should not be the main factor controlling the intensity of reservoir dissolution, which has been proved in Kela 2 thrust belt, Kuqa Depression, Tarim Basin [37]. The intensity of reservoir dissolution in the study area is closely related to the quality of source rocks, and the main reason may be that dissolution occurs in the semi-closed – closed system. In the semi-closed – closed system, the supply of dissolution fluid and migration of dissolution products are both limited. The pressure difference of source reservoir formed during the thermal evolution of hydrocarbon source and hydraulic fractures generated by excess pressure difference are the power and pathway for migration of dissolution fluid and dissolution products. But due to that the formation period of organic acids is earlier than the period of considerable amount of hydrocarbon generation and expulsion, the influence area of its generated power and channel effect, the migration of organic acids generated by generating rocks into the reservoir is characterized by near source and short distance. In addition, due to that the Xujiahe Formation, Northeast Sichuan Basin is a set of delta plain-front clastic deposit, the distributary channel, interchannel and shore-shallow lake deposit change frequently and form a “sandwich” source reservoir interbedded combination. The reservoir has a large contact area with the source

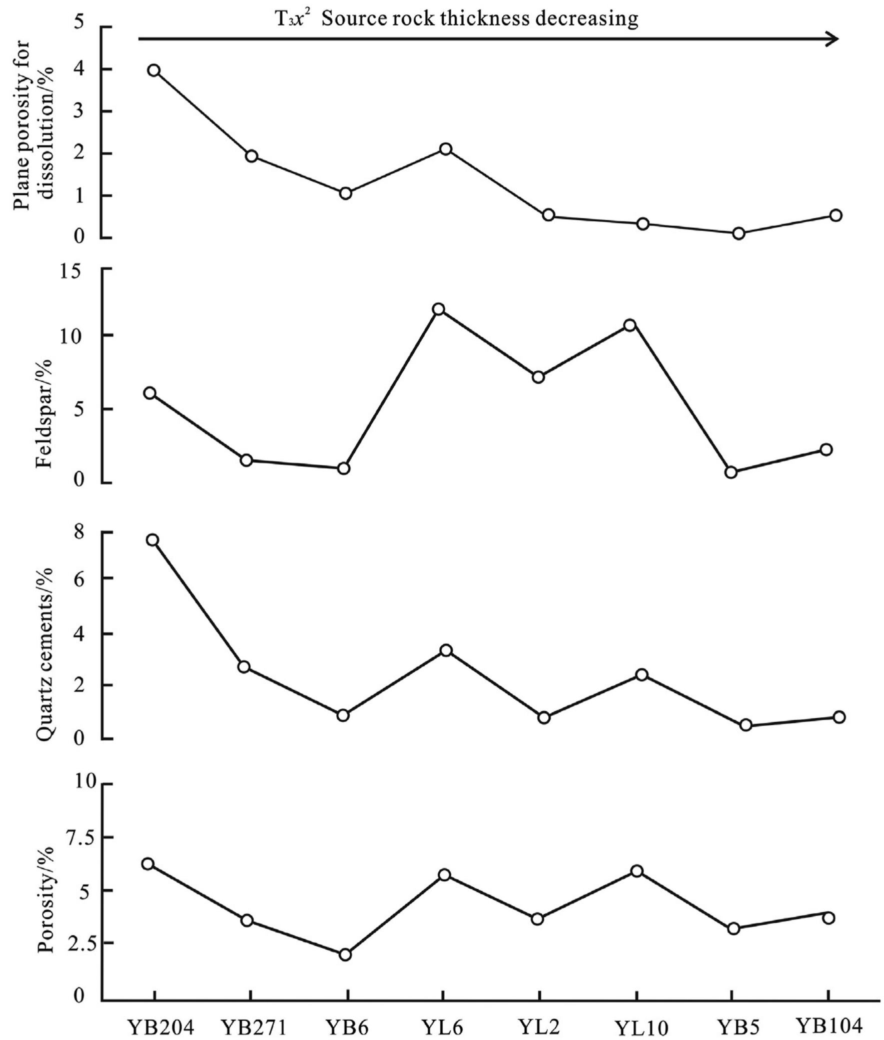

Fig. 7. The relationship of dissolution intensity and source rock thickness in the second member of the Xujiahe Formation, Yuanba−Tongnanba area of the Sichuan Basin YB = Yuanba, YL = Yuanlu.

rocks, so the dissolution is very common in the reservoir though its degree is weak.

3.3. Genesis and significance of authigenic illite

The reservoir clay mineral composition of the Xujiahe Formation, Yuanba−Tongnanba area of the Sichuan Basin is mainly illite with the relative content of 40%−60%, and a very low content of kaolinite and chlorite with the relative contents of about 10% and 15% respectively. Such as Well Yuanba 204, the relative content of illite in the clay mineral of the reservoir in the Xujiahe Formation accounts for 50%, kaolinite 8%, and chlorite 10%.

According to the distribution of illite in the reservoir in Xujiahe Formation in the study area, there are three kinds of illite: the first kind of illite is widely distributed among intergranular pores in the shapes of silk and flake. For this kind of illite, its symbiosis with kaolinite can be seen locally, and it has the phenomenon of kaolinite illitization (Fig. 8a) and should be mainly the products of kaolinite illitization. The second kind of illite is distributed in the dissolution pores of feldspar. Due to that the dissolution of feldspar occurs along with the cleavage, the illite distributes as a grid shape along with the feldspar cleavage (Fig. 8c−f). When the pores formed by feldspar dissolution are filled with illite, such pores appear as relatively intact moldic pores under the plainlight but disappears completely under the orthogonal light. It can be seen that illite divides these pores into innumerable micropores (Fig. 8e,f), and this kind of illite should be mainly the illite directly formed by feldspar dissolution. The third kind of illite is the illite which is developed by vertical clastic particles and distributes in the form of particle coating (membrane). The honeycomb structure of smectite may be generally seen indistinctly in this kind of illite and may be mainly formed by the smectite illitization (Fig. 8b). Overall, the illite in the reservoir in Xujiahe Formation in the study area is mainly produced by the first two modes, especially the second kind is very common, and the third kind is only developed in few samples.

The correlation between the quartz and clay mineral content in the reservoir of the Xujiahe Formation further shows

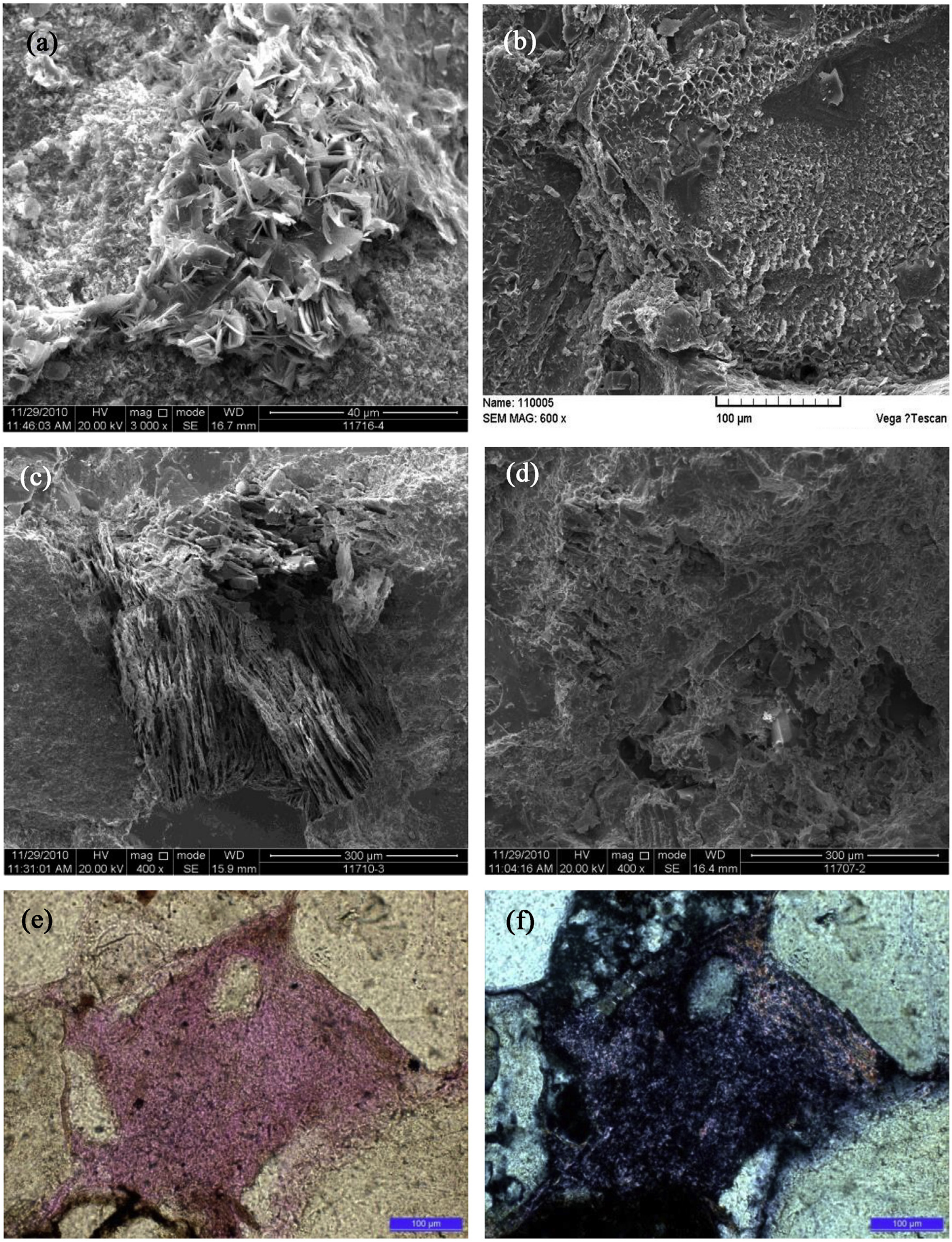

Fig. 8. SEM and thin-section photomicrographs for illites cement in Xujiahe Formation in Yuanba−Tongnanba area. (a) Scanning electron microscope (SEM) image from Well Yuanba 16, 4626.39 m showing intergranular pore-filling illite and kaolinite cement; (b) Scanning electron microscope (SEM) image from Well Yuanba 6, 4685.06 m showing grain coating illite cement; (c), (d) Scanning electron microscope (SEM) image from Well Yuanba 16, 4624.72 m and 4623.72 m respectively, showing residual feldspar, pore-filling quartz, and illite cement for dissolution of feldspar in the semi-closed to a closed diagenetic system; (e) Optical micrograph (plane-polarized light) from Well Yuanba 6, 4584 m showing partly dissolution of feldspar and pore-filling illite cement; (f) Crossed polarizers optical micrograph for (e).

that feldspar, especially the potassium feldspar, has a better derivation relationship with an illite. The content of illite is negatively correlated to that of feldspar (Fig. 9a), and especially has a higher negative correlation coefficient with potassium feldspar (Fig. 9c), which shows that the source relation between illite and potash feldspar is closer. Similarly, kaolinite and feldspar have a better negative correlation (Fig. 9b), which shows that kaolinite mainly derives from the feldspar dissolution. There is a low correlation between kaolinite and illite (Fig. 9d), which shows that the derivation relation between illite and kaolinite is not so close, and the kaolinite illitization process contributes little to the origin of illite in the reservoir. At the same time, we have mentioned that the smectite illitization also contributes little to the illite. Therefore, in the combination of the production mode of authigenic illite in the reservoir in Xujiahe Formation, this article holds that the illite distributing in feldspar intragranular dissolved pores as a grid shape comes from feldspar illitization, and the illitization of potash feldspar should be predominant due to there is no extra potassium source.

Previous studies show that the formation of illite in the clastic rock reservoir mainly has three mechanisms: smectite illitization [42], kaolinite illitization [34,43,44] and feldspar illitization [45]. It is usually hard for the feldspar dissolution to directly generate illite, and the generation should have a series of strict dynamic conditions, such as the feldspar dissolution rate, illite precipitation rate, and nucleation kinetics barrier. The most important are that the potassium ion concentration in the fluid should be greater than or equal to the critical value of illite precipitation, which is hard to achieve in the general diagenetic system. Especially in the open system, the potassium ions generated by feldspar dissolution and other potassium ions from other sources may rapidly migrate through convection and diffusion, which causes the potassium ion concentration hard to reach the critical value of illite precipitation, which is also the main reason that the feldspar dissolution product which is usually seen by us is kaolinite rather than illite. However, in the closed − semi-closed with the acidic fluid source, potassium ions are not easy to migrate and dissipate, and it is possible that the potassium feldspar

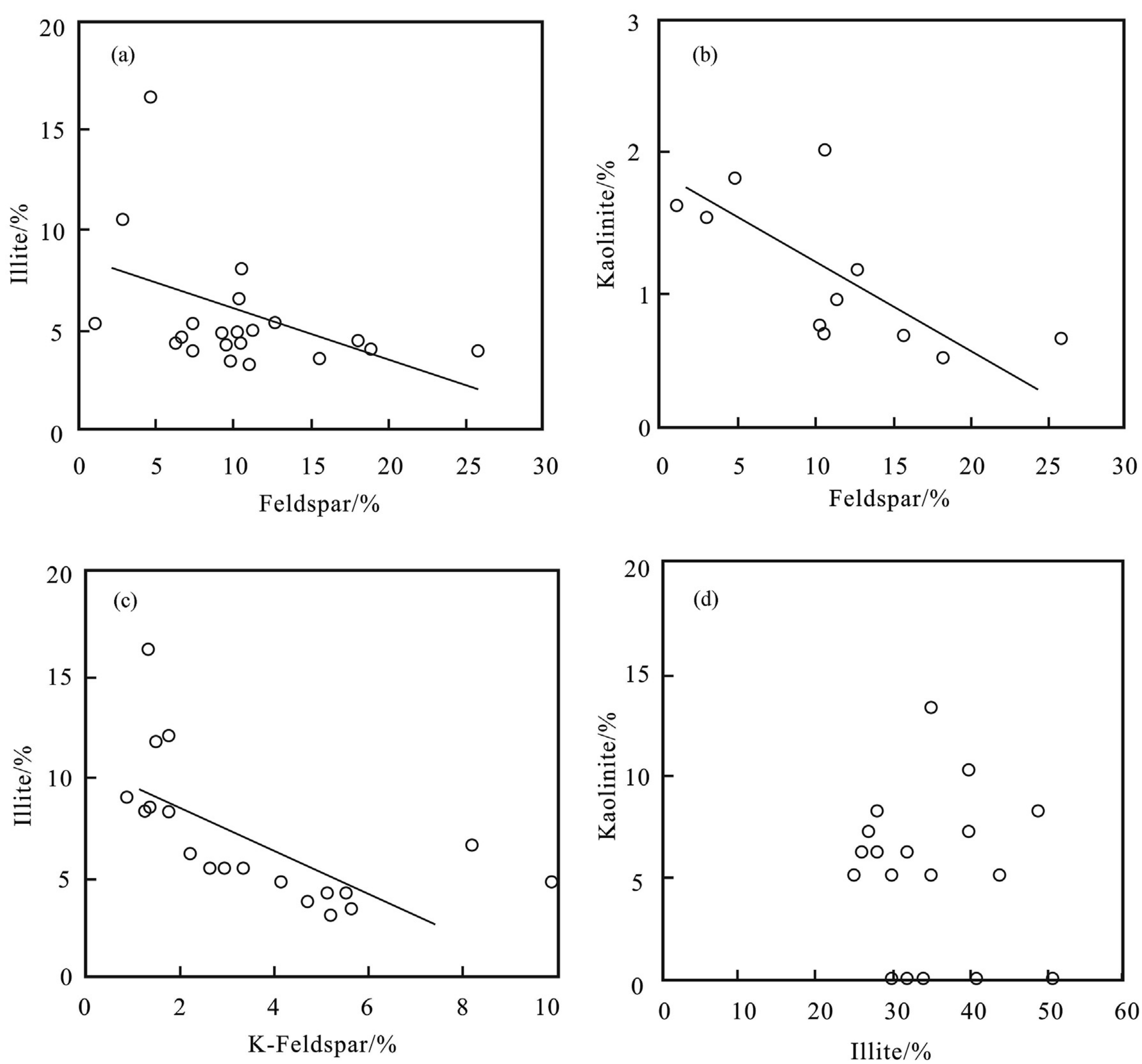

Fig. 9. Variation of feldspars with clay minerals in Xujiahe Formation in Yuanba−Tongnanba area.

dissolution directly generates illite. Under the condition of adequate potassium ions (if there is an additional source), it may be also possible that the dissolution of albite and anorthite directly feldspar generates illite [41]. In addition, the thermodynamic calculation results of Huang et al. [46,47] show that when there are enough in the fluid, the increment of Gibbs free energy of illite generated by feldspar dissolution is lower than that of generated kaolinite. So from the perspective of thermodynamics, the feldspar dissolution may also directly generate illite (reaction 1–3).

$$\underset{\text{K-feldspar}}{3KAlSi_3O_8} + 2H^+ + H_2O \rightarrow \underset{\text{illite}}{KAl_3Si_3O_{10}(OH)_2} + \underset{\text{quartz}}{6SiO_2} + 2K^+ + H_2O \quad (1)$$

$$\underset{\text{Ca-feldspar}}{3CaAl_2Si_2O_8} + 2K^+ + 4H^+ + H_2O \rightarrow \underset{\text{illite}}{2KAl_3Si_3O_{10}(OH)_2} + 3Ca^{2+} + H_2O \quad (2)$$

$$\underset{\text{Na-feldspar}}{3NaAlSi_3O_8} + K^+ + 2H^+ + H_2O \rightarrow \underset{\text{illite}}{KAl_3Si_3O_{10}(OH)_2} + 3Na^+ + 6SiO_2 + H_2O \quad (3)$$

In summary, the illite in the reservoir in Xujiahe Formation, Northeast Sichuan Basin is mainly from the illitization processes of potassium feldspar and kaolinite. And both of the two processes reflect one relatively closed diagenetic fluid system. The illite in the study area is especially predominated by the illitization of potassium feldspar. Meanwhile, this process mainly occurs in the period A of the diagenetic stage of the diagenetic stage of clastic rock generally due to that the sedimentation of illite has a threshold temperature. This means that the period A of the diagenetic stage in the reservoir in the Xujiahe Formation in the study area has been a semi-closed – closed diagenetic fluid system.

3.4. Diagenetic evolution and the tightening process of the reservoir

This article analyzes the pore evolution and tightening process of the reservoir in Xujiahe Formation in three stages on the basis of utilizing such analysis methods as identification of thin section, scanning electron microscope, X diffraction, electron probe, fluid inclusion to find out the reservoir pore type, authigenic mineral type and its diagenetic sequence, and in the combination of the above-mentioned analysis of typical diagenesis and characteristics of the diagenetic fluid system of the reservoir in Xujiahe Formation.

Stage 1: compaction

Previous studies [34,35,48] show that the compaction process of clastic rock reservoir is mainly at the time that buried depth reaches 2000–3000 m and the paleo-temperature reaches around 85 °C. In the study area, the homogeneous temperature of aqueous inclusions formed at the end of compaction process is within 75–120 °C, the main peak is within 85–105 °C.Therefore this stage is equivalent to the stage from deposition to the time that buried depth reaches 2000 m. At the end of this stage, the palaeogeothermal reaches around 85 °C, and the vitrinite reflectance reaches to 0.5%. Therefore, this stage is roughly equivalent to the early diagenesis stage, with the corresponding geological period of the Late Triassic–middle Middle Jurassic. The reason why this period is discussed as a stage is mainly that this stage is a stage where the compaction plays an important role. After this stage, the reduction of reservoir properties is mainly predominated by cementation (Fig. 10).

As mentioned above, the compaction of the reservoir in the Xujiahe Formation in the study area is intensive, and the factor with the greatest contribution to the reduction of reservoir properties. But the intensity of pore reducing by compaction at different intervals varies. 10%–12% of the average reservoir porosity remains after the main compaction period of the reservoir in lower somber of the 2nd member of Xujiahe Formation and is within 10%–15% after the main compaction period of reservoirs in the upper sub-member of the 2nd member of Xujiahe Formation, and the 4th member of Xujiahe Formation. Overall, the low porosity and permeability background of the reservoir have formed after the main compaction period, and the closed – semi-closed diagenetic fluid system forms.

Stage 2: dissolution and cementation

This stage is equivalent to the stage where buried depth reaches 2000–4000 m. At the end of this stage, the paleotemperature reaches around 140 °C, and the vitrinite reflectance reaches to 1.3%. Therefore, this stage is roughly equivalent to the period A of the diagenetic stage of the diagenetic stage of clastic rock, with the corresponding geological period of the middle Middle Jurassic – Late Jurassic. With the further increase of buried depth, organic matters enter the peak of production of organic acid around the buried depth around 2000–2500 m, and the organic acid migrates into the reservoir, which causes the dissolution of such aluminum silicate minerals as feldspar and rock fragments, especially the dissolution of feldspar. Due to that the reservoir fluid system has been in the semi-closed – closed system, such dissolution products as quartz and illite precipitation in situ or in the nearest place, fills the pore space and blocks the throat. The cementation and dissolution basically occur at the same place and time, and the secondary pores generated by dissolution are limited.

In the later period of this stage, with the reduction of acid production by organic matters and the continuous consumption of dissolution in the reservoir, the media environment of formation water gradually becomes into subacidity-alkalinity from acidity, and such carbonate cement as calcite start to form. Overall, although this stage is an important dissolution period, and a certain amount of secondary pores form, there is a lot of sedimentation of secondarily enlarged fringes of quartz, carbonate cement, and illite, and the reservoir is further compact (Fig. 10).

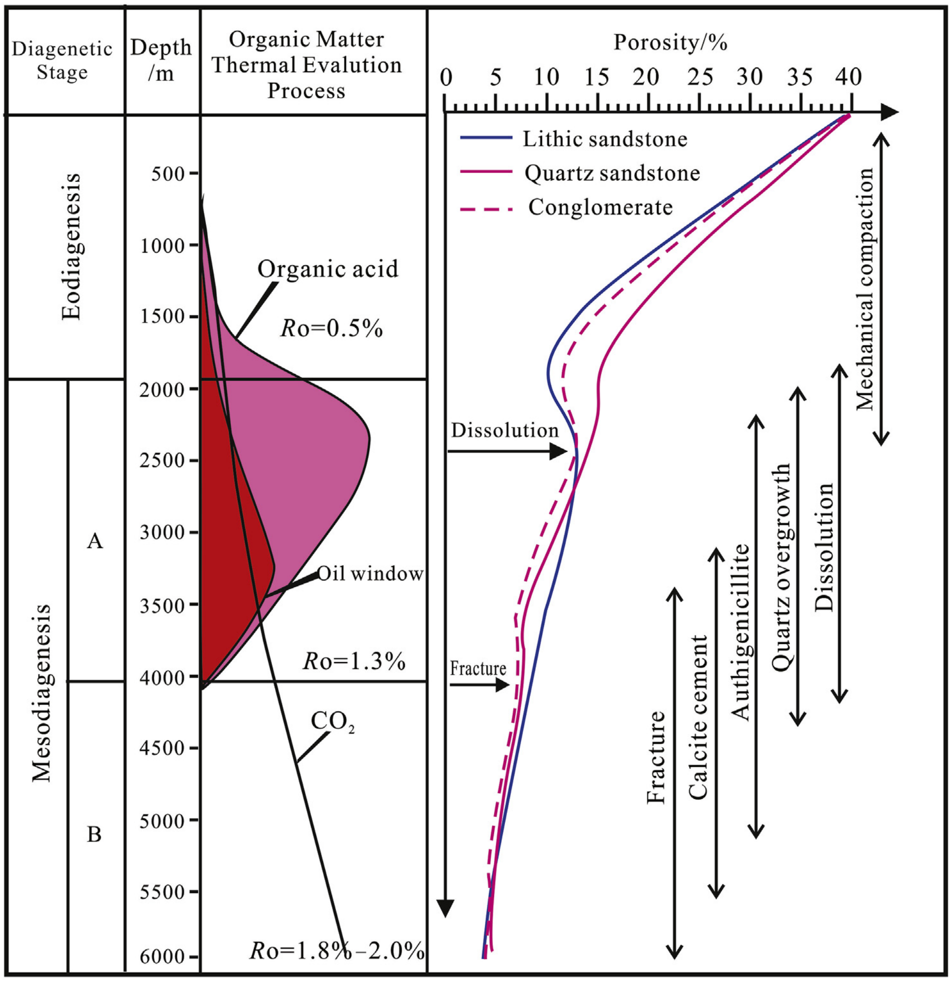

Fig. 10. The porosity evolution curve of Xujiahe Formation reservoirs in Yuanba−Tongnanba area.

Stage 3: fracture

At this stage, the buried depth of reservoir is greater than 4000 m, the paleo-temperature is higher than 140 °C, the vitrinite reflectance is higher than 1.3%, and the corresponding geological period is Early Cretaceous − now. Except that the formation of late-period carbonate cement and reaction of kaolinite illitization starts, the most important thing which is related to the reservoir quality is the formation of fractures (Fig. 10).

Since the Late Jurassic, especially the Himalayan period, local structures and fractures in the Yuanba and the Tongnanba area gradually formed due to the influence of orogenic activity at the basin edge in the Middle Yanshan period, and the related fractures in the reservoir in Xujiahe Formation also developed (Fig. 11). The development degree of fractures is macroscopically controlled by the in intensity of tectonic deformation and mainly related to lithology locally. The fractures in the quartz sandstone reservoir of the middle sub-member of the 2nd member of Xujiahe Formation, and conglomerate reservoir of the upper sub-member of the 4th member of Xujiahe Formation are relatively developed [25]. Although in the Xujiahe Formation in the study area, the fractures in the late period doesn't develop as the fractured reservoir with large-scale development in marine facies Changxing − Feixianguan Formation, its existence has greatly improved the performance of fluid passage system and is of important significance in the adjustment and transformation of gas reservoir as well as local accumulation with high productivity in the late period.

4. The relationship between the gas accumulation and the reservoir tightening period

4.1. Gas accumulation periods

The method of hydrocarbon generation and expulsion history of hydrocarbon source rocks is commonly-used in traditional qualitative analysis method for the research of hydrocarbon charge periods. The hydrocarbon generation and expulsion history of hydrocarbon source rocks in the Xujiahe Formation in the study area mainly utilizes the IES basin simulation software for simulation analysis. The stimulation of thermal history and hydrocarbon generation history respectively utilizes the IES, given the steady constant heat flow model and Kerogen oil−gas two-component model; the

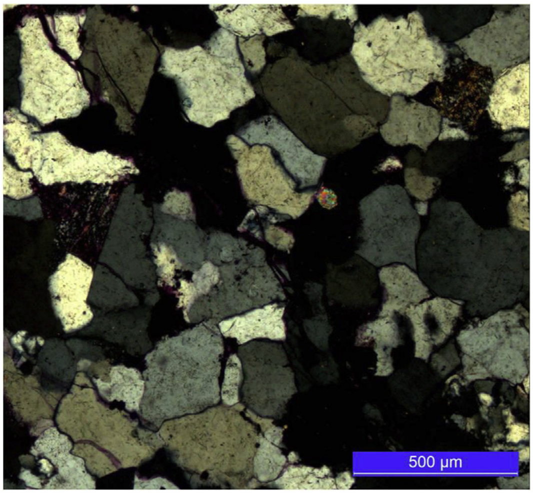

Fig. 11. Tectonic microfracture in thin section from the second member of Xujiahe Formation in Well Yuanba 204.

simulation of maturity history utilizes the Easy%*R*o chemical kinetics on the first-order reaction model established by Sweeney et al. [49], and the vitrinite reflectance data actually measured for calibration.

The stimulation results of the 17 wells in the study area show that the source rocks in the Xujiahe Formation undergo five evolution stages, namely, primary deposit, uplift erosion, sedimentation-rapid sedimentation, sedimentation, and large uplift erosion. The gas generation stage occurs at the rapid sedimentation stage and is characterized by a rapid gas generation. For the hydrocarbon source rocks in the Xujiahe Formation, *R*o reaches 0.5% in the middle of the Middle Jurassic (around 170 Ma), only then do gas generation begins. If the *R*o reaches 0.7% in the later Middle Jurassic (around 160 Ma), a considerable amount of gas generation begins. Then, with the increases depth, the buried depth fails to reach the maximum in the late Early Cretaceous, *R*o reaches 2.0%–2.2%, hydrocarbon source rocks enter the high-over maturation stage, and the maximum hydrocarbon generation and expulsion period reaches. In the Late Cretaceous (around 100 Ma), the Northeast Sichuan Basin began to drastically uplift as a whole, the geotemperature gradually reduced, and the hydrocarbon source rocks in the Xujiahe Formation gradually stopped generating hydrocarbons.

Currently, the most widely-used quantitative analysis method for hydrocarbon charge periods is to utilize the fluid inclusion testing technology in the combination of the thermal evolution history to determine the hydrocarbon charge time. The detailed micro luminescent observation of 106 reservoir samples shows that there are mainly four kinds of fluid inclusions in the reservoir in the Xujiahe Formation: aqueous inclusion, oil inclusion, pure gas inclusion, and gas-aqueous inclusion. The sizes of such inclusions are within 3–10 μm. Host minerals include quartz grain, quartz overgrowth, calcite cement, and fracture-filling calcite vein. Different kinds of inclusions have different characteristics under the microscope. Oil inclusions glow yellow fluorescence and yellow white fluorescence. Due to the high-temperature thermal evolution history, this kind of inclusions are generally rare and can only be seen in the Tongnanba area, where aqueous inclusions are more developed and can be viewed seriously in reservoirs in the Xujiahe Formation. Such inclusions are the residual products after the oil inclusions undergo a high-temperature thermal evolution. They are black under the transmitted light, they emit no light under the fluorescence nor do they glow faint white fluorescence, this which shows that the gas reservoir has the charge of liquid hydrocarbons at the early stage; gas inclusions doesn't glow fluoresce and are mainly distributed in fractures in quartz grains and fracture-filling calcite veins.

In the study area, the homogeneous temperature of aqueous inclusions associated with bitumen inclusions is within 80–120 °C, and the main peak is within 90–110 °C. The corresponding charge period for paleo-oil reservoir or heavy hydrocarbon gas is 170–160 Ma, which shows that the reservoirs in the Xujiahe Formation in the Yuanba area has a little crude oil or heavy hydrocarbon gas charge in the middle of the Middle Jurassic – early Late Jurassic. Gas inclusions are mainly distributed in fractures in quartz grains and fracture-filling calcite veins. The micro temperature measurement results of the homogeneous temperature of aqueous inclusions associated with gas inclusions show that both of the two inclusions form in the roughly same period. The gas inclusions in calcite veins come in much later than those in fractures in quartz grains. The homogeneous temperature of aqueous inclusions associated with gas inclusions is within 110–170 °C, the main peak is within 120–160 °C, and the corresponding charge period for natural gas is within 160–115 Ma, which shows that main charge period for natural gas in the Xujiahe Formation in the Late Jurassic – late Early Cretaceous (Fig. 12).

4.2. Coupling relationship between diagenesis and accumulation of tight sand reservoir

As mentioned above, when the main compaction period in the Late Triassic–middle Middle Jurassic is over, the reservoir porosity in the Xujiahe reduces to 10%–15%. At this time, the reservoir still has a certain of pore space, but the grain have had a close contact, and have a poor pore connectivity, and the tightening background has formed. The cementation in the middle of the Middle Jurassic – Late Jurassic makes the reservoir further tightening. The analysis of hydrocarbon generation and expulsion history of hydrocarbon source rocks and reservoir fluid inclusions shows that the gas charge just starts in the middle and late Middle Jurassic and the main charge period occurs in the Late Jurassic – late Early Cretaceous. Therefore, for the study area, the reservoir has been tightened during the main charge period of gas (Fig. 13).

In addition, the interaction sequence of the organic–inorganic aquiferous rock in tight sandstone can also prove that the reservoir has been compact during the main charge period of gas. It can be seen from above that the compaction forms the tightening background of the reservoir, and the dissolution and cementation make the reservoir further

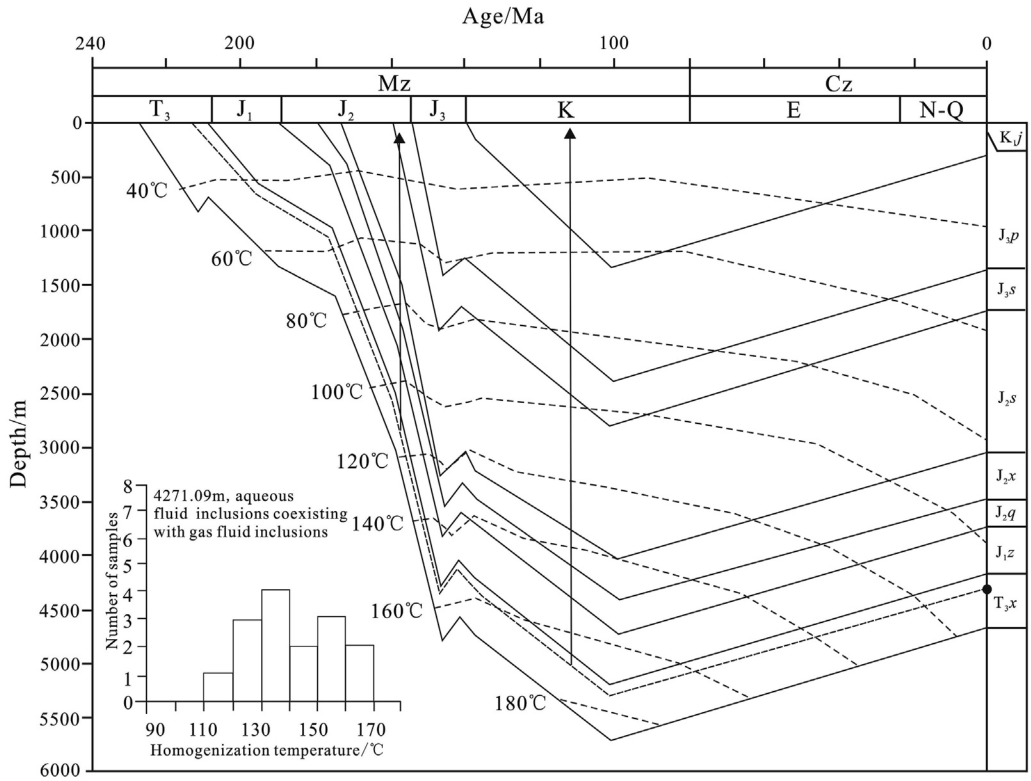

Fig. 12. The period of gas charging in Xujiahe Formation for Well Yuanba 16.

tightened. Previous studies show that the compaction mainly occurs at the stage where the buried depth is within 2000–2500 m, and the vitrinite reflectance is less than 0.5% [34,35], the fluid source of dissolution-organic acid mainly forms at the stage of 0.5%–0.7% [50], and the dissolution products undergo in situ precipitation and cementation, and form at roughly the same time with or slightly later than the dissolution. As for coal-measure source rocks, a considerable amount of gas generation begins when *R*o reaches 0.7%, and the peak of gas generation is even later. Therefore, the two main diagenetic processes are both basically earlier than the gas generation and expulsion stage, and the reservoir should have been densified in the main charge period of gas (Fig. 13).

5. Significance of the tight sand gas enrichment and depletion mechanisms

In conventional gas reservoirs, natural gas is charged into the reservoir with a good property, which is easy to form a certain degree of the continuous air column, of which the buoyancy is the main driving force of secondary migration. Unlike conventional gas reservoirs, tight sand gas reservoirs

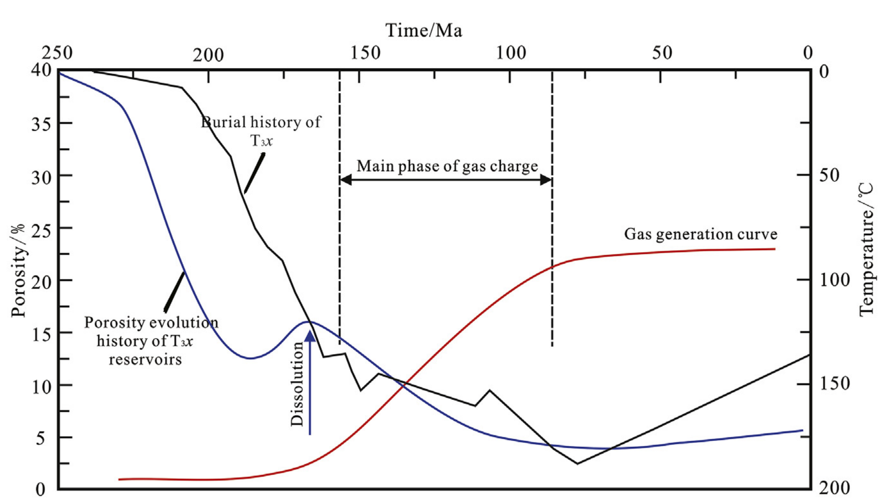

Fig. 13. Schematic diagram showing the diagenesis history and gas charging time of the Xujiahe Formation reservoirs in the Yuanba–Tongnanba area.

have been tight before the charging of natural gas, thus, it is difficult to form a continuous column after natural gas enters the reservoir. The effect of buoyancy on gas migration is weak or absent, and the main driving force of natural gas migration is hydrocarbon source rock swelling force, which is usually said as the hydrocarbon overpressure. Therefore, for tight sand gas reservoirs which the reservoir is firstly compacted before accumulation, the source rocks not only provide the gas source but also provide the driving force for natural gas migration. In addition, when the hydrocarbon generation of hydrocarbon source rocks reaches the rock fracture pressure, hydraulic fractures are formed which provide a good channel for the migration of natural gas. At the same time, in the tight sand reservoir, natural gas migration does not accord with Darcy's law and non-Darcy flow. Natural gas migration requires a certain starting pressure, which is also provided by the hydrocarbon generating pressurization. This results to a large extent that this kind of tight sand gas reservoir has the characteristics of adjacent source accumulation, and the hydrocarbon source rock conditions determine the location of the tight sand gas reservoir. Under the premise of gas source conditions, the reservoir controls the enrichment of natural gas, that is, the better the reservoir condition, the more abundant the natural gas is. The effective coupling of source rock conditions and reservoir conditions jointly control the formation and enrichment of tight sand gas reservoirs. Therefore, in the actual exploration and research process, the source rocks and reservoirs should be placed in the same important position.

The argument above has been supported by a large number of exploration practices. In the study area, the exploration gas wells get industrial gas flow in the T_3x^3 and T_3x^4, which are relatively low in physical properties, while in the T_3x^2 formation which is relatively high in physical properties, the wells get low production or even dry. It is concluded that the main reason is that the high development of source rocks of T_3x^3 formation and low development T_3x^2 and T_3x^1 formations. The development degree and distribution of source rock control the location of natural gas and the scale of gas reservoir [28]. In other areas of the Sichuan Basin, the source rock conditions of the Xujiahe Formation also play an important role in controlling the formation and distribution of tight sandstone gas reservoirs [51,52]. As well as for the Ordos basin, where the upper Paleozoic tight sand gas reservoirs are mainly distributed in areas where the hydrocarbon generation intensity is greater than 10×10^8 m^3/km^2, the vertical migration distance of natural gas increases with the increase of coal seam thickness and gas generation intensity, and there is a tendency that the gas-bearing property becomes better with the change of hydrocarbon source rock condition [12,53].

6. Conclusions

(1) The diagenesis in the semi-closed and closed diagenetic fluid system is the main reason for the formation of tight sandstone reservoir in the Xujiahe Formation, Yuanba−Tongnanba area of the Sichuan Basin. The intensive compaction in the early stage caused the reservoir porosity to reduce greatly and to form the semi-closed or closed diagenetic fluid system. At the later stage of the semi-closed − closed diagenetic fluid system, the fluid circulation is not smooth, and the migration of dissolution products is blocked, the dissolution products mainly undergo the in situ precipitation and cementation. Such dissolution products block the dissolution pores and residual primary pores. The stronger the dissolution is, the higher the cement content is, which makes the reservoir further tightened.

(2) The hydrocarbon generation and expulsion history of source rocks and reservoir fluid inclusion characteristics in the Xujiahe Formation show that the charge of natural gas occurs in the Middle Jurassic−Early Cretaceous (mainly Early Cretaceous). Comprehensive analysis of reservoir tightening history, gas charge history, and interaction sequence of the organic−inorganic aquiferous in rock indicate that the sandstone reservoir experienced the tightening process when gas charging in the Xujiahe Formation in the Yuanba−Tongnanba area of the Sichuan Basin.

(3) The hydrocarbon source rock conditions determine the location of the tight sand gas reservoir that experienced a sandstone reservoir was tightening process when gas was charging. The effective coupling of source rock conditions and reservoir conditions jointly control the formation and enrichment of tight sand gas reservoirs. Therefore, in the actual exploration and research process, the source rocks and reservoirs should be placed in the same important position.

Foundation item

Supported by National Natural Science Foundation of China (41472118, 41502132); Key Project of Education Department of Shaanxi Provincial Government, China (15JS093); Science Foundation of Xi'an Shiyou University, China (2013BS018); Changqing Oilfield Company of PetroChina.

Conflict of interest

The authors declare no conflict of interest.

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