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Diagenetic fluids evolution and genetic mechanism of tight sandstone gas reservoirs in Upper Triassic Xujiahe Formation in Sichuan Basin, China

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The reservoirs of the Upper Triassic Xujiahe Formation in Sichuan Basin have the characteristics of low compositional maturity, low contents of cements and medium textural maturity. The general physical properties of the reservoirs are poor, with low porosity and low permeability, and there are only a few reservoirs with medium porosity and low permeability in local areas. Based on the diagenetic mineral association, a diagenetic sequence of cements is established: early calcites (or micrite siderites) → first quartz overgrowth→chlorite coatings→dissolution of feldspars and debris→chlorite linings→ second quartz overgrowth (quartz widen or filled in remain intergranular pores and solution pores)→ dissolution→third quartz overgrowth (quartz filled in intergranular and intragranular solution pores)→ intergrowth (ferro) calcites→dolomites→ferro (calcites) dolomites→later dissolution→veins of quartz and calcites formation. Mechanical compaction is the main factor in making the reservoirs tight in the basin, followed by the second and third quartz overgrowth. In a long-term closed system, only feldspars and some lithic fragments are dissolved by diagenetic fluids, while intergranular cements such as quartz and calcit are not dissolved and thus have little influence on the porosity of the Xujiahe Formation. This is the third factor that may have kept the sandstones of Xujiahe Formation tight finally. The hydrocarbon was extensively generated from organic materials after the second quartz overgrowth, and selectively entered favorable reservoirs to form tight sandstone gas reservoirs.

diagenetic fluids, tight reservoirs, Xujiahe Formation, Sichuan Basin, inclusions

Tight sandstone gas reservoirs refer to those natural gas reservoirs that were developed in sandstones characteristic of low porosity (<12%), low permeability (0.1×10^{-3} μm^2), low gas saturation (<60%) but high water saturation (40%), in which gases flow slowly[1]. There are tight sandstone gas reservoirs almost in all oil and gas bearing areas in the world with tremendous gas reserves. It is estimated that the gas reserves that can be produced by existing technique in tight sandstones are up to $(10.5-24)\times 10^{12}$ m^3, which rank the first in all unconventional gases[2]. Tight sandstone gas reservoirs occur widely in China, such as in the Sichuan Basin, Ordos Basin, Turpan Basin, Songliao Basin, south of Junggar Basin, southwest of Tarim Basin, Chuxiong Basin and East China Sea Basin[3]. The genetic mechanism of tight sandstone gas reservoirs is very complicated and poses difficulties for field exploration. What made the reservoirs tight? When were the reservoirs tight? Is it earlier or later than the peak of hydrocarbon generation?

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Alternatively, is it bleeding out of source rocks in thermal evolution? Answering these questions is critical for a better understanding of the quality, distribution, and exploration potential of the tight sandstone gas reservoirs.

The quality of reservoirs may be influenced by many factors. For example, the depositional environments of sedimentary basins control the clastic components, textures and primary pores[4]. The diagenesis of reservoirs is a complicated geochemical process, controlled by tectonic evolution, deposition, mineral composition, nature of heat fluids, and fluid migration, etc. Among these, the interaction between minerals and fluids in pores, later fluid movement, and depositional positions are the most important[5−13]. The movement of fluids is the key factor to diagenesis, and its research includes the recovering of ancient fluids according to reaction between water and rocks and diagenetic quantification. Studies on fluids since the 1990s have made it clear that fluids contribute greatly to the formation of large and extra mineral deposits in the world. Recently, with advancements in oil and gas geological research, the relationship between fluid dynamics and formation of oil and gas reservoirs has attracted more and more attention[14−16]. Previous studies on the function of ancient fluids to diagenesis were mostly based on the current local water analytical data, but it is known that current field water has been changed greatly by later events and may not represent the characters of ancient fluids. Yet temperature measurement and composition analysis of fluid inclusions, trace element and isotope analysis of authigenic minerals can be used to determine the attributes of ancient fluids and paleogeothermal gradients, which are helpful to recover diagenetic environments and ancient fluid velocities and to derive fluid flow models[17−28].

The oil and gas exploration of the Upper Triassic Xujiahe Formation in Sichuan Basin started in 1940s. Since then, Zhongba, Pingluoba, Bajiaochang, Guangan gas fields have been founded, and numerous important gas-bearing structures with a favorable exploration prospect also have been discovered in Zhebachang, Laoguanmiao, Anyue-Tongxian, Tongnan, etc.[29−31] The Xujiahe Formation had experienced strong diagenesis, buried under 2000—5200 m and contains reservoirs of low porosity and low permeability, or lower porosity and lower permeability. What made them so tight? When were they tightened? Are rocks tight before reservoirs formed or reservoirs formed before rocks being tightened? This paper will discuss the alternating tendency of anion concentration and the evolution of ancient fluids by measuring ancient temperatures and testing anion concentration of inclusions from different intervals of the Xujiahe Formation in different areas of the Sichuan Basin. The goal of this research is to build a model for fluid evolution that may help to understand the genetic mechanism of tight reservoirs in general.

1 Geological background

The Sichuan Basin is a tectonic and landform rhombus basin, bounded by the Longmenshan Fault in the west, the Qiyaoshan Fault in the east, the Chenggou Fault in the north, and the Emei-Washan Fault in the south. The area of Sichuan Basin is about 180000 km^2. To the west, there are Longmenshan thrust nappe belt and Songpan-Ganzi fold belt. To the north, there is Micangshan-Dabashan thrust nappe belt that belongs to the Qinlin tectonic belt. Four secondary tectonic units are divided in Sichuan Basin, i.e., including the west Sichuan depressing zone, the northeast Sichuan depressing zone, the east Chongqing-southeast Sichuan depressing zone, and the central Sichuan uplift zone. These structures form the basin characterized by one uplift surrounded by three depressions. This structure had controlled the paleolandform of the Sichuan Basin from Late Triassic to Early Cretaceous and also the formation of oil and gas[29,31,32] (Figure 1). The Late Triassic Xujiahe Formation has been divided into six members (T_3x^1–T_3x^6), comprised of yellow to gray conglomerates, pebbled sandstones, sandstones, siltstones and mudstones with coal bench. On the vertical profiles, sandstones and mudstones usually form rhythmic layers with the thickness varying from hundreds to nearly one thousand meters[33,34]. Except the first member in which alternating terrestrial and marine deposits were developed, the other members of the Xujiahe Formation consists entirely of terrestrial deposits. From the basin margins to the depocenter, there are alluvial fan facies, fan delta facies, fluvial facies, fluvial delta facies and lake facies (Figure 2).

2 Sample distribution and testing methods

All samples are collected from the bore holes, including

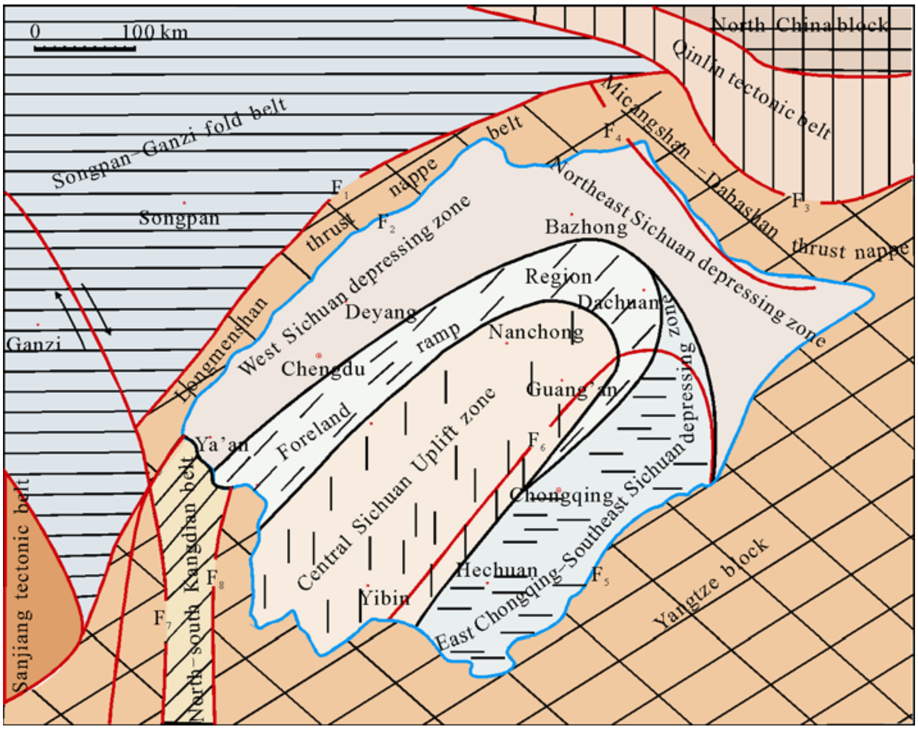

Figure 1 Tectonic map of Sichuan Basin. F_1, Longmenshan Fault; F_2, Pengguan Fault; F_3, Chengkou Fault; F_4, Wuxi-Tiexi Fault; F_5, Qiyaoshan Fault; F_6, Huayinshan Fault; F_7, Xiaojiang Fault; F_8, Puxiong Fault.

Zhong 46, Zhe 2, Long 9, Jiao 42, Pingluo 3, Qiongxi 1, Ping 1 in west, and Yue 2, Hechuan 1, Chongsheng 2, Xiandu 1, Ying 21, Guangan 1, Guangan 101, Guangan 102, Guangan 106, Guangan 109, Guangan 5, Guangan 13, Guangan 14, Guangan 15, Guangan 16, Guangan 18 in central and south (Figure 3). Among these, most samples are from the second, fouth and sixth members of the Xujiahe Formation. Petrographic observations are used to identify clastic compositon, paragenetic sequence of authigenic minerals, and characters of pore textures. Petrographic observation is aided by SEM (Scanning Electron Microscope), cathode luminescence, X-diffraction, carbon and oxygen isotope of carbonate cements to define the diagenetic evolution After that, representative samples were selected to measure homogenization temperatures of inclusions and analyze their compositions. The testing instrument is JY-1000 micro-laser Raman spectroscopy, the wavelength of laser is 514.532 nm, the diameter of beam spot is 1—5 μm, and the testing time is 30 s.

3 Petrography of the Xujiahe Formation reservoirs

Sandstones of the Xujiahe Formation have low compositional maturity, low cement contents and medium textural maturity. The compositional maturity is generally 0.32—2.45 with the highest value of 6.14. Quartz contents usually are 24%—70% with the highest of 86%. Feldspar contents usually are 0.5%—18%. Lithic fragments usually are 12%—65% with the highest of 75.5%. Lithic clasts consist mainly of volcanic rocks and metaquartzites, with minor sedimentary rocks and low-grade metamorphic rocks. The reservoir sandstones are grain supported. Grains are well to medium sorted, with subrounded shapes. Muddy matrix contents are less than 2%, and cements are mostly 5%—6% with the highest of 15%. The cements are mainly composed of chlorites, silica, (ferro) calcites, (ferro) dolomites and micritic siderites. The chlorites, silica and calcites may significantly affect the reservoir's physical properties.

4 Diagenetic sequence of the Xujiahe Formation reservoirs

Diagenesis is an important factor controlling the quality of reservoirs. The Xujiahe Formation had experienced a series of diagenetic events in its long geological history, such as mechanical compaction, pressure dissolution, cementation, dissolution, etc., which caused its obvious

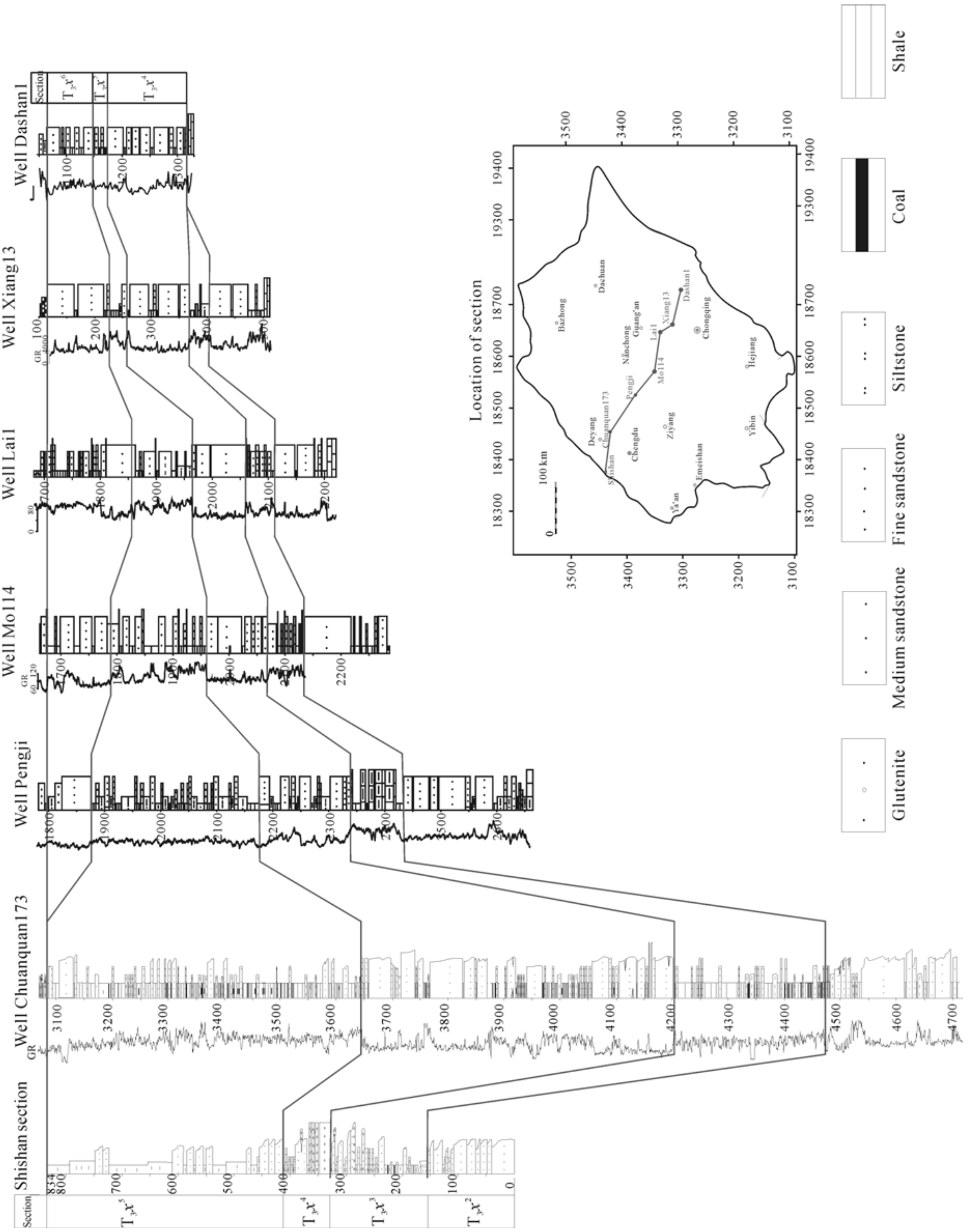

Figure 2 NW-SE sections of Xujiahe Formation in Sichuan Basin.

heterogeneity.

Mechanical compaction and pressure dissolution had important influences to the diagenetic history in the area. In the early diagenetic stage, mechanical compaction solidified sediments and caused the lose of intergranular pore spaces. After compaction, clastic grains changed from uncontact to point contact, and further to lineal contact. In the middle diagenetic stage, the mechanical compaction further compacted the secondary pores produced at period A of the middle diagenetic stage. During

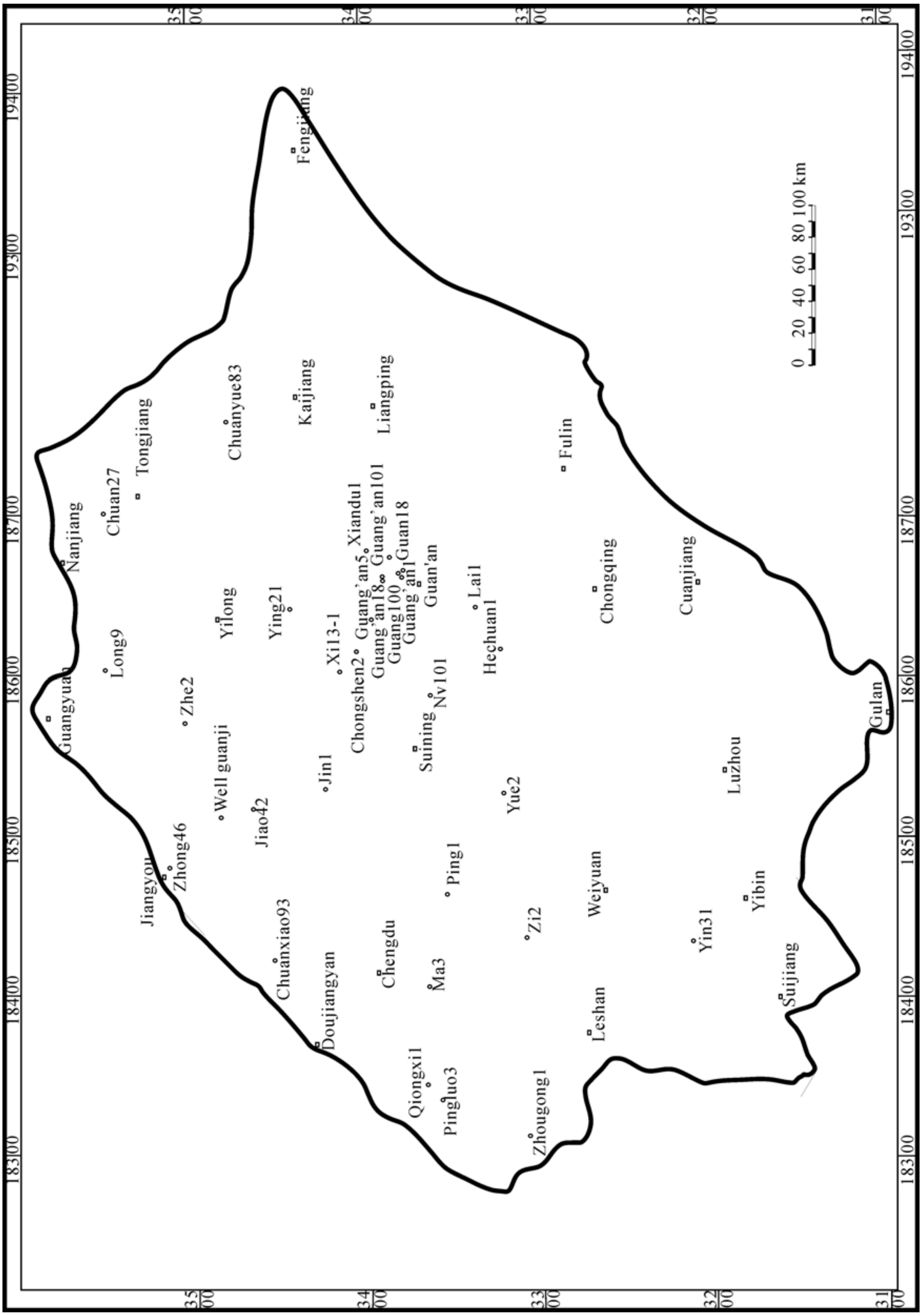

Figure 3 Location of important boring wells in Sichuan Basin.

this diagenetic stage, grain contacts formed concave-convex lines and occasionally, sutures. For example, multiple twins in lithic fragments and plagioclase were bended and fractured, and contacts between quartze grains formed microstylolites. Cementation were weak in general, with an average of 5%−6% and the

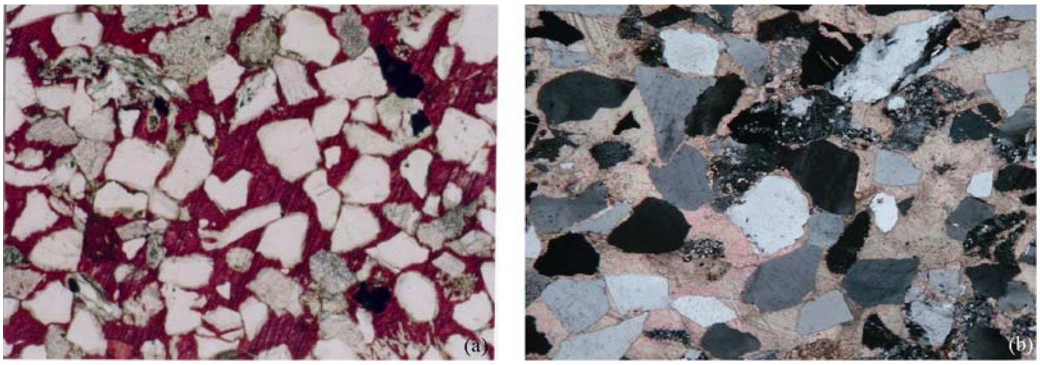

Figure 4 Calcite-cemented sandstones. (a) Well Guangan 101 (2223.69 m, T_3x^4, plane polarized light, ×50, stained-red); (b) Well Chongshen 2 (2227.65 m, cross-polarized light, ×50).

highest of 15%. The cements are mainly silica, chlorites, siderites, calcites, ferro calcites, dolomites and ferro dolomites, and minor kaolinites in some areas. Among these, silica, chlorite and calcite are the most common comments and have the most important influences on the reservoir's physical properties.

Pressure dissolution had constructive influences on the porosity of reservoirs in the area. Usually feldspar and volcanic clasts were dissolved. Present pores in reservoirs are mainly intragranular dissolved pores, with subordinate intergranular dissolved pores, muddy micropores, and localized intergranular pores.

A paragenetic sequence based on the textures and mineral compositions is identified as: early calcites (or micritic siderites) →first quartz overgrowth→chlorite coatings→dissolution of feldspars and lithic fragments →chlorite linings→ second quartz overgrowth (quartz widen or filled in remaining intergranular pores and solution pores)→dissolution→third quartz overgrowth (quartz filled in intergranular and intragranular solution pores)→intergrowth (ferro) calcites→dolomites→ferro (calcites) dolomites→later dissolution→quartz and calcite veins.

5 Composition and evolution of diagenetic fluids in Xujiahe Formation

5.1 Early calcite cements

Calcareous sandstone interbeds and calcite-cemented sandstones in the Xujiahe Formation of the Sichuan Basin have the following characteristics. (1) Calcites appear either as carbonate clasts (Figure 4) or as intergrowth cements fill in primary pores. In calcite-cemented sandstones, except of minor muddy infills, there is no quartz overgrowth. This phenomenon suggests that calcite cements were formed before the main compaction stage. (2) Feldspars were dissolved but no calcites filled in pores formed by feldspar dissolution, indicating that calcite cements were formed before feldspar dissolution. (3) The contents of calcite cements are closely related to the grain sizes and clastic compositions. Statistics of 47 calcareous sandstone samples from 7 wells in the area show that the carbonate contents vary from 15%—35%, with an average of 23.17%. Samples with high carbonate contents are mainly from siltstones, fine- to medium-grained sandstones, and conglomerates with high percentage of carbonate clasts. (4) There are little fluid inclusions in calcite cements and, when present, they are mainly liquid inclusions of a single phase. Laser Raman Spectroscopy of fluid inclusions shows that the mineralizing fluids are composed of carbonates without organic constituent, indicating that organic matter had not become mature at that time. (5) Calcite cements have not been dissolved since their formation.

Therefore, it is concluded that the calcite cements were formed during early diagenetic stage before burial compaction. The precipitation of calcites in early diagenetic stage was likely related to hydration of (aluminum) silicate minerals. For example, the sericitization of feldspars and decoloration of dark minerals observed in thin sections are all relevant to the hydration. Hydration increased the pH of fluids in pores, making the fluids more alkaline and providing metallic ions, such as Fe^{2+}, K^+, Na^+, Ca^{2+}, Mg^{2+}, etc. The hydration also provided the chemical conditions favorable for siderite formation in the early diagenetic stage.

5.2 Chlorite coatings

Although chlorite cements are present only in some samples of the Xujiahe Formation and their contents are normally less than 1%－3%, they are important to the reservoir quality. Observed under the microscope, the chlorite coatings have the following attributes. (1) Fibrous chlorites grow perpendicular to mineral grains or distribute among siliceous cements of two generations and form coatings on grains. The coatings usually are oriented and have identical thickness (Figure 5). (2) The chlorite coatings usually are 3－5 μm thick. There is no chlorite coating formed when clasts are in point-to-point contact and few are observed when grains are in linear contact. This indicates that chlorites were formed after compaction in the early diagenetic stage. (3) There are little impure matrix and soft debris in samples with chlorite coatings. (4) There are little early calcite cements in samples with chlorite coatings. This indicates that the growth of early calcite cements in intergranular pores may have occupied the pore space, preventing chlorite precipitation. (5) High and low quartz contents are unfavorable to form chlorite coatings. Too high quartz contents mean that there is little materials for chlorite growth because quartz grains could widen significantly to prevent chlorite cementation. Too low quartz contents mean that the rocks had been compacted tightly and left no intergranular pore space for chlorite growth. (6) The chlorite coatings are most abundant in sandstones mainly composed of igneous clasts (>17%). This is because igneous clasts were more resistant to compaction (providing required growth space) and compositionally more favorable for chlorite precipitation.

Chlorite coatings must have formed after mechanical compaction had made clastic grains contact each other (point-to-point and linear). Little change in the volume of pore spaces in rocks has happened after the formation of chlorite coatings. The chlorite coatings should have formed before most of the feldspar dissolution. It is common that feldspars were dissolved partly or completely, leaving molded pores where chlorite coatings are still present. This suggests that the formation of chlorite coatings not only protected primary intergranular pores but also protect secondary pores formed by feldspar dissolution. Chlorite coatings inhibited quartz grain overgrowth by inhibiting authigenic quartz nucleation. The presence of localized quartz cements in some chlorite-bearing sandstones indicates that quartz overgrowth was not exclusive. Chlorite growth may have lasted to the early periods of the late diagenetic stage or even later. Once chlorite coatings were formed, continuous chlorite growth on the surface of original chlorites may be easier[35,36]. Only when chlorite coatings grew to certain thickness, they can inhibit quartz overgrowth. In samples without chlorite coatings, quartz

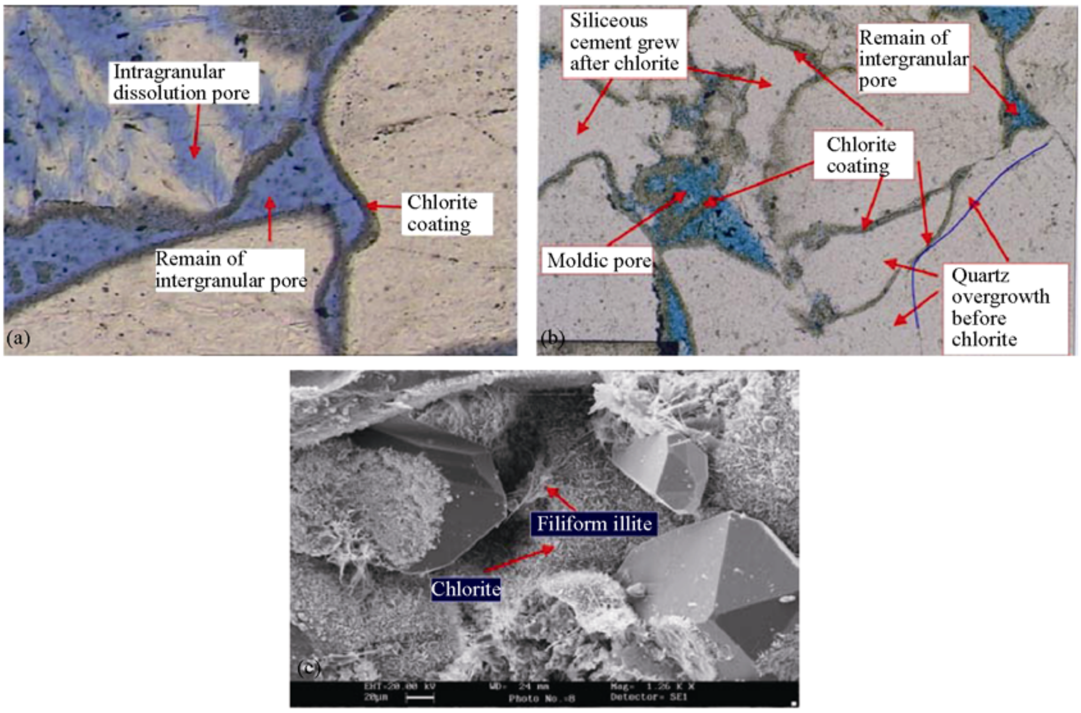

Figure 5 Chlorite cements and coatings in sandstone. (a) Well Guangan 101 (2061.21 m, T_3x^6 , plane polarized light, ×100); (b) Well Guangan 1 (1928.00 m,T_3x^4, plane polarized light, ×100); (c) Well Guangan 101 (2081.2 m, T_3x^6 , SEM, ×1260).

overgrowth usually reaches the third or even fourth generation.

One additional point is that chlorite formation is commonly associated with high Fe concentration. It is also observed that chlorite coatings are more common in sandstone with high percentage of volcanic clasts. This indicates that alteration of volcanic materials may have provided cations for chlorite formation. Ferric ions may react with mud in rocks to form chlorites through the following process:

$$\underset{\text{ferro volcanics}}{4Fe^{2+}+2Mg^{2+}}+\underset{\text{mud}}{3Al_2Si_2O_5(OH)_4}+9H_2O=\underset{\text{chlorite}}{Fe_4Mg_4Al_6Si_6O_{20}(OH)_{16}}+14H^+$$

Temperature may have also been important for chlorite formation. Examples have shown that the threshold temperature for chlorite precipitation is 90－120℃. The chlorites in the Xujiahe Formation were formed after the first quartz overgrowth and before feldspar dissolution, which may have lasted from period B of the early diagenetic stage to period A of the middle diagenetic stage.

5.3 Quartz cements and their fluid inclusions

Quartz overgrowth is very common in sandstones of the Xujiahe Formation, normally with a thickness of 0.05－0.3 mm. Two generations of quartz widening and two types of authugenic quartz can be observed, indicating their formation in different diagenetic stages. The first quartz overgrowth only forms thin edges or amorphous crystal faces on quartz grains (Figure 6(a)) and is packaged by chlorite coatings, indicating that they were formed before chlorite coatings. Inclusion analyses indicate that their formation temperatures are 60.3－79.4℃, with an average of 73.9℃. The second quartz overgrowth is common, expressed as amorphous shapes or small quartz crystals (Figure 6(b)). The homogenization temperatures of inclusions are 79.9－110.9℃, with an average of 92.9℃. The third quartz overgrowth appears as mosaic with contacts along sutures where automorphic crystal faces disappeared. The homogenization temperatures of inclusions are 83.3－147.5℃, with an average of 100.4℃. The second and third quartz overgrowths were developed after chlorite coatings. The fourth quartz overgrowth mainly appear in veins with homogenization temperatures of inclusions of 125.9℃ (Table 1).

The inorganic compositions of fluid inclusions in quartz cements are similar, as tested by Laser Raman spectroscopy (Table 2), with the except of salinities. This suggests that that the inorganic composition of diagenetic fluids remained similar during silica precipitation and the diagenetic fluids may have come from a single source. No organic material is found in inclusions of the first quartz overgrowth, but abundant organics are found in inclusions of the second and third quartz overgrowths. This indicates that hydrocarbon was immature and was notdecomposed during the first quartz overgrowth, and there was no hydrocarbon migration in fluids. The organic matter had become mature and hydrocarbon had been formed when the second quartz overgrowth happened. Gaseous hydrocarbon entered the reservoirs with fluids. The contents of gaseous hydrocarbon of inclusions in the third quartz overgrowth are obviously higher than those of inclusions in the second quartz overgrowth, indicating that it was the peak time of hydrocarbon generation and migration during the third quartz overgrowth. At that time oil and gas extensively migrated and entered the reservoirs, and the sandstones of the Xujiahe Formation became hydrocarbon gas reservoirs.

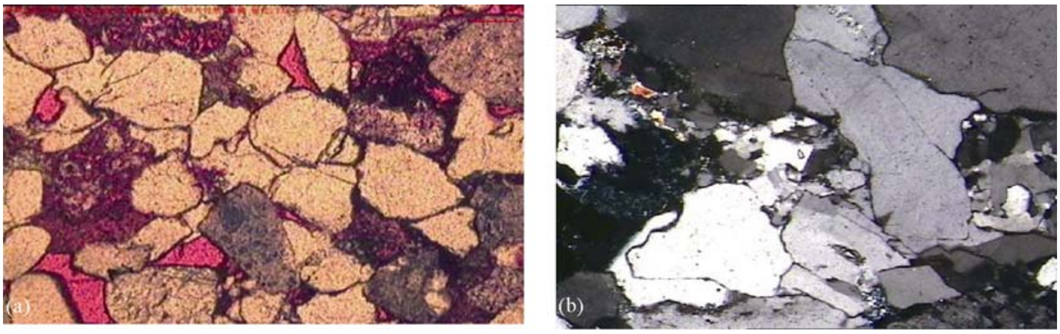

Figure 6 Quartz overgrowth in sandstone. (a) Well Chongshen 2 (2231 m, first quartz overgrowth, plane polarized light , ×50); (b) Well Qiongxi 1 (4201 m, the second quartz overgrowth, cross-polarized light , ×100).

Table 1 Homogenization temperatures of inclusions of Xujiahe Formation in Sichuan Basin

Well	Depth (m)	Horizon	Host minerals	Type	Homogenization temperature (℃)	Well	Depth (m)	Horizon	Host minerals	Type	Homogenization temperature (℃)
Guangan 18	2143.86	T_3x^6	third quartz overgrowth	primary	103.6	Long 9	3482	T_3x^2	calcite cements	primary	105.8
Guangan 16	2358.86	T_3x^6	first quartzovergrowth	primary	79.4	Long 9	3543.2	T_3x^2	second quartz overgrowth	primary	102.5
Guangan 102	1979	T_3x^6	first quartzovergrowth	primary	76.5	Long 9	3543.2	T_3x^2	third quartz overgrowth	primary	120.8
Chongshen 2	2228.88	T_3x^4	second quartzovergrowth	primary	80	Long 9	3486	T_3x^2	second quartz overgrowth	primary	94
Chongshen 2	2230.7	T_3x^4	first quartzovergrowth	primary	74.9	Long 9	3486	T_3x^2	third quartz overgrowth	primary	108.8
Qiongxi 1	4176.04	T_3x^2	third quartzovergrowth	primary	83.3	Zhe 2	4172	T_3x^2	dolomite cements	primary	92.9
Qiongxi 1	4178	T_3x^2	third quartzovergrowth	secondary	93.7	Zhe 2	4172	T_3x^2	dolomite cements	primary	84.9
Qiongxi 1	4178	T_3x^2	third quartzovergrowth	primary	100.9	Zhe 2	4172	T_3x^2	dolomite cements	primary	93.3
Qiongxi 1	4178	T_3x^2	third quartzovergrowth	primary	102.3	Zhe 2	4172	T_3x^2	calcite cements	primary	86.6
Qiongxi 1	4178	T_3x^2	first quartzovergrowth	primary	78.9	Zhe 2	4172	T_3x^2	calcite cements	primary	86.6
Qiongxi 1	4201.95	T_3x^2	second quartz overgrowth	primary	79.9	Zhe 2	4172	T_3x^2	calcite cements	primary	92.4
Qiongxi 1	4202	T_3x^2	second quartzovergrowth	primary	89	Zhe 2	4192.1	T_3x^2	first quartz overgrowth	primary	76.4
Qiongxi 1	4206.81	T_3x^2	second quartzovergrowth	primary	92.7	Zhe 2	4365	T_3x^2	first quartz overgrowth	primary	75.6
Qiongxi 1	4233	T_3x^2	second quartzovergrowth	primary	94.7	Zhe 2	4401.2	T_3x^2	second quartz overgrowth	primary	83.4
Qiongxi 1	4233	T_3x^2	second quartz overgrowth	primary	81.9	Zhe 2	4406.9	T_3x^2	second quartz overgrowth	primary	84.3
Qiongxi 1	4247.07	T_3x^2	second quartz overgrowth	primary	100.4	Zhe 2	4451.9	T_3x^2	second quartz overgrowth	primary	87.9
Qiongxi 1	4276	T_3x^2	late fracture	secondary	81.2	Zhe 2	4451.9	T_3x^2	first quartz overgrowth	primary	77.8
Qiongxi 2	3795.91	T_3x^2	quartz veins	primary	125.9	Hechuan 1	1928.67	T_3x^5	calcite veins	primary	112.9
Yue 2	1808.7	T_3x^6	third quartz overgrowth	primary	89.9	Hechuan 1	1929.26	T_3x^5	calcite veins	primary	120.7
Yue 2	1808.7	T_3x^6	second quartz overgrowth	primary	108.3	Hechuan 1	1929.26	T_3x^5	calcite veins	primary	121.8
Yue 2	1815.37	T_3x^6	calcite cements	primary	105.6	Hechuan 1	1929.26	T_3x^5	calcite veins	primary	135.8
Yue 2	2111.88	T_3x^4	first quartz overgrowth	primary	60.3	Hechuan 1	2158.37	T_3x^2	first quartz overgrowth	primary	75.1
Yue 2	2111.88	T_3x^4	second quartz overgrowth	primary	89.3	Hechuan 1	2158.37	T_3x^2	second quartz overgrowth	primary	83.8
Yue 2	2111.88	T_3x^4	second quartz overgrowth	primary	83.7	Hechuan 1	2158.37	T_3x^2	second quartz overgrowth	primary	97.2
Yue 2	2111.88	T_3x^4	second quartz overgrowth	primary	88.1	Hechuan 1	2156.01	T_3x^2	second quartz overgrowth	primary	80.6
Yue 2	2111.88	T_3x^4	second quartz overgrowth	primary	95.5	Hechuan 1	2156.01	T_3x^2	second quartz overgrowth	primary	95.6
Yue 2	2190.72	T_3x^4	second quartz overgrowth	primary	89.9	Hechuan 1	2156.01	T_3x^2	second quartz overgrowth	primary	101.7
Yue 2	2190.72	T_3x^4	second quartz overgrowth	primary	105.6	Hechuan 1	2151.97	T_3x^2	calcite cements	primary	100.7
Yue 2	2190.72	T_3x^4	second quartz overgrowth	prim-ary	110.9	Hechuan 1	2123.16	T_3x^2	first quartz overgrowth	prim-ary	62.5
Yue 2	2190.72	T_3x^4	first quartz overgrowth	primary	80.6	Jiao 42	3453.56	T_3x^2	second quartz overgrowth	primary	97.1
Long 9	3452	T_3x^2	first quartz overgrowth	primary	74	Jiao 42	3453.56	T_3x^2	second quartz overgrowth	primary	105.4
Long 9	3474.2	T_3x^2	second quartz overgrowth	primary	96.2	Jiao 42	3455.71	T_3x^2	first quartz overgrowth	primary	68.9
Long 9	3482	T_3x^2	dolomite cements	primary	81.5	Jiao 42	3479.82	T_3x^2	second quartz overgrowth	primary	95.1

Table 2 Testing results of fluid inclusions in different quartz overgrowth in sandstone reservoirs in Xujiahe Formation by Laser Raman spectroscopy

Well	Depth (m)	Position	Stage	SO_4^{2-}(%)	NO_3^-(%)	HCO_3^-(%)	CO_3^{2-}(%)	CO_2(%)	SO_2(%)	C_3H_8(%)	CH_4(%)	C_2H_6(%)	Salinity (%)
Qiongxi 1	4247.07	T_3x^2	first	0.10	0.65	0.75	0.27	2.17					3.94
Chongshen 2	2230.70	T_3x^4	first			0.33	0.40	1.07					1.80
Yue 2	2111.88		first			0.96	0.65	0.68			0.21		2.50
Guangan 102	1979.00	T_3x^6	first	0.21		0.80		0.87	0.73				2.61
Qiongxi 1	4178.56	T_3x^2	second			6.56	2.93	2.54			0.36	1.91	14.3
Qiongxi 1	4201.95		second			0.54	0.88	0.27			0.35	0.69	2.73
Qiongxi 1	4233.69		second								1.68		1.68
Long 9	3543.20		second	0.41	0.43	0.28	0.28	0.77					2.18
Chongshen 2	2228.88	T_3x^4	second				0.00	0.29		0.16	0.18		0.63
Yue 2	2111.88		second				0.49	0.71			2.30	4.56	8.06
Guangan 16	2358.86	T_3x^6	second	0.13	0.16		0.40	0.74			0.99		2.42
Guangan 18	2143.86		second	0.26	0.93		3.75				1.02		5.97
Yue 2	1808.70		second		0.29	0.46	0.26	2.12			0.11		3.25
Qiongxi 1	4176.04	T_3x^2	third		0.00	2.93	0.79	2.26	0.00		2.01	5.91	13.90
Qiongxi 1	4178.56	T_3x^2	third		0.00	0.65	0.64	0.00	1.29		1.45	3.54	7.57
Long 9	3474.20	T_3x^2	third	0.23	0.14	0.61	0.89	0.31	0.00		8.48		10.66
Guangan 18	2143.86	T_3x^6	third				0.60	0.32			1.66	8.22	10.80

Diagenesis of clastic rocks in the Xujiahe Formation is characterized by compaction before chlorite coatings. So the first quartz overgrowth should be the results of diagenetic compaction of period B in the early diagenetic stage and caused by pressure dissolution of existing quartz grains. The presence of organic matter in the inclusions of the second and third quartz overgrowth suggests that organic matter had existed in diagenetic fluids by that time. Hydrocarbons generated from mudstone source rocks in the Xujiahe Formation entered the sandstone reservoirs. The diagenetic fluids rich in organic acid caused feldspar dissolution and formed aluminosilicates, which migrated later in form of complex organic compounds. This in turn increased the feldspar solubility and promoted quartz cement precipitation through the following process:

$$\underset{\text{feldspar}}{2KAlSi_3O_8}+\underset{\text{ethanoic acid}}{2CH_3COOH}+9H_2O$$
$$=\underset{\text{kaolinite}}{Al_2Si_2O_5(OH)_4}+2K^++\underset{\text{quartz}}{SiO_2}+\underset{\text{organic material}}{2CH_3COO^-}$$

Therefore, the silica cements in the second and third quartz overgrowth were sourced dissolution of feldspars and may have formed from period B of the early diagenetic stage to period A of middle diagenetic stage. During the later stage, quartz may have the source partly from pressure dissolution of existing quartz grains.

5.4 Late carbonate cements and fluid inclusions in veins

Except the early carbonate cements, there are minor ferron calcite and dolomite cements in reservoirs. Less than 2% of patchy ferron calcite cements usually fill in intergranular and dissolution pores, in cases alternating with remains from corrosion of feldspar and silica. Dolomites usually appear as rhombus crystals overprinting early carbonate cements. They may have formed during deeper burial through local Mg concentration from internal sources (dissolution of clasts and earlier cements), most likely at period B of the middle diagenetic stage. The ferron calcites are distributed as spotted forms and they have been seen to alternate with siliceous cements and feldspars (Figure 7), which indicates that they were formed at period B of the middle diagenetic stage and the alternation took place in the same time when calcite cements were formed.

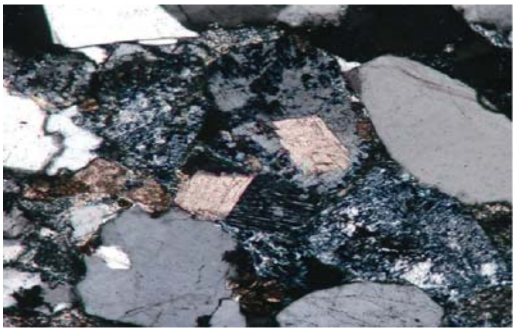

Figure 7 Ferro dolomites alternated feldspars. Well Qiongxi 13-1 (2450.87 m, cross-polarized light , ×100).

The homogenization temperatures of inclusions in ferron calcites and dolomites are 81.5－105.8℃, with an average of 93.03℃, and their salinities are as high as

9.4%−18.07%. Inclusions are rich in organic compositions (Table 3), thus it is concluded that the diagenetic fluids at that time had high salinity and were rich in organic acid. Laser Raman spectroscopy shows little difference in inorganic compositions of fluid inclusions between carbonate cements and quartz overgrowths. This indicates that the reservoir sandstones in the Xujiahe Formation was a close system without external fluid mixing at that time, and the increased salinity and organic compositions may have been caused from progressive dissolution of feldspars and other volcanic clasts. The ferron dolomites commonly have a lower percentage in rocks (< 1%) and appear as rhombus crystals. They usually occupy the space formed by feldspar dissolution, likely have the Mg source from feldspar (especially plagioclases) dissolution and clay mineral transforming.

There are usually calcites and/or quartzes filled or semi-filled in cracks in the Xujiahe Formation with the forming temperatures up to 120℃, and there are CO and H_2S in fluid inclusions of veins (Table 3), which do not appear in inclusions of diagenetic cements. These indicate that there might be external fluid mixing when these veins formed. Moreover, the organic compositions of saline inclusions in veins are high and there were abundant gaseous hydrocarbon inclusions in veins. These may indicate that the evolution of the Xujiahe Formation had reached the peak hydrocarbon generation so that abundant organic materials entered reservoirs.

6 Discussion on the porosity changes and origin of tight reservoirs

Statistics from more than 36000 samples collected from 200 wells and 20 field profiles show that the average porosity of reservoirs in the Xujiahe Formation is 4.77%, with the lowest of 0.1% and highest of 18.27%. The mean permeability is 0.19×10^{-3} μm^2, with the lowest $< 0.001\times10^{-3}$ μm^2 and highest $> 50\times10^{-3}$ μm^2 (when cracks developed). In general, the physical properties of reservoirs are poor, with low porosity and low permeability or lower porosity and lower permeability.Reservoirs with medium porosity and low permeability are present only locally. The correlation between porosity and permeability is low, with R^2 of 0.27, which indicates that the permeability is not only related to the amounts of total pores but also controlled by pore structures and cracks.

Based on the evolution of pores discussed above and tectonic evolution and hydrocarbon generation history in this area, the genetic mechanism of tight reservoirs in the Xujiahe Formation is discussed as follows.

It is measured that the values of vitrinite reflectance (R_o) of samples collected from different cores in the Sichuan Basin are 0.71%−1.62%. The clay minerals are illites, chlorites, mixtures of illites and smectite, and kaolinites determined by X-diffraction analysis. The contents of illites are 17%−85% with an average of 58.2%. The contents of chlorites are 0−73% with an average of 24.5%. The mixtures of illite and smectite are 2%−65% with an average of 14%, among which smectites are commonly lower than 15%. The contents of kaolinites are 1%−51% with an average of 7.5%, which are mainly distributed in western Sichuan. The illites usually were filamentous and filiform and the chlorites usually were lamelliferous observed under Scanning Electron Microscope. Therefore, the clastic reservoirs of

Table 3 Testing results of fluid inclusions in carbonate cements and veins in sandstone reservoirs in Xujiahe Formation by Laser Raman spectroscopy

Well	Depth (m)	Position	Host minerals	SO_4^{2-}(%)	NO_3^-(%)	CO_3^{2-}(%)	SO_2(%)	HCO_3^-(%)	CO_2(%)	CO(%)	H_2S(%)	CH_4(%)	C_2H_6(%)	Salinity (%)
Qiongxi 1	4201.95	T_3x^2	calcite cements			2.20			3.11					5.31
Qiongxi 1	4233.69			2.78		2.33		2.34				1.81		9.25
Long 9	3482.00			0.59	1.25	0.92		0.56	1.02			0.40		4.74
Pingluo 3	3659.30			4.50		3.99	3.12	5.85	4.95			3.87		26.27
Zhe 2	4172.00				2.24	1.25		2.11	3.18			0.36		9.13
Yue 2	2058.19	T_3x^4		1.07	1.59			3.35	0.92			1.07		8.00
Yue 2	1815.37	T_3x^6		2.90		4.33		3.58	2.45			1.69	4.53	19.47
Long 9	3482.00	T_3x^2	dolomite cements	0.66		0.95		0.97				0.94		3.52
Hechuan 1	1928.67	T_3x^5	calcite veins	0.30	0.52	0.39		0.17	0.25			0.32		1.95
Hechuan 1	1929.26			0.53	0.58	1.32	0.59	0.00	0.73	0.17	0.25	0.25	2.10	6.51
Qiongxi 2	3795.91	T_3x^2	quartz veins	0.67	1.12	1.87		0.93	0.67			1.22	13.04	19.52

the Xujiahe Formation were formed mainly in period A-B of the middle diagenetic stage based on the PRC Petroligenic Natural Gas Profession Standard (SY/T5477-2003). The Xujiahe Formation experienced four diagenetic stages, namely penecontemporaneous and period A and B of the early diagenetic stage, and period A and B of the middle diagenetic stage. The accumulating ability of reservoirs in the Xujiahe Formation was controlled by many factors, such as deposition, diagenesis, tectonic action and filling of hydrocarbons.

6.1 Pore evolution during penecontemporaneous and period A of early diagenetic stage

The Xujiahe Formation in Sichuan Basin is a suite of terrestrial clastic rocks with low compositional maturity but high textural maturity. The grains in reservoir sandstones are mainly subangular to subrounded and medium sorted. It is demonstrated that the primary pores are not related to grain sizes but to sorting, according to artificial experiment of unconsolidated sand[37]. It has been estimated that he content of primary pores in Xujiahe Formation is about 34%. The detrital components controlled the physical properties of reservoirs. Statistics show that the physical property of reservoirs is poor when the content of quartz is lower than 35% (e.g. T_3x^6 of well Guangan 102) and higher than 75% (e.g. T_3x^6 of well Guangan 12). The physical property can also be poor when the content of feldspars is lower than 1% (e.g. T_3x^6 of well Guangan 102). The compressive resistance of debris especially plastic debris (such as epimetamorphic debris, muddy debris, and mica flakes) is the lowest. More fine-grained clasts and higher contents of plastic debris may lead to poorer physical property of reservoirs.

Period A of the early diagenetic stage appromately corresponds to a buried depth of 0—1000 m with the temperature lower than 50℃. During this stage, the main diagenesis was compaction, early carbonate and chlorite-hydromica cementation. The early calcite cementation took place in some place where pH value was high, especially in silt and fine-grained sandstones near the sediment/water interface. At these places the intergranular pores were small and exchanges between intergranular water was weak, which was easy to cause carbonate oversaturation and form intergrowth calcite cements. The intergrowth calcite cements eventually formed calcareous layers at some places. With increased buried depth and compaction, intergranular waters were squeezed out and the porosity decreased significantly. In general, medium-grained sandstones have higher resistance against compaction than fine-grained sandstones and siltstones. After the compaction made grains position relatively fixed, the chlorite-hydromica linings started to form. It can be observed on thin sections that chlorite-hydromica linings mainly distributed in megaclast rocks with better physical property. Till the end of this diagenetic stage, the porosity of reservoir sandstones of Xujiahe Formation in Sichuan Basin decreased to 11%—20%. The porosity of sandstones lack of chlorites linings in pores is 11%—16%, and the porposity of sandstones with chlorites lingings developed in pores is 17%—20%.

6.2 Pore evolution during period B of early diagenetic stage

This period corresponds to the buried depth of 1000—2000 m with R_o of 0.35%—0.5%. Along with the buried depth increased, sandstones were compacted continuously, which resulted in point-to-point or linear grain contacts. Pressure dissolution of quartz started and the first quartz overgrowth formed. Early silica cements distributed continuously along quartz grains like horse teeth, or in forms of narrow automorphic crystals and widen edges. They were formed before chlorites, and their contents were low as 0.5%—1%. At this period, the primary porosity decreased greatly. The physical properties of reservoirs became worse and most fine-grained sandstones and siltstones had become tight due to intensive compaction and pressure dissolution in sandstones lack of chlorite-hydromica linings, while there were partial primary pores preserved in medium-grained sandstones with chlorite-hydromica linings.These preserved pores became the pathway of later acidic water. Till the end of this diagenetic stage, the porosity of reservoir sandstones of the Xujiahe Formation decreased to 7%—16%. The porosity of sandstones lack of chlorites linings in pores is 7%—8%, and the porosity of sandstones with chlorites lingings developed in pores is 12%—16%. At the meantime, organic matter became mature gradually, and dissolvable components like feldspars began to dissolve when the pH value in pores decreased.

6.3 Pore evolution during period A of the middle diagenetic stage

This period corresponds to a buried depth of 2000—3500 m with R_o of 0.5%—1.3%. The temperatures increased with buried depth and acidic water rich in organic acid entered the reservoirs. Dissolved feldspars and volcanic clasts formed secondary pores. Dissolution by acidic water was the main diagenetic process during this stage. Silica in diagenetic fluids became oversaturated with continuous dissolution of feldspars and pressure dissolution of depositional quartz grains. The second and third quartz overgrowth reduced the porosity of tight sandstones. The second quartz overgrowth is inhomogeneously distributed around quartz grains and the third quartz overgrowth is mainly distributed in intergranular pores. The loss of intergranular pores may not have been caused by compaction but by the amounts of quartz overgrowth. Therefore, the great quantity of quartz overgrowth is an important factor to make sandstones tight in this area.

The development of secondary dissolution pores controlled the reservoirs' quality when the sandstones had already been tight. The dissolution capacity is related to to the source of acidic water and its migration pathway such as unconformities, sequence boundaries and fracture zones. The dissolution may have been more effective to unstable components, for example, feldspars and volcanic clasts. More primary intergranular pores would facilitate for the migration of acidic water, therefore more secondary pores from the dissolution of feldspars and volcanics would develop. Thus there is a intimate relationship between primary and secondary pores. The rocks buried deep in western Sichuan were in a long-term close system without changes in inorganic compositions of the diagenetic fluids. In this case, only feldspars and some volcanic fragments were dissolved while intergranular cements such as quartzes and carbonates did not dissolve. The porosity of tight sandstones of the Xujiahe Formation did not change significantly since their final closure by diagenetic cements. This is that the reason for the tightness of the sandstones of the Xujiahe Formation in western. The rocks in central and southern Sichuan were buried relatively shallow, and active dissolution occurred in depositional components and diagenetic cements, forming reservoirs with better quality. This period is also the formation time of diagenetic traps f. During this time, hydrocarbon generation reached the maximum and abundant oil and gas migrated and entered the reservoirs, as evidenced by the high percentage of organic matter in inclusions in cements of the second and third quartz overgrowth.

6.4 Pore evolution during period B of the middle diagenetic stage

This stage corresponds to buried depth lower than 3500 m with R_o of 1.3%—2.0%. Organic materials started to generate condensate oil and gas. The fluids in pores had little organic acid, and the intergranular water was (weakly) alkaline. The diagenetic fluids were oversaturated at this time. Feldspars were no longer dissolved, and (ferro) calcites and (ferro) dolomites were precipitated. This made the porosity and permeability of reservoirs decrease gradually and physical properties become worse. The final porosity of reservoir sandstones in Xujiahe Formation is 3%—12%. The porosity of sandstones lack of chlorites linings in pores is usually lower than 7%, while the porosity of sandstones with chlorites developed in pores is often higher than 8%, and in cases even higher than 10%.

7 Conclusions

In summary, mechanical compaction is the main factor to have made the sandstones of the Xujiahe Formation in the Sichuan Basin solidify and tight. The second and third quartz overgrowth is another important factor to make sandstones tight. In addition, the rocks in the Sichuan Basin were in a long-term, closed system, diagenetic fluids did not have significant changes through time and only feldspars and some lithic fragments were partially dissolved during diagenetic modifications. In contrast, intergranular cements such as quartzes and carbonates were stable, making no contribution to the porosity of sandstone reservoirs. This is the third factor to keep the sandstone reservoirs of the Xujiahe Formation tight. The major hydrocarbon generation from organic materials occurred after the second quartz overgrowth, and hydrocarbons entered favorable reservoirs selectively to form hydrocarbon gas reservoirs in tight sandstones.

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