Variations of sedimentary environment under cyclical aridification and impacts on eodiagenesis of tight sandstones from the late Middle Jurassic Shaximiao Formation in Central Sichuan Basin

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Abstract

Understanding eodiagenesis is essential to decoding the diagenetic pathways of tight sandstones that act as excellent unconventional oil & gas reservoirs. Great paleoclimate change is capable of influencing eodiagenetic processes of tight sandstones through variations of sedimentary environment. However, it is less noted how climate gradients between the greenhouse and the hothouse conditions impact the eodiagenesis of tight sandstones. We examined eodiagenetic processes that has been operated in the Shaximiao Formation sandstones using petrographic observation, scanning electron microscopy, geochemistry, and XRD analysis to reveal impacts of the transitional climate changes on the differential eodiagenesis and implications for the diagenesis-porosity evolution. Based on sequence stratigraphy, the Shaximiao Formation is divided into four sub-members SXM1, SXM2, SXM3, and SXM4, respectively. Dark sandstones and mudstones mainly occurred in the SXM1 and the SXM2. Gray-green clastic rocks are dominant in the SXM3, whereas red mudstones frequently appear in the SXM4. Paleoclimate indices denote that a cyclical aridification from the warm-humid to hot-semiarid conditions took place from the SXM1 to the SXM4. It could have been caused by the megamonsoon effect and the paleogeographic shift along with the breakup of the Pangaea supercontinent. Combined with the migration of depocenters, the paleoclimate change resulted in transformation of sediment provenances from mafic igneous rocks to quartzose sedimentary rock along with the decreasing textural maturity. Therefore, sedimentary environments varied from the high-saline to low-saline and from low-oxygen to high-oxygen conditions respectively, which had a crucial impact on eodiagenetic cements which were formed in the Shaximiao Formation. Chlorite and laumontite cement precipitation was promoted by high-saline alkaline fluids. Chlorite proportions show an arched trend from the SXM1 to the SXM4, compatible with those of primary and secondary porosities. In contrast, laumontite proportions exhibit a decreasing variation from the SXM1 to the SXM4. High percentages of early cements are favorable to improving resistance to the compaction and preservation of primary pores. However, high chlorite (>5%) and laumontite (>10%) proportions are destructive for the reservoir quality. Large quantities of laumontite cements occupy primary pores and impede diagenetic

fluids flowing and are not favorable to the dissolution. By contrast, an excess of chlorite cements can be dissolved to produce secondary pores during the organic acid release. Thus, the SXM2 is potential as a reservoir for oil & gas. Therefore, those eodiagenetic cements can control the late diagenetic evolution and the reservoir quality. Observations made here have implications for understanding tight sandstone reservoirs elsewhere in the world.

Keywords: Eodiagenesis; Sedimentary environment; Aridification; Shaximiao Formation; Sichuan Basin; Middle Jurassic

1. Introduction

Diagenesis encompasses a broad range of physical, chemical and biological processes by which original sedimentary assemblages react with their interstitial pore fluids in an attempt to reach textural and geochemical equilibrium after deposition (Burley et al., 1985). These processes further control the densification and physical properties of sandstones as oil & gas reservoirs by compaction, cementation, replacement, and dissolution (Dos-Anjos et al., 2000; Higgs et al., 2007). For example, the compaction shortens space intervals among particles so that porosity and permeability decrease, being destructive for oil & gas reservoirs. In contrast, dissolution removes soluble minerals so that porosity and permeability increase, being constructive for oil & gas reservoirs. Eodiagenesis is an initial stage of diagenesis from the syn-deposition to the shallow burial (Worden and Burley, 2003), which is essential to understanding later diagenetic pathways of tight sandstones. The mechanical compaction and cementation are striking at the eodiagenetic stage, but their intensities are subject to lithological parameters (including grain components, size, sorting, and shape) and interstitial waters (covering salinity, pH value, and temperature) which are further influenced by the depositional system (Worden and Burley, 2003; Ajdukiewicz and Lander, 2010). Nevertheless, the depositional system is complex which is a composite result of paleoclimate conditions, sediment provenances, and relative sea-level fluctuations (Marenssi et al., 2002; Worden and Burley, 2003; Berra et al., 2010; Morad et al., 2010).

Paleoclimate condition is the most important factor for the depositional system, because climate change can influence not only continental weathering but also relative sea-level fluctuations (Stanev and Peneva, 2001; Le-Hir et al., 2009; Hessler et al., 2017). For instance, a humid and warm climate can strengthen chemical weathering in the presence of fine-grained sediments with soluble elements diluted. An arid and hot climate can weaken chemical weathering in the presence of coarse-grained sediments and melt glacier leading to sea-level rise, whereas a dry and cold climate will freeze seawater along with causing sea-level fall. These processes directly constrain variations of the sedimentary environment such as high energy, low energy, oxidation, reduction, and salinization (*e.g.* Clifton et al., 1971; Miall, 1977; Liu et al., 2022). Large numbers of previous studies suggest that multiple hyperthermal events occurred on the Earth, such as the Permian-Triassic boundary (PTB), the Toarcian Oceanic Anoxic Event (TOAE), and the Paleocene-Eocene thermal maximum (PETM) (Röhl et al., 2007; Suan et al., 2008; Joachimski et al., 2012). The abrupt climate change is generally linked to life evolution, mass extinction, and global tectonic events (Knoll et al., 1996; Sluijs et al., 2005; Röhl et al., 2007; Frieling et al., 2016), so they are research topics of international interest. Furthermore, paleoclimate changes and links to hydrocarbon resources have been investigated extensively (*e.g.* Hackley et al., 2016; Liu et al., 2018a; Xie et al., 2021). However, there is still less information on how climate gradients affect the eodiagenesis as well as late diagenetic evolution of tight sandstones acting as excellent unconventional oil & gas reservoirs. Hence further study is needed.

The Shaximiao Formation is a critical target for oil & gas explorations. It comprises tight sandstones and is extensively developed in the Sichuan Basin of the western Yangtze Block (Li et al., 2018; Zhang et al., 2020, 2021; He et al., 2023; Tan et al., 2023). It was deposited at the fluvio-lacustrine facies in the late Middle Jurassic Bathonian to Callovian epoch (Li et al., 2018; Zhang et al., 2021; Zhou et al., 2022). The Jurassic paleoclimate has been considered as a greenhouse climate with high atmospheric CO_2 concentrations (Hallam, 1993; Sellwood and Valdes, 2006). Nonetheless, a zonal climate pattern was still proposed (Fig. 1a; Dera et al., 2011; Boucot et al., 2013; Yi et al., 2019). The Chinese landmass was located on the northeast of the Pangea supercontinent at that moment and stayed in the arid-boreotropical zone (Fig. 1a). The Jurassic paleoclimate was further divided into five evolution stages for the Chinese landmass based on low-resolution fossil data, and the paleoclimate regionalization was distinct at each stage (Deng et al., 2017). The sub-humid climate gradually transitioned to the arid climate in the Sichuan Basin during the Jurassic period based on low-resolution paleontology, sedimentology, and fossil plants (Deng et al., 2017). However, paleoclimate changes in the late Middle Jurassic when the Shaximiao

Formation has been the subject of much debate with various interpretations have been described as warm-humid, semiarid, cold-dry, and dry-humid alternating paleoclimates (Kan et al., 2006; Wang et al., 2007; Cao et al., 2010; Qian et al., 2012; Li et al., 2022; Dai et al., 2022). Nonetheless we observe heterogeneous eodiagenetic variations in the Shaximiao Formation (Zhang et al., 2020; Tan et al., 2023; He et al., 2023). Such variations have hindered exploration and development for the oil and gas. Therefore, it is necessary to decode the causal mechanism of differential eodiagenesis of the Shaximiao Formation under the transitional climate change. We analyzed lithology, geochemistry, X-ray diffraction analysis, and scanning electron microscopy to explore variations of sedimentary environment of the Shaximiao Formation in Central Sichuan Basin. This contributed to our understanding of the differential eodiagenesis of tight sandstones and their implications for the diagenesis-porosity evolution.

2. Geological background

The Sichuan Basin is located in the western South China Block and close to the North China Block and the Tibet (Fig. 1b). The tectonic evolution of the Sichuan Basin can be divided into three stages including basement formation, cratonization and foreland basin formation (Liu et al., 2021). The foreland basin was transformed from the carbonate platform with a collision between Yangtze Block and North China Block in the Late Triassic. The Sichuan Basin underwent multi-stage tectonic movements since the Late Triassic, including the Indosinian, Yanshanian, and Himalayan orogeneses (Liu et al., 2021), which have generated multiple fold and fault belts. The Sichuan Basin is separated from the Songpan-Ganzi terrane by the Longmenshan fold belt to the west and from the Qinling Orogen by the Micangshan-Dabashan fold belt to the north, and it is bounded by the Qiyaoshan fold belt to the southeast and by the Daliangshan fold belt to the south (Fig. 1c). These structure belts have significant influences on the evolution of the Sichuan Basin (Liu et al., 2012). The Sichuan Basin is surrounded by ancient terranes with Precambrian basements except for the Songpan-Ganzi terrane (Fig. 1c; Li et al., 2018). The Songpan-Ganzi terrane formed by the convergence of North China, South China, and Qiangtang blocks in the Late Triassic is characterized by the exposure of 510-km-thick Late Triassic flysch and Mesozoic granitoids (Fig. 1c; Roger et al., 2010; Jian et al., 2019). Those Precambrian basement rocks are exposed mainly along the Longmenshan fold belt, Micangshan-Dabashan fold belt, and Jiangnan orogenic belt, which was reworked in the Paleozoic and Mesozoic tectonic events (Fig. 1c).

After the collision of Yangtze Block and North China Block in the Late Triassic, the Early Jurassic sedimentary facies are mainly the intracontinental lacustrine facies within the Sichuan Basin where dark mudstones and limestones have developed extensively (Liu et al., 2021). The fluvial and delta facies are dominant in the Middle Jurassic in the Sichuan Basin with thick red beds. Depocenters migrated from the Dabashan thrust belt to the Micangshan thrust belt in the late Middle Jurassic Shaximiao Formation due to the Yanshanian movement (Qian et al., 2015). The Shaximiao Formation overlies the Middle Jurassic Qianfoya Formation and underlies the Upper Jurassic Suining Formation, comprising interbedded siltstones and sandstones (He et al., 2023). The thickness of the Shaximiao Formation is >1000 m (Song et al., 2023), and further divided into two members by Estheria fossils, the lower Shaximiao Formation and the upper Shaximiao Formation (He et al., 2023). The lower Shaximiao Formation has a thickness of 290–400 m interval, and the upper Shaximiao Formation of more than 800 m (Song et al., 2023). The depositional thickness of the Shaximiao Formation increases from southwest to northeast, and the thickest succession was found at the front of the Micangshan-Dabashan fold belt (Liu et al., 2018b). Vertically, according to the sequence stratigraphic work of Liu et al. (2018b), the Shaximiao Formation was subdivided into four sub-members based on sequence boundaries and flooding surfaces. The first and second sub-members concentrate on the lower Shaximiao Formation. And the third and fourth sub-members belong to the upper Shaximiao Formation. The four sub-members correspond to four system tracts.

3. Samples and Methods

3.1 Sample description

Seventy-six representative samples from the Shaximiao Formation were collected from ten wells in Central Sichuan Basin where the greatest interval between wells is above 50 km (Fig. 1d). According to detailed observations for the Shaximiao Formation from ten wells, the lower part shows dark gray and grey-green colors, but the upper gray, grey-green and red colors. Lithological types include pebbly sandstones, medium-fine sandstones, siltstones and mudstones. Moreover, the Shaximiao Formation has the approximate thickness in the ten wells (1205–1410 m), indicating that they are likely isochronous. Sedimentary structures can be identified including horizontal bedding, cross-bedding, and climbing-ripple bedding (Fig. 2a–b). A discontinuous surface can be distinguished as a boundary within the lower Shaximiao Formation on behalf of the maximum flooding surface (Fig. 2c). Likewise, erosion surfaces have been found extensively within the upper Shaximiao Formation (Fig. 2d–e), and large-scale red mudstones have just developed above the erosion surface (Fig. 2f). Subsequently, multiple erosion surfaces with different levels occur at the upper part of the upper Shaximiao Formation (Fig. 2g–i), inferring that the water-level fluctuation was frequent at that moment. Therefore, combined with previous studies (Xiao et al., 2020; Wang et al., 2020; Zhang et al., 2021), the Shaximiao Formation has been subdivided into four stages of the sedimentary-facies evolution from lacustrine to fluvial facies, corresponding to the four sub-members (SXM1, SXM2, SXM3, SXM4) using the scheme of Liu et al. (2018b) on the basis of petrology and logging and seismic data (Fig. 1e).

All samples were made into casting thin sections following injection of rock chips with blue epoxy resins and stained with the Alizarin Red for petrographic observations. Meanwhile, sixty-five samples were crushed to pass through a 200 μm mesh for geochemical and X-ray diffraction analyses. These samples cover 1–4 sub-members of the Shaximiao Formation as shown in Fig. 3. The depth of samples from other wells are converted into equivalent depths of JQ5H based on strata data of four sub-members (*e.g.* Xia et al., 2020), because the Well JQ5H is located in the center of the studying area (Fig. 1d). Thirty-three samples among them were measured by major and trace elements, consisting of twenty-five mudstones and eight siltstones. Given the accuracy of geochemical indices, non-tuffaceous clastic rocks were chosen for analysis. Thirtytwo sandstone samples were carried out on X-ray diffraction analysis to confirm major minerals and abundance. Authigenic minerals and pore types of five sandstones were observed by the field emission scanning electron microscope.

3.2 Lithological observation

Under the binocular microscope, thin sections of casting and petrography were examined. The plane- and cross-polarized lights can be used to distinguish various lithic and mineral fragments. Thin sections can be utilized to observe pores and diagenetic phases and their relative relationship. In the petrographic thin sections dyed with Alizarin Red, calcite cement can be clearly seen, and various cements can be also distinguished. Additionally, thin sections can be used to calculate proportions of different lithic pieces. Results of petrographic observations are presented in Supplementary Table S1.

3.3 Scanning electron microscopy

Scanning electron microscopy was conducted at The Center of Material Analysis and Testing, Chongqing University of Science & Technology, using a JSM-7800F field emission scanning electron microscope (FE-SEM) equipped with an energy dispersive spectrometer (EDS). Each sample was coated with chromium (Cr) before analysis.

3.4 X-ray diffraction analysis

X-ray diffraction analysis (XRD) was carried out at Chongqing Institute of Geology and Mineral Resources and used to determine the mineralogy of the powdered samples, using a Bruker D8 Advance. All the XRD diffractograms of the samples were recorded with a 3–45° 2θ interval and with a step size of 0.02°. The semi-quantitative

XRD analysis was performed utilizing the K value approach with the X'Pert High Score Plus instrument software. XRD results of bulk rocks and clay minerals are listed in Supplementary Table S2.

3.5 Major and trace elements

Major and trace elements were measured at Qingdao Sparta Analysis & Test Co., Ltd (www.qdspt.com.cn). A Varian 720ES inductively coupled plasma-optical emission spectrometer (ICP-OES) with high dispersion Echelle optics was used to investigate the major elements. Results are accurate within 3% for all major elements. An Elan DRCII element inductively coupled plasma mass spectrometer (ICP-MS) was used to measure trace elements, and it was calibrated using international standards and replication samples. For trace elements, the analytical error is often less than 5%. Before analysis, samples were heated for 6 hours at 200 °C in pressure-tight Teflon vessels while being digested with a mixed acid (HF + HNO_3 + $HClO_4$ + HCl). ICP-MS was then used to measure residues in the vessel. Major and trace elements results of the studied samples are listed in Supplementary Table S3.

4. Results

4.1 Petrographic features

Detrital components of the Shaximiao Formation consist of quartz, feldspar, and lithic fragments (Fig. 4a). Quartz fragments are mainly monocrystals with an average abundance of 48%, feldspar fragments average of 25% and lithic fragments average of 27%. Further, the four sub-members show distinct features. The SXM1 has a high proportion of lithic fragments as same as the SXM2, but the SXM3 and the SXM4 have more quartz fragments (Fig. 4a). Lithic fragments include metamorphic, volcanic, and sedimentary deduced from thin section analysis (Fig. 5a–b). Volcanic fragments are mainly mafic-intermediate extrusive rocks. Metamorphic fragments are dominated by phyllites and quartzites. Furthermore, sedimentary fragments are mudstones and siltstones. There likewise exist large variations of lithic fragment types. The SXM1 and the SXM2 contain more volcanic fragments, but those of the SXM3 and SXM4 visibly decrease (Fig. 4b). Except for detrital particles, interstitial materials in sandstones consist of cements including calcite, laumontite, chlorite and quartz cements as well as small quantities of argillaceous matrix (Fig. 5d–h). The content of calcite cements is 0–30% with an average of 3.42%. The SXM1 and SXM2 sub-members have lower calcite contents than those of the SXM3 and SXM4 sub-members (Table S1). The calcite cement appears in two modes, pore filling and replacing feldspar (Fig. 5b, d). The secondary overgrowth of quartz is occasionally seen in thin sections. The laumontite cement exists by pore filling and is mainly distributed in the lower Shaximiao Formation (Fig. 5f). The proportion of laumontite cement is 0–18% with an average of 3.41%. The SXM1 and SXM2 sub-members have laumontite proportions up to 6–9%, much higher than those of the SXM3 and SXM4 sub-members (Table S1). The chlorite cement mainly exists as grain-coating type (Fig. 5e, g, h, j, l), with the content of 0–7%. Perpendicular chlorite crystals grow on detrital grains. In addition, a globular pyrite has grown on the surface of chlorite at local areas (Fig. 5i). And diagenetic fluids dissolved some minerals such as feldspar and laumontite to produce secondary pores (Fig. 5j–l).

4.2 Diagenetic characteristics

The Shaximiao Formation experienced significant compaction, cementation, and dissolution at the process of diagenesis. The mechanical compaction strongly reduces reservoir quality at the eodiagenetic stage. Under the compaction, contact models of grains transformed from point-point contact to point-line and even line-line contact with the burial deepening (Fig. 5b–e). The lower Shaximiao Formation mainly shows the point-line contact (Fig. 5a, c), whereas the upper Shaximiao Formation predominates the line-line contact (Fig. 5d–e). Grain-coating chlorite grew on the surface of detrital grains at the eodiagenetic stage (Fig. 5e). Laumontite exhibits the basal cementation (Fig. 5f). Quartz overgrowth was later than chlorite coating. Calcite showing the pore-filling texture was formed at the late eodiagenetic stage when the compaction is weak (Fig. 5b, d). At the mesodiagenetic stage, feldspars, lithic fragments, and early cements were dissolved to produce secondary pores due to organic acid release (Fig. 5k). Late calcite cements fill pores and replace feldspar (Fig. 5d). Compaction and cementation are important factors for the densification of sandstones of the Shaximiao Formation. Meanwhile, large amounts of feldspar, laumontite and pyroclastic grains were dissolved at the different diagenetic stages so that the secondary porosity increase (Fig. 5c, d, f). Based on petrographic statistics (Table S1), the lower Shaximiao Formation has the porosity of 2%–18% with the average of 10%. Its primary porosity (~6.98%) is obviously higher than the secondary porosity (~3.28%). Differently, the upper Shaximiao Formation exhibits the porosity of 0%–19% with the average of 6% (Table S1). Its primary porosity (~3.15%) is slightly higher than the secondary porosity

(~2.38%). The primary pore is intergranular pores (Fig. 5c), and the secondary pore are mainly intragranular and intergranular dissolved pores (Fig. 5c, j, l). Furthermore, laumontite and chlorite are dominant eodiagenetic cements. The lower Shaximiao Formation shows stronger cementation than the upper Shaximiao Formation at the eodiagenetic stage due to high proportions of eodiagenetic cements (Fig. 6a). The chlorite cement exhibits a rising and then falling trend from the SXM1 to the SXM4, slightly different from the laumontite cement (Fig. 6a). Those early cements can not only resist compaction at the eodiagenetic stage but be dissolved at the late diagenetic stage. Therefore, the primary porosity has a characteristic of rising and then falling from the SXM1 to the SXM4 (Fig. 6b). The secondary porosity likewise shows a trend similar to the primary porosity (Fig. 6b). Furthermore, the laumontite cement shows a rising and then falling trend with the total, primary, and secondary porosities respectively (Fig. 7a–c), with a threshold of ~10%. Differently, the chlorite proportion exhibits a rising and then falling trend with the total and primary porosities (Fig. 7d–e), but the secondary porosity displays a positive correlation with the chlorite proportion (Fig. 7f).

4.3 XRD analysis

Major mineral components predominate quartz, feldspar, and clay minerals occupying 66.2–99.1% (Table S2). Plagioclase is dominant in the feldspar. Laumontites mainly occur in the SXM1 and the SXM2 (Table 1), consistent with statistics of thin sections. K-feldspar proportions rise and then decrease, whereas plagioclase proportions increase from the SXM1 to the SXM4 (Table 1). The varying trend of quartz contents is similar to the plagioclase from bottom to up (Table 1). Furthermore, clay minerals consisting of chlorite, I/S and C/S mixed layers as well as small quantities of illites have a periodic trend from the SXM1 to the SXM4 (Table 1). The chlorite is dominant in the clay minerals and its average proportions likewise show a cyclical variation as same as the total clay mineral contents (Table 2). It is interesting that this trend is opposite to that of I/S mixed layers (Table 2). Differently, average proportions of the C/S mixed layers are ascending slowly from the SXM1 to the SXM4 (Table 2).

4.4 Major elements

All samples contain total contents of SiO_2, Al_2O_3 and $Fe_2O_3^T$ more than 60 wt% (Fig. 8a, c). Minor MgO, Na_2O, CaO, and K_2O contents range from 0.6 wt% to 5 wt% (Fig. 8d–g). Concentrations of MnO, TiO_2, and P_2O_5 are mostly <1 wt% (Fig. 8b, h). In addition, four sub-members of the Shaximiao Formation have approximate SiO_2, Al_2O_3, TiO_2, $Fe_2O_3^T$, and P_2O_5 contents (Fig. 8a, b, c, h), similar to those of the Northern American shale compositions (NASC; Gromet et al., 1984). However, MgO and CaO contents are much lower than those of the NASC (Fig. 8d–e), in addition to MgO of the SXM4. Likewise, the SXM3 and the SXM4 have higher Na_2O and K_2O contents than the other two (Fig. 8f–g). Based on functions of Nesbitt and Young (1982), Fedo et al. (1995), Cox et al. (1995), and Garzanti et al. (2014), the CIA, PIA, CIX, and ICV values acting as chemical weathering indices calculated by major elements after correcting CaO contents range from 66.8 to 81.6, from 60.5 to 81.8, from 73.0 to 85.2, and from 0.79 to 1.37, respectively (Table S3). The average values of the CIA and CIX ratios show a rising and then falling trend from the SXM1 to the SXM2 (Table 3). The PIA values have a trend similar to the CIA and CIX. Differently, the ICV ratios are gradually increasing (Table 3).

4.5 Trace elements

The lower Shaximiao Formation has rare earth element contents (ΣREE) of 142–240 ppm similar to that of the upper Shaximiao Formation, in addition to the sample QL17-21 with ΣREE of 818 wt% (Table S3). The Shaximiao Formation roughly exhibits a weak-moderate Eu negative anomaly with Eu/Eu^* of 0.60–0.77 (Table S3). Under the normalization of the upper continental crust (UCC), they show flat REE patterns, except for the SXM3 (Fig. 9a). The SXM3 shows light-medium REEs enrichment, whereas the SXM4 has low REE contents (Fig. 9a). It is obvious that the SXM1 and the SXM2 intervene in the two sub-members of the upper Shaximiao Formation (Fig. 9a). Besides, the Shaximiao Formation has outstanding negative anomaly of Ba, Sr, Zr and Hf with the normalization of the UCC (Fig. 9b). The SXM1 shows a pattern roughly consistent to the SXM2, but the SXM3 changes largely (Fig. 9b). The SXM4 has lower Ba and Sr contents (Fig. 9b). Some geochemical proxies, Rb/Sr, Sr/Cu, V/Cr, V/(V+Ni), and Rb/K_2O raitos, exhibit large varying ranges from 0.32 to1.30, from 3.58 to 9.95, from 0.85 to 1.64, from 0.38 to 0.83, and from 3.13 to 5.89, respectively (Table S3). From the SXM1 to the SXM4, the average values of Rb/Sr, V/Cr, V/(V+Ni) and Rb/K_2O ratios have consistent variations rising and then falling (Table 3), compatible with the CIA and CIX. Furthermore, those of the Sr/Cu and Eu/Eu^* have a trend similar to the ICV values (Table 3).

5. Discussion

5.1 Paleoclimate conditions from Bathonian to Callovian

The Jurassic paleoclimate has been considered as a typical greenhouse with high atmospheric CO_2 concentrations (Hallam, 1993; Sellwood and Valdes, 2006). At that moment, the Sichuan Basin in the Chinese landmass roughly experienced a climate evolution from the sub-humid to arid conditions based on low-resolution fossil data (Deng et al., 2017). However, there are many contradictory viewpoints on high-resolution climate changes that the late Middle Jurassic Shaximiao Formation underwent. Kan et al. (2006) and Wang et al. (2007) proposed a semiarid paleoclimate when the Shaximiao Formation was deposited using geochemical data. Oppositely, Cao et al. (2010) thought that a dry and cold climate happened in the late Middle Jurassic based on clay minerals. Qian et al. (2012) further argued for a transition from warm-dry to arid climate on the basis of geochemical data. Differently, Dai et al. (2022) reported the seasonally dry and humid alternation in the Middle Jurassic. Li et al. (2022) agreed on a semiarid-sub-humid climate alternating with arid-humid and cool/warm climate in this time interval using paleosol data. Ascertaining paleoclimate conditions of the Sichuan Basin in the late Middle Jurassic contribute to inferring impacts on the continental weathering and the sedimentary environment.

Rb/Sr and Sr/Cu ratios are frequently utilized as paleoclimate indices. Low Rb/Sr ratios represent a hot-dry paleoclimate with weak rainfall, whereas high Rb/Sr ratios represent a warm-humid paleoclimate with strong rainfall (Tao et al., 2017). Sr/Cu ratios point to a warm-humid condition with itself decreasing or a hot-dry condition with itself increasing (Lerman, 1978). It is noteworthy that carbonate-host Sr contents should be excluded prior to calculation. Because there is no correlation between CaO and Sr in Fig. 10a ($R^2 = 0.0033$), it is feasible to ignore impacts of carbonate-hosted Sr on the Rb/Sr and Sr/Cu ratios. Vertically, Rb/Sr ratios show a cyclical falling trend, whereas Sr/Cu values cyclically rise from the SXM1 to the SXM4 (Fig. 11a). Thereby it is indicated that a cyclical aridification from humid to semiarid climates took place in the late Middle Jurassic in Central Sichuan Basin. Furthermore, C-value, likewise as a reliable climatic indicator, is defined as the ratio of Σ (Fe + Mn + Cr + Ni + V + Co) / (Ca + Mg + Sr + Ba + K + Na) (Zhao et al., 2007). High C-value points to a humid condition, whereas low C-value points to an arid condition. Coincidently, C-value ratios show cyclical decrease from bottom to up (Fig. 11b), consistent with the varying trend of Rb/Sr values. This feature is also supported by paleo-weathering indices. The CIA value has a close correlation with the paleoclimate. The high CIA value corresponds to a warm-humid climate (Fedo et al., 1995). It is noteworthy that a reliable assessment must be done before using them. There is no obvious correlation between CIA and Th/Sc ($R^2 = 0.0011$) and SiO_2/Al_2O_3 ($R^2 = 0.3262$) (Fig. 10b–c), indicating that changes of weathering indices are not affected by grain sorting and size, and the source composition (Zeng et al., 2022). And the A-CN-K (Al_2O_3-(CaO^*+Na_2O)-K_2O) ternary diagram is used to further estimate whether the samples are subject to diagenesis (Nesbitt and Young, 1984). As shown in Fig. 10d, samples from the Shaximiao Formation basically have been weathered along the ideal trend with weak K_2O metasomatism, implying that diagenetic effect is negligible. Thereby paleo-weathering proxies are reliable in this study. It is shown that CIA values cyclically decrease from bottom to up with several fluctuations (Fig. 11c). Likewise, the CIX values show a varying trend compatible with that of the CIA (Fig. 11c). They could reflect that the chemical weathering weakened and the paleoclimate varied from humid to arid conditions toward to the upper. In addition, the PIA value represents the weathering of plagioclase (Fedo et al., 1995). High PIA values symbolize strong weathering of plagioclase, just opposite to the property of Eu/Eu^* (Eu enriched in plagioclase; Drake and Weill, 1975). Variations of PIA and Eu/Eu^* ratios verify the plagioclase weathering degree weakening from the SXM1 to the SXM4 (Fig. 11d). Thus, the SXM1 stayed at the warm-humid condition, the SXM2 transformed into the aridification, the SXM3 re-entered into the warm-humid condition, and the SXM4 transited to the aridification again being consistent with occurrence of red mudstones (Fig. 2f). Overall, the climate in the Sichuan Basin transformed from the humid to semiarid conditions by the cyclical aridification in the Bathonian to Callovian age.

Lacustrine source rocks and coal seams in the Qaidam Basin of northwestern China have likewise recorded an aridification event in the late Middle Jurassic (Wang et al., 2005; Shao et al., 2014; Xie et al., 2021). Therefore, the cyclical aridification climate prevailed at that moment in the Chinese landmass. Besides, this aridification can be traced northward to southern Mongolia (Traynor and Sladen, 1995) and westward to Iran (Mattei et al., 2014) and Central Asia (*e.g.* Brunet et al., 2017). In the Yanliao area of the northern NCB, the Yanliao Biota transformed from the acme to the collapse during the late Middle-Late Jurassic time corresponding to the humid to arid climate transformation (Chu et al., 2016; Huang, 2019). Therefore, the late Middle Jurassic seems to be a prelude to global warming which lead to a peak of aridity in the Late Jurassic (Wang et al., 2005; Deng et al., 2017; Xie et al., 2021). This is probably related to a climate zonation with arid- to cool-environmental conditions from the equator to the poles in the late Middle Jurassic recorded by global lithologic features (Fig. 1a; Boucot et al., 2013). Coevally, the South China Block transferred from the middle to low latitude in the Middle Jurassic on the basis of paleomagnetic data of clastic rocks, accompanied by paleoclimate changes from the warm-humid to hot-semiarid zones (Yi et al., 2019; Zhao et al., 2020). Therefore, it is plausible that the aridification event in the Chinese landmass resulted from the paleogeographic shift resulting from the breakup of Pangaea supercontinent in the late Middle Jurassic, and the cyclical records may be related to perturbations of monsoon intensity (Dai et al., 2022).

5.2 Difference of sediment provenances

Four sub-members of the Shaximiao Formation have distinct characteristics of detrital components and geochemistry. Lithic fragments are more in the SXM1 and the SXM2, but quartz fragments are more abundant in the SXM4 (Fig. 4a). The SXM3 is intervening (Fig. 4a). Furthermore, the SXM1 and the SXM2 contain more volcanic fragments than those of the SXM3 and the SXM4 (Fig. 4b). Likewise, the SXM1 and the SXM2 have a higher proportion of intermediate-mafic magmatic fragments, the SXM4 mainly sourced from the quartzose sedimentary provenance (Fig. 12a). However, the SXM3 has complex provenances from quartzose to mafic materials (Fig. 12a), consistent with observation of thin sections (Fig. 4a). Hence its REE and trace elements show large fluctuations (Fig. 9a–b). This feature can be supported by laumontite proportions (Fig. 11e), because laumontite was formed by the dissolution of volcanic materials in the eodiagenetic process (Kaley and Hanson, 1955). Likewise, the SXM1 and the SXM2 have higher chlorite proportions in clay minerals (Fig. 11f), corresponding to more mafic sources.

Detrital zircon analyses point to that the Shaximiao Formation has abundant Precambrian materials with ages of ~2.50 Ga, ~1.88 Ga and 0.81 Ga (Luo et al., 2014; Qian et al., 2016; Li et al., 2018). Those Precambrian fragments could be recycled (Fig. 12b). In addition, Caledonian (490–390 Ma), Hercynian (380–280 Ma) and Indosinian (245–208 Ma) detrita are less, but Magmatic materials with ages of ~165 Ma are relatively more (Luo et al., 2014; Qian et al., 2016; Li et al., 2018). The synchronous magmatism supports derivation of volcanic fragments of the Shaximiao Formation. According to comparisons of provenances, sediments of the Shaximiao Formation mainly originated from the Songpan-Ganzi terrane, Sanjiang Orogen, South Qinling Belt, and Emeishan large igneous province, with minor input from Western Jiangnan Orogen (Fig. 1c; Luo et al., 2014; Qian et al., 2016; Li et al., 2018). Compared with the upper Shaximiao Formation, the lower contains more Caledonian but less middle Neoproterozoic clasts (Li et al., 2018). The Caledonian magmatic rocks are dominant in the South Qinling Belt (Dong et al., 2013), and the middle Neoproterozoic magmatism developed in the western margin of the Yangtze Block along the Longmenshan fold belt (Zhou et al., 2002). It is suggested that depocenters of the

Shaximiao Formation migrated from the east to the west in the Bathonian to Callovian age. This migration resulted from foreland fold-thrust belts beginning to develop in the northern Yangtze Block (Dong et al., 2016). Therefore, the depocenter was located in the front of the Daba Mountain for the lower Shaximiao Formation, but the depocenter shifted to the front of the Micang Mountain for the upper Shaximiao Formation (Qian et al., 2015).

The weathering extent of provenances is governed by paleoclimate conditions in the process of source migration. Based on the paleo-weathering proxies, provenances of the Shaximiao Formation suffered from intermediate chemical weathering (Fig. 11c). Vertically, the weathering degree cyclically falls from the SXM1 to the SXM4 in terms of CIA and CIX indices (Fig. 11c). Meanwhile, the ICV shows a cyclical rise which is negatively correlated to the CIA (Fig. 11c), suggesting that a low weathering degree results in a low maturity of sedimentary rocks. Eu/Eu^* ratios and PIA values likewise reflect to weaken the weathering for plagioclase of provenances upward (Fig. 11d). Those features coincide with facts that proportions of plagioclase increase from bottom to up (Fig. 11e). Thus, combined with paleoclimate conditions, the SXM1 and the SXM2 sourced from more intermediate-mafic provenances which suffered from strong chemical weathering under the warm-humid condition in the front of Dabasha fold belt (Fig. 13a–b), although the paleoclimate is relatively arid during deposition of the SXM2 sub-member. The SXM3 and the SXM4 have higher MgO, Na_2O and K_2O contents (Fig. 8d, f, g), probably resulting from the weaker chemical weathering. Provenances of the lower Shaximiao Formation suffered from the loss of soluble elements due to the strong chemical weathering, whereas the upper Shaximiao Formation contains more pyroxene and feldspar fragments due to the weak chemical weathering which leads to its high MgO, Na_2O and K_2O contents (Fig. 11e). Thereby the SXM3 was derived from complex provenances where the relatively strong chemical weathering happened under the slightly humid condition at the process of source migration (Fig. 13c). Differently, the SXM4 originated from more quartzose sedimentary provenances which suffered from the weak chemical weathering under the semiarid condition in the Micangshan fold belt (Fig. 13d).

5.3 Variations of sedimentary environment

The paleo-redox and paleo-salinity proxies are used to constrain influences of the paleoclimate and material provenance on depositional settings. Ascending V/(V + Ni) ratio corresponds to an anoxic depositional condition (Lewan, 1984). Likewise, the oxygen concentration decreases as the V/Cr ratio increases (Emerson and Huested, 1991). V/(V+Ni) and V/Cr ratios indicate an anoxic setting where the Shaximiao Formation was deposited (Fig. 11a–b). Vertically, oxygen concentrations of the depositional setting cyclically increase (Fig. 11a–b), consistent with the trend of paleoclimate changes. Further, the oxygen concentration gradually decreases from the SXM1 to the SXM2 but slowly increases from the SXM3 to the SXM4 (Fig. 11a–b), just matching with the evolution of the sedimentary facies from a meander river delta to a shallow lake and then to a meandering river (Liu et al., 2018b; Xiao et al., 2020). It is obvious that the cyclical aridification climate induced narrowing of the lake area and broadening of the river channel. In addition, Rb/K_2O value is a paleo-salinity proxy.

High Rb/K_2O value reflects a high salinity (Fu et al., 2018). The Shaximiao Formation stayed in the brackish water field (Fig. 11d). Variation of the Rb/K_2O ratios suggests that paleo-salinity values of the depositional setting ascended and then fell from bottom to up (Fig. 11d), roughly keeping pace with paleo-redox indices. In addition, the Mn/Ti value is used to reflect the lake-level fluctuation (Peng et al., 2012). High Mn/Ti ratios denote the lake level rise. The outstanding lake-level fluctuation occurred in the SXM1 and the SXM2 (Fig. 11b), consistent with variations of the sedimentary facies.

In the SXM1, mafic materials were dissolved into soluble ionic fluids under the strong chemical weathering. Fluids enriched in alkali and alkaline-earth metal elements, Na^+, K^+, Ca^{2+}, Mg^{2+}, Fe^{2+}, Fe^{3+}, Sr^+, and Ba^{2+}, were injected into the depositional setting (Fig. 13a). Meanwhile, rainfall increase can lead to ascending the lake level and the water stratification (Fig. 11b). Thereby oxygen contents decreased and salinity increased at the bottom of the lake when the paleoclimate was gradually humid (Fig. 11a–d). It is favorable of the organic matter preservation. However, in the SXM2, oxygen contents and salinity continued to decrease and increase respectively when the paleoclimate transformed into the relatively arid condition (Fig. 11a–d). It could have been caused by the evaporation strengthening which can lead to a high salinity of the lake (Fig. 11b). Meanwhile, the salinity increasing can result in a stronger water stratification so that the oxygen content decreases at the bottom of the lake (Fig. 13b). By contrast, in the SXM3, oxygen contents increased and salinity decreased when the paleoclimate turned to the humid condition again (Fig. 11a–d), possibly resulting from variation of sediment provenances. The SXM3 is different from underlying two sub-members and contains more quartzose sedimentary provenances and less mafic materials (Fig. 12a). Sedimentation of more quartzose sediments with little alkali and alkaline-earth metal elements could trigger the desalination of the depositional setting and the water stratification weakening (Fig. 13c). In the SXM4, water flow contains more detrita and less alkali and alkaline-earth metal elements due to the weak chemical weathering and quartzose provenances. Oxygen contents and salinity continued to increase and decrease respectively when the paleoclimate transformed into the semiarid condition (Fig. 11a–d), suggesting that the lake level falling and quartzose provenances together control the variation of the depositional setting (Fig. 13d). Overall, the depositional setting of the Shaximiao Formation varied from high-saline to low-saline and from low-oxygen to high-oxygen conditions with the cyclical aridification respectively. Noticeably, the desalination of the depositional setting under the cyclical aridification is different from the conventional view that the arid climate makes depositional environments salty. Variations of source supply is likely to be an important factor.

5.4 Impacts on eodiagenesis of the Shaximiao Formation

The late Middle Jurassic Shaximiao Formation in Central Sichuan Basin is considered to stay at the mesodiagenetic stage (Tan et al., 2023), and suffered a series of complicated diagenetic modifications, resulting in the dentification of sandstone reservoirs. The Shaximiao Formation shows strongly differential diagenesis. Tan et al. (2023) identified five reservoir types from the Shaximiao Formation. The lower Shaximiao Formation exhibits the weak-medium compaction and the strong cementation, but the upper Shaximiao Formation have characteristics of the strong compaction and the weak cementation. Those differences are likely to result from the eodiagenetic processes.

Diagnostic eodiagenetic cements are mainly chlorite and laumontite (Fig. 5e–f), which played a crucial role in the diagenetic evolution of the Shaximiao Formation. Chlorite cements act as grain-coating type (Fig. 5e, g, h, j, l), being euhedral and strawberry-like on the surface of grains (Fig. 5e, i). Fine-grained smectite detrita was absorbed to the surface of grains and formed coats at the primary depositional environment. Subsequently, smectite coats were transformed into grain-coating chlorites under the Fe^{2+}- and Mg^{2+}-rich fluids at the eodiagenesis (Worden et al., 2020; Fig. 5h). The alternative chlorite coating was precipitated directly from the alkaline interstitial fluid at the eodiagenetic stage. Likewise, the laumontite as the basal cement can be considered to form at the eodiagenetic stage (Fig. 5f). The lower Shaximiao Formation has markedly higher laumontite and chlorite proportions than those of the upper Shaximiao Formation (Fig. 6a). The SXM1 further shows a larger range of laumontite than that of the SXM2, but the former has the lower chlorite content than that of the latter (Fig. 6a). The SXM3 exhibits more laumontite and chlorite proportions than those of the SXM4 (Fig. 6a). Differences of chlorite and laumontite proportions are likely to be triggered by different provenances and depositional environments from the SXM1 to the SXM4.

The chlorite cement of the Shaximiao Formation was formed by alteration of volcanic detritus and transformation of smectite (Wu et al., 2020). Alteration of volcanic detritus will release Na^+, Ca^{2+}, Fe^{2+}, and Mg^{2+} ions into interstitial fluids, supplying materials for authigenic chlorite (Worden et al., 2020). Decomposition of volcanic materials makes diagenetic fluids alkaline because of alkali and alkaline-earth metal elements releasing, which can not only facilitate the formation of chlorite cement but also provide prerequisites for precipitation of laumontite cement. Laumontite cements are likewise formed by the hydrolysis of volcanic fragments and albitization of plagioclases at the alkaline condition with low CO_2 content (Kaley and Hanson, 1955; Petzing and Chester, 1979; Wopfner et al., 1991). Nevertheless, the pH value of laumontite formation is higher than that of chlorite (Bai et al., 2009). Worden and Burley (2003) proposed that the interstitial water of the eodiagenetic stage is influenced by the depositional environment. The paleo-salinity index, Rb/K_2O ratio, denotes the brackish water in which the Shaximiao Formation was deposited (Fig. 11d). The eodiagenetic environment was gradually transformed into the more alkaline condition with the hydrolysis of volcanic detrita until it favored to the precipitation of laumontite. The SXM1 was sourced from many mafic-intermediate volcanic fragments as same with the SXM2 (Fig. 4b; Fig. 12a), consistent with high chlorite and laumontite proportions in the SXM1 and the SXM2. However, the SXM2 features higher chlorite but slightly lower laumontite average values than those of the SXM1 (Fig. 6a), which was probably controlled by the low-oxygen and high-saline depositional environment and the falling compositional maturation compared with the SXM1 (Fig. 11a–d; Fig. 13a–b). The anoxic stable depositional environment is more favorable to forming smectite coating which was transformed into chlorite coating at the eodiagenetic stage.

Differently, the paleo-salinity indices of the SXM3 and the SXM4 significantly decline due to variations of paleoclimate and detrital provenance (Fig. 4b; Fig. 11a–d; Fig. 12a), resulting in that proportions of their chlorite and laumontite cement likewise sharply decrease (Fig. 6a; Fig. 13c–d). Therefore, paleoclimate, provenance, and paleo-environment all are crucial for eodiagenetic cement types and proportions.

5.5 Implications for the diagenesis-porosity evolution

The eodiagenetic process is essential to govern the late diagenetic evolution. The compaction and the cementation are dominant at the eodiagenesis and have considerable impacts on reservoir quality evolution (Higgs et al., 2007). The compaction is markedly destructive for the reservoir quality at the eodiagenetic stage, resulting in that the porosity decreased from >30% to 5–12% (Tan et al., 2023). Nonetheless, there are the compaction and the cementation with different extents among four sub-members. The SXM1 and the SXM2 in the lower Shaximiao Formation experienced the strong cementation and the weak-medium compaction, whereas the SXM3 and SXM4 in the upper Shaximiao Formation are opposite. Primary and secondary porosities show identical trends with the arched shape varying from the SXM1 to the SXM4 (Fig. 6b). It is interesting that high proportion of early cements is responsible for high porosity (Fig. 6a–b), suggesting that the early cementation is constructive for tight sandstone reservoirs. However, the SXM1 has a larger range of laumontite proportions but a lower primary porosity than the SXM2 (Fig. 6a–b), probably resulting from the relationship between the cement content and the porosity. In Fig. 7a, the laumontite proportion shows an ascending and then falling trend with the total porosity with a threshold of ~10%. The primary porosity has the same features with the total porosity, as well as the secondary porosity (Fig. 7b–c). It is suggested that laumontite cements indeed improve resistance to the compaction, but it is constructive for the reservoir quality only if its proportion is no more than 10%. The SXM1 has laumontite proportions of ~5%–14% with the average of 9%, but the SXM2 contains that of 6%–12% with the average of 8% (Table S1). Therefore, many laumontite cements occupy primary pores and impede diagenetic fluids flowing so that both primary and secondary porosities of the SXM1 are lower than those of the SXM2. Appropriate laumontite cements of the SXM2 were easily dissolved during organic acids charging to produce secondary pores. Moreover, the chlorite proportion exhibits a rising and then falling trend with the total and primary porosities (Fig. 7d–e), but the secondary porosity displays a positive correlation with the chlorite proportion (Fig. 7f). It is inferred that chlorite coating can effectively inhibit quartz overgrowth only if the proportion is no more than 5% (Fig. 7e). It is destructive for the reservoir quality once the chlorite proportion is more than 5%. However, chlorite cements can be dissolved by organic acids to produce secondary pores, so the constructive role is more significant. The SXM2 has higher chlorite contents than other three sub-members and appropriate laumontite proportions (Fig. 6a), so it shows the highest primary and secondary porosities. The SXM3 and the SXM4 contain low laumontite and chlorite proportions so that primary and secondary porosities both are low (Fig. 6a–b). Thus, the SXM2 sub-member is potentially favorable for oil & gas explorations.

Based on this study, paleoclimate change has a close association with global tectonics, which together govern sedimentary environments by changing material provenances and redox conditions. Thereby eodiagenetic differentiations occurred in the different sub-members. High-content volcanoclastic materials can improve the resistance to compaction by the strong cementation. Those early cements can control the late diagenetic evolution and the reservoir quality. Only appropriate early cement proportion is constructive for tight sandstone reservoirs. It is an important reference to tight sandstone reservoirs with differential eodiagenesis all over the world.

6. Conclusions

The Shaximiao Formation in Central Sichuan Basin was deposited under the cyclical aridification from the warm-humid to hot-semiarid climate during the late Middle Jurassic. The climate change was caused by the global megamonsoon effect and the paleogeographic shift along with the breakup of the Pangaea supercontinent.

From the SXM1 to the SXM4, mafic-intermediate igneous provenances which underwent the relatively stronger chemical weathering gradually reduce, but quartzose sedimentary provenances which experienced the relatively weaker chemical weathering persistently increase. Differences of sediment provenances resulted from the migration of depocenters induced by regional tectonic movements.

Under controls of paleoclimate and provenance, the salinity and the oxygen concentration of sedimentary environments varied from high-saline to low-saline and from low-oxygen to high-oxygen conditions, respectively. The desalination of depositional waters could be caused by variations of source supply.

Compaction and cementation were dominant and strongly destruct the reservoir quality at the eodiagenetic stage. The chlorite and laumontite are mainly early cements, and their proportions vary as a curved shape from the SXM1 to the SXM4. Variations of material provenances and depositional environments govern chlorite and laumontite contents. High chlorite and laumontite proportions of the SXM2 result from more volcanoclastic sediments and salinized and stable sedimentary environments.

The SXM2 has higher chlorite and appropriate laumontite contents compared with other three sub-members so that it has the highest primary and secondary porosities. Only appropriate early cement proportion is constructive for tight sandstone reservoirs. It is an important reference to tight sandstone reservoirs with differential eodiagenesis.

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Figure caption

Fig. 1 Location and geological context for the study area. (a) Paleogeographic reconstruction and paleoclimate for the Middle Jurassic showing the location of Chinese landmass (modified from the ~170 Ma map of the webpage https://deeptimemaps.com and Boucot et al. (2013)); (b) Tectonic units of the Chinese landmass; (c) Simplified tectonic map of the Sichuan Basin and adjacent orogenic belts with emphasis on the stratigraphic distribution of the Jurassic strata as well as granitoids and Precambrian basements (after Li et al., 2018); (d) Well locations of the study area; (e) Stratigraphic framework and division of the late Middle Jurassic Shaximiao Formation from well JQ5H in Central Sichuan Basin (after Liu et al., 2018b).

Fig. 2 (a) Gray fine-grained sandstones, parallel bedding, well JQ2, J_2S^2, SXM3, 2271.03-2271.17m; (b) Light-gray fine-grained sandstones, cross-bedding, well JQ1, J_2S^2, SXM3, 1976.12-1976.33m; (c) Dark sandstones and mudstones, discontinuous surface, well JQ7, J_2S^1, SXM1, 1768.29-1768.46m; (d) Grey-green pebbly sandstones, discontinuous surface, well QL17, J_2S^2, SXM4, 2178.88-2179.20m; (e) Dark purple mudstones and grey sandstones, erosion surface, well ZQ1, J_2S^2, SXM4, 2254.12-2254.31m; (f) Purple mudstones, well QL17, J_2S^2, SXM4, 2183.15-2183.32m; (g) Light-gray pebbly sandstones, erosion surface, well ZQ1, J_2S^2, SXM4, 1825.20-1825.32m; (h) Grey-green pebbly sandstones, erosion surface, well JQ5H, J_2S^2, SXM4, 1530.10-1530.18m; (i) Grey pebbly sandstones, erosion surface, well JQ7, J_2S^2, SXM4, 974.76-974.94m.

Fig. 3 Profiles of the Shaximiao Formation in Central Sichuan Basin showing the lithology, stratigraphic distribution and sample locations in the ten wells. 1-19 sections from ten wells are studied in this study. These sections correspond to parts of the lithological column of well JQ5H by the depth conversion according to the sequence-stratigraphic relationship (Liu et al., 2018b; Xiao et al., 2020; Wang et al., 2020; Zhang et al., 2021). The method is described in the text in detail.

Fig. 4 Ternary diagrams of sandstone petrography (Garzanti, 2019). Q = quartzose (qQ = pure quartzose); F = feldspathic; L = lithic; lFQ = litho-feldspatho-quartzose; lQF = litho-quartzo-feldspathic; qLF = quartzo-lithofeldspathic; qFL = quartzo-feldspatho-lithic; fQL = feldspatho-quartzo-lithic; fLQ = feldspatho-litho-quartzose; Lm = metamorphic fragment; Lv = volcanic fragment; Ls = sedimentary fragment. Data are from statistics of thin sections in the Shaximiao Formation presented in Supplementary Table S1.

Fig. 5 (a) Three kinds of lithic fragments, well JH9, J_2S^1, SXM2, 2224.48 m; (b) Point-line to line-line contact of grains, well JQ1, J_2S^2, SXM3, 1973.38 m; (c) Point-piont to point-line contact of grains and primary pores, well JH9, J_2S^1, SXM2, 2224.75 m; (d) Calcite cements, well JQ5H, J_2S^2, SXM3, 2144.53 m; (e) Line-line contact of grains and intergranular pores, well QL18, J_2S^2, SXM3, 2104.35 m; (f)

Laumontite cements filling in intergranular pores, well JQ7, J_2S^1, SXM2, 1784.72 m; (g) Plagioclase surrounded by chlorite coating, well JH9, J_2S^1, SXM2, 2221.61 m; (h) Minerals surrounded by I/M mixed layer well QL16, J_2S^1, SXM2, 2417.04 m; (i) Globular pyrite growing in chlorite, well QL16, J_2S^1, SXM2, 2412.40 m; (j) Authigenic quartz filling in dissolved pores of feldspar, well JH9, J_2S^1, SXM2, 2221.61 m; (k) Dissolved pores and replacement, well JQ7, J_2S^2, SXM3, 1605.31 m; (l) Authigenic albite filling in dissolved pores of plagioclase surrounded by chlorite coating, well QL18, J_2S^2, SXM3, 2104.35 m.

Fig. 6 Box diagrams for proportions of cements and porosities by statistical data from thin sections in the Shaximiao Formation. Black lines denote weighted means. Data are presented in Supplementary Table S1.

Fig. 7 Cross-plots of total porosity, primary porosity, and secondary porosity with laumontite and chlorite proportion. Data are presented in Supplementary Table S1.

Fig. 8 Harker diagrams of major elements in the Shaximiao Formation. UCC-upper continental crust, MCC-middle continental crust, LCC-lower continental crust, NASC- north American shale compositions. Data of the UCC, MCC, and LCC are cited from Rudnick and Gao (2003). Data of NASC is from Gromet et al. (1984).

Fig. 9 (a) Upper Continental Crust (UCC)-normalized rare earth elements and (b) Upper

Continental Crust (UCC)-normalized trace elements for samples from the Shaximiao Formation. Data of the Upper Continental Crust are from Rudnick and Gao (2003).

Fig. 10 Cross-plots of (a) Sr versus CaO, (b) Chemical Index of Alteration (CIA) versus Th/Sc ratios, (c) Chemical Index of Alteration (CIA) versus SiO_2/Al_2O_3 ratios, (d) A-CN-K ternary diagram for the Shaximiao Formation (after Nesbitt and Young, 1984; Fedo et al., 1995).

Fig. 11 Vertical variations of geochemical proxies including paleoclimate, paleoweathering, paleoredox, and paleosalinity and XRD data of the Shaximiao Formation in the Central Sichuan Basin. On the basis of the scheme of Liu et al. (2018b), XRD data and geochemical proxies here shown are further calculated by average values of several adjacent samples which are isochronous laterally depending on logging and seismic comparisons from the work of Xiao et al. (2020), which enables to effectively uncovering the profound meaning of data compared with the comparative method among different sub-members.

Fig. 12 (a) Discrimination diagram of sediment provenance using major elements ratios (after Roser and Korsch, 1988). (b) Th/Sc vs. Zr/Sc diagram (after McLennan et al., 1993).

Fig. 13 Schematic reconstructions to show paleoclimate changes and material sources controlling sedimentary environments and eodiagenetic processes of four sub-members of the Shaxinmiao Formation in Central Sichuan Basin.

Table caption

Table 1 Bulk-rock major minerals of four sub-members of the Shaximiao Formation in the Central Sichuan Basin based on XRD analyses. A = average, N = number of samples, SD = standard deviation.

Table 2 Bulk-rock clay minerals of four sub-members of the Shaximiao Formation in the Central Sichuan Basin based on XRD analyses. A = average, N = number of samples, SD = standard deviation.

Table 3 Geochemical proxies of the Shaximiao Formation in the Central Sichuan Basin for paleoclimate, paleoweathering, paleoredox, and paleosalinity. A = average, N = number of samples, SD = standard deviation. The values of CIA, PIA, CIX, ICV and C-value are calculated by functions of Nesbitt and Young (1982), Fedo et al. (1995), Cox et al. (1995), Garzanti et al. (2014), and Zhao et al. (2007) respectively.