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RESEARCH

Geological characteristics and major factors controlling the high yield of tight oil in the Da'anzhai member of the western Gongshanmiao in the central Sichuan basin, China

Cunhui Fan · Shan Nie · Hu Li · Qingchuan Pan · Xiangchao Shi · Sumei Qin · Minzhi Zhang · Zongheng Yang

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Abstract The Da'anzhai Member limestone in the central Sichuan Basin holds significant importance as a tight oil-producing formation. Despite its crucial role, the intricate patterns of hydrocarbon enrichment and the elusive geological factors dictating high-yield production have impeded tight oil exploration and development in the Sichuan Basin. This study delves into the geological characteristics of tight oil and identifies key factors influencing high-yield production, utilizing comprehensive data derived from cores, thin sections, well logging, seismic studies, and production tests of the Da'anzhai Member in the western Gongshanmiao within the central Sichuan Basin. Our findings reveal that the primary productive strata for tight oil are the Da 1 (1st Submember of the Da'anzhai Member) and Da 3 (3rd Submember of the Da'anzhai Member) Submembers, characterized by high-energy and low-energy shell beach microfacies. The kerogen type is sapropelic, ranging from mature to highly mature, positioning it as a moderately good hydrocarbon source rock. The predominant lithology of the reservoir consists of coquina and argillaceous coquina, with secondary dissolved pores, fractures, and nano-scale micropores serving as the predominant reservoir spaces. The overall lithology represents a dense limestone reservoir of the pore-fracture type, featuring low porosity and permeability. Critical controlling factors for achieving high-yield production of tight oil encompass lithological composition, fracture development, tectonic position, and source-reservoir configuration. Notably, substantial coquina thickness, fracture development, and the strategic relationship between the lower reservoir and upper source rocks contribute significantly to unlocking high tight oil yields. Additionally, thin-layer coquina emerges as a potential area for realizing increased oil and gas production capacity during later stages of development. This comprehensive analysis sheds light on the intricate dynamics governing tight oil production in the Da'anzhai Member, offering valuable insights for advancing exploration and development strategies in the Sichuan Basin.

C. Fan (✉) · S. Nie · Hu. Li (✉) · Q. Pan · S. Qin
School of Geoscience and Technology, Southwest Petroleum University, Chengdu 610500, China
e-mail: fanchswpi@163.com

Hu. Li
e-mail: lihu860628@126.com

Hu. Li
Sichuan College of Architectural Technology, Chengdu 610399, China

X. Shi
State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu 610500, China

M. Zhang · Z. Yang
Chuanzhong Division of PetroChina Southwest Oil and Gasfield Company, CNPC, Suining 629000, China

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Article highlights

- The lithological combination, fracture development, tectonic position, and source-reservoir configuration are the major factors controlling the high-yield production of tight oil.

- Substantial coquina thickness, fracture development, and the strategic relationship between lower reservoir rocks and upper source rocks contribute significantly to high tight oil yields.
- Thin-layered limestone plays a crucial role in the oil and gas production capacity of the western Gongshanmiao area as a vital replacement and direction.

Keywords Tight oil · Limestone reservoir · Geological characteristics · Controlling factors · Source-reservoir configuration · Da'anzhai member · Western Gongshanmiao

1 Introduction

In recent years, breakthroughs have been made in exploring unconventional oil and gas resources such as shale gas, coalbed methane, and tight oil and gas, which have become sought-after fields and targets of global oil and gas exploration (Hooker et al. 2018; Guo et al. 2018; Li et al. 2019a, 2020a, b, c, 2022a; Ma et al. 2020, 2022; Liu et al. 2020a; Radwan 2021; Li 2022a). Tight oil is a new resource driving China's increasing reserves and production. In particular, progress and discoveries have been made in exploring tight oil in the Junggar Basin, Songliao Basin, Ordos Basin, and Sichuan Basin (Liu et al. 2020b; Mahdi et al. 2021; Pang et al. 2022; Tang et al. 2022; Xie et al. 2022). Tight oil refers to oil accumulations sandwiched in or immediately adjacent to dense clastic rock or carbonate rock reservoirs of high-quality oil source formations and has not migrated over long distances on a large scale. The physical property limits of the dense layer are determined as the permeability of less than 1×10^{-3} μm^2 under standard atmospheric pressure and the permeability under the subsurface overburden pressure of less than 0.1×10^{-3} μm^2 (Guo et al. 2019; Hu et al. 2022a, b; Tian et al. 2022). The shale gas in China's Sichuan Basin has become the world's second-largest shale gas production base after the United States, whereas the progress of tight oil exploration and development has been slow (Nie et al. 2020; Fan et al. 2020a, b; 2022; Li et al. 2022b, 2023a, 2023b). The Da'anzhai Member of the Jurassic Ziliujing Formation is the most important oil source formation in the Sichuan Basin, and many oil reservoirs and oil-bearing structures have been discovered in the central and northern regions of Sichuan. By the end of 2021, 50% of the crude oil had been produced by the Da'anzhai Member of the Ziliujing Formation in the Sichuan Basin, demonstrating the high resource exploration and development potential of the Da'anzhai Member (Jia et al. 2012; Pang et al. 2018; Li et al. 2020a; Luo et al. 2022; Chang and Yin 2022). Exploration and development practices have confirmed that this type of reservoir is ultra-tight and generally has no natural production capacity but can yield industrial production capacity only through artificial fracturing. Lithological combination and characteristics, fault (fracture) development degree, diagenesis, and source-reservoir configuration may be the principal factors affecting tight oil enrichment and high yield. Yu et al. (2018) investigated the diagenetic characteristics of the thick-shelled oyster reef deposits in the Cretaceous Mishrif Formation of the H oilfield in Iraq and their control on reservoirs. Based on changes in relative sea level, lithological evolution of thick-shelled oyster reefs, and sedimentary structural characteristics, a single intact thick-shelled oyster reef was divided into four lithological intervals. The relationships between lithological combinations, diagenetic processes, and hydrocarbon occurrences were analyzed separately. Jiang et al. (2023) classified four types of lithological combinations of shale in the marine-continental transitional facies of the Ordos Basin based on core, outcrop, and logging response characteristics and provided exploration and development suggestions for shale oil in different lithological combinations. Li et al. (2020b, 2021) researched fracture characteristics of carbonate reservoirs in the Jiulongshan structure of the Sichuan Basin using outcrop, core, imaging logging, production testing data, and numerical simulation of paleostructural stress fields. They pointed out that the degree of fracture (fault) development is a key factor affecting the high production of tight carbonate reservoirs. Rock mechanics parameters are the basis for stress field numerical simulation in the study of tight reservoir fractures (Rasouli and Vaseashta 2023; Dalla Chiesa et al. 2022; Shan et al. 2021; Wang and Wang 2021). Based on the study of natural fracture characteristics, Wu et al. (2022a, 2022b) clarified the influence of natural fractures in shale on hydraulic fracturing using numerical simulation methods and then analyzed the relationship between natural fractures and productivity. However, it remains unknown whether these influencing factors control the productivity of the Da'anzhai Member, and the main controlling factors affecting the exploration and development of tight oil reservoirs in the study area of the Da'anzhai Member remain to be investigated.

The Da'anzhai Member primarily comprises shale and limestone, serving as hydrocarbon source rock and reservoir space for tight oil. The lithological combination of substantial limestone thickness and a well-structured source-reservoir arrangement forms the foundation for the accumulation of tight oil. Furthermore, the limestone reservoir exhibits low porosity, permeability, and heterogeneity (Qiao et al. 2016). The fractures within this reservoir are paramount as primary storage spaces and conduits for the migration of tight oil (Afsar et al. 2014). The determination of whether the limestone in the Da'anzhai Member can attain high productivity hinges significantly on this aspect.

This comprehensive study focuses specifically on the western region of Gongshanmiao in the central Sichuan area. By integrating data from various sources such as core samples, thin sections, well logging, seismic studies, and production dynamics, the research delves into the reservoir characteristics, degree of fracture development, and structural conditions of the Da'anzhai Member limestone. The analysis adeptly tackles the challenges posed by the intricate enrichment patterns and robust heterogeneity of tight oil, pinpointing the key factors that exert control over well productivity (Su et al. 2020). Concurrently, it sheds light on the distribution of tight oil in the Sichuan Basin. The findings of this study carry substantial theoretical and practical implications, offering valuable insights for the exploration of tight oil in the study area and analogous regions. Importantly, the research outcomes effectively guide the exploration of tight oil and gas in the designated area and similar geological contexts.

2 Geologic setting

The western Gongshanmiao is located between the Gongshanmiao-Zhongtaishan structure in the mid-slope gentle belt of the palace high in central Sichuan, with the Yingshan structure in the east, the Lianchi and Nanchong structures in the south, and the Bajiaochang structure in the west (Fig. 1a) (Lei et al. 2023; Xiong et al. 2023). The major structure is a gentle slope with a south-to-north inclination. There is a slight anticline in the middle, with an undulating height of less than 50 m; the overall development degree of the fault is low, and only some small-scale and short-extending secondary faults are developed on the slope with a steep stratum attitude (Fig. 1b).

In the late Early Jurassic, the central Sichuan area was principally a set of inland deep-semi-deep lacustrine deposits (Fig. 1a) with a relatively stable tectonic setting total thickness of the Da'anzhai Member is between 68 and 120 m. According to the depositional environment and lithological combination characteristics, the Da'anzhai Member can be divided into Da 1(1st Submember of the Da'anzhai Member), Da 2 (2nd Submember of the Da'anzhai Member), and Da 3 (3rd Submember of the Da'anzhai Member) Submembers from top to bottom (Zhu et al. 2022a, b; Liu et al. 2022; Xiong et al. 2023). The overall thickness of the Da 1 Submember is 18–35 m, and the upper section is composed of thick-layer coquina and argillaceous coquina partially intercalated with a thin layer of black argillutite. The thickness of the Da 2 Submember is mostly 35–45 m, with common thin-layer coquina strips on the top and thick-layer black argillutite in the middle and lower sections, making it the major source bed in the study area. The Da 3 Submember is 5–10 m thick and is principally composed of medium-thick-layer gray-brown couquina and argillaceous coquina (Fig. 1c). Among the Submembers, the Da 1 and Da 3 Submembers are major productive strata of tight oil. A number of oil-bearing structures have been found in central Sichuan, such as the Gongshanmiao, Zhongtaishan, Guihua, Lianchi, and Jinhua structures (Xu et al. 2017; Hu et al. 2019; Dong et al. 2022).

3 Samples and methods

This study examined more than 100 m cores of 8 wells, including Gong 4 (Hereafter G4, similar to

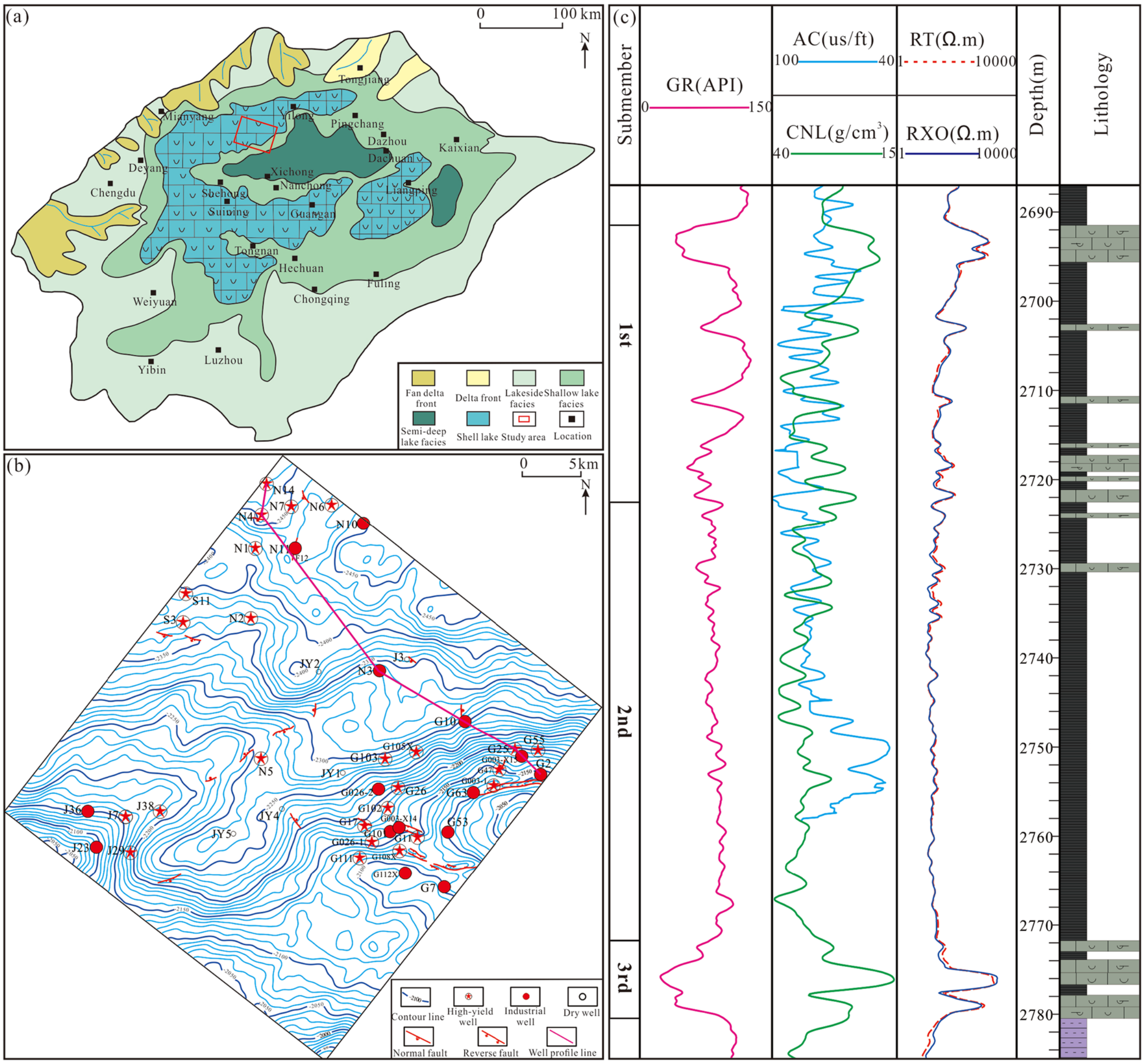

Fig. 1 Regional geological background of the west Gongshanmiao in central Sichuan. **a** Distribution of depositional facies in Jurassic Da'anzhai member in the Sichuan basin and location of the study area; **b** Top structural map of the Da'anzhai member; c. Comprehensive stratigraphic column chart of the Da'anzhai member

other wells), G6, and G7, to describe the lithological and fracture characteristics. Thirty tight oil reservoir samples were drilled from the Da'anzhai Member, and X-ray diffraction (XRD), Cast thin section, scanning electron microscopy (SEM), physical property measurements, and other experimental tests were conducted on the core samples (Table 1). More than ten typical samples with a diameter of 2.5 cm were drilled. The porosity and permeability of the samples were analyzed using a helium porosimeter and a gas permeability meter, respectively. The following experiments were then conducted on the remaining samples.

3.1 X-ray diffraction (XRD) experiment

Selecting previously prepared powdered core samples, the powder is pressed into pellets to maintain uniformity and smoothness during X-ray irradiation. The powdered sample is then placed in the XRD,

Table 1 Overview of samples and experimental methods

Well	Submember	Experimental method
G4, G6, N3, S3, G26, G101	Da 1 and Da 3 submembers	XRD
G4, G6, N3, S3	Da 1 and Da 3 submembers	Cast thin section
G4, G6, G10	Da 1 and Da 3 submembers	Scanning electron microscope (SEM)
G4, G6, G10, G1, N4, J7	Da 1 and Da 3 submembers	Physical properties

where X-rays are emitted from the X-ray tube toward the sample, resulting in specific diffraction patterns (Cheng et al. 2022). Information about various minerals in the sample, such as their relative abundance and crystalline structure, can be obtained by measuring the diffraction peaks in the pattern.

3.2 Scanning electron microscope (SEM) experiment

The analysis using SEM with argon ion beam milling incorporates the LEICA EM RES102 argon ion beam milling system coupled with a high-resolution field emission scanning electron microscope (FESEM) from FEI (He et al. 2021). The electron beam acceleration voltage is adjustable from 20 V to 30 kV, while the ion acceleration voltage spans from 500 V to 30 kV. The technique employed is Focused Ion Beam Scanning Electron Microscopy FIB–SEM), where a FESEM is equipped with a gallium ion beam positioned at a 52° angle to the electron beam. The gallium ion beam, perpendicular to the sample surface, is employed for precision cutting, while the electron beam scans at a 38° angle to capture high-resolution images of the sample surface. The examined sample area measures approximately 600 µm × 400 µm, enabling meticulous analysis of shale micropores within the micro–nano range and precise differentiation of nanopores within the 1–2 nm range (Abraham-A et al. 2022; Zhu et al. 2022a, b; Li et al. 2023a).

In addition, the production data of 78 wells (e.g., Shi 3, S5, S6, G4, G9, G11, etc.) in the study area were collected and organized to classify the types of wells (high-yield wells, industrial wells, and low-yield wells) and analyze the factors that contribute to the high yield of tight oil. At the same time, the conventional well logging data of 78 wells and the imaging well logging interpretation data of some wells were collected to carry out well-logging lithology and lithofacies identification. To analyze the seismic response patterns of high-yield oil wells, seismic profiles of more than 10 typical wells were obtained. The above-described data were obtained from PetroChina Southwest Oil and Gas Field Company.

4 Results

4.1 Depositional characteristics

Lake basin deposits dominated the early Jurassic of the Sichuan Basin, and the basin entered the evolution stage of the annular depression foreland basin, forming a pattern of being steep in the north and gentle in the south. The study area is located in the central and northern parts of the lake basin, near the lake basin's center. The depositional environment is predominantly characterized by the shore-shallow lake and semi-deep lake subfacies, with a primary emphasis on the development of shell beach depositional microfacies (Tan et al. 2011; Lai et al. 2015). The Da 2 Submember, as a whole, is situated in a semi-deep lake environment near the sedimentary center of the Da'anzhai Basin, characterized by calm and relatively deep water conditions. Positioned below the storm wave base, the hydraulic conditions are extremely weak, with low energy levels. Consequently, the development of shell beaches in this region is limited, marking the primary deposition period for dark mud shale. Based on parameters such as the Da 1 and Da 3 Submembers' thickness and the shale-to-limestone ratio, the Da'anzhai Member in the study area is stratified into high-energy and low-energy shell beach depositional microfacies.

Based on the examination of core samples, thin sections, and well logging data within the study area, and considering the regional depositional setting, lithological compositions, and distributions, the area is classified into littoral-lacustrine subfacies (including high-energy shell beach and low-energy shell beach microfacies), semi-deep lake subfacies (Table 2)

(Xu et al. 2019; Lei et al. 2023). The lithology of the high-energy shell beach primarily comprises thick-bedded, blocky pure shell limestone, characterized by low gamma-ray (GR) values and containing minor interbedded mudstone layers. The low-energy shell beach is typified by thin interbeds of argillaceous shell limestone and mudstone with moderate GR values. The semi-deep lake subfacies are predominantly composed of thick-bedded mud shale (with occasional occurrences of shell limestone), exhibiting high GR values. Utilizing this information and single-well and multi-well sedimentary facies analyses, the sedimentary facies distribution characteristics of the Da'anzhai Member were delineated.

During the deposition period of the Da 3 Submember, the water depth increased, and the water energy intensified as the basin started to develop. Due to the relatively short duration of the Da 3 Submember, the stable and extensive deposition of high-energy shell beach, it occurred predominantly in the uplifted portions of the water with the strongest wave action. This setting facilitated the formation and development of intertidal limestone, primarily depositing thicker and more intact intertidal shells.

As the Da 1 Submember deposition period commenced, a regression occurred, leading to shallower water conditions. With reduced water energy, processes such as transport and sorting weakened. Consequently, the lithology transitioned to muddy, mud-rich intertidal limestone, with a relatively lower mud content compared to high-energy shell beaches and smaller thicknesses.

On a planar scale, the distribution range of high-energy shell beaches during the Da 3 Submember is larger than that during the Da 1 Submember. The Da 3 Submember exhibits a dispersed and patchy distribution in the study area (Fig. 2a), while the Da 1 Submember is predominantly found in the northern and northwestern parts of the study area (Fig. 2b). Low-energy shell beach is less developed during the Da 3 Submember, mainly in the southern part of the study area, where the Da 1 Submember is more extensively developed, albeit on a smaller scale.

4.2 Characteristics of hydrocarbon source rock

The depositional stage of the Da'anzhai Member of the Sichuan Basin during the Jurassic occurred during the lake flooding period, was not affected by foreign matters, and had an under-compensated "hungary" lake basin background (Zhao et al. 2013; Zhang and Tang 2023). In particular, developed during the longest lake flooding period, Da 1 and Da 3 Submembers are a set of shallow lake-semi-deep lacustrine deposits with strong reduction conditions. They are more than 70 m thick in the Yilong-Dazhou area and are major hydrocarbon source rocks of self-generating and self-storage oil and gas reservoirs in central Sichuan. According to the research results of Hou et al., the total organic carbon (TOC) content of dark argillutite in the Da'anzhai Member is 0.54–2.32%, with an average of 1.30%. The oil production potential rate (S1 + S2) is 0.38–13.33 mg/g, with an average of 4.46 mg/g, the hydrocarbon production index (PI) is 0.22–0.51, with an average of 0.32, the hydrogen index (HI) is 49.91–360.34 mg/g, with an average of 201.09 mg/g, the available carbon (PC) is 0.03–0.77%, with an average of 0.37%, and

Table 2 Sedimentary facies division of the Da'anzhai member in the western Gongshanmiao

Sedimentary facies	Subfacies	Microfacies	Primary rock types	Sedimentary environments	Main distribution strata
Lake facies	Littoral-lacustrine	High-energy shell beach	Thick-bedded shell limestone	Highest energy	Da 1 and Da 3
		Low-energy shell beach	Thin-bedded shell limestone	Moderate energy	Da 1 and Da 3
	Semi-deep lake	Shoreface slope	Interbedded black mudstone and shell limestone	Low energy, reducing environment	Da 1
		Semi-deep lake mud	Predominantly black mudstone with thin intercalations of shell limestone	Reducing—strongly reducing environment, lowest energy	Da 2

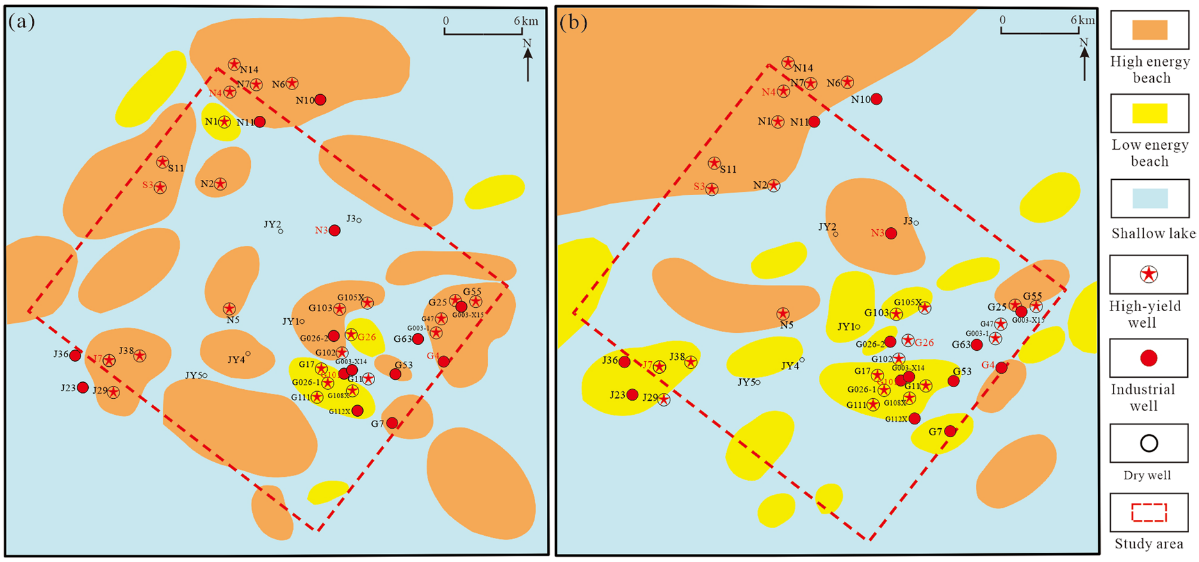

Fig. 2 Plane distribution of depositional facies in western Gongshanmiao in central Sichuan (Modified according to Ni et al. 2015). **a** The Da 3 submember; **b** The Da 1 submember

the hydrocarbon index (HCI) is 20.33–214.22 mg/g, with an average of 97.73 mg/g. This shows that the dark argilutite in the Da'anzhai Member has high organic matter content and is a set of medium-good hydrocarbon source rocks. The organic matter's vitrinite reflectance (Ro) is 0.78–1.76%, with an average of 1.16%; the sapropelic type dominated the kerogen (Chen et al. 2005; 2015; Du et al. 2005). Both the burial depth and maturity of organic matter of argillutite increase from south to north in the Da'anzhai Member, and most areas are in the peak period of oil production, with favorable oil production conditions.

4.3 Tight oil reservoir characteristics

4.3.1 Lithological characteristics

The lithology of the Da'anzhai Member in the west of Gongshanmiao is mostly sedimentary rocks mixed with terrigenous clasts and carbonates under the freshwater lake system. According to the cores, thin section observation, well logging curves, and XRD mineral composition analysis, the major lithology is coquina, argillaceous coquina, and mud-bearing coquina, of which the former two are major reservoirs (Moosavi et al. 2022; Chen et al. 2019; Zhang et al. 2020; Liu et al. 2021).

Coquina includes crystalline limestone, sparry coquina, and micrite coquina, mostly grayish brown and thick-layer blocks (Subrahmanyam and Reddy 2008; Lima et al. 2020). As microscopy observations show, the shell is closely directionally aligned and highly fragmented. The coquina mostly comprises biological carbonate rock supported by 30–90% of biological debris. The biodetritus was mostly that of lamellibranchiates, with a small amount from gastropods and ostracods. The shape of the well logging curve is generally flat and exhibits a stable box, and the natural gamma curve presented low values, which are 10–30 API in most cases; the deep and shallow dual-lateral resistivity is high and is greater than several thousand Ω m in most cases. The mineral composition is mostly calcite, accounting for 92%, followed by mud, which has a content of 4.5% (Fig. 3a).

Argillaceous coquina mostly is dark gray-grayish black thin-layer strips and is observed to be directionally aligned and highly fragmented by microscopy; the interstitial matter between the shells is mostly argillaceous, with a content of 25–45%. The biodetritus is dominated by lamellibranchiates, including a small amount of ostracoid biodetritus, and the shell is dominated by aragonite, with a small amount of calcite. The well logging curve is micro-dentate, the natural gamma value is higher overall, generally between 50 and 70 API, and the deep and shallow dual-lateral

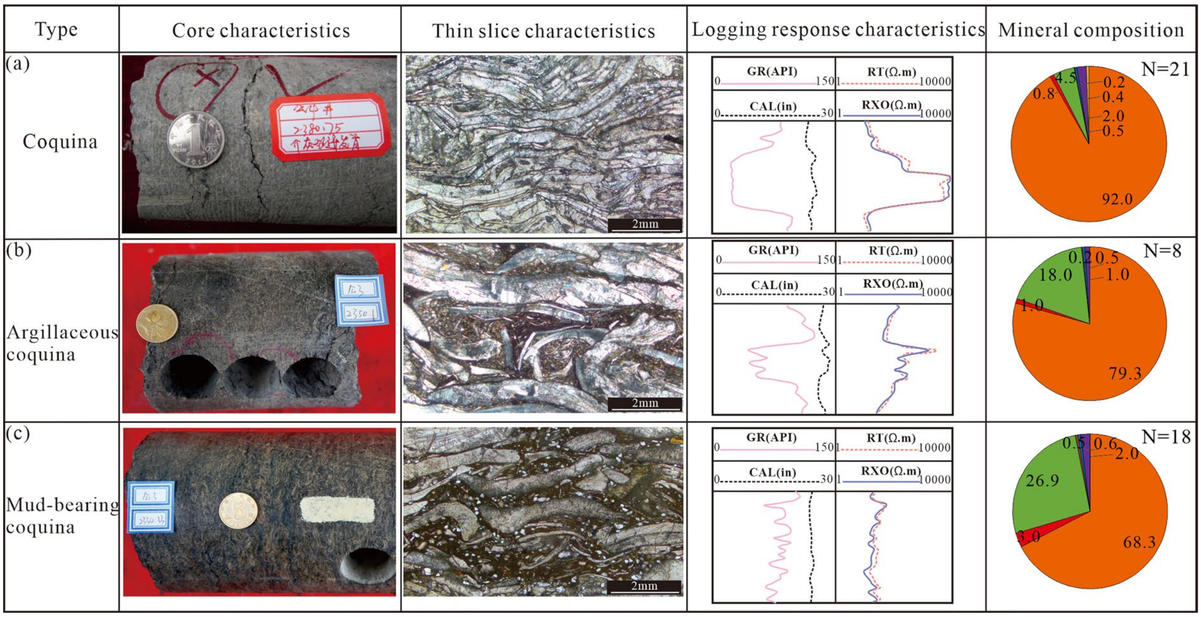

Fig. 3 Lithological characteristics of the reservoir in the Da'anzhai member in the western Gongshanmiao in central Sichuan. **a** Coquina; **b** Argillaceous coquina; **c** Mud-bearing coquina

resistivity is lower overall, with a smaller variation range. The mineral composition is mostly calcite, accounting for 68.3%, and the mud content is higher, reaching 26.9% (Fig. 3b).

Mud-bearing coquina can be subdivided into mud-bearing sparry coquina and mud-bearing micrite coquina. It is mostly gray-dark gray and is found in medium-thin layers, and the shells were observed to be complete but disorderly aligned by microscopy. In addition to calcite, a small amount of argillaceous matter is present between the shells, with a content of approximately 10–25%. The well-logging curves are mostly finger-shaped, the natural gamma value is slightly higher than that of the coquina, and the deep and shallow dual-lateral resistivity is slightly lower than that of the coquina, with an evident tooth shape. The mineral composition is still dominated by calcite, accounting for 79.3%, which is between the coquina and the argillaceous coquina, with a content of 10–25%; the content of argillaceous matter is 18% (Fig. 3c).

4.3.2 Types and characteristics of reservoir spaces

According to the genesis of pore spaces in carbonate reservoirs, they are generally classified into primary pore, secondary pore, and fracture (Zhang et al. 2015; Zhao et al. 2013). According to the observation of casting thin sections and scanning electron microscopy, the primary pore is relatively limited in the study area, while nano-scale micropores are highly developed. Therefore, the reservoir space of the tight oil reservoir in the Da'anzhai Member mainly included secondary dissolved pores (holes), fractures, and nano-sized micropores. The secondary dissolved pores (holes) can be divided into intergranular (intragranular) dissolved pores and intergranular (intragranular) dissolved pores; the fractures were mostly macroscopic structural fractures and microfractures.

4.3.2.1 Secondary dissolved pores (holes) Intergranular (intragranular) dissolved pores: the dissolved pores in the study area are nearly round and irregular and are mostly distributed along sutures and microfractures in the shape of a string of beads or are directly dissolved by the shell fragments (Xu et al. 2021; Ahmad et al. 2021; Marghani et al. 2022). Due to dissolution, the pore morphology is irregular, and the pore size generally ranges from a few microns to several hundred microns, mostly showing independent pores (Fig. 4a). In addition, there is also a small amount of intergranular pores and intergranular solution pores between the fractures or the sparry calcite filling of solutional caves (Fig. 4b) (He et al. 2021). Solutional caves are mostly formed by further erosion and expansion of the pores formed in the early stages (Hu et al. 2022a, b). Although the number of secondary dissolved holes is small, they are well-connected with the fractures, effectively improving the reservoir permeability and making the secondary dissolved hole an important oil and gas reservoir space.

Intergranular (intragranular) dissolved pores: calcite in coquina often recrystallizes into polygons, forming intergranular gaps between calcite crystals, and these pores are mostly developed in crystallized mesoscopic grains with oil traces or asphalt filling in the gaps in most cases.

4.3.2.2 Fractures Tectonic fracture is formed by rock cracking under the action of structure (Fan et al. 2020a, b; He et al. 2022a; Li et al. 2022a, b, c, d). Most of the fractures are narrow and small low-sloped ones in the horizontal direction, and few are high-angle fractures and large fractures extending in a particular direction (Fig. 4c) (Gao 2019; Hou et al. 2020; Wang et al. 2022). The fracture wall is often corroded, and the calcite in the fractures is semi-fully filled with oil immersion and oil traces (Fig. 4d). Such fractures have a reservoir capacity and can connect many holes

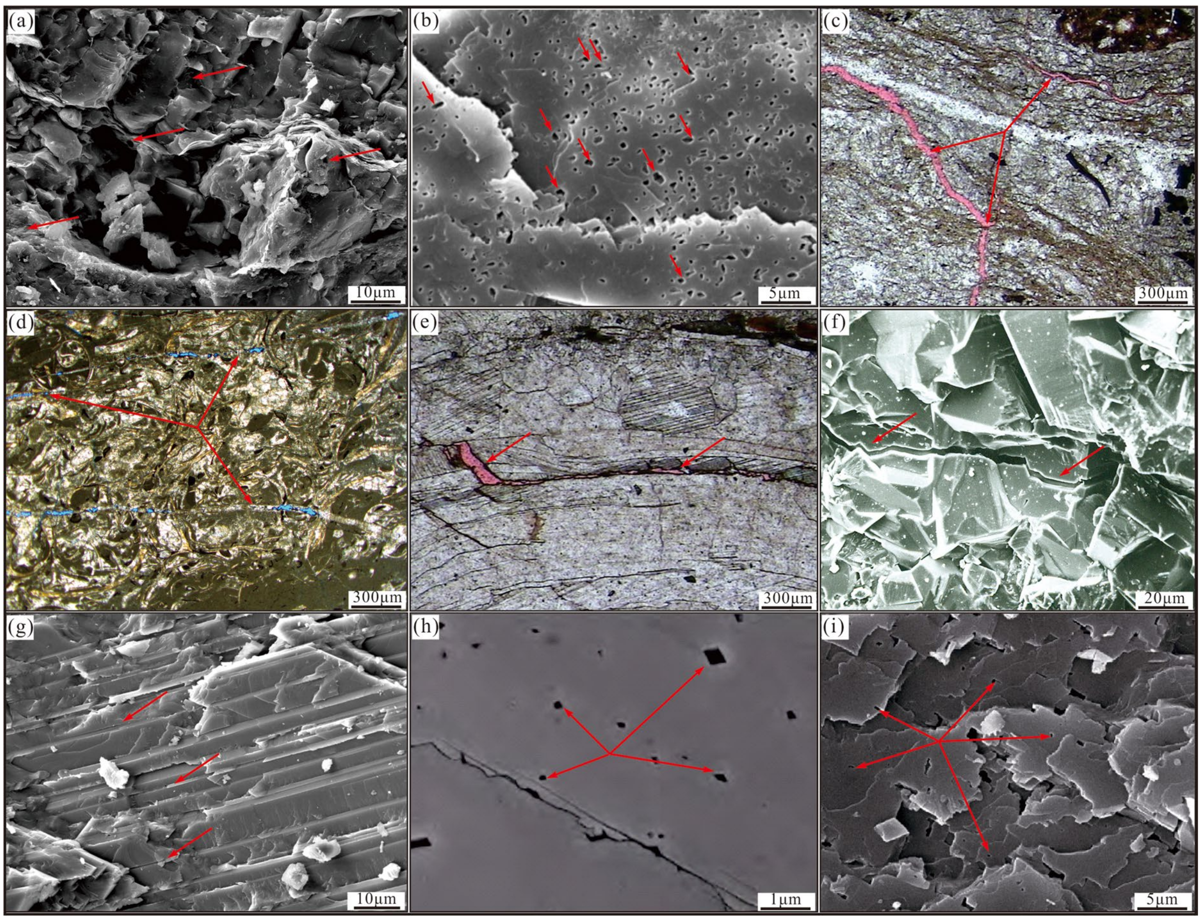

Fig. 4 Pore space and reservoir characteristics in the Da'anzhai member in western Gongshanmiao in central Sichuan. **a** Solution pores, G4, 2080.60 m; **b** Intergranular solution pores, G4, 2439.00 m; **c** Tectonic fractures, G4, 2439.90; **d** Tectonic fractures are semi-filled-fully filled, with oil immersion and oil traces, G6, 2578.59 m; **e** The connection between dissolution pores and dissolution fracture, G6, 2581.00; **f** Micro-fracture, G6, 2580.45; **g** Non-tectonic fracture, secondary calcite with laminated cleavage, G4, 2080.60 m; **h** and **i** are nano-scale pores

or matrix pores, increasing the connectivity between pores (Yang et al. 2022; Li 2021).

Dissolution fracture: new fracture branches or independent fracture systems formed by the dissolution and transformation of early fractures under fluid action (Tan et al. 2022; Li 2022b; Li et al. 2019b). For example, the small holes formed along the dissolution of early fractures seen in the core are distributed in the shape of a string of beads, not only developed in the coquina but also observed in the argillutite, and distributed in a serpentine or dendritic shape (Fig. 4e). Dissolution fractures make the fractures more interactive to a certain extent, making the connection between various types of fractures closer and more frequent.

Micro-fracture: micro-scale fractures principally include tectonic micro-fractures, diagenetic micro-fractures, and calcite cleavage fractures. The width of the fractures is mostly less than 0.02 mm (Fig. 4f). Compared with macro-tectonic and non-tectonic fractures, although the monomer scale of the micro-fracture is much smaller, it far outnumbers the former two types, has reservoir capacity, and plays a major role in permeability, connecting a large number of other finer pore and fracture spaces.

Non-tectonic fracture: including bedding fractures and diagenetic fractures (Fan et al. 2024; Dong et al. 2020). Bedding fractures are less developed in the layered mud-bearing and argillaceous coquina and are mostly developed at the layer where the mesoclastic layer meets the mudstone. The parallel bedding is generally narrow, and small dissolution holes can sometimes be observed along the fractures (Fig. 4g). Diagenetic fracture mainly refers to that formed under the action of diagenetic compaction. The non-tectonic fracture has a short extension distance without a clear extension direction.

4.3.2.3 Nano-scale pores The nano-scale pores in the coquina are also relatively developed and are characterized by an irregular shape, isolated distribution, and small pore size (Sun et al. 2022; Guo et al. 2022). The pore size of nano-scale pores is mostly 60–4000 nm and, in most cases, is less than 250 nm (Fig. 4h, i). In the case of the overall tight reservoir, many of these nano-scale pores interact with each other, improving the reservior property of the tight oil reservoir.

4.3.3 Reservior property

Examination of the results of the porosity and permeability analysis of different lithology samples from 7 wells in the study area shows that the overall physical properties of the reservoir in the Da'anzhai Member are poor, and overall, the reservoir is characterized by low porosity and low permeability. The porosity is 0.3–2.5%, with an average value of 0.90%, and is in the 0.5–1.5% range for 80% of the reservoir. The permeability is between 0.001 and 1.0 mD, and the permeability of most samples is less than 0.1 mD. The physical properties of different lithologies show no noticeable differences. Specifically, when the porosity of the coquina is low, the permeability is still high, indicating that fractures are developed in the lithology in most cases. The mud-bearing and argillaceous coquina show no evident linear porosity–permeability relationship. The porosity and permeability of mud-bearing and argillaceous coquina show a positive correlation. The positive correlation is more obvious when the porosity is less than 1.5% (Fig. 5). In fact, this is related to the samples we used for the physical property experiments. In these lithological samples, fractures are almost undeveloped and micro- to nano-scale pores dominate. When the porosity is relatively low (1.5%), there is a synergistic increase in porosity and permeability. However, as the porosity continues to increase, due to the lack of micro-fractures connecting isolated pores, porosity, and permeability do not increase simultaneously (Yokoyama and Takeuchi 2009; Hossain and Zhou 2015). On the other hand, it also indicates that the degree of fracture development in Coquina should be greater than in the other two lithologies.

5 Discussion

5.1 Determination of the standard for the high yield of tight oil

Jurassic tight oil reservoirs in the Sichuan Basin are highly densified, have a small thickness, change rapidly in the longitudinal and transverse directions, and are highly non-homogeneous. In the development process, there are large differences in single-well productivity, cross-distribution of high-yield, low-yield,

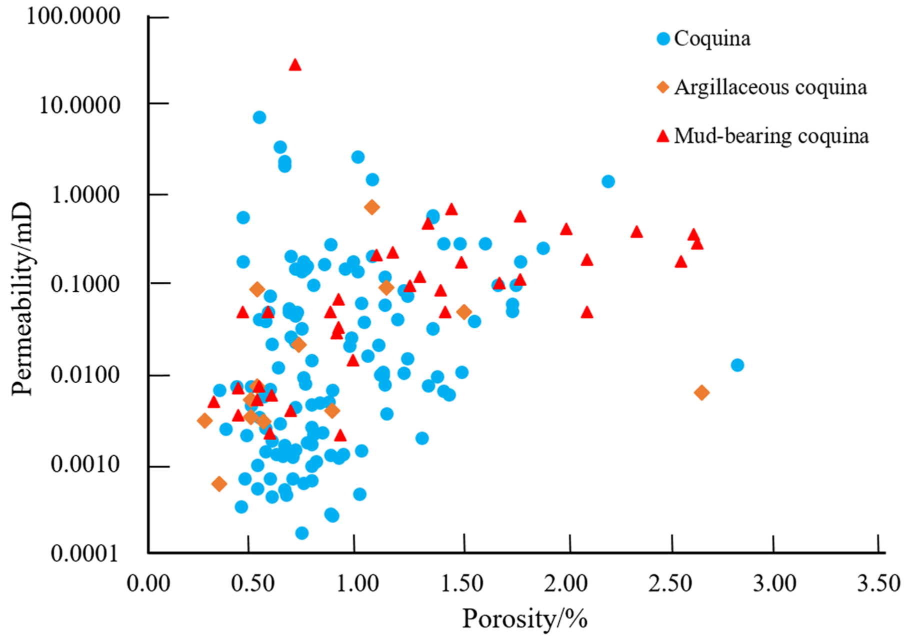

Fig. 5 Intersection diagram of the porosity–permeability relationship of the reservoir in the Da'anzhai Member in the west of Gongshanmiao in central Sichuan

and dry wells, and complex geological factors controlling the high yield.

According to industry standards in the petroleum (Ministry of Land and Resources of the People's Republic of China. Oil and gas reserves calculation specifications: DZ/T 0217-2005 2005), wells within the Da'anzhai Member generally have a depth of less than 2500 m. Consequently, the lower limit for well production in industrial oil flow is 1 ton per day (t/d). When test production exceeds 5 t/d, cumulative production often surpasses 5000 t (Yang et al. 2017). Based on the practical production experience with Jurassic tight oil in the central Sichuan region, and considering the current exploration and development status in the western Gongshanmiao, under similar production systems and geological conditions, wells with test production exceeding 5 t/d and cumulative production exceeding 5000 t are defined as high-productivity wells. Wells with test production below 1 t/d are classified as low-productivity wells, while the remaining fall into the category of industrial wells. There are 46 production wells in the Da'anzhai Member of the area, including 26 high-yield wells (15 wells with a production of 10,000 t) and 9 low-yield wells. Among these, drilled wells with a cumulative output greater than 10,000 t account for 34.7% of the total number of wells, but their cumulative output accounts for 85.0%. A few high-yield wells contribute most of the output and create significant economic effects.

5.2 Main controlling factors of high yield of tight oil

5.2.1 Characteristics of lithological combination

The favorable depositional facies zones of the reservoir in the Da'anzhai Member in central Sichuan are high-energy and low-energy shell beaches (Tian et al. 2017; Xu et al. 2020). High-energy shell beaches in the Da'anzhai Member of the area are mostly developed in the Da 1 Submember and are locally developed in the Da 1 Submember. High-energy shell beaches are a product of the high-energy environment in shallow lakes. The shells are broken by wave elutriation, forming thick pure coquina with a very thin layer of mudstone (shale), which is a favorable facies belt for the development of fractures and holes in later stages; low-energy shell beaches are mostly developed in the bottom section of the Da 1 and Da 3 Submembers; they form a medium-thin layer of mub-bearing and argillaceous coquina due to the relatively weak hydrodynamic conditions, are often interbedded with thin layers of mudstone (shale), and are the main locations for the formation of micron-scale and nano-scale pores (Fig. 6).

Based on the results of thin section identification, well logging interpretation, and dynamic production comparison, for the thick-layer massive coquina developed in the high-energy shell beach environment, the proportion of high-yield wells is the largest in the case of the single-layer thickness of 4–6 m and for thin layers of mudstone (shale) located between the coquina layers. Overall, with the increase in total limestone thickness, there is a certain degree of increase in single-well daily production rate. However, there are still many instances where the total limestone thickness is less than 5 m, yet the daily production rate remains high. Total limestone thickness is just one factor influencing production rate, and its correlation with production rate is not strong (Fig. 7a). Among the 23 high-yield wells in the area, there are 12 wells with 10,000 t of output produced by the layered-massive coquina. For argillaceous coquina in a low-energy shell beach environment, the limestone with a thickness of 1–2 m and thin-layer mudstone (shale) have no equal thickness and are not interbedded is also the most favorable lithological combination for high-yield oil wells. Of the 23 high-yield oil wells in the area, 5 wells (The red data points in Fig. 7b) with 10,000 t of output were produced by the interbed between argillaceous coquina and thin mudstone (shale). Apart from these few wells, there is a general exponential relationship between the thickness of a single limestone layer and the cumulative production capacity (Fig. 7b). Clearly, neither the total limestone thickness nor the thickness of single layers exhibits a strong correlation with production capacity. This further confirms that there are many controlling factors for high oil and gas production in the study area.

The oil source formations of high-yield wells are mostly distributed in the lithological combination belt with thick-layer-massive limestone, a very thin layer of mudstone (shale) and interbedded argillaceous coquina, and a thin layer of mudstone (shale). The oil source formations are well-matched with the high-energy and low-energy shell beaches in the Da 1 and Da 3 Submembers. It can be seen that the lithological combination under the control of the microfacies of the dominant shell beach plays an important role in the enrichment and control of the tight oil reservoir.

5.2.2 Characteristics of fracture development

The tight oil reservoir's matrix pore permeability is poor and insufficient to form an effective reservoir. The superposition of different types of fractures of different origins effectively promotes the development of dissolved pores, holes, and fractures, effectively improves the storage and infiltration capacity of the reservoir, and directly controls the development of tight oil reservoirs and well oil production.

The drilling and logging data of 20 high-yield wells in the study area show that more than 90% of the 10,000 t high-yield wells are developed in the productive stratum, with clear acceleration at the time of drilling, drilling tool emptying, well leakage, and blowout and other oil and gas phenomena; secondary minerals such as natural fractures and calcite crystals are found in the cores or cuttings of the corresponding stratum (Table 3). Moreover, according to the fracture development index forecast by geophysics

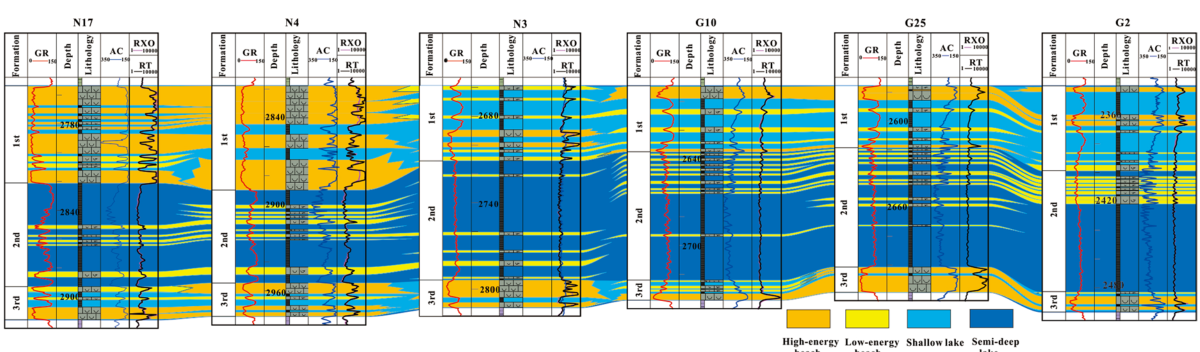

Fig. 6 Comparison of sedimentary connected wells in the Da'anzhai Member in the west of Gongshanmiao in central Sichuan (The well profile is shown in Fig. 1b)

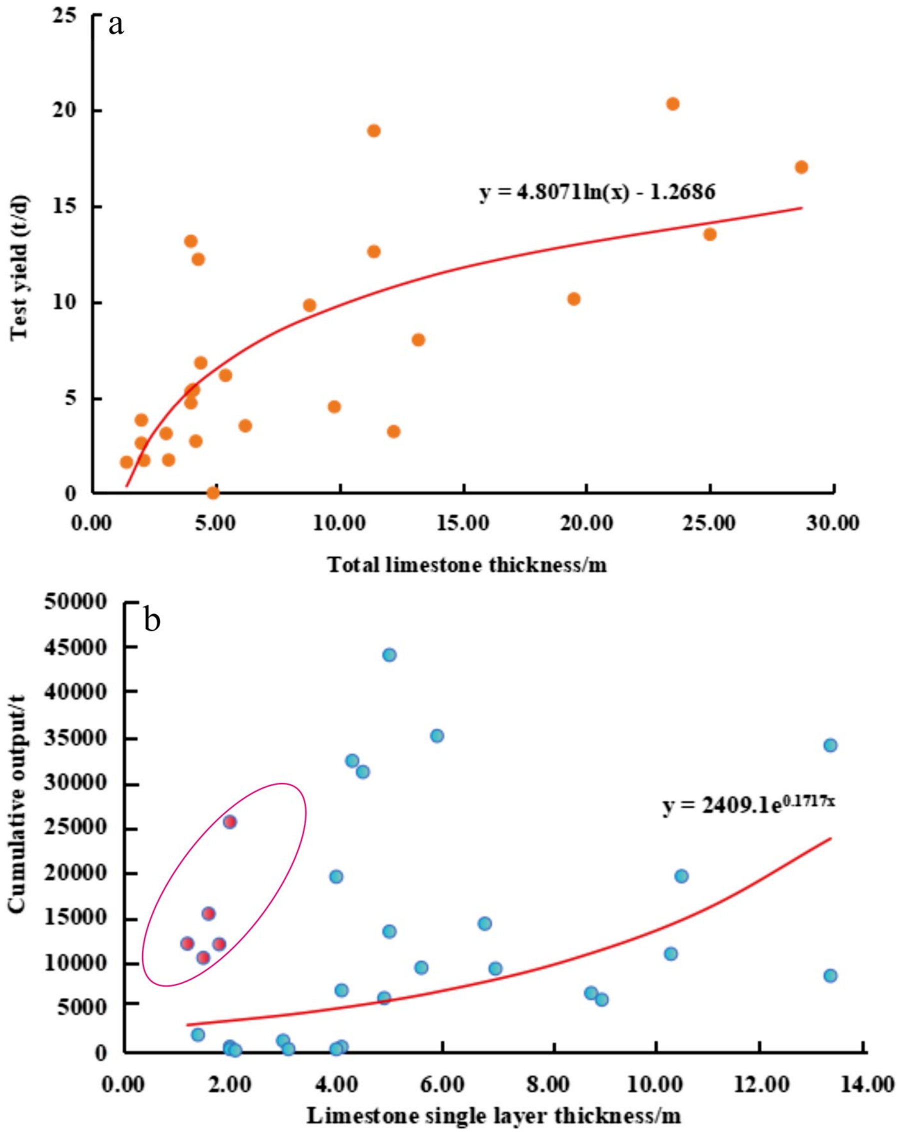

Fig. 7 The relationship between the thickness of the coquina and oil production in the Da'anzhai Member in western Gongshanmiao in central Sichuan. **a** Total thickness versus test yield; **b** single layer thickness versus cumulative output

and the high-yield well overlay planar graph, more than 80% of the high-yield wells are located in the fracture development area with a fracture development index greater than 0.3 (Fig. 8). It is shown that the fracture is an important factor for the enrichment of tight oil in the Da'anzhai Member, and it is also a necessary condition for the oil wells in the study area to achieve high yields.

5.2.3 Tectonic position

The tectonic trace of the whole central Sichuan region is relatively simple, and the tectonic amplitude is relatively flat. The Da'anzhai Member of the study area is characterized by a sloping pattern of being low in the north and high in the south and having a local uplift overall. The stratum is relatively continuous overall. Only small faults are developed in areas under a strong force, such as the local uplift and steep slope in the east. The small faults are mostly found in the northeast and northwest directions. Generally, the local tectonic structure difference will affect tight oil and gas enrichment and high yield. For example, the G65 and G003-1 wells located in the same fault zone that are relatively close to each other vary greatly

Table 3 Comparison of fracture development and drilling and logging display of high-yield wells in the Da'anzhai Member in western Gongshanmiao in central Sichuan

Well	Fracture display in mud logging	Fracture display in well logging	Well	Fracture display in mud logging	Fracture display in well logging
G4	Calcite crystals can be seen during mud logging	√	S1	Calcite and quartz can be seen during mud logging	√
G9	×	×	S3	Secondary quartz can be seen during mud logging	√
G11	Significant acceleration of drilling time	√	S5	Significant acceleration of drilling time, calcite can be seen during mud logging	√
G17	Calcite crystal can be seen during mud logging	√	S6	×	√
G25	×	√	S10	Calcite can be seen during mud logging	√
G26	×	√	S11	calcite can be seen during mud logging	√
G35	×	√	N2	Well blowout	√
G47	×	√	N4	Well leakage and calcite can be seen during mud logging	√
G55	×	√	N5	×	√
G102	×	√	N6	Calcite crystals can be seen during mud logging	√
G103	×	√	N7	Well blowout, and calcite crystal can be seen during mud logging	√
G003-1	Well leakage	√	N14	Well blowout	√
G105X	×	√	N15	Drilling time acceleration, and calcite crystal can be seen during mud logging	√
G026-1	×	√	N16	×	√
G003-X2	×	×	N17	Well blowout, drilling time acceleration, and calcite crystal can be seen during mud logging	√
G108X	×	√	N18	Calcite crystals can be seen during mud logging	√
G111	Well leakage	√	J29	×	√
J7	×	√	J38	×	×

in production. The two wells' limestone thickness, porosity, fracture development, and other conditions are similar. Considering that these wells are located in the same fault zone, the fault provides conditions for the migration of oil and gas to the higher position so that the G003-1 well in the higher position has a high yield (Fig. 9); this effect is also observed for the G11 and G003-X14 wells. The area where micro-faults develop is more likely to derive micro-fractures under the tectonic action, improving the oil and gas enrichment ability.

5.2.4 Source-reservoir configuration characteristics

The most important feature of tight oil is the source-reservoir coexistence or the proximity of source and reservoir, and the spatial source-reservoir configuration is the key to controlling the enrichment degree of tight oil (Liu et al. 2017; Shi et al. 2023). Due to the strong heterogeneity of tight oil reservoirs, oil and gas can only undergo short-distance migration and are enriched in hydrocarbon source rocks or adjacent reservoirs. Therefore, near-source accumulation

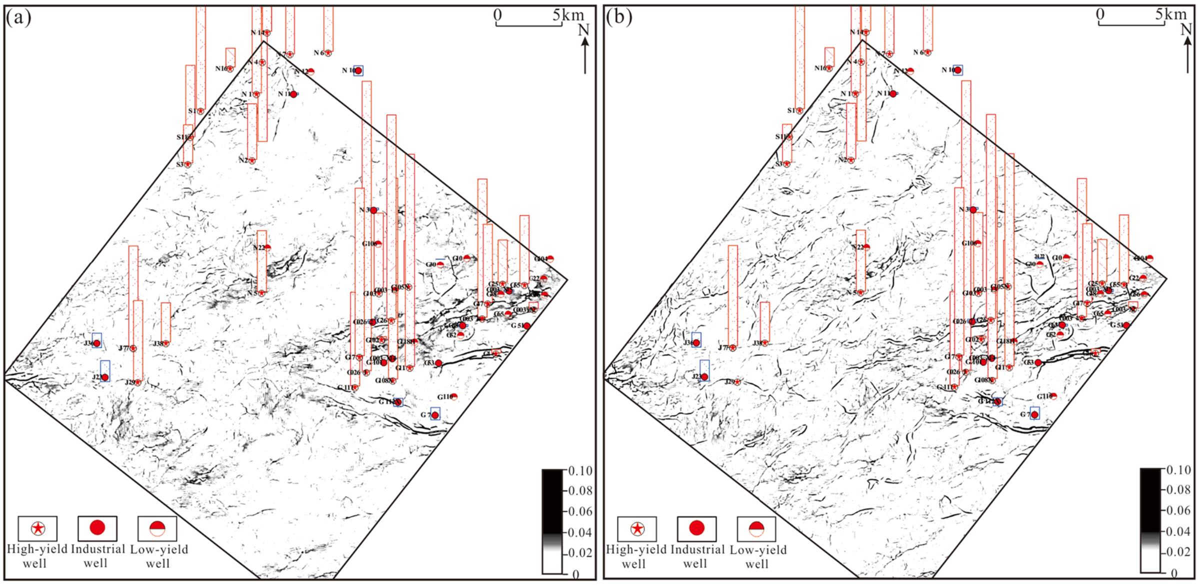

Fig. 8 Comparison of fracture forecast and yield in Da 1 submember (left) and Da 1 submember (right) in the western Gongshanmiao in central Sichuan

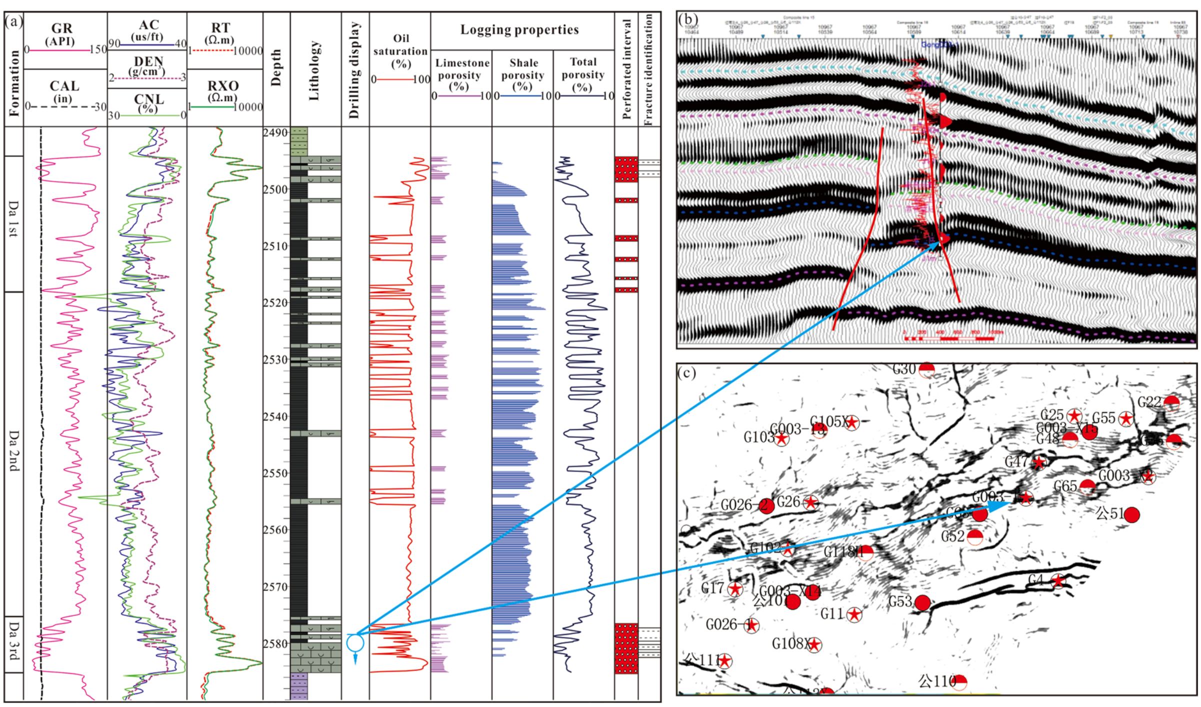

Fig. 9 Fracture logging and seismic fracture prediction response in the G003-1 well. **a** Logging response characteristics; **b** Seismic section characteristics; **c** Plane distribution of predicted fractures

is vital for the enrichment and high yield and is longitudinally manifested as the hydrocarbon source interbedded with the reservoir, hydrocarbon source rocks under reservoirs, and hydrocarbon source rocks overlying reservoirs, corresponding to the three source-reservoir configuration relationships (Fig. 10): source-reservoir interbedding, the combination of lower reservoir rocks with upper source rocks, and the combination of upper reservoir rocks with lower source rocks (Yang et al. 2017).

The tight oil reservoir of the Da 1, Da 2, and Da 3 Submembers of the Da'anzhai Member in western Gongshanmiao shows evident source-reservoir configuration zoning. The combination of lower reservoir rocks with upper source rocks is distributed in the east and north, and the bottom is longitudinally located in the upper part of the Da 1 Submember. The lithological combination of the reservoir is dominated by thick-layer-massive coquina; the thickness of the coquina in the east near Gongshanmiao Oilfield is 4–6 m, and the thickness of the single-layer coquina in the north near Zhongtaishan can reach 10 m. The stably developed dark organic matter-rich mudstone (shale) lies beneath the coquina, micro-faults and fractures develop in the area, and the oil and gas near-source migration efficiency is high, forming the most favorable source-reservoir combination. The existing high-yield wells with more than 20,000 tons of output are located in this area. The combination of upper reservoir rocks with lower source rocks is distributed in the east, and the hydrocarbon source rock in the Da 2 Submember overlays the reservoir rock in the Da 3 Submember. The reservoir lithological combination is dominated by thick-layer coquina with a thickness of 4–6 m, the microfractures are relatively developed, and the dark argillute in the Da 2 Submember is more than 20 m thick. This forms a relatively favorable source-reservoir combination. The existing high-yield wells with an output of 10,000–20,000 t or higher are located in this area. The source-reservoir interbedding type is widely distributed in the study area. It is commonly found at the top or middle and upper part of the Da 2 Submember and the bottom of the Da 1 Submember. The hydrocarbon source rock and the reservoir are interbedded with unequal thicknesses. The lithological combination is mostly argillaceous coquina with a thin layer of mudstone or thin interbeding and is 0.5–3 m thick. This forms a sub-favorable source-reservoir combination. The existing high-yield wells with more than 5000–10,000 t output are mostly distributed in this area.

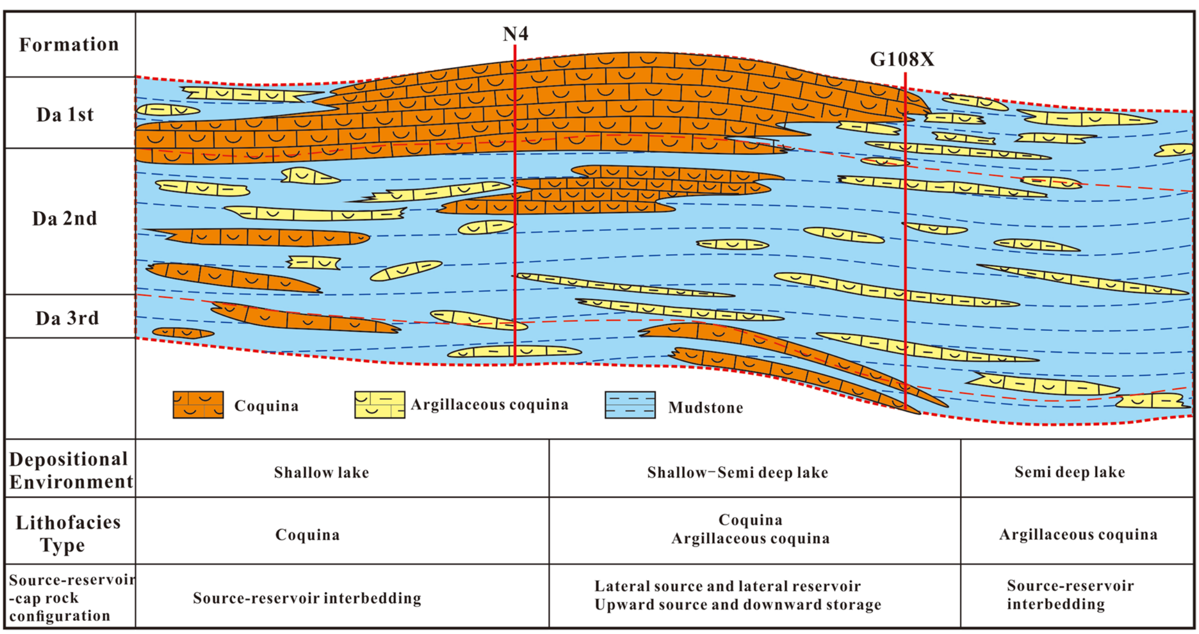

Fig. 10 Reservoir-forming model of the Da'anzhai member in the western Gongshanmiao in central Sichuan (Modified according to Hou et al. 2021)

5.3 High- yield well patterns in tight oil reservoirs

5.3.1 *Geophysical response characteristics of high-yield tight oil wells*

According to the statistics for the perforated interval of the well under test, the major oil source formations of the high-yield wells are located in the development section of thick-layer (≥ 3 m) limestone, but some high-yield wells are still present in the thin-layer (< 3 m) limestone. Therefore, the geophysical response characteristics of high-yield wells were analyzed based on thickness.

By collecting statistics regarding the logging values of thick-layer limestone oil source formations of 16 typical high-yield wells in the Da'anzhai Member and its surrounding areas, natural Gamma, acoustic time difference, and resistivity were selected for intersection analysis. There was no evident difference in the distribution of the logging data between the high-yield wells in the Gongshanmiao and Wannanchang areas. The natural Gamma (Fig. 11a), acoustic time difference (Fig. 11b), and resistivity values were 14–32 API, 48–56 us/ft, and 300–5000 Ω m, respectively.

Based on the collected statistics of the response characteristics of various types of drilled wells for conventional seismic profiles, they can be roughly divided into three seismic response characteristics: encountering large faults while drilling or close to large faults, encountering small faults or distortions while drilling, and other forms without evident distortion and variation. For example, the coquina of the G17 well in the Da 3 Submember is 6–7 m thick, with oil saturation of approximately 85–90%, limestone porosity of 2.8–3.2%, and favorable petroliferous and physical properties (Fig. 12a). Moreover, the Da 3 Submember is located at the micro-amplitude structure's turning end, developing small twists and turns. At the same time, it is close to the fault in the northeast direction and develops micro-fractures (Fig. 12b, c). The test output of the well was 6.15 t/d, and the cumulative output by the end of 2020 was 25,481.07 t.

Similarly, the acoustic time difference and resistivity values of high-yield wells in the study area, such as J34, J38, and J15, were selected for the intersection. Excluding the data and abnormal data of the increased time difference of sound waves caused by fractures, the characteristics of the thin interbed that may achieve high yield were obtained: when the sound waves were 52–82 us/ft, the resistivity was 20–600 Ω m; more than 70% of the data are distributed in this range. The statistics of the geological, logging, and seismic characteristics of limestone in the thin-layer section of the high-yield wells in the study area show that the thin-layer sections of the high-yield wells, including G11, G003-1, G47, G111, S3, S11, and N5, contributed little to the output.

5.3.2 *Comprehensive patterns of high- yield well*

The above analysis shows that the characteristics of lithological combination, fracture development degree, tectonic position, and source-reservoir configuration jointly affected the high yield of tight oil

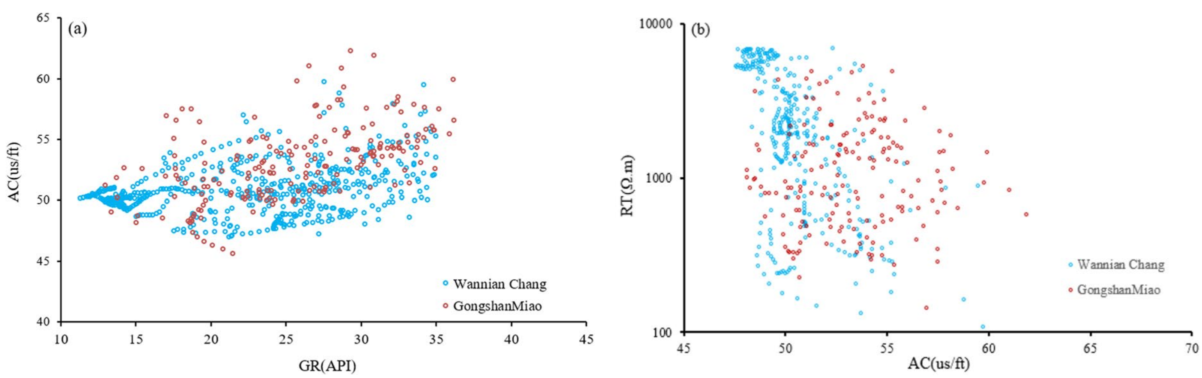

Fig. 11 Logging and intersection of the thick-layer limestone in the Da'anzhai member in the western Gongshanmiao in central Sichuan. **a** Natural gamma versus acoustic time difference; acoustic time difference versus resistivity

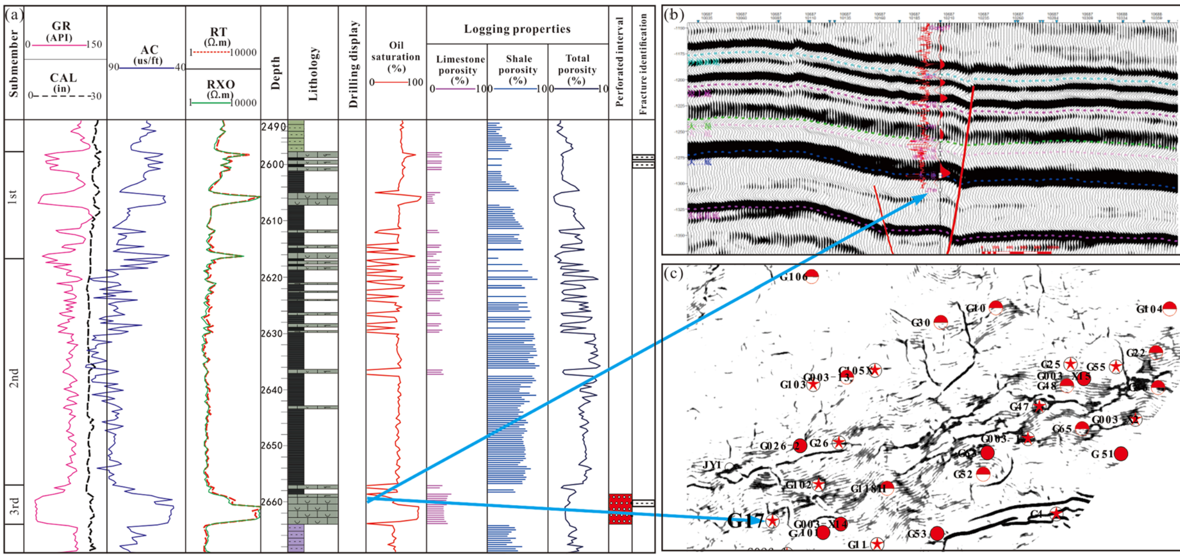

Fig. 12 Fracture logging and seismic fracture prediction response in the G17 well. **a** Logging response characteristics; **b** Seismic section characteristics; **c** Plane distribution of predicted fractures

wells (Li et al. 2022c; He et al. 2022b). High-yield wells have clear logging and seismic response characteristics compared to low-yield wells. Combined with lithological combination, fracture development, and analysis of reservoir conditions in the study area, the major characteristics of high-yield wells were summarized (Table 4). In thick-layer limestone, high-yield wells generally had the following characteristics: the thickness of the pure limestone section is approximately 4–6 m (up to 9–13 m in the Wannianchang area); there are fracture responses on the logging curves, seismic prediction or logging; the oil saturation (> 80%) and limestone porosity (2.0–3.5%) are high; the natural Gamma is between 14 and 32 API; the acoustic compensation wave is between 48 and 56 us/ft; resistivity is between 300 and 5000 Ω m; located at the position with a high fracture density (> 0.3), less strongly related to the tectonic position. The seismic test data show that the high-yield wells are located in the favorable area where the reservoir overlaps with fractures. Thin-layer limestone may contribute to high-yield wells to a certain extent and can be used to tap the production potential and improve recovery.

6 Conclusions

Tight oil is a significant unconventional hydrocarbon resource in the Sichuan Basin, following shale gas's extensive exploration and development. The tight limestone reservoir in the western Gongshanmiao serves as a typical representative. However, there is considerable variation in well productivity in this area, and the controlling factors for the high-yield accumulation of oil and gas remain unclear. This lack of clarity poses challenges for the large-scale commercial development of tight oil. This paper begins by examining geological characteristics and analyzes the primary controlling factors for the high-yield accumulation of tight oil, ultimately establishing a model for high-yield wells in tight oil reservoirs. The key conclusions drawn from this study include:

(1) A typical low-porosity and low-permeability limestone reservoir characterizes the Da'anzhai Member in the western Gongshanmiao area of Central Sichuan. High-energy and low-energy shell beaches dominate sedimentary microfacies. The reservoir exhibits diverse storage space types and a complex structure, representing a typical

Table 4 Characteristics of high-yield wells in the Da'anzhai Member in the western Gongshanmiao in central Sichuan

Oil-bearing interval	Characteristics of oil and gas accumulation								Logging response characteristics			Seismic response characteristics
	Fracture			Lithological combination		Fracture density	Reservoir conditions					
	Logging curve	Mud logging	Seismic	Thickness (m)	Bed layers		Oil saturation (%)	Limestone porosity (%)	GR (API)	AC (us/ft)	RT (Ω m)	
Thick-layer limestone	All show developed fractures			4–6 m	1–3	> 0.3 m^{-1}	> 80%	2.0–3.5	14–32	48–56	300–5000	1. Local distortion or faulting in a conventional profile 2. Encountering small faults or being close to a major fault while drilling 3. Favorable area where limestone overlays with fractures 4. Thick interbedded limestone, about 8 m in the Lower Permian and 7 m in the Upper Permian 5. Located on a zone of developed microfractures

Table 4 (continued)

Oil-bearing interval	Characteristics of oil and gas accumulation								Logging response characteristics			Seismic response characteristics
	Fracture			Lithological combination		Fracture density	Reservoir conditions					
	Logging curve	Mud logging	Seismic	Thickness (m)	Bed layers		Oil saturation (%)	Limestone porosity (%)	GR (API)	AC (us/ft)	RT (Ω m)	
Thin-layer limestone	All show developed fractures			Limestone 1.0–2.5 m Shale 0.75–2.5 m	3–4	> 0.3 m^{-1}	> 50%	1.6–2.4	38–72	52–82	20–600	1. Conventional profile: Local occurrence of a certain degree of distortion or faulting 2. Encountering faults or being close to a fault while drilling 3. Favorable area where limestone overlays with fractures 4. Located on a zone of developed microfractures

pore-fracture reservoir. Fractures enhance the reservoir porosity and connect pores within intricate structures, leading to an exponential increase in permeability.

(2) Fracture development is the key factor for high and stable yield. The wells with well-developed fractures generally yield high production from the reservoir. Tectonic positions and fractures control oil and gas enrichment by affecting the degree of development of micro-fractures. Combining upper reservoir rocks with lower source rocks is the most favorable source-reservoir configuration combination; the oil and gas produced by the dark mudstone in the Da 2 Submember migrate upward to the Da 1 Submember.

(3) The characteristics of lithological combination, fracture development degree, tectonic position, and source-reservoir configuration are controlling factors for the high yield of tight oil. A single layer of shell limestone with a thickness of 4–6 m represents the most favorable lithological combination. Fracture development is a key factor for achieving high production in oil wells. Structural locations and faults control the enrichment of oil and gas by influencing the degree of development of micro-fractures. By controlling the degree of tight oil enrichment, the' down-generation, up-storage' configuration is the most favorable source-reservoir combination.

Author contribution CF: Writing—review and editing, writing—original draft, data curation; SN: Writing—original draft, formal analysis. HL: Writing—review and editing, writing—original draft, data curation, validation. QP, XS, SQ, MZ, and ZY contributed to formal analysis, validation, and reviewing.

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Declarations

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Competing interests The authors declare no competing interests.

References

Abraham-A RM, Taioli F, Nzekwu AI (2022) Physical properties of sandstone reservoirs: implication for fluid mobility. Energy Geosci 3(4):349–359

Afsar F, Westphal H, Philipp SL (2014) How facies and diagenesis affect fracturing of limestone beds and reservoir permeability in limestone-marl alternations. Mar Petrol Geol 57:418–432

Ahmad F, Quasim MA, Ahmad AM (2021) Microfacies and diagenetic overprints in the limestones of middle Jurassic fort member (Jaisalmer formation), Western Rajasthan, India: implications for the depositional environment, cyclicity, and reservoir quality. Geol J 56(1):130–151

Chang XC, Yin S (2022) Recent advances in evaluation, evolution and quantitative characterization of tight reservoirs: introduction. Energy Geosci 3(4):381–382

Chen L, Jiang ZX, Liu QX (2019) Mechanism of shale gas occurrence: insights from comparative study on pore structures of marine and lacustrine shales. Mar Petrol Geol 104:200–216

Chen SJ, Wan MX, Du M (2005) Jurassic oil-gas source correlation and hydrocarbon source condition in central Sichuan region. Nat Gas Explor Dev 28(2):11–14

Chen SJ, Zhang HX, Lu JG, Yang YM, Liu CW, Wang L, Zou X, Yang JJ, Tang HP, Yao YT, Huang YL, Ni S, Chen YY (2015) Controlling factors of Jurassic Da'anzhai member tight oil accumulation and high production in central Sichuan basin, SW China. Petrol Explor Dev 42(2):206–214

Cheng W, Cheng H, Yu HY, Zhang SH, Wang ZL, Li XL, Johnson L (2022) X-ray fluorescence for laminated silty shale reservoirs in Ordos Basin, China: implications for lithology identification. Geofluids 2022:3207575

Dalla Chiesa D, Miguel LFF, Riera JD (2022) On the selection of wavelet models in the simulation of seismic accelerograms through evolutionary optimization. Prev Treat Nat Disasters 1(1):1–21

Dong L, Bian CS, Guo BC, Zeng X, Liang S (2022) Pore structure and reservoir physical properties for effective development of tight sandstone gas: a case study from the Central Sichuan Basin, China. Geol J 57(7):2497–2510

Dong S, Zeng L, Lyu W, Xia D, Liu G, Wu Y, Du X (2020) Fracture identification and evaluation using conventional logs in tight sandstones: a case study in the Ordos basin, China. Energy Geosci 1(3–4):115–123

Du M, Chen SJ, Wan MX (2005) Study on distribution and geochemical features of Jurassic source rocks in Sichuan basin. Nat Gas Explor Dev 28(2):15–17

Fan CH, Li H, Qin QR, He S, Zhong C (2020a) Geological conditions and exploration potential of shale gas reservoir in Wufeng and Longmaxi formation of southeastern Sichuan basin, China. J Petrol Sci Eng 191:107138

Fan CH, Li H, Zhao SX, Qin QR, Fan Y, Wu JF, Zhang J (2020b) Formation stages and evolution patterns of structural fractures in marine shale: case study of the lower Silurian Longmaxi formation in the Changning area of the Southern Sichuan Basin, China. Energy Fuel 34(8):9524–9539

Fan CH, Nie S, Li H, Radwan AE, Pan QC, Shi XC, Li J, Liu YY, Guo Y (2024) Quantitative prediction and spatial analysis of structural fractures in deep shale gas reservoirs within complex structural zones: a case study of the Longmaxi formation in the Luzhou area, southern Sichuan basin, China. J Asian Earth Sci 263:106025

Fan CH, Xie HB, Li H, Zhao SX, Shi XC, Liu JF, Meng LF, Hu J, Lian CB (2022) Complicated fault characterization and its influence on shale gas preservation in the southern margin of the Sichuan basin, China. Lithosphere S12:8035106

Gao FQ (2019) Use of numerical modeling for analyzing rock mechanic problems in underground coal mine practices. J Min Strata Control Eng 1(1):013004

Guo B, Li Y, Jiao F, Luo T, Ma Q (2018) Experimental study on coal and gas outburst and the variation characteristics of gas pressure. Geomech Geophys Geo-Energy Geo-Resour 4(4):355–368

Guo QL, Wang SJ, Chen XM (2019) Assessment on tight oil resources in major basins in China. J Asian Earth Sci 178:52–63

Guo H, Wang Z, Wang B, Zhang Y, Meng H, Sui H (2022) Molecular dynamics simulations of oil recovery from dolomite slit nanopores enhanced by CO_2 and N_2 injection. Adv Geo-Energy Res 6(4):306–313

He S, Li H, Qin QR, Long SX (2021) Influence of mineral compositions on shale pore development of Longmaxi formation in the Dingshan area, southeastern Sichuan basin, China. Energy Fuel 35(13):10551–10561

He S, Qin QR, Li H, Wang SL (2022b) Deformation differences in complex structural areas in the southern Sichuan basin and its influence on shale gas preservation: a case study of Changning and Luzhou area. Front Earth Sci 9:818155

He S, Qin QR, Li H, Zhao SX (2022a) Geological characteristics of deep shale gas in the Silurian Longmaxi formation in the Southern Sichuan basin, China. Front Earth Sci 9:818543

Hooker JN, Laubach SE, Marrett R (2018) Microfracture spacing distributions and the evolution of fracture patterns in sandstones. J Struct Geol 108:66–79

Hossain Z, Zhou YJ (2015) Petrophysics and rock physics modeling of diagenetically altered sandstone. Interpretation 3(1):107–120

Hou EK, Cong T, Xie XS, Wei JB (2020) Ground surface fracture development characteristics of shallow double coal seam staggered mining based on particle flow. J Min Strata Control Eng 2(1):013521

Hou GF, Song B, Ni C, Chen W, Wang LB, Dou Y, Li YZ, Peng B (2021) Tight oil source-reservoir matching characteristics and its significance for oil and gas exploration: A case study of the Jurassic Da'anzhai member in the central Sichuan Basin. Acta Sedimentol Sin 39(5):1078–1085

Hu MY, Gao D, Wei GQ, Yang W, Xie WR (2019) Sequence stratigraphy and facies architecture of a mound-shoal-dominated dolomite reservoir in the late Ediacaran Dengying formation, central Sichuan basin, SW China. Geol J 54(3):1653–1671

Hu CE, Tan JQ, Lyu Q, Feng G, Shi JD, Wang KX, Wang ZH (2022a) Variations of shale's pore characteristics and hydraulic properties after long-term imbibition in hydraulic fracturing fluids. Geomech Geophys Geo-Energy Geo-Resour 8(6):183

Hu T, Wu G, Xu Z, Pang X, Liu Y, Yu S (2022b) Potential resources of conventional, tight, and shale oil and gas from Paleogene Wenchang formation source rocks in the Huizhou depression. Adv Geo-Energy Res 6(5):402–414

Jia CZ, Zheng M, Zhang Y (2012) Unconventional hydrocarbon resources in China and the prospect of exploration and development. Petrol Explor Dev 39(2):139–146

Jiang YQ, Wen SM, Cai GY, Li SX, Xiong XY, Li XT, Dong DZ, Qiu Z, Gu YF, Wang ZL, Fu YH, Lu JG (2023) Lithologic assemblage characteristics and shale gas exploration potential of transitional shale in the Ordos Basin. Nat Gas Sci 43(4):62–75

Lai J, Wang GW, Ran Y, Zhou ZL (2015) Predictive distribution of high-quality reservoirs of tight gas sandstones by linking diagenesis to depositional facies: evidence from Xu-2 sandstones in the Penglai area of the central Sichuan basin, China. J Nat Gas Sci Eng 23:97–111

Lei WZ, Chen DX, Liu ZY, Cheng M (2023) Paleoenvironment-driven organic matter accumulation in lacustrine shale mixed with shell bioclasts: a case study from the Jurassic Da'anzhai member, Sichuan basin (China). Geoenergy Sci Eng 220:111178

Li H (2021) Quantitative prediction of complex tectonic fractures in the tight sandstone reservoirs: a fractal method. Arab J Geosci 14(19):1986

Li H (2022b) A review of mechanical mechanism and prediction of natural fracture in shale. Arab J Geosci 15(6):474

Li H (2022a) Research progress on evaluation methods and factors influencing shale brittleness: a review. Energy Rep 8:4344–4358

Li J, Li H, Wu XuJL, YJ, Gao Z, (2022d) Effects of fracture formation stage on shale gas preservation conditions and enrichment in complex structural areas in the southern Sichuan basin, China. Front Earth Sci 10:921988

Li J, Li H, Yang C, Ren XH, Li YD (2023a) Geological characteristics of deep shale gas and their effects on shale fracability in the Wufeng–Longmaxi formations of the southern Sichuan basin, China. Lithosphere 1:4936993

Li J, Li H, Yang C, Wu YJ, Gao Z, Jiang SL (2022b) Geological characteristics and controlling factors of deep shale gas enrichment of the Wufeng–Longmaxi formation in the southern Sichuan basin, China. Lithosphere 2022:4737801

Li QW, Liu ZB, Chen FR, Zhang K, Tang L (2023b) Behavior and controlling factors of methane adsorption in Jurassic continental shale, northeastern Sichuan basin. Energy Geosci 4(1):83–92

Li JJ, Qin QR, Li H, Wan YF (2022c) Numerical simulation of the stress field and fault sealing of complex fault combinations in Changning area, Southern Sichuan basin, China. Energy Sci Eng 10:278–291

Li H, Qin QR, Zhang BJ, Ge XY, Hu X, Fan CH, Tang HM (2020b) Tectonic fracture formation and distribution in ultradeep marine carbonate gas reservoirs: a case study of the Maokou formation in the Jiulongshan gas field, Sichuan basin, SW China. Energy Fuel 34:14132–14146

Li H, Tang HM, Qin QR, Wang Q, Zhong C (2019b) Effectiveness evaluation of natural fractures in Xujiahe formation of Yuanba area, Sichuan basin, China. Arab J Geosci 12(6):194

Li H, Tang HM, Qin QR, Zhou JL, Qin ZJ, Fan CH, Su PD, Wang Q, Zhong C (2019a) Characteristics, formation periods, and genetic mechanisms of tectonic fractures in the tight gas sandstones reservoir: a case study of Xujiahe Formation in YB region, Sichuan basin, China. J Petrol Scie Eng 178:723–735

Li B, Wang XZ, Liu HQ, Wang YJ, Tian J, Huo F, Gao ZL (2020a) Tight carbonate microstructure and its controls: a case study of lower Jurassic Da'anzhai member, central Sichuan basin. Acta Geol Sin-Engl 94(2):305–321

Li H, Wang Q, Qin QR, Ge XY (2021) Characteristics of natural fractures in an ultradeep marine Carbonate gas reservoir and their impact on the reservoir: a case study of the Maokou formation of the JLS structure in the Sichuan basin, China. Energy Fuel 35:13098–13108

Li H, Zhou JL, Mou XY, Guo HX, Wang XX, An HY, Mo QW, Long HY, Dang CX, Wu JF, Zhao SX, Wang SL, Zhao TB, He S (2022a) Pore structure and fractal characteristics of the marine shale of the Longmaxi formation in the Changning area, Southern Sichuan basin, China. Front Earth Sci 10:1018274

Li Y, Zhou D, Wang W, Jiang T, Xue Z (2020c) Development of unconventional gas and technologies adopted in China. Energy Geosci 1(1–2):55–68

Lima MCO, Pontedeiro EM, Ramirez M, Boyd A, Van Genuchten MT, Borghi L, Couto P, Raoof A (2020) Petrophysical correlations for the permeability of coquinas (Carbonate rocks). Transp Porous Med 135(2):287–308

Liu Z, Chen D, Lei W, Liu Y, Xie G, Dang W, Lv X, Li S, Yuan S (2022) Controls of the paleoenvironment on differential organic matter enrichment of lacustrine finegrained rocks: a case study of the Jurassic Da'anzhai member, central Sichuan basin, SW China. J Asian Earth Sci 236:105319

Liu Y, Ma TS, Wu H, Chen P (2020a) Investigation on mechanical behaviors of shale cap rock for geological energy storage by linking macroscopic to mesoscopic failures. J Energy Storage 29:101326

Liu ZJ, Qiu HY, Jiang ZX, Liu RB, Wei XF, Chen FR, Wei FB, Wang DJ, Su ZF, Yang ZW (2021) Types and quantitative characterization of microfractures in the continental shale of the Da'anzhai member of the Ziliujing formation in Northeast Sichuan, China. Minerals 11(8):870

Liu Y, Xian C, Li Z, Wang J, Ren F (2020b) A new classification system of lithic-rich tight sandstone and its application to diagnosis high-quality reservoirs. Adv Geo-Energy Res 4(3):286–295

Liu ZG, Zhu C, Li SM, Xue JQ, Gong QS, Wang YQ, Wang P, Xia ZY, Song GY (2017) Geological features and exploration fields of tight oil in the Cenozoic of western Qaidam basin, NW China. Petrol Explor Dev 44(2):217–225

Luo S, Ding C, Cheng H, Zhang B, Zhao Y, Liu L (2022) Estimated ultimate recovery prediction of fractured horizontal wells in tight oil reservoirs based on deep neural networks. Adv Geo-Energy Res 6(2):111–122

Ma TS, Peng N, Chen P (2020) Filter cake formation process by involving the influence of solid particle size distribution in drilling fluids. J Nat Gas Sci Eng 79:103350

Ma TS, Qiu Y, Zhang Y, Liu Y (2022) Numerical simulation of progressive sand production of open-hole completion borehole in heterogeneous igneous formation. Int J Rock Mech Min 150:105030

Mahdi DS, Al-Khdheeawi EA, Yuan Y, Zhang Y, Iglauer S (2021) Hydrogen underground storage efficiency in a heterogeneous sandstone reservoir. Adv Geo-Energy Res 5(4):437–443

Marghani MMA, Zairi M, Radwan AE (2022) Facies analysis, diagenesis, and petrophysical controls on the reservoir quality of the low porosity fluvial sandstone of the Nubian formation, east Sirt basin, Libya: insights into the role of fractures in fluid migration, fluid flow, and enhancing the permeability of low porous reservoirs. Mar Petrol Geol 147:105986

Ministry of Land and Resources of the People's Republic of China (2005) Oil and gas reserves calculation specifications: DZ/T 0217-2005. China Standard Publishing House, Beijing

Moosavi SA, Bakhtiari HA, Honarmand J (2022) Estimation of pore volume compressibility in carbonate reservoir rocks based on a classification. Geotech Geol Eng 40:3225–3244

Ni C, Yang JJ, Chen W, Lin JP, Hou GF, Wang Y (2015) Reservoir characteristics and development model of dense limestone: A case study from Da'anzhai member in central Sichuan Basin. Lithol Res 27(6):38–47

Nie H, Li D, Liu G, Lu Z, Hu W, Wang Ru, Zhang G (2020) An overview of the geology and production of the Fuling shale gas field, Sichuan basin, China. Energy Geosci 1(3–4):147–164

Pang YM, Guo XW, Chang XC, Zhang JJ, Zhou JQ, Cai LX (2022) Characteristics and classification of paleozoic tight reservoirs in the central uplift of the South Yellow sea basin. Energy Geosci 3(4):383–393

Pang ZL, Tao SZ, Zhang Q, Yang JJ, Zhang TS, Yang XP, Fan JW, Huang D, Wei TQ (2018) Reservoir micro structure of Da'anzhai member of Jurassic and its petroleum significance in Central Sichuan basin, SW China. Petrol Explor Dev 45(1):68–78

Qiao CH, Johns R, Li L (2016) Modeling low-salinity waterflooding in chalk and limestone reservoirs. Energy Fuel 30(2):884–895

Radwan AE (2021) Modeling the depositional environment of the sandstone reservoir in the middle Miocene sidri member, badri field, gulf of Suez Basin, Egypt: integration of gamma-ray log patterns and petrographic characteristics of lithology. Nat Resour Res 30:431–449

Rasouli H, Vaseashta A (2023) Investigation of physicochemical properties of Qalay Abdul Ali Soil, Kabul, Afghanistan. Adv Geol Geotech Eng Res 5(3):55–68

Shan SC, Wu YZ, Fu YK, Zhou PH (2021) Shear mechanical properties of anchored rock mass under impact load. J Min Strata Control Eng 3(4):043034

Shi J, Zhou X, Jia P, Cai K (2023) Ion separation together with water purification via a new type of nanotube: a molecular dynamics study. Int J Mol Sci 24(7):6677

Su J, Tian ZP, Shen Y, Liu B, Xu QL, Wang YJ (2020) Differential diagenetic evolution and hydrocarbon charging of the tight limestone reservoir of the Da'anzhai member in the central Sichuan basin, China. Interpretation 8(4):T1007–T1022

Subrahmanyam AV, Reddy LS (2008) Incidence of molybdenite in the crystalline limestone of Ghansali formation at Thayeli area, Tehri district, Uttaranchal. J Geol Soc India 72(2):225–228

Sun Y, Ju Y, Zhou W, Qiao P, Tao L, Xiao L (2022) Nanoscale pore and crack evolution in shear thin layers of shales and the shale gas reservoir effect. Adv Geo-Energy Res 6(3):221–229

Tan P, Kao J, Cheng F (2022) A review on hydraulic fracture height growth for layered formation. Geotech Geol Eng 40:4057–4067

Tan XC, Li L, Liu H, Luo B, Zhou Y, Wu JJ, Ding X (2011) General depositional features of the carbonate platform gas reservoir of the lower triassic Jialingjiang formation in the Sichuan basin of southwest China: Moxi gas field of the central basin. Carbonate Evaporite 26(4):339–350

Tang Y, Tan SH, Wang RF, Wang H, Xia CM, Chen KY (2022) Analysis of tight oil accumulation conditions and prediction of sweet spots in Ordos basin: a case study. Energy Geosci 3(4):417–426

Tian J, Liu HQ, Wang L, Sima LQ, Liu SQ, Liu XJ (2022) Identification of fractures in tight-oil reservoirs: a case study of the Da'anzhai member in the central Sichuan Basin, SW China. Sci Rep 11(1):23846

Tian Z, Song X, Wang Y, Ran X, Liu B, Xu Q, Li Y (2017) Classification of lacustrine tight limestone considering matrix pores or fractures: a case study of Da'anzhai member of Jurassic Ziliujing formation in central Sichuan basin, SW China. Petrol Explor Dev 44(2):234–246

Wang SL, Li H, Lin LF, Yin S (2022) Development characteristics and finite element simulation of fractures in tight oil sandstone reservoirs of Yanchang formation in western Ordos basin. Front Earth Sci 9:823855

Wang J, Wang XL (2021) Seepage characteristic and fracture development of protected seam caused by mining protecting strata. J Min Strata Control Eng 3(3):033511

Wu ZW, Cui CZ, Jia PF, Wang Z, Sui YF (2022b) Advances and challenges in hydraulic fracturing of tight reservoirs: a critical review. Energy Geosci 3(4):427–435

Wu ZH, Tang MT, Zuo YJ, Lou YL, Wang WT, Liu H, Sun WJB (2022a) Acoustic emission-based numerical simulation of tectonic stress field for tectoclase prediction in shale reservoirs of the northern Guizhou area, China. Energy Geosci 3(4):436–443

Xie RC, Luo ZW, Zhang MY, Wang YF, Chen J, Zhu M (2022) Factors controlling tight oil and gas reservoir development in the Jurassic siliciclastic-carbonate rocks in Sichuan Basin, China. Energy Geosci 3(4):453–464

Xiong SL, Gao ZY, Wei WH, Wang YH (2023) Differential effects of pore structure of mineral and maceral components on the methane adsorption capacity evolution of the lower Jurassic Da'anzhai member of the Ziliujing formation lacustrine shale, Sichuan basin, China. Mar Petrol Geol 147:106017

Xu WG, Deng HW, Wang YT (2021) The sandstone reservoir characteristics and controlling factors of Shanxi formation and lower Shihezi formation in Southeastern Ordos basin. Geol J 56(3):1673–1698

Xu QL, Hao F, Ma YS, Liu B, Song XM (2020) Effects of the matrix on the oil production of supertight limestone in a lacustrine mixed sedimentary environment: the case of the Jurassic Da'anzhai member in the central Sichuan basin, China. Mar Petrol Geol 121:104583

Xu Q, Liu B, Ma Y, Song X, Wang Y, Chen Z (2017) Geological and geochemical characterization of lacustrine shale: a case study of the Jurassic Da'anzhai member shale in the central Sichuan Basin, southwest China. J Nat Gas Sci Eng 47:124–139

Xu QL, Ma YS, Liu B, Song XM, Su J, Chen ZX (2019) Characteristics and control mechanism of nanoscale pores in lacustrine tight carbonates: examples from the Jurassic Da'anzhai member in the central Sichuan basin, China. J Asian Earth Sci 178:156–172

Yang G, Huang D, Huang PH, Yan WP, Yang TQ, Dai HM, Lin JP (2017) Control factors of high and stable production of Jurassic Da'anzhai member tight oil in central Sichuan basin, SW China. Petrol Explor Dev 44(52):817–826

Yang YM, Li X, Ju Y (2022) Influence mechanisms of plasticity and horizontal stress difference on the fracture propagation in plastic reservoir rocks: a 3D XFEM-based plastic fracturing model. Geomech Geophys Geo-energ Geo-resour 8(5):145

Yokoyama T, Takeuchi S (2009) Porosimetry of vesicular volcanic products by a water-expulsion method and the relationship of pore characteristics to permeability. J Geophys Res-Solid Earth 114:B02201

Yu YC, Sun LD, Song XM, Guo R, Gao XJ, Lin MJ, Yi LP, Han HY, Li FF, Liu HY (2018) Sedimentary diagenesis of rudist shoal and its control on reservoirs: a case study of cretaceous Mishrif formation, H Oilfield, Iraq. Petrol Explor Dev 45(6):1075–1087

Zhang ZC, Li PP, Yuan YJ, Liu KQ, Hao JY, Zou HY (2020) Quantitative prediction of fractures in shale using the lithology combination Index. Minerals 10(6):569

Zhang TT, Sun YF, Dou QF, Zhang HR, Guo TL, Cai XY (2015) Improving porosity-velocity relationships using carbonate pore types. J Comput Acoust 23(4):1540006

Zhang R, Tang LX (2023) Oil-bearing evaluation of different lithofacies in Da'anzhai member, Central Sichuan basin: implications for shale oil development. Petrol Sci Technol 41(15):1477–1491

Zhao LX, Nasser M, Han DH (2013) Quantitative geophysical pore-type characterization and its geological implication in carbonate reservoirs. Geophys Prospect 61(4):827–841

Zhu HH, Chen L, Cao ZL (2022a) Microscopic pore characteristics and controlling factors of black shale in the Da'anzhai member of Jurassic Ziliujing formation, central Sichuan basin. Oil Gas Geol 43(5):1115–1126

Zhu YX, Li ZZ, Zeng LB, Liu ZY, Wang XY (2022b) Diagenesis and its impact on the reservoir quality of continental shales: a case study of the lower Jurassic Da'anzhai member of the Ziliujing formation in the Sichuan basin, China. Geofluids 2022:5942370