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Characteristics and Genesis of Alkaline Lacustrine Tight Oil Reservoirs in the Permian Fengcheng Formation in the Mahu Sag, Junggar Basin, NW China

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Abstract: Through optical microscopic examination, scanning electron microscope analysis, whole rock X-ray diffraction analysis, X-ray fluorescence spectrum analysis, carbon and oxygen isotope analysis, and temperature measurement of fluid inclusions, the characteristics and formation mechanism of the alkaline lacustrine tight oil reservoirs of the Permian Fengcheng Formation in the Mahu Sag of the Junggar Basin have been systematically studied, and a genetic model has been proposed. Porosity of tight oil reservoirs of the Fengcheng Formation in the Mahu Sag is mostly less than 4%, with permeability mostly less than 0.1 mD. The lithology of the Fengcheng Formation in the Mahu Sag is mainly tuff, and the authigenic minerals mainly consist of feldspar, quartz, dolomite, and salt minerals (e.g., shortite, trona). The authigenic feldspar and quartz of the Fengcheng Formation in the Mahu Sag mainly originate from devitrification of volcanic glass in pyroclastic rocks. Reservoir space is dominated by dissolution pores of feldspar and salt minerals, followed by intercrystalline pores among feldspar, quartz, and other minerals formed by devitrification. Fractures are mainly comprised of shrinkage fractures, structural fractures, and bedding seans. The Permian Fengcheng Formation was mainly formed in an alkaline lake in the Mahu Sag, and the alkaline lacustrine sedimentary setting plays a decisive role in the formation of the tight oil reservoirs of the Fengcheng Formation. Volcanic glass in the tight oil reservoirs was generally devitrified within the alkaline lacustrine diagenetic fluid in the early diagenetic stage, and the devitrified micropores become an important reservoir space. Feldspars and salt minerals were mainly dissolved by acidic fluids generated by burial thermal evolution of the alkaline lacustrine source rocks of the Fengcheng Formation in the Mahu Sag, which produces the most developed dissolution pores in the tight oil reservoir. The abnormal high pressure formed by the early hydrocarbon generation and expulsion of the alkaline lacustrine source rocks in the Fengcheng Formation is one of the main reasons for porosity preservation. In the alkaline lake sedimentary environment of the Fengcheng Formation, widespread dolomitization and precipitation of a large number of salt minerals in the early diagenetic stage resisted partial compaction, which not only effectively protected early porosity, but also provided material conditions for dissolution porosity enhancement.

Keywords: Junggar Basin; Mahu Sag; Fengcheng Formation; alkaline lake; tight oil reservoir



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1. Introduction

Tight oil refers to the oil retained in the in situ source rocks or in the reservoir rocks with air permeability less than 1mD, which are interbedded with source rocks such as tight sandstone or tight carbonate rock, including tight oil (other tight rock oil except shale oil) in a narrow sense and shale oil [1–3]. Since the beginning of the 21st century, the production of tight oil in the United States has soared and become a hot spot for the exploration and development of unconventional oil and gas resources in the world [4–6]. Tight oil is the main driving force for the continuous growth of crude oil production by 2050 [7]. Tight oil is also widely distributed in major petroliferous basins in China, with resources of 308.47×10^8 t, and accounts for 28% of total oil resources, a key field in China's current and future oil and gas exploration and development [8,9].

According to chemical composition differences in lake water, continental salt lakes (salinity > 3.5%) can be divided into carbonate-type lake (alkaline lake), sulfate-type lake, and chloride-type lake [10]. The above three types of saline lake sedimentary environment favor development of high-quality source rocks and hydrocarbon accumulation [11–13]. Alkaline lakes are mostly distributed in the districts related to igneous rock or volcanic activity and those with an arid climate in ancient and modern times [14,15]. Typical examples of ancient alkaline lake tight reservoirs include the oil shale of the Paleogene Green River Formation in the western United States, the lower Cretaceous Coqueiro Formation and Macabu Formation in the Campos Basin, Brazil, the lower Permian Fengcheng Formation in the Junggar Basin, China, the Middle Permian Lucaogou Formation in the Santanghu Basin, the Paleogene Hetaoyuan Formation in Biyang Sag, and the Paleogene Shahejie Formation in Bohai Bay Basin [15–18]. Compared to sedimentary rocks of freshwater sedimentary environments, alkaline lacustrine sedimentary rocks are characterized by thin and frequent alternating beds, diverse lithologies [17], complex diagenetic evolution due to intense cementation and early hydrocarbon generation, and high heterogeneity, which benefits typical tight reservoir formation [17–20]. Alkaline lacustrine sedimentary rocks often undergo extensive dolomitization to generate dolomitic rocks [17,18]. For example, the dolomite content of the tight oil reservoirs of the Middle Permian Lucaogou Formation in the Santanghu Basin is 5%–61% [11,17]. Generally, in alkaline lakes, pH value is in the range of 9–11, total salinity is 100–350 g/L, and main cations are K^+ , Na^+ , Ca^{2+} , and Mg^{2+} [10,21]. Its special fluid geochemical conditions make sedimentary rocks of alkaline lakes exhibit different diagenetic evolution characteristics from classical diagenesis (emphasizing the influence of acid fluid on diagenesis). In the early stage of alkaline lacustrine diagenesis, carbonate cements (e.g., calcite, dolomite, and trona) occupy part of intergranular pores to inhibit later compaction and retain a large number of primary pores, and dissolution of carbonate cements in the late diagenetic stage can effectively improve the physical properties of the reservoir [18,22,23]. In an alkaline environment, siliceous and aluminosilicate minerals benefit the formation of dissolution pores (Shan et al., 2018). Lima and De Ros (2019) studied the lower Cretaceous alkaline lake carbonate reservoir in the Campos Basin, Brazil, and indicated that lake water chemistry changes and mineral precipitation and dissolution caused by the episodic flow of hydrothermal solution under burial conditions controls the formation, redistribution, and loss of reservoir pores [18]. In an alkaline lacustrine tight reservoir rich in volcanic materials, porosity produced by devitrification of volcanic glass is often regarded as one of the main pores [24–26]. However, devitrification is generally completed in the early diagenetic stage [27–29], while the contribution rate of devitrified porosity to the reservoir depends on the degree of preservation. In an alkaline environment, devitrification products are different from those in an acidic environment [24,30]. Saline lakes have considerable biological yield, more developed algae, and easy preservation of organic matter, which is characterized by early hydrocarbon generation, longer duration, and oil production due to catalysis of salt minerals [31,32]. The coupling relationship between diagenesis and hydrocarbon generation controls the diagenetic evolution characteristics of

tight oil reservoirs, and development of secondary pores is closely related to the thermal evolution of organic matter [32,33].

The Permian Fengcheng Formation in the Mahu Sag of the Junggar Basin is mainly composed of alkaline lacustrine fine-grained rock, with most porosities less than 5% and most permeabilities less than 1mD, in which oil resources amount to 46.66×10^8 t; the current exploration rate is less than 10%, showing huge potential for exploration [34,35] (Zhi et al., 2019; Tang et al., 2021). The tight oil reservoirs of the Permian Fengcheng Formation in the Mahu Sag is mainly rich in volcanic materials and contains many types of salt minerals closely related to alkaline lake fluids, which is different from those hosted in sandstones, carbonate rocks, and shale in other areas of the world [36]. Xu et al. (2019) stated that the Fengcheng Formation in the Mahu Sag is mainly composed of siltstone-finegrained stone containing organic matter and microcrystalline dolostones; its low alkaline mineral content (<40%) is favorable for reservoir development, and its main reservoir space consists of dissolved pores and fractures [37]. Some scholars suggest that the dissolved pores, fractures, and dolomite content are the key factors affecting reservoir development of the Fengcheng Formation in the Mahu Sag [38]. Yu et al. (2021) established the alkaline diagenesis model of the Fengcheng Formation in the Mahu Sag and reported that the quartz dissolution pores and dissolution fractures provided a new type of secondary reservoir space for oil and gas [39]. Zhu et al. (2014) discovered that volcanic materials affect reservoir diagenetic evolution, and plastic tuff fragments are unfavorable for reservoir formation [40]. Zhi et al. (2021) considered that tight oil in the Fengcheng Formation in the Mahu Sag is mainly enriched in dolomitic sandstones, with shale oil mainly accumulated in dolomitic siltstones and argillaceous siltstones [41]. There are numerous studies that have focused on the source rocks and hydrocarbon generation and expulsion characteristics of the Fengcheng Formation in the Mahu Sag [15,42], but there are few research results being published regarding the impact of source rock evolution on reservoirs. Zhi et al. (2019) pointed out that there is a good corresponding relationship between the source rock development interval of the Fengcheng Formation in the Mahu Sag and the "sweet point" reservoir development interval [34]. Hu et al. (2017) recognized that the tight reservoir of the Fengcheng Formation in the Mahu Sag is a typical "densification before hydrocarbon accumulation" type [43]. At present, research about the alkaline minerals of the Fengcheng Formation in the Mahu Sag focuses on type, genesis, and the paleoenvironment of alkaline minerals; however, research on the controlling factors of reservoir development is still limited to qualitative description [44–46]. To sum up, the following main problems still exist in the study of the tight oil reservoirs of the Fengcheng Formation in the Mahu Sag: (1) Is the main reservoir space dominated by microfractures or dissolution pores, or other pore types? (2) Is the main reservoir lithology terrigenous clastic rock, pyroclastic rock, shale, or dolomitic rock? (3) What is the relationship between reservoir development and the alkaline lake environment? (4) What are the main causes of reservoir development? Therefore, based on the results of optical microscope (including fluorescence mode), scanning electron microscope (including argon ion polishing), and X-ray diffraction analysis, this paper systematically studies the rock mineralogical characteristics, diagenesis, and reservoir space characteristics of the tight oil reservoirs of the Fengcheng Formation in the Mahu Sag. To solve the above problems, typical samples are selected for elemental analysis, micro-zone oxygen and carbon isotope analysis, fluid inclusion analysis, and energy spectrum analysis in order to deeply analyze the formation and preservation mechanism of reservoir pores, clarify the genesis of the alkaline lacustrine tight oil reservoirs, establish the development model of the tight oil reservoirs of the Fengcheng Formation in the Mahu Sag, and provide a theoretical basis for the prediction of tight oil reservoirs in the Fengcheng Formation in the Mahu Sag.

2. Geological Background

The Junggar Basin (Figure 1a,b), located in the eastern segment of the Kazakhstan Plate, is a large, superimposed basin developed on the basis of the Paleo-Asian Ocean [39].

The Mahu Sag is located in the northwest of the Junggar Basin [42,47] (Figure 1c) and is the major hydrocarbon-generating sag with the highest hydrocarbon enrichment in the basin [31]. The Junggar Basin entered the foreland basin evolution stage at the end of the Carboniferous period and, until the end of the Triassic period, the Mahu Sag was always the subsidence center of the basin [48]; the Yanshan Movement and the Himalayan Movement caused overall uplift of the Mahu Sag [48-50]. The Early Permian volcanic activity in the Mahu Sag was frequent and large scale [48,51], and volcanic and pyroclastic rocks were widely developed in the Lower Permian. Due to the influence of geothermal anomalies related to volcanic activity, the paleothermal gradient from Permian to Jurassic was 3.9–5 °C/100 m [50], much higher than the current geothermal gradient of 2.0-2.6 °C/100 m [49]. During the depositional period of the Fengcheng Formation in the Early Permian, the Mahu Sag was a semi-closed lake [52] with a paleo-latitude of roughly 35° N [53,54], which is significantly lower than the current latitude of 44–48° N, and was in the subtropical zone, thus alkaline lacustrine deposits were widely developed. The frequent volcanic activities during deposition of the Fengcheng Formation in the Mahu Sag, superimposed with alkaline lake salt minerals and terrigenous clastic sediments, resulted in complex and diverse rock assemblages [41,46]. The Fengcheng Formation in the Mahu Sag covers an area of about 1500 km² with a thickness between 200 m and 1000 m, which mainly consists of dolomitic rocks, including dolomitic tuff, dolomitic siltstone, and dolomitic mudstone, as well as pyroclastic rock and terrigenous clastic rock (Figure 1d) [48]. The Fengcheng Formation is the major hydrocarbon source stratum in the Mahu Sag, which is characterized by a high abundance of organic matter (TOC = 0.51%-3.19%, mean 1.20%), type II kerogen, medium maturity (Ro = 0.56%-1.14%, mean 0.80%), early hydrocarbon generation, and continuous hydrocarbon generation [44,48].



Figure 1. (a) Location of the Junggar Basin in China; (b) tectonic unit divisions of the Junggar Basin; (c) location map of the Mahu Sag and the drilling wells from which the study samples were collected; and (d) the composite column of the Fengcheng Formation.

3. Samples and Methods

Two hundred and twenty samples from 20 drilling wells (Figure 1c) in the Fengcheng Formation in the Mahu Sag were selected for thin section preparation and analytical techniques.

Thirty-two core plugs 2.5 cm in diameter were washed with chloroform to clean up the pore fluids before physical property (porosity and permeability) analysis, and 217 physical property data were collected from the Xinjiang Oilfield Company. In accordance with the national standard [55], porosity was tested through the alcohol saturation method and permeability was measured using a flowmeter by flowing air through the core.

Thin sections were double-sided polished and not covered for multiple purposes. In order to ensure fluorescence observation accuracy, the prepared samples were casted with blue resin in an oil-unwashed state and three-fourths of the thin sections were stained with alizarin red. An optical microscope was used to study rock and mineralogical characteristics, reservoir space types and development characteristics, characteristics of oil and gas charging periods, as well as fracture types, forming periods and their relationship with other diagenetic phenomena. Fluorescence mode observation was focused on the fluorescence of unfilled pores and cracks, as well as the fluorescence of fluid inclusions captured by minerals.

A total of 30 samples were selected for scanning electron microscope analysis on a ZEISS EVO MA15/LS15, and 6 of these samples were polished with argon ion. The mineral types that could not be identified by optical microscope were determined by energy spectrum analysis (EDS) on a TEAMTM XLT EDS.

In view of fine-grained rocks and soluble salt minerals which are easy to dissolve during thin section making, 48 samples with different petrological characteristics were selected for X-ray diffraction whole-rock composition analysis. The solids formed by evaporation crystallization of the solution from thin section making was analyzed by X-ray diffraction (XRD). The XRD detection device was a D/max-2500pc X-ray diffraction analyzer, and the test standard used was the Chinese petroleum industry standard SY/T 5163-2010 [56].

In order to analyze element composition of the tight oil reservoir, 39 samples were determined by X-ray fluorescence spectrometry. The analytical instrument used was a PW2404 X-ray fluorescence spectrometer (XRF), and the detection standard used was the Chinese national standard GB/T 14506 28-2010 [57].

In order to determine the formation temperature of diagenetic minerals, the well depth intervals with obvious gas–liquid inclusions under polarizing and fluorescent microscope were firstly selected, and 8 fluid inclusion thin sections from 6 wells were prepared. According to the fluid inclusion temperature measurement standard [58], the homogenization temperature and freezing point temperature were measured by a Linkam THMS-600 cold and hot platform, with absolute deviations of 2 °C and 0.2 °C, respectively. The carbonates of the same samples were then decomposed by a FUSION CO₂ laser system (laser wavelength 1064 nm, focusing beam spot 20 μ m), and thirteen samples with a single composition of dolomite, calcite, or other carbonates under optical microscopic observation were finely ground into samples to be reacted with 100% orthophosphoric acid at room temperature (25 °C) in order to obtain CO₂. The extracted CO₂ was analyzed by a MAT253 mass spectrometer to obtain carbon and oxygen isotope values (VPDB standard), with relative standard deviations of 0.2‰ and 0.3‰, respectively, based on the petroleum industry standard [59].

In this study, the fluid oxygen isotope values of dolomite and other carbonate minerals (calcite, shortite, and so on) are inversed by using the samples with both inclusion homogenization temperatures and in situ oxygen isotope values. The fractionation equations for dolomite and other carbonate minerals (calcite, carbonaceous sodalite, and so on) are quoted after Land (1983) and Friedman and O'Neil (1977) [60]. $\delta^{18}O_{SMOW}$ of the early diagenetic fluid was 3.86–5.55‰ (average 4.69‰; based on three samples of authigenic dolomite and one sample of authigenic calcite) and the deep fluid $\delta^{18}O_{SMOW}$ was 14.46–15.78‰ (average 15.06‰; based on four fracture- and cave-filling dolomite samples). The oxygen isotope temperatures of the samples without homogenization temperatures were then calculated.

According to the homogenization temperatures, oxygen isotope temperatures, and paleogeothermal gradient in the Mahu Sag, paleoburial depth of authigenic minerals is calculated by the following formula.

Paleoburial depth of authigenic minerals = (diagenetic temperature – paleosurface temperature)/paleogeothermal gradient

Temperature and paleogeothermal gradient are measured in °C and °C/100 m, respectively. The paleogeothermal gradient from Permian to Eogene was averaged to 4.5 °C/100 m [50], and a paleosurface temperature of 25 °C was selected [15].

Major and trace elements, in situ carbon and oxygen isotopes, fluid inclusion temperature measurement, scanning electron microscope (energy spectrum) experimental analysis, and physical property measurements were completed by the CNOOC Experimental Center (Tianjin, China). The whole rock carbon and oxygen isotope test was completed by the Key Laboratory of Natural Gas Accumulation and Development of the CNPC (Chengdu, China). Polarizing microanalysis, fluorescence microanalysis, and whole rock mineral X-ray diffraction analysis were completed by the State Key Laboratory of Oil and Gas Reservoir Geology and Development Engineering of Chengdu University of Technology (Chengdu, China).

4. Results

4.1. Rock and Mineral Characteristics

The rock types of the Permian Fengcheng Formation in the Mahu Sag are complex, including pyroclastic rock, salt rock, sandstone, siltstone, mudstone, basalt, and so on (Figure 2a). Basalt is less distributed in the Fengcheng Formation, so basalt was not included in this study. Pyroclastic rocks mainly comprise tuffs, and the pyroclastic materials mainly consist of volcanic dust, shards, and a small amount of crystal debris. The minerals in tuffs are mainly albite, followed by quartz, with less K-feldspar and clay minerals (Figure 2b); the clay minerals mainly consist of I/S mixed-layer minerals and illites. The most developed authigenic minerals of the sandstones are dolomite, followed by ankerrite, calcite, and salt minerals (Figure 2c). The salt minerals mentioned in this article refer to salt minerals excluding calcites and dolomites (mainly including reedmergnerite, followed by wegscheiderite, shortite, trona, and northupite) (Figure 2d).

4.2. Characteristics of Diagenesis

4.2.1. Devitrification of Volcanic Glass

Chemical composition is the most important factor controlling devitrification degree, and volcanic glass with high SiO₂ content is easy to devitrify [30]. Major element analysis results of 27 tuff samples show that 91% of the samples have SiO₂ content greater than 52% (Table 1). According to the classification standard of magmatic rocks [61], tuff samples are mainly medium–acidic rocks (dacites), the material basis for extensive devitrification of the Permian pyroclastic rocks.



Figure 2. Rock and mineral composition characteristics of the Fengcheng Formation in the Mahu Sag. (a) Frequency histogram of rock type distribution according to optical observation; (b) histogram of mineral composition content for tuff according to XRD analysis; (c) histogram of authigenic mineral composition in sandstone according to optical observation; and (d) histogram of salt minerals composition according to XRD analysis.

Well	Depth	Al_2O_3	CaO	Fe ₂ O ₃	MgO	MnO	P_2O_5	K ₂ O	SiO ₂	Na ₂ O	TiO ₂
FN14	4079.13	9.42	2.48	1.78	6.58	0.02	0.11	6.27	61.40	2.02	0.49
FN15	4031.90	3.25	15.99	1.10	1.90	0.09	0.08	0.58	61.72	0.52	0.13
FN16	4023.04	13.80	6.44	5.51	4.64	0.09	0.33	3.33	54.56	1.72	0.73
FN17	4106.10	5.01	9.22	2.19	6.67	0.04	0.08	1.21	52.67	4.30	0.20
FN18	4174.00	3.31	2.97	2.71	4.94	0.09	0.03	1.81	63.32	6.36	0.16
K204	4348.50	12.62	5.93	5.32	2.68	0.14	0.15	1.13	53.45	6.82	0.53
K207	4751.30	14.28	3.32	4.53	1.62	0.11	0.41	2.78	57.16	9.34	0.74
K207	4750.65	15.39	3.66	2.90	1.44	0.10	0.06	2.15	57.73	9.50	0.41
M49	4820.32	11.94	12.46	3.26	1.60	0.18	0.28	1.88	50.32	4.82	0.50
M49	4815.66	17.67	0.68	1.92	2.13	0.01	0.02	0.70	64.77	9.03	0.11
MY1	4676.92	6.24	11.29	2.75	9.01	0.13	0.07	3.48	43.72	1.42	0.26
MY1	4857.41	5.66	10.46	2.83	13.10	0.08	0.04	4.39	40.03	0.99	0.29
MY1	4669.85	6.50	9.08	3.00	9.68	0.07	0.08	2.76	48.35	2.02	0.32
MY1	4798.10	11.24	5.01	4.77	2.45	0.10	0.19	5.91	55.27	2.63	0.49
MY1	4877.04	14.35	1.20	4.98	3.16	0.06	0.16	9.62	57.89	2.03	0.65
MY1	4651.35	14.50	0.97	6.27	2.58	0.09	0.25	4.34	59.82	5.35	0.99
MY1	4716.84	7.93	6.73	4.06	6.45	0.10	0.09	3.07	53.24	2.54	0.41
MY1	4894.17	14.04	1.20	3.27	0.74	0.01	0.15	8.34	63.46	2.63	0.38
MY1	4786.03	10.15	3.52	2.35	0.14	0.11	0.12	3.17	70.83	3.79	0.04
MY1	4598.11	4.54	3.77	2.78	2.82	0.15	0.09	1.72	75.65	1.38	0.23
MY1	4610.86	6.88	5.62	3.17	4.55	0.14	0.10	4.23	62.78	1.13	0.31
MY1	4814.13	4.28	3.60	3.03	2.57	0.15	0.07	2.95	75.46	0.47	0.20
MY1	4634.11	10.13	1.09	0.89	0.56	0.04	0.07	3.07	76.33	3.92	0.06
MY1	4152.20	5.77	6.11	2.81	4.50	0.08	0.05	1.49	40.73	16.02	0.24
X72	4561.00	5.30	9.17	2.79	5.79	0.08	0.10	0.82	62.28	0.63	0.21
X87	4357.69	7.55	16.63	3.01	3.15	0.10	0.24	1.63	45.03	2.52	0.37
X88	4354.89	12.73	5.18	4.72	3.63	0.10	0.26	3.06	55.33	4.08	0.55

Table 1. Major element analysis data of tuff samples.

Devitrification mainly produces a large quantity of albite, potassium feldspar (K-feldspar), and quartz microcrystals, or fibrous crystals with a spherulitic texture (Figure 3). According to the occurrence of crystals and their aggregates (Yang, 1993; Xiao et al., 2009), devitrification of volcanic glass in the Permian tight oil reservoir in the Mahu Sag can be divided into three types: (1) Weak devitrification (crystallite texture; Figure 3a,b). (2) Medium devitrification (microcrystalline texture; Figure 3c,e). (3) Strong devitrification (spherulite texture and mosaic crystal texture; Figure 3f).



Figure 3. Types and characteristics of devitrification of the Permian tight oil reservoir in the Mahu Sag. (a) Crystallite produced by devitrification, FN14, P₁f, 4036.34 m, PPL (plane-polarized light). (b) The same view as (a), XPL (perpendicular polarized light). (c) Microcrystalline quartz formed by devitrification and stylolite filled with asphalt, FN 14, P₁f, 4106.10 m, XPL. (d) Microcrystalline quartz formed by devitrification, F21, P₁f, 3373.27 m, SEM (scanning electronic microscopy). (e) Albite formed by devitrification, MY1, P₁f, 4852.18 m, SEM. (f) Devitrified shard exhibits microcrystalline texture \rightarrow spherical texture \rightarrow mosaic crystal texture from the edge to the middle, FN14, P₁f, 4061.50 m, XPL.

4.2.2. Precipitation of Authigenic Minerals

Various types of authigenic minerals are developed in the Fengcheng Formation tight oil reservoirs in the Mahu Sag, including calcium and magnesium carbonates such as dolomite, calcite, iron dolomite and siderite, among which dolomite is the most developed one. Dolomite has multiple phases and different crystal forms, including histogram, semihedral, semihedral–hedral, and euhedral (Figure 4a,b), with semihedral and semihedral– hedral the most developed. Calcite mainly has two major types: grain-replacement and matrix and pore-filling (Figure 4c). The authigenic siliceous minerals are mainly fractureand pore-filling quartz (Figure 3c,e,f). The authigenic aluminosilicate minerals are mainly feldspar and zeolite. Feldspar is mainly distributed in rocks with strong devitrification and appears as devitrification products (Figure 3e). Zeolites are mainly distributed in relatively coarse sandstones, which often appear as intergranular cements. The authigenic salt minerals include shortite, northupite, trona, wegscheiderite, eitelite, reedmergnerite, and halite (Figure 4d–f), which are mainly enriched in layers and lenses. The distribution of pyrite is common.



Figure 4. Photomicrographs of the main diagenetic minerals of the Fengcheng Formation in the Mahu Sag. (**a**) Fine–silt crystal subhedral dolomite is distributed in strips, MY1, P₁f, 4595.34 m, PPL. (**b**) Euhedral dolomite filled in the dissolution pores, MY1, P₁f, 4814.13 m, XPL. (**c**) Calcite filling pores and metasomatizing clastic particles, K201, P₁f,4166.2 m. (**d**) Reedmergnerite (yellow arrow) replacing sodalite (blue arrow) in bedding fractures, AK1, P₁f,5667.25 m, XPL. (**e**) Wegscheiderite in mudstone (green arrow), K207, P₁f, 4753.98 m, SEM. (**f**) Eitelites are dyed pink and dissolved, MY2, P₁f, 4433.85 m, PPL.

Dolomite is generally developed in the Fengcheng Formation of the Mahu Sag. Inclusion temperatures and isotopic geological temperatures show that dolomite is developed in four temperature ranges: less than 60 °C, 60–90 °C, 90–120 °C, and 120–150 °C (Figure 5). According to the main temperature range and microscopic characteristics (Figure 4a) of dolomites, dolomites in the Fengcheng Formation of the Mahu Sag are mainly precipitated in the shallow–middle burial stage.



Figure 5. Temperature distribution of dolomites in the Fengcheng Formation of the Mahu Sag.

4.2.3. Dissolution

Dissolution pores are the main storage space for tight oil reservoirs of the Fengcheng Formation in the Mahu Sag. Feldspar crystal pyroclasts and terrigenous clastic feldspar are widely dissolved (Figure 6a–e), dissolution of siliceous minerals can be seen occasionally (Figure 6f), and dolomites (Figure 6g), salt minerals such as wegscheiderite (Figure 6h), shortite (Figure 6i), and northupite (Figure 4f) are also widely dissolved. Except for some salt minerals, such as halite and trona that are soluble in hot or cold water, most minerals are dissolved in an acidic environment.



Figure 6. Photomicrographs showing dissolution of the Permian Fengcheng Formation in the Mahu Sag. (a) Feldspar dissolution pore and calcite replacing feldspar, K201, P₁f, 4250.55 m, PPL. (b) The ejected rock fragments are strongly dissolved and the dissolution pores are filled with calcite, K201, P₁f₁, 4250.55 m, PPL, (c) The same view as (b), XPL. (d) Intergranular laumontite-dissolved pores, K201, P₁f, 3803.91 m, PPL. (e) The same view as (d), XPL. (f) Quartz dissolution in the fracture, MY1, P₁f, 4592.45 m, PPL. (g) Reedmergnerite metasomatizing dolomites (reedmergnerite intercrystalline dolomites are dissolved), FN14, P₁f, 4165.90 m, PPL. (h) Wegscheiderite dissolution, MY1, P₁f, 4899.9 m, PPL. (i) Shortite dissolution, MY2, P₁f, 4429.70 m, PPL.

4.2.4. Fractures

According to fracture origins, fractures of the Fengcheng Formation can be divided into two types [62]: structural fractures (Figure 7a,c,e,f) and diagenetic fractures. Diagenetic fractures can be divided into four types, namely shrinkage fractures (Figure 7a), stylolite (Figure 3c), expansion fractures, and bedding fractures (Figure 7b). Under an optical



microscope, the fractures mainly consist of micro-fractures (fracture width less than 0.1mm), and some fractures are filled with quartz, dolomites, bitumen, and so on.

Figure 7. Characteristics of fractures in the Permian Fengcheng Formation in the Mahu Sag. (**a**) Syngenetic shrinkage fracture (blue arrow) is filled with fine-crystalline dolomite (red arrow) and microcrystalline quartz (yellow arrow); structural fracture (white arrow), FN14, P₁f, 4062.90 m, PPL. (**b**) Well-developed bedding fracture, MY2, P₁f, 4152.35–4152.55 m, drilling core. (**c**) Fracture networks, K207, P₁f, 4862 m, PPL. (**d**) The same view as (**c**); the fracture with green fluorescence, (FL, fluorescence photomicrograph). (**e**) Unfilled structural fracture cutting across the filled shrinkage fracture, MY1, P₁f, 4840.21 m, PPL. (**f**) Dissolution pores in calcites along structural cracks, Fengnan 14, P₁f, 4061.50 m, PPL.

4.2.5. Mechanical and Chemical Compaction

Tight oil reservoirs of the Fengcheng Formation generally exhibit linear grain contacts (Figures 3a and 5a) and stylolites (Figure 3c), which expresses strong compaction. Intergranular pores of some reservoir rocks are filled with dolomites and salt minerals, and the grains exhibit tangential contacts or non-contact, indicating that these reservoir rocks experienced less compaction during burial.

4.3. Reservoir Characteristics

4.3.1. Physical Properties

In most reservoir rocks samples of the Fengcheng Formation in the Mahu Sag, porosity was less than 4% and permeability was less than 0.1 mD (Figure 8). Pyroclastic rocks and sandstones had relatively better porosity (Figure 8a), with porosity greater than 8% accounting for 18.4% and 24.0%, respectively. Tuff and sandstone–conglomerate, followed by salt rock, had the highest permeability, while mudstone–siltstone had the lowest permeability (Figure 8b).



Figure 8. Histogram of porosity (**a**) and permeability (**b**) distribution of different reservoir rocks in the Fengcheng Formation.

4.3.2. Reservoir Space

Dissolution pores are the most developed reservoir space type (Figure 9) of the tight oil reservoir of the Fengcheng Formation, mainly including feldspar dissolution pores (Figure 6a,b) and salt mineral dissolution pores (Figure 6h,i). Intercrystalline pores are less frequent and mainly comprise micropores less than 10 µm among micro- and silt-crystalline feldspars, microcrystalline quartz (Figure 3d), dolomites (Figure 4a), or other salt minerals (Figure 4d,f). In addition, there are very few residual intergranular pores in the Fengcheng Formation due to the intense compaction and early cementing.





4.4. Hydrocarbon Charging

The alkaline lacustrine source rocks of the Fengcheng Formation in the Mahu Sag are characterized by high organic matter abundance, type II kerogen, medium maturity, early hydrocarbon generation, and continuous emplacement [48]. The Permian tight oil reservoirs in the Mahu Sag have three stages of oil and gas emplacement from early to late: (1) The first stage is asphalt distributed in intergranular residual pores and early shrinkage fractures, with no fluorescence or brownish yellow fluorescence (Figure 10a). (2) The second stage has orange-yellow fluorescence (Figure 10c,e,g). (3) The third stage has green fluorescence (Figure 10i). The homogenization temperatures of authigenic minerals, such as dolomite and its associated calcite, quartz, and salt mineral fluid inclusions, is in a range of 68–123 °C (average 95 °C), which can be divided into three temperature ranges: 68–80 °C, 80–100 °C, and 110–123 °C (Figure 11). There is a good correlation between the micro fluorescence color of fluid inclusions and homogenization temperature (Figure 10).

According to the thermal evolution history of the source rocks of the Fengcheng Formation in the Mahu Sag (Figure 12), the source rocks experienced three stages of hydrocarbon generation and expulsion [48]: phase 1 in the late Permian, phase 2 in the early Triasic, and phase 3 in the early Jurassic.



Figure 10. Fluid inclusion characteristics in authigenic minerals of the Fengcheng Formation in the Mahu Sag. (**a**) Brine inclusions in fine-crystalline subhedral dolomite, homogenization temperature 68 °C, δ^{13} C = 2.07‰, δ^{18} O = -0.86‰ (laser isotope), MY1, P₁f, 4899.86 m, PPL. (**b**) Hydrocarbon inclusions in fine-crystalline calcite, homogenization temperature 88 °C, MH28, P₁f, 4932.35 m, PPL. (**c**) Hydrocarbon inclusions with orange-yellow fluorescence, the same view as (**b**), FL. (**d**) Hydrocarbon inclusions in reedmergnerite, homogenization temperature 86 °C, MH28, P₁f, 4932.35 m, PPL. (**e**) Hydrocarbon inclusions with orange-yellow fluorescence, the same view as (**d**), FL. (**f**) Hydrocarbon inclusions in reedmergnerite, homogenization temperature 96 °C, FN14, P₁f, 4165.90 m, PPL. (**g**) Hydrocarbon inclusions with orange-yellow fluorescence, the same view as (**f**), FL. (**h**) Hydrocarbon inclusions in coarse-crystalline dolomite in solution pores, homogenization temperature 121 °C, δ^{13} C = 3.65‰, δ^{18} O = 2.29‰ (laser isotope), K207, P₁f, 4854.3 m, PPL. (**i**) Hydrocarbon inclusions with green fluorescence, the same view as (**f**), FL.



Figure 11. Homogenization temperature distribution of authigenic mineral fluid inclusions in the Fengcheng Formation in the Mahu Sag.



Figure 12. Burial history and thermal evolution history of FN1 in the Mahu Sag, revised from Tian et al. (2019) [63].

5. Discussion

5.1. Genesis of Tight Oil Reservoirs

5.1.1. Devitrification Porosity Genesis

By summarizing several research results on the main occurrence period of devitrification [27,29], it is concluded that there is no clear lower limit depth for existence of volcanic glass, and devitrification mainly occurs in the early diagenetic stage. Both acidic and alkaline conditions are favorable for devitrification of volcanic glass [64]. From the syngenesis to early eodiagenesis stage, the diagenetic fluid is strongly alkaline in the Fengcheng Formation in the Mahu Sag. The medium–acidic volcanic glass, rich in alkaline metal elements such as K and Na, is strongly hydrated and hydrolyzed, and the devitrification is carried out rapidly, resulting in the precipitation of a large number of microcrystalline feldspar and quartz. In the late stage of eodiagenesis to the early stage of mesodiagenesis (about 65–120 °C), a lot of organic acids are produced in the source rocks of the Fengcheng Formation. The complexation of organic acids destroys the structure of volcanic glass, further devitrifies the volcanic glass, and the precipitated Si⁴⁺, Al³⁺ and Na⁺ makes some crystallitic, microcrystalline feldspar and quartz grow into fibrous crystals and mature grains of a spheroidal texture.

Devitrification of dacite volcanic glass is taken as an example that illustrates the contribution of devitrification to the reservoir. The average contents of plagioclase, quartz, K-feldspar, and clay minerals are 27.5%, 22.2%, 4.3%, and 2.6%, respectively (Figure 2). Thus, the chemical reaction process of devitrification of dacite volcanic glass is simplified as follows: dacite volcanic glass \rightarrow albite + quartz + potassium feldspar + illite. In the process of devitrification, quartz and feldspar crystallize first, followed by condensate minerals [30,65]. Therefore, it is assumed that the generation order of minerals in the process of devitrification is albite, quartz, potassium feldspar, and illite. According to the mass conservation principle, using the content ratio, molar mass, and density data of diagenetic minerals (Table 2), the volume of 1mol dacite volcanic glass is 178 cm³, and the total volume of albite, quartz, potassium feldspar, and illite generated after devitrification is 158 cm³, with a net volume reduction of 9%, which is equivalent to porosity being increased by about 9% after devitrification. In thin sections, it can be seen that intergranular pores are developed in the middle of shards with strong devitrification (Figure 3f), indicating that devitrification can enhance porosity.

Table 2. Mineral composition, molar mass, and density of pyroclastic rock.

Composition	Illite	Albite	K-Feldspar	Quartz	Dacite
Chemical formula	KAl ₃ Si ₃ O ₁₀ (OH) ₂	NaAlSi ₃ O ₈	KAlSi ₃ O ₈	SiO ₂	
Molar mass (g/mol)	398	262	278	60	420
Density (g/cm ³)	2.75	2.61	2.57	2.65	2.36

Notes: Density of dacite is quoted from [19] Ma (2016) and its molar mass is calculated according to the mineral composition data of granodiorite provided by Xiao et al. (2009) [61]; Molar mass and density of illite, albite, potassium feldspar and quartz are quoted from Yuan et al. (2016) [58].

Most devitrified micropores couldn't be observed under optical microscope (Figure 13a,c), which may be the main reason why some scholars suggested that the fracture plays a role equivalent to the dissolution pore in the reservoir space of the tight oil reservoirs of the Fengcheng Formation in the Mahu Sag [34,37]. Through SEM observation, especially SEM observation after argon ion polishing, more nano intercrystalline pores can be seen (Figure 13b,d). For example, the alcohol porosity of the 2926.6 m tuff sample from well W35 is 9.93%, but few pores can be seen in the casting thin sections under polarized light (Figure 13c); however, more micropores are observed under SEM after argon ion polishing (Figure 13d). Therefore, devitrification of volcanic glass in the Permian tight oil reservoir in the Mahu Sag is one of the most important mechanisms of porosity formation.



Figure 13. Devitrified micropores in the Permian tight oil reservoir in the Mahu Sag. (**a**) Few visible pores in tuff, W35, P₁f, 2927.20 m, porosity 3.97%, PPL. (**b**) Nano-pores formed by devitrification, the same sample as (**a**), SEM (argon ion polishing). (**c**) Relatively developed visible pores, W35, P₁f, 2926.60 m, porosity 9.93%, PPL. (**d**) (**b**) Nano-pores and micropores formed by devitrification, the same sample as (**c**), SEM (argon ion polishing).

5.1.2. Fracture Genesis

Shrinkage fractures include thermal shrinkage fractures in tuff and dry shrinkage cracks in mudstone (Figure 7a). Expansion fractures, mostly lenticular, are formed by mechanical compaction and abnormal high pressure produced by thermal maturation of the alkaline lake source rock and are often filled with asphalt. Microwave-like and horizontal bedding fractures (Figure 7b) are mainly distributed in fine-grained rocks formed during the sedimentary period, which mostly keep closed under burial conditions and can be reopened by tectonic movement and hydrocarbon generation pressurization. Structural fractures (Figure 7c–f) are mainly related to three stages of tectonic movements—the late Permian, the late Triassic, and the late Jurassic—and the Himalayan Movement has little impact on the Mahu Sag [66]. There are a large number of structural fractures in the Permian tight oil reservoirs in the Mahu Sag, which greatly improves reservoir properties and permeability.

5.1.3. Dissolution Porosity Genesis

The Permian tight oil reservoir in the Mahu Sag is characterized by self-generation, self-accumulation, and frequent source–reservoir interbedding [41]. The organic acid and carbonic acid generated by the source rock enter the adjacent reservoir through primary migration with little loss [67], which is an important cause of secondary solution pore development in tight oil reservoirs.

Acidic fluids can be produced earlier or at the same time as hydrocarbon generation [67]. In the eodiagenesis stage (less than 80 $^{\circ}$ C), organic acids are rapidly consumed by

bacteria and the acidic fluid is mainly carbonic acid; however, the dissolved pores in this stage are difficult to preserve due to compaction and cementation [68]. The peak temperature range of organic acid generation is 80–120 °C, and the generation of carbonic acid continues in the whole hydrocarbon generation process [67,69]. Due to the consumption of carbonic acid by authigenic carbonate minerals such as dolomite, the acid fluid in the middle–late diagenetic stage is mainly organic acid. Thin section observation shows that feldspar dissolution is later than calcite cementation (Figure 6b,c). The homogenization temperature of brine inclusions in calcite in this period is 88 °C (Figure 10d,e), and it can be inferred that feldspar dissolution mainly occurs after 88 °C, which corresponds to the peak temperature range of organic acid.

Because the rocks of the Fengcheng Formation in the Mahu Sag are fine-grained, and intergranular and intercrystalline throats are very poor, faults and fractures are necessary for acid fluid to migrate to further rocks rich in feldspar and salt minerals. Early shrinkage fractures widely developed in the Fengcheng Formation of the Mahu Sag and structural fractures formed by multi-stage tectonic movement [47] (Figure 7a,c,e,f) provide channels for the migration of acid fluid, water, and oil and gas (Figure 7b–d,f). Therefore, dissolved pores are more developed near fractures or faults (Figure 7b,f).

The most frequently observed salt minerals in thin sections are insoluble reedmergnerites and relatively insoluble shortites. Other salt minerals are often dissolved and lost during thin section preparation, and it is believed that, in the early study stage, salt minerals are one of the factors that lead to densification of the reservoir. In this study, through XRD and EDS, it is found that wegscheiderite, trona, northupite, gordaite, eitelite, and so on, are distributed widely. Through an evaporation crystallization experiment and XRD analysis, many salt minerals were precipitated from the solution collected from thin section preparation. For example, 50% of thermonatrite and 10% of halite were detected in the evaporative crystalline solid from the sample at 4750.65 m from well K207 (Figure 14). Most of these salt minerals are easily soluble in acid, and their solubility in acid is much greater than that of aluminosilicate minerals such as feldspar and zeolite; some salt minerals are also easily soluble in water, such as nahcolite, trona, thermonatrite, gordaite, and so on [70]. Therefore, acidic fluids generated during evolution of the source rocks of the Fengcheng Formation not only dissolved aluminosilicates such as feldspar and zeolite, but also dissolved salt minerals. It can even be proposed that in rocks with more developed salt minerals, there may be more dissolved pores of salt minerals, which is also observed in the imaging logging and cores of some salt-rich wells (Figure 7b). According to correlation analysis between porosity and the content of trona, wegscheiderite, halite, and other salt minerals obtained by XRD of selected samples, there is a medium positive correlation (r = 0.55) between the two (Figure 15).



Figure 14. (a) Dolomitic tuff, K207, P₁f, 4750.65 m, XPL; (b) XRD analysis of evaporated crystal, the same sample as (a).



Figure 15. Relationship between content of soluble salt minerals and porosity in the Fengcheng Formation of the Mahu Sag.

Microscopic observation shows that siliceous mineral dissolution is not common in the Permian tight oil reservoir in the Mahu Sag, and the dissolved minerals are mainly aluminosilicate and salt minerals that are soluble in acidic fluid (Figure 6). The reasons are: (1) Solubility of feldspar is still very low under strong alkaline conditions [71]. (2) Acidic fluid being produced during the early thermal evolution of alkaline lake source rocks gradually reduces the pH value of formation water, which is conducive to the dissolution of aluminosilicates such as feldspar and unfavorable to siliceous mineral dissolution.

It can be concluded that the alkaline lacustrine high-quality source rocks of the Fengcheng Formation in the Mahu Sag released abundant acidic fluids during burial thermal evolution, which dissolved feldspar and salt minerals in the Permian tight oil reservoir to produce well-developed dissolution pores.

5.1.4. Porosity Preservation

In most cases, in fine-grained rocks with a burial depth of more than 3000–4000 m, porosity is mostly less than 5% [72]. However, in the fine-grained rocks over 3500 m or close to 5000 m in the Fengcheng Formation, some porosities exceed 10%, and devitrified micropores and some dolomite intercrystalline pores are well preserved.

Devitrified pores and dolomite intercrystalline pores in the Fengcheng Formation are formed at shallow burial and shallow-medium burial depths. How can these pores be effectively preserved after entering deep burial? During the deposition of the Fengcheng Formation, the multi-stage salinization resulted in the precipitation of more salt minerals in the stratum, some of which appeared in the form of intergranular and intercrystalline cements and were mostly enriched in layers (Figure 7b). From the microscopic features, it can be seen that the dolomite crystals are still in point contact with the rocks at a depth of nearly 5000 m today (Figure 4a). It is obvious that these salt cements resist further compaction. The salt minerals deposited in the Fengcheng Formation are mainly trona, sodalite, wegscheiderite, and northupite. These minerals have low density and are generally distributed at 2-2.3 g/cm³, while the density of other aluminosilicate minerals is generally greater than 2.5 g/cm³ [70]; therefore, it is easy to identify the salt layer through density logging. From the macroscopic characteristics of salt minerals of the Fengcheng Formation, which is mostly stratified and does not cut the stratification, it can be seen that the salt minerals are mainly formed in the contemporaneous-penecontemporaneous period and belong to the chemical sediments caused by the salinization of lake water. The formation period of salt minerals can also be further understood by measuring isotopes and inclusions. In this study, a total of five in situ isotopes of salt minerals were obtained. The carbon

and oxygen isotope distribution is 0.112‰–3.916‰ and 2.06‰–4.42‰, respectively, which is obviously heavier. According to the isotope temperature calculation, its formation temperature distribution is 17–27.9 °C, further indicating that these salt strata formed very early.

Salt rock strata are the product of chemical precipitation, and the pores are generally poorly developed and are usually the caprock of salt-bearing hydrocarbon basins [11,73]. Two modern kinds of salt crusts are commonly found in salt lakes. One is very thin (only a few mm thick) but hard and dense, generally composed of microcrystalline alkaline carbonate; the other is porous, generally composed of soluble salts such as trona and thermonatrite, can be preserved under water-deficient conditions, and is hard (an example of this type is the salt crust landscape in the Salt Valley of California where, although the thickness is only about 30 cm, it is very hard and requires a pick to dig out) [11]. It can be seen that many early-formed salt crusts have strong compression resistance when buried shallowly. In addition, the tightness of the salt strata can also cause abnormally high pressure in the lower strata, which is conducive to the preservation of deep reservoir pores [11]. During the deposition of the Fengcheng Formation, salt strata which formed earlier due to the alkaline lake environment could effectively resist further compaction damage to the storage space. The main reason for its preservation, especially the devitrified pores formed in the early stage, may be difficult to preserve without the effective support of the overlying early salt strata. Under the polarized light microscope, the development area of early dolomite crystals is also common. In the dolomite-enriched area, the devitrification of the volcanic glass is strong, and the mutual support between the dolomite crystals is responsible for the devitrification of pores. For example, authigenic dolomite at 4794.95 m in Well MY1 was enriched in the early stage, and it also showed strong devitrification of volcanic glass. Although no pores were seen under polarized light, the measured porosity reached 6.7%, which is undoubtedly the reason why more devitrified micropores were preserved.

In addition to the preservation of pores by the salt strata, the abnormal pressure formed by hydrocarbon charging in the Fengcheng Formation may be another important factor for porosity preservation. Many scholars believe that hydrocarbon charging can inhibit compaction and delay cementation to protect pores, especially early hydrocarbon charging [58]. Two kinds of green fluorescence and orange-yellow fluorescent inclusions (Figure 10) are captured in authigenic dolomite, calcite, reedmergnerite, and quartz in the Permian tight oil reservoirs in the Mahu Sag, and homogenization temperatures of the fluid inclusions with orange fluorescence range from 88 °C to 95.6 °C. Formation pressure coefficients of the Fengcheng Formation in the Mahu Sag mostly vary from 1.20 to 1.80, which indicates typical abnormal high pressure. Hydrocarbon generation pressurization is an important reason for the formation of the abnormal high pressure of the Fengcheng Formation in the Mahu Sag [74]. The most common fluorescence in thin sections is orange-yellow fluorescence, which reflects that there is strong oil and gas charging in the medium-shallow burial period and that the oil and gas emplacement in the period of the asphalt is much earlier. Therefore, it is speculated that the early and strong oil and gas charging is very beneficial to porosity preservation.

5.2. Genetic Model of Reservoir Development

Tight oil reservoirs of the Permian Fengcheng Formation in the Mahu Sag have undergone various diagenesis, such as devitrification, compaction, pressure solution, cementation, metasomatism, dissolution, and rupturing. Devitrification, dolomitization, and so on, have formed more intergranular micropores. The acid fluids released during evolution of the high-quality alkaline lake source rocks further improve the storage capacity of the reservoir by dissolving feldspar and salt minerals. The early and continuous hydrocarbon charging in the shallow–middle burial stage, the early precipitation of salt minerals closely related to the alkaline lake environment, and the large content of early authigenic dolomite effectively protect the porosity of the reservoir. Above all, a genetic model for the Permian alkaline lacustrine tight oil reservoirs in the Mahu Sag was established (Figure 16).

Diagenetic period		Syngenetic period	Shallow burial period		Middle-deep	At present	
Evolution of reservor space		a	b	C	d	e	f
Diagenesis that promotes reservoir formation	Devitrification	_					
	Dissolution						
	Fracture	-				-	
	Hydrocarbon charging						
	Devitrified products						
	Formation of salt crusts						
	Formation of early dolomite						
					•		
Volcan glass	nic Muda s lag	stone Salt yer int	mineral Hy erlayer	ydrocarbon charging R	lock fragment	Feldspar	Quartz
٠		>	4	*.*•		\$	
Dolom	nite Vi frag	tric Devi ment	trification I	Devitrified pores	Dissolution pores	Fracture	

Figure 16. Genetic model of tight oil reservoirs of the Fengcheng Formation in the Mahu Sag. (a) Shrinkage fractures and salt crusts formed in the syngenetic period. (b) Devitrification mainly occurred in the early stage of the shallow burial period. (c) Early dissolution pores formed in the late stage of the shallow burial period accompanied by early hydrocarbon charging. (d) Dissolution pores notably formed with the peak acidic fluids period of the source rock. (e) Structural fractures notably formed and dissolution pores continued forming in the late stage of the middle–deep burial period. (f) Present situation of the tight oil reservoirs.

The Fengcheng Formation in the Mahu Sag was deposited in an alkaline lake with complex lithologies (Figure 16a). Volcanic glass in the medium–acidic volcanic rocks is prone to devitrification due to changes in fluid, temperature, and pressure and crystallizes to form albite, K-feldspar, zeolite, quartz, and so on. The devitrification porosity provides a foundation for reservoir formation (Figure 16b). The magnesium ions released during the devitrification process also led to the formation of more dolomites during the shallow burial period. After the formation of devitrified micropores and dolomites, the early hydrocarbon emplacement and the early salt crust effectively inhibited porosity destruction by compaction and cementation (Figure 16c). The alkaline lake source rocks of the Fengcheng Formation have the characteristics of early and strong hydrocarbon generation and expulsion, which provides abundant acidic fluids for the formation in the middle and shallow burial stages. Fractures formed by strong tectonic movements provided good channels for acidic fluids to enter into fine-grained rocks, leading to dissolution of feldspar and salt

minerals in the tight oil rocks which significantly improves reservoir properties; eventually, more tight oil reservoirs were formed in the Fengcheng Formation (Figure 16e,f).

6. Conclusions

The tight oil reservoirs of the Permian Fengcheng Formation in the Mahu Sag in the Junggar Basin are mainly composed of tuff, pyroclastic materials mainly originating from medium–acidic magma. The authigenic minerals are mainly dolomite, followed by calcite and other salt minerals including shortite and trona. Reservoir space mainly consists of dissolution pores of feldspar and salt minerals, as well as micro–nano intergranular pores formed by devitrification. Fractures are mainly shrinkage fractures, structural fractures, and bedding fractures.

Abnormal pressure formed by early hydrocarbon charging of the Permian Fengcheng Formation in the Mahu Sag weakens mechanical compaction, and benefits the preservation of early devitrified pores.

Due to the sedimentary environment of the Permian Fengcheng Formation in the Mahu Sag in the Junggar Basin, which is mainly a high-salinity alkaline lake, relatively developed salt crusts (layers) composed of dolomite, hydrocarbon sodalite, wegscheiderite, trona, and other minerals are formed in the rocks. Early formation of the salt crusts not only has an excellent protective effect on the early devitrification micropores and other pores formed in the early stage, but also provides material conditions for dissolution during burial.

The acid fluid released during the evolution of the alkaline lake high-quality source rocks of the Permian Fengcheng Formation in the Mahu Sag in the Junggar basin, under the action of multi-type and multi-stage fracture communication, dissolved feldspar and salt minerals in dense rocks and effectively improved the reservoir.

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