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Reservoir Characteristics and Controlling Factors of Sedimentary Pyroclastic Rocks in Deep-Buried Basins: A Case Study of Yingtai Fault Depression, Southern Songliao Basin

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Abstract: In this article, based on core description, thin section, scanning electron microscope (SEM), well logging and reservoir physical properties, the reservoir controlling factors of sedimentary pyroclastic rocks in deep-buried basins are assessed via the relation between reservoirs and defining factors, including lithological characteristics, sedimentary microfacies and diagenesis. In addition, the contributing factors of anomalously high-porosity and high-permeability zone are analyzed. The lithological characteristics and diagenesis of the sedimentary pyroclastic rocks are closely related to reservoirs. The reservoir porosity–permeability of sedimentary pyroclastic rocks with large volcanic clastic particles is better than in those with small volcanic clastic particles. Sedimentary pyroclastic rocks with high content of unstable clastic particles, such as feldspar and rock debris, are easier to form the high-quality reservoirs than those with high content of quartz. The dissolution is the most important and direct reason to form the anomalously high-porosity and high-permeability zones of the sedimentary pyroclastic rocks in deep-buried basins. It is concluded that the size and composition of the clastic particles in the sedimentary pyroclastic rocks are the internal-controlling factors of the effective reservoirs, while the diagenetic fluid and the burial process are the external-controlling factors which form the effective reservoirs.

Keywords: deep-buried basin; sedimentary pyroclastic rocks; reservoir controlling factor; anomalously high-porosity and high-permeability zone; clastic particles composition; diagenesis

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1. Introduction

Sedimentary pyroclastic rocks which are formed under the dual action of volcanism and sedimentary transformation are a transitional rock between pyroclastic rocks and sedimentary rocks. In sedimentary pyroclastic rocks, the content of pyroclast, such as crystal fragment, vitric fragment and rock debris, is 50–90%; their main diagenesis is compaction and consolidation. The rocks with sedimentary pyroclastic structure mean that different degrees of grinding round can be seen in the clastic particles [1]. Accordingly, the rock-formed sedimentary environment can be divided into three subfacies: these are epiblast-bearing volcanogenic sediments, reworked volcanogenic sediments and coal-bearing tuff sediments. Sedimentary pyroclastic rocks are widely developed in volcanic-filled basins, whereas the genesis is related to volcanic activity. In previous studies, sedimentary pyroclastic rocks were often studied and classified into pyroclastic rocks [2]. Some scholars have studied the reservoir porosity–permeability, diagenesis, reservoir formation mechanism, reservoir distribution pattern and reworked volcanogenic sediments facies model of pyroclastic rocks, including sedimentary pyroclastic rocks from the outcrop or the middle-shallow layer within the basins [3–9]. They have found that the better reservoirs can be formed in the middle and shallow layers of the basins and the rocks from the outcrop show the good porosity–permeability. Generally, the clastic structure reservoir porosity–permeability will gradually decrease with increasing buried depth. The sedimentary pyroclastic rock reservoirs in the deep-buried basins, as a kind of important volcanic genetic reservoir, are often ignored due to the influence of large, buried depth and high degrees of diagenesis, resulting in poor reservoir porosity–permeability. In recent years, with the improvement of economy-technology levels and the further development of oil and gas exploration in the deep-buried basins, it has been found that a certain anomalously high porosity–permeability zone under certain geological conditions can also be formed in sedimentary pyroclastic rocks of the deep-buried basins (>3000 m) [10–14]. With the oil and gas exploration of deep volcanic rocks in the Yingtai Fault Depression (YFD), Southern Songliao Basin (SSB), industrial gas flow is found in several wells of sedimentary pyroclastic rocks reservoirs in the second member of Yingcheng Formation(K_1y^2). The statistics of gas test results show a good prospect for oil and gas exploration. The thickness of gas reservoirs is mostly 2–14 m, while the thinnest is 0.6 m and the thickest is 42 m. It is of great guiding significance for the study of similar reservoirs in this area and other regions to conduct in-depth research on sedimentary pyroclastic rocks reservoirs in the deep SSB, especially the characteristics and genetic analysis of relatively high-quality reservoirs.

Based on core, rock debris, sidewall coring, well logging, thin section, SEM and other data, this paper analyzes the characteristics of sedimentary pyroclastic rocks reservoirs in K_1y^2, YFD, deep SSB, and discusses the controlling factors and the genesis of anomalous high-porosity and high-permeability zones. This is to provide reference and guidance for the research and prediction of volcanic-sedimentary reservoirs.

2. Materials and Methods

2.1. Materials

The study covered a representative collection of rock samples of sedimentary pyroclastic rocks and well logging data in YFD. YFD is located in the north of the Western Fault Depression Belt in the SSB (Figure 1a,b), with an area of 1800 km^2, which is an asymmetric fault depression basin with west-faulting and east-overlapping [15,16]. The Huoshiling Formation (K_1h), Shahezi Formation (K_1sh) and Yingcheng Formation (K_1y) in Lower Cretaceous zones are mainly developed in the deep layers of YFD. Among them, K_1y^2 mainly develops a set of complex volcanic-sedimentary rock lithology combinations, which consists interbedded sedimentary pyroclastic rocks and mudstones with coal-bearing, including a few pyroclastic rocks, and a few intrusive rocks develop in some areas. The research into sedimentary pyroclastic rocks reservoirs in K_1y^2 is considerably lacking relative to other areas. Some scholars have studied it from the perspectives of sequence stratigraphic frameworks, provenance of sedimentary pyroclastic rocks and post-stack seismic geostatistical inversion methods to predict thin-layer reservoirs [17,18]. However, there are less studies on the reservoir porosity–permeability and its influencing factors of the sedimentary pyroclastic rocks in this section. The fault-depression layer in the Yingtai area has undergone four stages of tectonic movement transformation, which were in the periods of K_1sh, K_1y^1, K_1y^2 and the end of K_1y from early to late [19]. Affected by tectonic movement and large-scale volcanic eruption, the structural pattern with depressions and uplifts in the fault depression is gradually formed. In K_1y^2, there are two uplifts in the well LS1 area and well LS3 area, with one depression between them (Figure 1b).

The target collection of rock samples related to mostly sedimentary pyroclastic rocks. Target rock samples came from 21 wells located in Jilin Province, northeast China. The entire collection of rock samples was provided by Jilin Oilfield, including 78.36 m whole cores and more than 300 drilled core plugs corresponding to K_1y^2 of YFD, SSB. Together with the core samples, the Jilin Oilfield supplied well logging data of sedimentary pyroclastic rocks in 12 wells, with 5128.95 m footage and 30 sets data of vitrinite reflectance. The locations of all sampling wells have been marked in Figure 1.

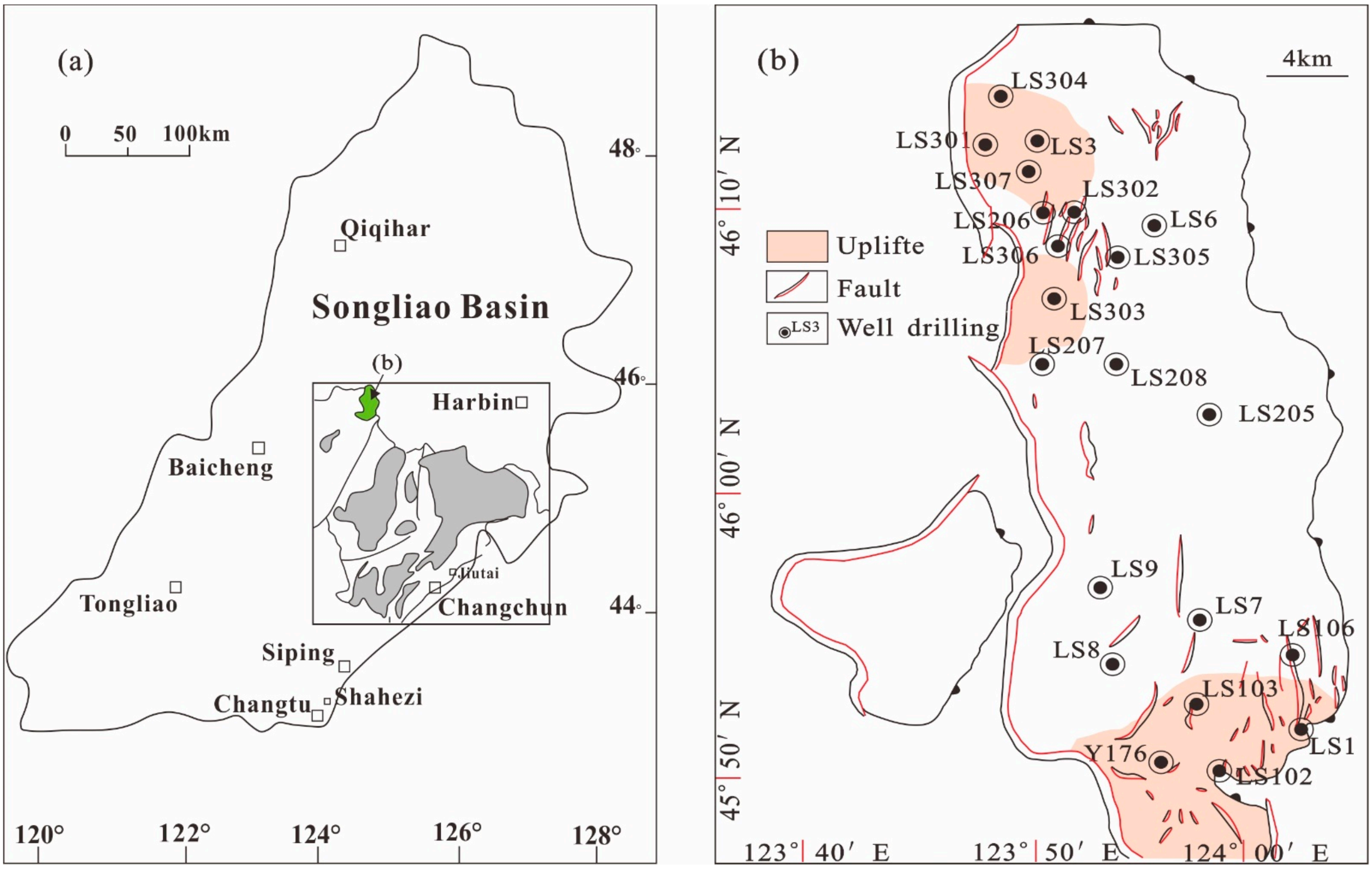

Figure 1. The distribution of wells and research areas. (**a**) The geographic location of YFD in SSB. (**b**) The location of sampling wells and structural characteristics of K_1y^2, YFD.

2.2. Methods

The samples were subjected to cast thin section and conventional thin section observation, conventional porosity–permeability analysis, X-ray diffraction whole-rock composition analysis (XRD), and scanning electron microscope (SEM) observation. The core description and interpretation of the well logging data were also completed simultaneously.

The core description was done by the authors on a centimeter scale. Microscopic observation of the cast thin section and conventional thin section, including lithology identification, pore types, mineral compositions and diagenesis, was conducted using a Leica DMLP Polarizing Light Microscope produced by the Leica company (Wezlar, Germany). Mineral point counting was used to determine the mineralogical characteristics and porosity of thin sections. The maximum error range varied with the percentage of composition, from 3.6% at 50% content to 2.1% at 10% content. Each sample was quantified at approximately 200 points.

The conventional porosity and permeability measurements were conducted using the automated gas permeameter–porosimeter produced by Coretest Systems, Inc. (400 Woodview Avenue, Morgan Hill, CA 95037, USA), model AP608. The test was based on the petroleum and natural gas industry standard (SY/T 5336-2006 Method of Core Analysis) at 25 °C in a 35–50% humid environment. Permeability measurements were made using an unsteady state pressure decay technique. The permeability range of the AP-608 was from 10,000 md to 0.001 md. Measurements on samples less than 0.05 millidarcies should be made using Nitrogen as the flowing gas to reduce errors. Porosity and pore volume are measured using the Boyle's law technique. The entire procedure, like permeability, is completely automated for accurate, repeatable measurements. All calibration information, including raw test data, is saved in ASCII files for later review if necessary.

The total rock content and the relative content of clay minerals were analyzed using the A D/max-2200 X-ray diffractometer produced by Olympus (Tokyo, Japan), and the analysis data were processed by Clayquan (2018 version, Research Institute of Petroleum Exploration and Development, Beijing, China). JSM- 5500LV produced by the JEOL (Akishima, Japan) company in Japan was used to perform scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS). The detection environment, i.e., temperature and humidity, was 25 °C and 40%, respectively, and the samples were all plated with gold during sample preparation.

3. Reservoir Lithology Characteristics

Referring to the classification scheme of sedimentary pyroclastic rock types by Fisher [20] and Wang et al. [21] (Figure 2), combined with observation and identification of core, casting thin section, ordinary core thin section and rock debris thin section. According to the size and content of pyroclastic particles, the sedimentary pyroclastic rocks in K_1y^2, YFD can be divided into three types: sedimentary tuff, sedimentary breccia tuff and sedimentary volcanic breccia including a few sedimentary tuff agglomerates and sedimentary volcanic agglomerates.

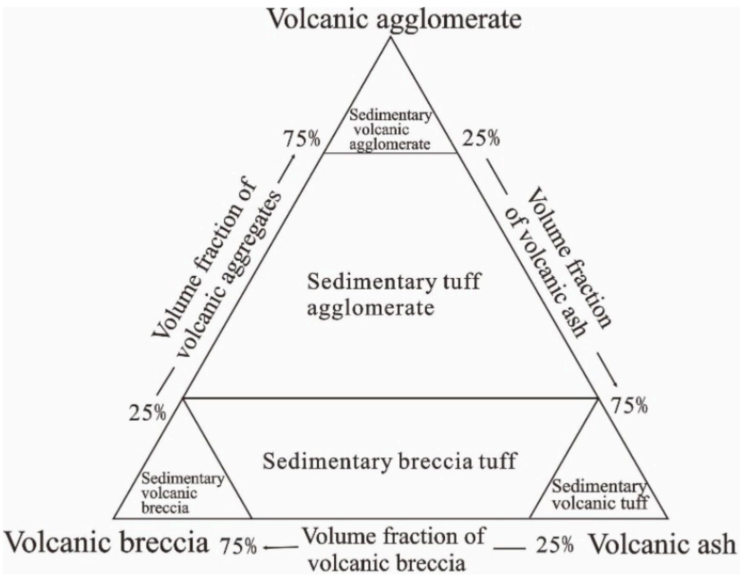

Figure 2. Grain-size diagram for naming sedimentary pyroclastic rocks (Modified from Fisher; Wang et al.; Zhou et al. [20–22]). The pyroclastic particle size above 64 mm is volcanic agglomerate. From 2 mm to 64 mm is volcanic breccia, and less than 2 mm is volcanic ash.

Core observation and microscopic identification of rock thin sections show that the clastic particles in the sedimentary pyroclastic rocks revealed by K_1y^2, YFD are rhyolitic volcanic breccia (Figure 3a), rhyolitic volcanic rock debris(Figure 3b,f), andesitic volcanic rock debris (Figure 3b,f), quartz crystal fragment(Figure 3b,c,f) feldspar crystal fragment (Figure 3b,c) and other pyroclastic are mainly found, some mudstone debris (Figure 3b,f), metamorphic rock debris (Figure 3c), muscovite fragments (Figure 3c), etc. are also found. In addition, the fillings are volcanic ash and mud. The sphericity of volcanic detritus varies from angular—subangular—subrounded. The structure such as inclined bedding (Figure 3d), coal-bearing (Figure 3d) and contact interface between sedimentary pyroclastic rocks and volcanic clastic sedimentary rocks (Figure 3e) can be found. It can be seen that the contents of rock debris including breccia and crystal fragment, as two major components of pyroclast, are quite different due to the influence of transportation and sorting (Figure 3c,d).

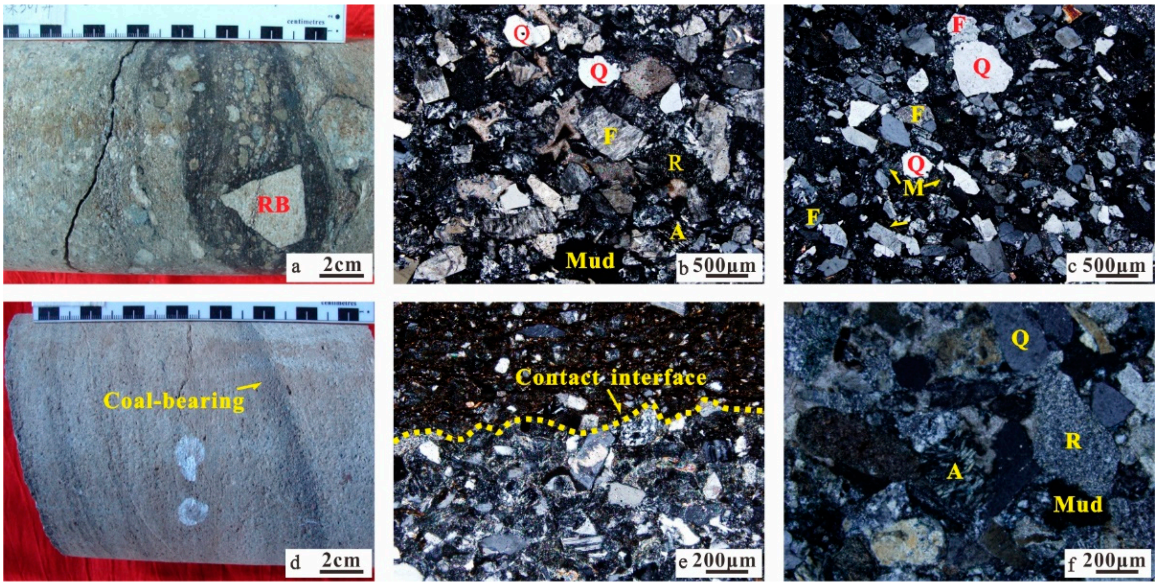

Figure 3. Lithologic features of sedimentary pyroclastic rocks in K_1y^2, YFD. (**a**) Sedimentary breccia tuff with sedimentary pyroclastic structure from well LS307 at a depth of 3620.0 m. The breccia rounded into angular-subangular form is tuff or rhyolite (RB), and the maximum is 3.5 cm. (**b**) Rock debris sedimentary tuff from well LS8 at a depth of 3837.2 m. The content of rock debris is about 60%, and most of which are rhyolite or rhyolitic pyroclastic rock debris (R), a few mudstone debris or mud and andesite debris (A). The content of crystal fragment is less than 30%, mainly quartz (Q) and feldspar crystal fragments (F). All the particles are rounded into angular–subangular. formation (**c**) Crystal fragment sedimentary tuff from well LS8 at a depth of 3584.9 m. The content of rock debris(R) is about 40%, and the content of crystal fragment (QandF) is more than 50%, including several piece pf mudstone debris, metamorphic rock debris (M) and muscovite fragment (Ms). The particles rounded into subangular-subrounded is 0.2–2.5 mm. The fillings are mud and volcanic ash, which own obvious devitrification and recrystallization to form illite. Feldspar alteration and calcite metasomatism are strong. (**d**) Rock debris crystal fragment sedimentary tuff from well LS307 at a depth of 3638.0 m. Inclined bedding, coal-bearing and carbonized plant fragments are developed. (**e**) Sedimentary tuff from well LS8 at a depth of 3578.5 m. Its clastic particles are mainly quartz, feldspar, rhyolite debris, mudstone debris, including some metamorphic rock debris and muscovite; the particle rounded into subangular-subrounded is 0.1–1 mm. The fillings are mud and volcanic ash which own obvious devitrification and recrystallization to form illite. Feldspar alteration and calcite metasomatism are strong. The contact interface between Sedimentary tuff and tuffaceous siltstone can be seen. (**f**) Rock debris sedimentary tuff from well LS8 at a depth of 3685 m. Its rock debris content is more than 80%, mainly rhyolite debris and andesite debris, while the content of crystal fragment is about 15%, mainly quartz and feldspar crystal fragment. All the particles are rounded into subangular-subrounded.

4. Characteristics of Reservoir Porosity–Permeability and Anomalously High Porosity–Permeability Zone

Generally, with the increase of burial depth and diagenesis intensity, the primary pores in sandstone reservoirs decrease rapidly. When the burial depth exceeds 3000 m, the primary pores have been exhausted, and the dominated pores are secondary pores [23–25]. The drilling of YFD, SSB reveals that the sedimentary pyroclastic rocks in K_1y^2 are generally developed at the depth from 3100 m to 4600 m. The statistical analysis about 297 sets of measured porosity–permeability data of sedimentary pyroclastic rocks in K_1y^2 shows medium–low porosity–permeability characteristics. The reservoir porosity of the various sedimentary pyroclastic rocks in question is 0.10–11.40% (average 5.65%) and the permeability is 0.001×10^{-3} μm^2–1.000×10^{-3} μm^2 (average 0.059×10^{-3} μm^2). Based on the 297 sets of measured porosity–permeability data, the relation between porosity–

permeability and buried depth of sedimentary pyroclastic rocks reservoir is established (Figure 4). It can be seen from the Figure 4 that with the increasing burial depth, the reservoir porosity–permeability has an overall decreasing trend, but the more prominent feature is that there are several abnormally high porosity–permeability development zones that are finger-shaped.

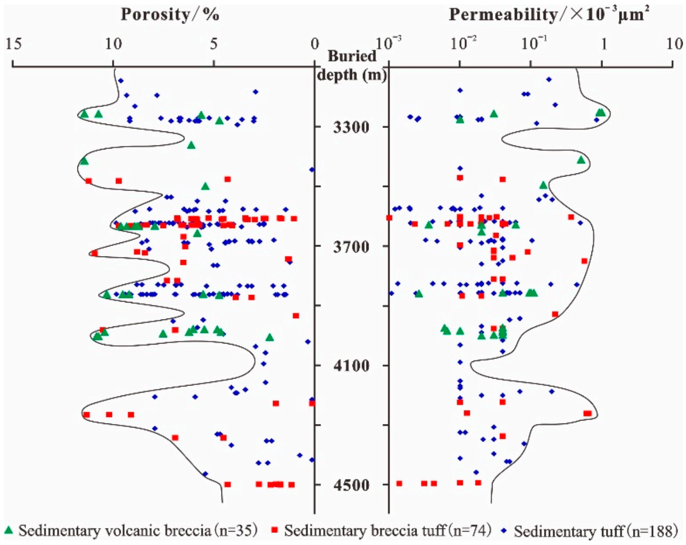

Figure 4. Relation between porosity–permeability and buried depth of sedimentary pyroclastic rocks reservoirs in K_1y^2, YFD.

5. Controlling Factors of a Reservoir

5.1. Influence of Lithologic Characteristics on Reservoir

The clastic particle size and composition of sedimentary pyroclastic rocks has a direct impact on reservoir porosity–permeability [26–30].

5.1.1. Relation between Clastic Particle Size and Reservoir

Based on the statistical analysis of 297 sets of porosity–permeability data and the reservoir forming efficiency data of 5128.95 m reservoirs in terms of sedimentary pyroclastic rocks from 12 wells in K_1y^2, YFD, it is evident that the overall porosity–permeability is relatively lower, and that this site belongs to low porosity–permeability reservoirs. The clastic particle size of sedimentary pyroclastic rocks has a certain relation with porosity–permeability, which is mainly manifested in such a way that the greater the volcanic clastic particle size, the better the porosity–permeability and the higher the reservoir forming efficiency (Table 1, Figure 5).

Table 1. Reservoir characteristics of sedimentary pyroclastic rocks in K_1y^2, YFD.

Lithology	Porosity * /%	Permeability * /$\times 10^{-3}$ μm^2	Number of Samples	Drilling Footage/m	Reservoir Space Combination
Sedimentary volcanic breccia	2.20–11.40 / 7.84	0.003–1.000 / 0.123	35	357.90	Inter-gravel solution pore + Intra gravel solution pore + Fissure + Intra gravel gas cavity
Sedimentary breccia tuff	0.90–11.30 / 5.56	0.001–0.660 / 0.061	74	1092.30	Inter-gravel solution pore + Solution pore + Fissure
Sedimentary tuff	0.30–9.83 / 5.28	0.001–0.850 / 0.040	188	3678.75	Intergranular solution pore + Intragranular solution pore + Fissure

* (Minimum − Maximum)/Average.

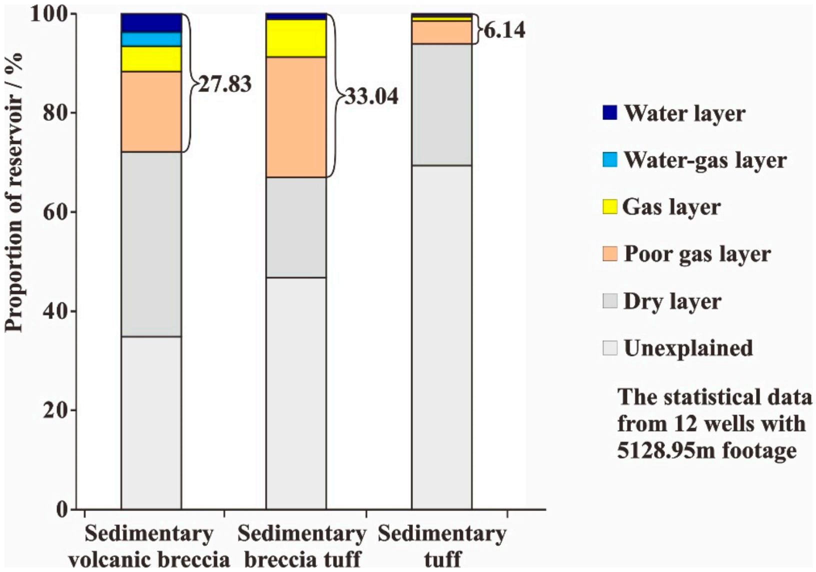

Figure 5. Proportion of sedimentary pyroclastic rocks in reservoir at K_1y^2, YFD.

According to this core observation, microscopic identification of casting thin sections and SEM analysis, it is found that there is some differentiation in the reservoir space combination of different lithology. Among them, the reservoir space of sedimentary volcanic breccia is mainly composed of inter-gravel dissolution pores (Figure 3b), supplemented by intragranular solution pores, intragranular gas cavities (Figure 3a) and fissures; the sedimentary breccia tuff has both secondary solution pores and fissures; the sedimentary tuff is dominated by secondary pores (Figure 3c) (Table 1).

5.1.2. Relation between Clastic Particle Component and Reservoir

Volcanic clastic particles and their content are important factors controlling the macro-distribution of sedimentary pyroclastic rocks reservoirs. Generally, due to the developed primary pores and later stronger dissolution of normal sedimentary rocks, under the conditions of high content, pure composition, well sorting and medium particle size of relatively stable quartz with strong compressive strength, they are easy to form high-quality reservoirs. Meanwhile, it is often easier for the large amounts of rock debris with low compressive strength to form a pseudo-matrix, resulting in undeveloped primary pores and fewer secondary pores formed by dissolution [12]. However, based on the statistical analysis of the quartz, feldspar and rock debris content of 107 thin sections from K_1y^2, YFD, via XRD analysis, the relation between porosity and clastic particles content is established. It is found that the porosity is negatively correlated with quartz content and positively correlated with feldspar and rock debris content (Figure 6).

5.2. Relation between Sedimentary Microfacies and Reservoirs

The sedimentary facies of K_1y^2, YFD belongs to fan delta facies. Combined with drilling data, four kinds of sedimentary microfacies are identified: inter-lobe argillaceous sedimentary microfacies, distributary estuary bar sedimentary microfacies, slump gravity flow sedimentary microfacies and underwater distributary channel sedimentary microfacies. There are some differentia in the development of effective reservoirs in different sedimentary microfacies. In the process of clastic particle transportation, the differentia of hydrodynamic conditions leads to the change in size and composition of clastic particles, and then affects the generation and reservation of primary reservoir space and the formation of secondary reservoir space.

Table 2. Data of XRD for sedimentary pyroclastic rocks in K_1y^2, YFD.

Well	Depth/m	Lithology	Relative Content of Clay Minerals/%								Quantitative Analysis/%					
			K [1]	C [2]	I [3]	S [4]	I/S [5]	%S	C/S [6]	%S [7]	Total Clay	Quartz	Potassium Feldspar	Plagioclase	Calcite	Dolomite
LS302	3770.0	Sedimentary tuff	4	8	12	/	76	/	/	10	22.7	36.2	12.8	26.1	/	2.2
	3864.2	Sedimentary breccia tuff	14	37	23	/	26	/	/	25	2	58	6	34	/	/
LS306	3680.0	Sedimentary breccia	5	7	18	/	70	/	/	10	11.6	43.9	8.1	21.9	13.3	1.2
	3692.1	Sedimentary tuff	/	5	13	/	82	/	/	10	11.2	52.2	8.3	23.9	2.8	1.6
	3820.0	Sedimentary breccia tuff	2	4	13	/	81	/	/	10	17.4	41.1	14.6	24.9	0.4	1.6
	3850.0	Sedimentary tuff	9	18	13	/	60	/	/	10	11.7	39.9	14.6	30.9	0.9	2
	3886.0	Sedimentary breccia tuff	7	10	14	/	69	/	/	10	12.3	45.5	13.8	25.7	1.1	1.6
	4050.0	Sedimentary breccia tuff	7	7	20	/	66	/	/	10	14.8	47.3	7.7	28.7	/	1.5
	4090.0	Sedimentary tuff	8	11	16	/	65	/	/	10	7.8	49.8	11.6	28.4	/	2.4
	4345.0	Sedimentary breccia tuff	8	6	10	/	76	/	/	5	8	36.7	14.9	16.6	1.4	1.1
LS307	3620.0	Sedimentary breccia tuff	11	18	15	/	56	/	/	5	20.5	31.7	8.9	28.9	8.6	1.4
	3635.0	Sedimentary breccia	3	3	26	/	68	/	/	5	23.3	50.1	5.0	18.9	1.3	1.4
LS7	3800.0	Sedimentary tuff	6	7	7	/	80	/	/	5	20.3	44.0	/	32.3	2.3	1.1
	3840.0	Sedimentary tuff	7	7	23	/	63	/	/	5	17.4	47.6	3.3	27.6	3.2	0.9
	3945.0	Sedimentary tuff	4	8	12	/	76	/	/	10	24.0	40.2	3.1	31.0	1.1	0.6
	4420.0	Sedimentary tuff	/	6	9	/	85	/	/	15	38.8	31.4	/	27.4	1.9	0.5
LS8	3579.4	Sedimentary tuff	4	/	4	/	92	/	/	10	32.2	29.9	6.4	30.2	0.3	1.0
	3584.7	Sedimentary tuff	11	16	11	/	62	/	/	15	10.5	56.0	8.1	24.5	/	0.9

[1] Kaolinite. [2] Chlorite. [3] Illite. [4] Smectite. [5] Illite/Smectite inter-layer. [6] chlorite/Smectite inter-layer. [7] Inter-layer ratio.

In order to further discuss the relation between sedimentary microfacies and reservoir of sedimentary volcaniclastic rocks, the sedimentary microfacies and its logging porosity are statistically analyzed, and a frequency distribution histogram of logging porosity of different sedimentary microfacies (Figure 7) is made. It is found that the reservoir porosity–permeability of slump gravity flow sedimentary microfacies is better than underwater distributary channel sedimentary microfacies, and the others are poor. The best reservoir porosity of slump gravity flow sedimentary microfacies may be attributed to the fact that it contains more particles with larger hardness and coarser particle size. Corresponding to the above research results on the size and composition of detritus, the later diagenetic evolution process is more conducive to the reservation of primary pores and the formation of secondary pores.

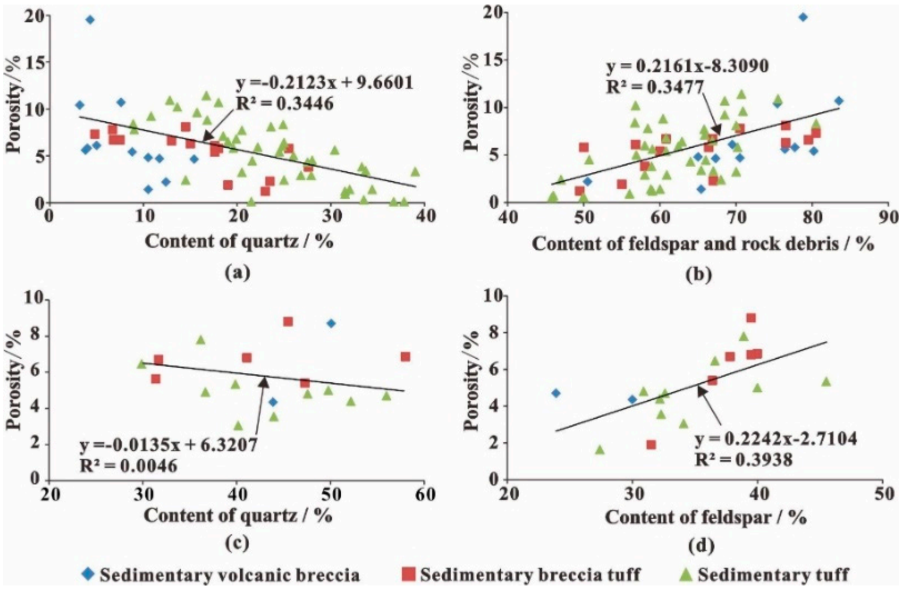

Figure 6. Relation between porosity and the content of various clastic particles. (**a**,**b**) The data of clastic particles content comes from the statistical analysis of 68 thin section samples. (**c**,**d**) The data of clastic particle content comes from the XRD data (Table 2). As the volcanic rock debris in the sedimentary pyroclastic rocks in the study area were mainly rhyolitic rocks, which are counted in the content of "feldspar and clastic particles", while the quartz content in the rhyolitic rocks is also counted in passing. Therefore, the content of quartz in the statistical data is much lower than the XRD.

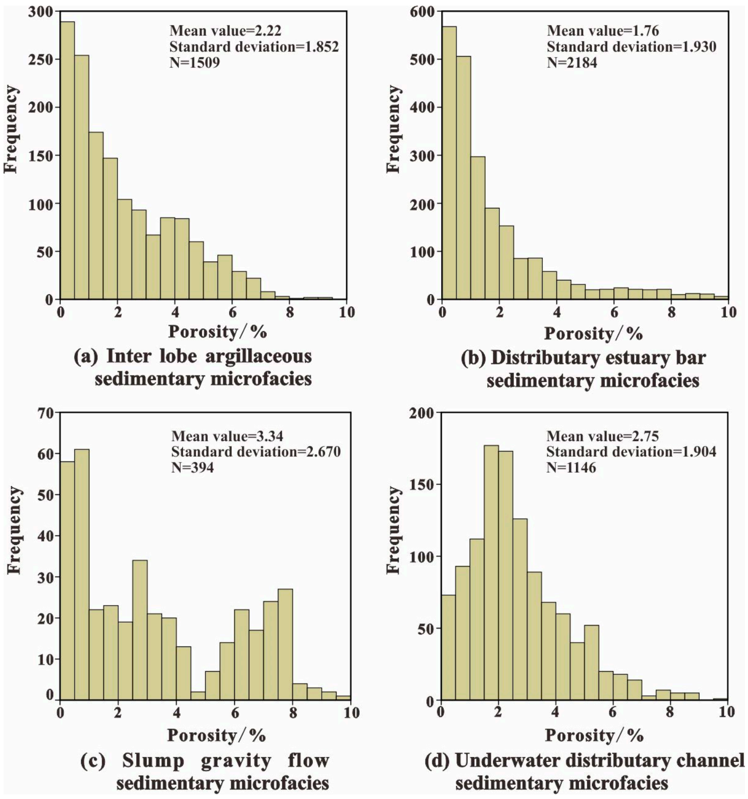

Figure 7. Distributions of logging porosity in different sedimentary microfacies (5235 logging porosity data from 675 m of 4 wells).

5.3. Controlling of Diagenesis on Reservoir

The burial depth of the sedimentary pyroclastic rocks reservoirs is generally greater than 3100 m in K_1y^2, YFD, SSB. Its compaction is stronger, so that the primary reservoir space is strongly damaged. The type of reservoir space is mainly secondary pores (feldspar solution pores and rock debris solution pores) formed by dissolution [31]. Lithologic characteristics and sedimentary microfacies form the original differentia of sedimentary pyroclastic rocks reservoirs, and subsequent diagenesis further transforms the reservoir and enhances the differentia. The development of reservoir space of K_1y^2, YFD is mainly controlled by diagenesis. Referring to the previous classification of volcanic diagenesis, according to the microscopic identification of rock thin section and the analysis of SEM, it is found that the main diagenesis of sedimentary pyroclastic rocks in K_1y^2, YFD, SSB are compaction, filling, dissolution, devitrification recrystallization and clay mineralization [32,33].

5.3.1. Diagenesis Stage

The diagenesis stage is a comprehensive reflection of various factors such as burial depth, temperature, pressure, diagenesis and organic matter evolution, which can comprehensively reflect the control in effective reservoirs [34,35]. In this paper, the diagenesis stages of sedimentary pyroclastic rocks in the deep-buried basins are divided according to clay mineral assemblage and inter-layer ratio of S layer in I/S inter-layer and vitrinite reflectance (R_o), typical reservoir space type, the types and distribution and generation sequence of authigenic minerals and contact characteristics of clastic particles. Based on the data collected in the study area and referring to the current burial depth and other relevant parameters, the above parameters are analyzed and studied. When the study layer is buried under 3100 m in K_1y^2, YFD, the maturity of organic matter has been into the stage of high maturity over maturity, for $R_o > 1.3\%$ (1.37–2.2%) (Figure 8). XRD data (Table 2) shows that smectite of clay minerals in volcanic rocks have completely disappeared (Table 2), illite (Figure 9g) and chlorite (Figure 9h) have been generated, I/S inter-layer (Figure 9i) has developed with $\%S < 15\%$. Table 2 shows that a certain amount of calcite (Figure 9b) and dolomite began to form in this set of sedimentary pyroclastic rocks. Secondary enlarged edges of quartz can be seen in rock thin sections from some wells (Figure 9a). The contact relations among clastic particles are mainly concave–convex contact and point-line contact (Figure 9f). Based on the above data, combined with the previous division of diagenesis stages [36–39], and referring to the evolution and burial stage of volcanic reservoirs in this area [40], it is considered that the sedimentary pyroclastic rocks in K_1y^2, YFD have been into the medium burial stage (B) and deep burial stage.

5.3.2. Dissolution

The secondary pores formed by dissolution effectively improve the physical properties of the sedimentary pyroclastic reservoir in the deep-buried basins, and significantly improve the reservoir quality. The reservoir space types of sedimentary pyroclastic rocks in this area are mainly intracrystalline dissolution pores of potassium sodium feldspar fragments (Figures 3f and 9c), intergranular solution pores (Figures 3c and 9e), solution pores and fissures formed after the dissolution of fillings in intragranular gas cavity and structural fissures, and solution pores formed after the dissolution of intragranular matrix.

Three factors are required for the dissolution which has an effective impact on the sedimentary pyroclastic rock reservoirs, including clastic particles with unstable composition, dissolved diagenetic fluid and its migration channel. Unstable composition particles mainly refer to skeleton particles such as feldspar and unstable volcanic rock debris. The relation between them and the reservoir has been described in Section 5.1.2. The dissolution fluid required for the generation of secondary pores mainly comes from meteoric water, acid water released by the conversion of clay minerals and organic acids released during the thermal evolution of organic matter [6,41]. The strata of sedimentary pyroclastic rocks reservoirs with anomalously high-porosity and high-permeability zones in K_1y^2, YFD are mainly composed of thin interbedded sand and mudstone. It is presumed that the acidic fluid mainly comes from the thermal evolution of organic matter.

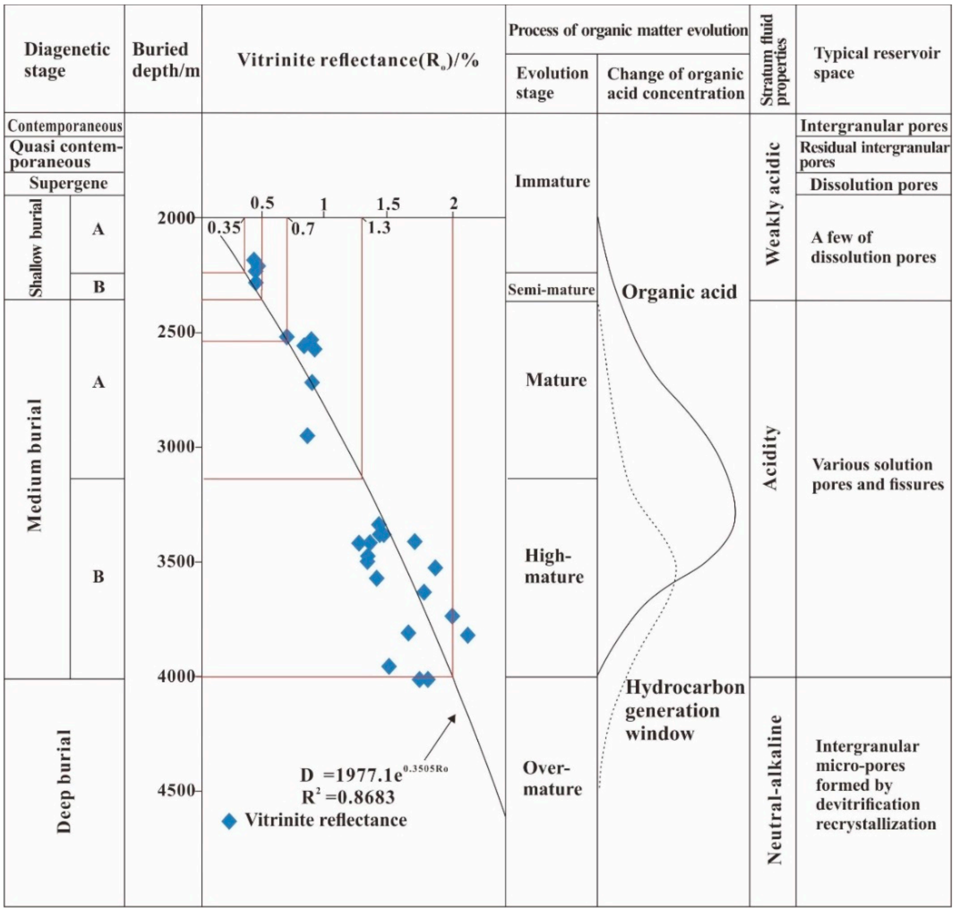

Figure 8. Diagenesis stage of sedimentary pyroclastic rocks in K_1y^2, YFD (the data of R_o from Jilin Oilfield).

It can be seen in Figure 8 that with the increase of burial depth, organic matter has successively experienced several stages, including immature, semi-mature, mature, highly mature and over-mature. The diagenesis of the sedimentary pyroclastic rock reservoir in K_1y^2, YFD experienced the diagenesis sub-stage A and B of the medium buried stage, which corresponds to the generation period of a lot of organic acids. Therefore, the development of solution pores is matched with the generation of organic acids in time. In addition, the transformation depth corresponding to the diagenetic sub-stage B of the medium buried is 3120–4010 m, which has a good correspondence with the anomalously high pore zone depth (3100–4500 m) (Figure 4), indicating that the development of solution pores and the generation of organic acids are also matched in the longitudinal depth.

5.3.3. Other Diagenesis

(1) Devitrification recrystallization

Devitrification recrystallization is the diagenesis that volcanic vitric fragment or volcanic ash transform into primary crystals and micro-crystals in sedimentary pyroclastic rocks. This area is characterized by the devitrification of volcanic vitric fragment or volcanic ash filled in intergranular (gravel) pores and recrystallized into potassium feldspar pellets (Figure 9d) and clay minerals. The intergranular micro-pores developed between the recrystallized mineral crystals can increase the plane porosity by 5.2% [42]. The diagenesis mainly developed in the deep-buried diagenesis stage.

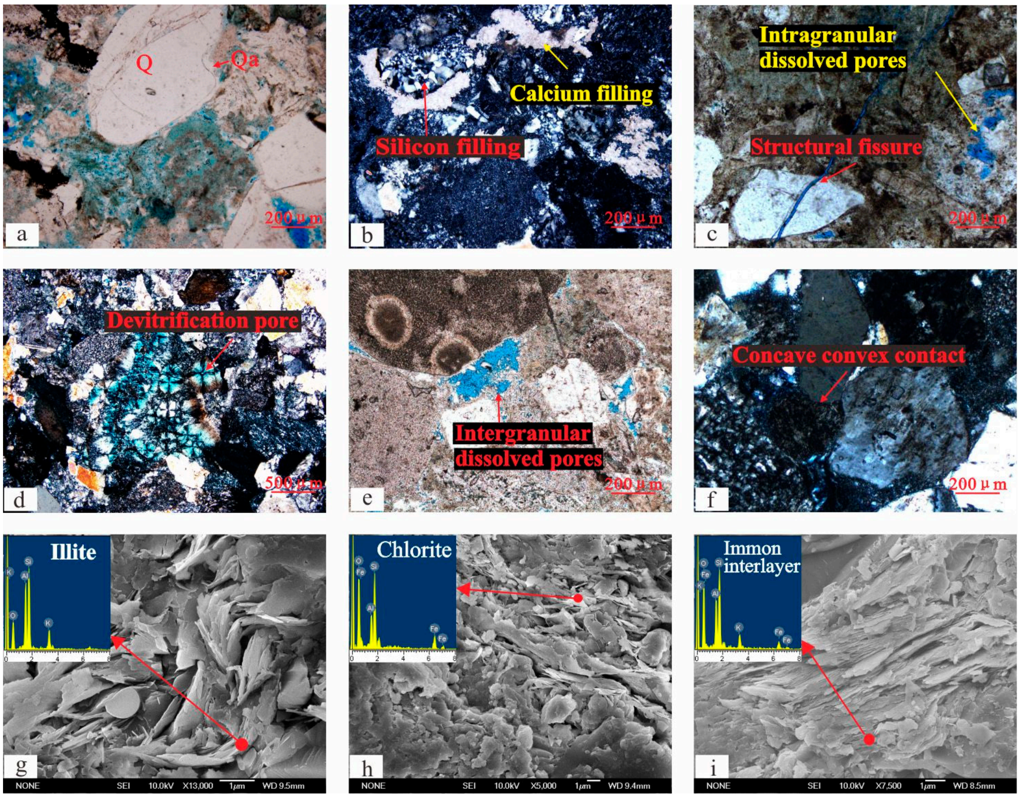

Figure 9. Typical characteristics in different diagenesis stages of sedimentary pyroclastic rocks in K_1y^2, YFD. (**a**) Quartz secondary enlargement (Q: quartz, Qa: enlarged edge of quartz) in gray sedimentary tuff form well LS302 at a depth of 3864.2 m. (**b**) Silicon filling and calcium filling in gray sedimentary tuff from well LS306 at a depth of 3686.3 m. (**c**) Structural fissures and intragranular solution pores in rock debris crystal fragment sedimentary tuff from well LS306 at a depth of 4047.8 m. (**d**) Devitrification hole in gray sedimentary tuff from well LS302 at a depth of 3864.74 m. (**e**) Intergranular solution pores in gray sedimentary tuff from well at a depth of LS303 -3216.0 m. (**f**) Concave–convex contact containing breccia debris crystal fragment sedimentary tuff from well LS305 at a depth of 4070 m. (**g**) Illite from well LS307 at a depth of 3627.5 m. (**h**) Chlorite from well LS307 at a depth of 3636.0 m. (**i**) Immon interlayer from well LS307 at a depth of 3620.14 m.

(2) Compaction

In the early stage of diagenetic evolution, compaction greatly reduces the size of primary reservoir space of sedimentary pyroclastic rocks reservoirs. In K_1y^2, YFD, the buried depth of the sedimentary pyroclastic rocks with strong compaction is more than 3100 m. The primary reservoir space is greatly damaged, and the particle contact relation is characterized by linear-contact and concave–convex contact (Figure 9f). In general, the anti-compaction ability of quartz clastic particles is the strongest, followed by feldspar and rock debris. Therefore, the anti-compaction ability of reservoirs with high content of feldspar and rock debris is poor, and forms poor reservoirs. However, this is contrary to the above conclusion obtained from the relation between the clastic particle composition and the reservoirs, which also reflects that secondary dissolution is the main factor for the formation of anomalously high-porosity and high-permeability zones of sedimentary pyroclastic rocks in YFD.

(3) Filling

Filling is the diagenesis that the pores and fissures are filled with material formed by later hydrothermal processes after the sedimentary pyroclastic rocks formed. In this area, calcite, zeolite, chlorite and other minerals are mainly filled or semi-filled into intergranular pores, intragranular gas cavities and fissures (Figure 9b). The higher the filling degree is, the lower the reservoir porosity is.

(4) Clay mineralization

Clay minerals in this area mainly include kaolinite, illite, chlorite and illite/smectite inter-layer minerals (Table 2, Figure 9g–i). During the diagenesis process, feldspar particles in the sedimentary pyroclastic rocks are altered, resulting in clay minerals such as illite. In addition, with the evolution of diagenesis, the diagenetic environment began to transform from acidic to alkaline in the middle and late stages (Figure 8), and authigenic illite, chlorite and other clay minerals began to form in rocks. These clay minerals can inhibit or promote the formation of effective reservoirs. On the one hand, as mentioned above, the generated clay minerals are filled into the reservoir pores, resulting in porosity decrease. On the other hand, there are still some intergranular micro-pores between these clay minerals crystals, which can increase the plane porosity by 6.5–10.1% [38].

6. Discussion

To sum up, the sedimentary pyroclastic rocks reservoirs in K_1y^2, YFD is affected by many factors, such as sedimentary conditions, dissolution and geological structure of the basins. The causes of the anomalously high-porosity and high-permeability zone of the sedimentary pyroclastic rocks in the deep-buried basins can be summarized as the following:

(1) The original sedimentary conditions provide the material basis

The anomalously high-porosity and high-permeability zones of the sedimentary pyroclastic rocks in the deep-buried basins are closely related to their lithological characteristics and sedimentary microfacies. The reservoirs with larger volcanic clastic particles develop more reservoir space than that with smaller volcanic clastic particles. This is because after the same dissolution, the intergranular solution pores between large volcanic clastic particles are larger. In addition, some volcanic breccias also contain some primary gas cavity (Figure 3a). The characteristics of reservoir pore structure show that, although the sorting of coarse clastic sedimentary pyroclastic rocks is relatively poor, other pore structure parameters are better as a whole. Because of more primary porosity saved and secondary porosity formed, and coupled with better reservoir pore structure, the coarse clastic reservoirs are better than those with fine clastic particles. During the transport process, the sedimentary pyroclastic rocks with higher content of unstable clastic particles such as feldspar and rock debris are easier to be ground, and form better sorting reservoirs. In addition, the reservoirs are more strongly affected by later dissolutions, which are more likely to form high-quality reservoirs. When the sedimentary pyroclastic rocks with high quartz content are buried more than 3100 m in the deep basin, although the compressive strength is high and compaction is weak, the pore is also difficult to be saved. When the quartz content is high, it is more likely to form secondary enlargement edge and plug pores to form poor reservoirs. In addition, the later dissolution has a smaller impact on quartz particles. Therefore, sedimentary pyroclastic rocks with more quartz are not easier to form high-quality reservoirs than those with more feldspar and rock debris.

In different sedimentary microfacies, there are some differences in the process of effective reservoirs forming. It is mainly showed that different hydrodynamic conditions cause the size and composition of clastic particles to change during the transportation of clastic particles, which then affect the forming and saving of primary reservoir space as well as the secondary reservoir space forming in the diagenesis process. Also, it corresponds to the lithologic characteristics analyzed above.

(2) Diagenesis plays a key role

Diagenesis, especially dissolution, plays a decisive role in the formation of anomalously high-porosity and high-permeability zones of sedimentary pyroclastic rocks reservoirs in K_1y^2, YFD. The various evidence shows that the sedimentary pyroclastic rocks reservoirs in this area have been into the medium burial stage (B) and deep burial stage. The compaction makes rocks tight during diagenesis, which is destructive diagenesis. Filling makes primary pores plugged in rocks and reduces the porosity–permeability of reservoirs, which is destructive diagenesis. Devitrification recrystallization can produce intergranular micro-pores, which is the process of ameliorated diagenesis. Clay mineralization can produce some intergranular micro-pores, but also plug some intergranular pores, so its effect on reservoirs is dual. The observation of rock thin sections under a microscope shows that secondary solution pores are generally developed. The dissolution is the most important factor for the formation of anomalously high-porosity and high-permeability zones of the sedimentary pyroclastic rocks in the deep-buried basins. The organic acids generated during the maturation of organic matter mainly cause the alteration of unstable detritus. The dissolution fluid is mainly derived from the organic matter of mudstone that appears in thin sand-shale interbed. The decarboxylation of organic matter in the thermal evolution process produces a large amount of organic acid fluids and flows into the reservoir, which makes some cements and clastic particles dissolve to form secondary solution pores, thereby improving the reservoir conditions of the sedimentary pyroclastic rocks in the deep-buried basins.

(3) Structural fissures provide auxiliary function

The existence of fissures is also one of the reasons for the formation of high-porosity and high-permeability of the sedimentary pyroclastic rocks in the deep-buried basins. Some fissures are formed in the deep underground due to tectonic action (Figure 9c). On the one hand, these fissures provide a certain reservoir space, and on the other hand, they also support the migration channels of various fluids. In particular, the acidic fluid generated by the thermal evolution of organic matter is mainly transported to the reservoir through fissures, and dissolution occurs in a way that forms secondary solution pores.

To sum up, the sedimentary conditions, diagenetic stage, diagenesis and tectonic action of the reservoir are important factors controlling the development of anomalously high-porosity and high-permeability zones of the sedimentary pyroclastic rocks in the deep-buried basins. Sedimentary conditions, such as lithologic characteristics and sedimentary microfacies, are the prerequisite and basis for the formation of high-quality reservoirs. The diagenetic stage controls the evolution of reservoirs macroscopically. Dissolution is the direct cause and main controlling factor for the formation of high-quality reservoirs. Devitrification-recrystallization, clay mineralization, structural fissures and thin sand-shale interbed are auxiliary factors for the formation of high-quality reservoirs. During burial diagenesis, the size and composition of clastic particles in the sedimentary pyroclastic rocks are the internal controlling factors for the formation of effective reservoirs, while diagenetic fluid and burial process are the external controlling factors.

7. Conclusions

The porosity–permeability of sedimentary pyroclastic rocks reservoirs with large volcanic clastic particles is better than in those with small volcanic clastic particles. The sedimentary pyroclastic rocks with high content of unstable clastic particles, such as feldspar and rock debris, are more likely to form high-quality reservoirs than those with high quartz content.

The slump gravity flow sedimentary microfacies reservoir is better than underwater distributary channel sedimentary microfacies, inter-lobe argillaceous sedimentary microfacies and distributary estuary bar sedimentary microfacies are poor. Slump gravity flow sedimentary microfacies can form best reservoirs because they contain so many more hard-coarse particles that they are more conducive to the preservation of primary pores and the formation of secondary pores in the later diagenetic evolution process.

The sedimentary pyroclastic rocks in the study area have been into the medium burial stage (B) and deep burial stage, and the main diageneses are compaction, filling, dissolution, devitrification-recrystallization, and clay mineralization. Among them, compaction and filling are destructive diageneses. Clay mineralization has both destructive and ameliorating effects on the formation of effective reservoirs. Devitrification recrystallization is mainly developed in the deep burial diagenetic stage, which has an ameliorated effect on reservoirs. Dissolution has an ameliorated effect on the reservoirs, and it is the main effect.

For the sedimentary pyroclastic rocks with burial depth more than 3000 m in the deep basins, with the increase of burial depth, the porosity and permeability of the reservoirs have an overall decreasing trend. Whereas, there are several finger-like anomalously high-porosity and high-permeability zones developed for the dissolution, which is the most important and direct reason. The dissolution fluid is mainly derived from the organic matter of mudstone that appears in the thin sand-shale interbed. The decarboxylation of organic matter in the thermal evolution process produces a large amount of organic acid fluids and flows into the reservoir, which makes some cements and dissolved clastic particles to form secondary solution pores, thereby improving the reservoirs conditions of the sedimentary pyroclastic rocks in the deep-buried basins. During the burial process of diagenesis, the size and composition of clastic particles in sedimentary pyroclastic rocks are the internal controlling factors to form the effective reservoirs, while diagenetic fluid and burial process are the external controlling factors.

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