minerals

MDPI

Article

Comprehensive Physical Properties and Exploration Potential of the Permian Igneous Rocks in the Southwestern Sichuan Basin

Kui Xiang [1], Liangjun Yan [1,*], Zhigang Wang [2] and Yao Lu [2]

[1] Key Laboratory of Exploration Technologies for Oil and Gas Resources, Yangtze University, Wuhan 430100, China; xiangkui@yangtzeu.edu.cn
[2] Bureau of Geophysical Prospecting, China National Petroleum Corporation, Zhuozhou 100083, China; wangzhigang1@cnpc.com.cn (Z.W.); luyao6@cnpc.com.cn (Y.L.)
* Correspondence: yljemlab@163.com

Abstract: The Permian igneous rocks in the Sichuan Basin represent a major breakthrough, opening up a new prospect for oil and gas exploration, and igneous reservoirs have become a new field of oil and gas exploration. Gravity-magnetic-electric exploration is an effective means of identifying igneous rocks and helps in reducing the multiplicity of the prediction results. However, the lithology of igneous rocks is quite different, and the exploration theory and evaluation techniques need urgently to be improved. In order to deeply study the response characteristics of the gravity-magnetic-electric and physical properties of the Permian igneous rocks in the Sichuan Basin and their relationships with the reservoir parameters, physical property testing was carried out on outcrop samples of the Permian igneous rocks in southwestern Sichuan. The comprehensive physical properties of the samples with different lithologies, including basalt, tuff, and volcanic breccia, were analyzed and studied. Based on the geological characteristics of the igneous rocks, such as the mineral composition, microstructure, and reservoir properties, a multi-parameter intersection relationship model for the resistivity, polarizability, density, magnetic susceptibility, and their relationships with the reservoir parameters was established, and effective parameters favorable for igneous rock identification and reservoir evaluation were identified. The results of this study provide a physical basis and technical support for non-seismic exploration of igneous oil and gas reservoirs in the Sichuan Basin.

Keywords: Sichuan Basin; igneous rocks; density; magnetic susceptibility; complex resistivity

Citation: Xiang, K.; Yan, L.; Wang, Z.; Lu, Y. Comprehensive Physical Properties and Exploration Potential of the Permian Igneous Rocks in the Southwestern Sichuan Basin. *Minerals* **2022**, *12*, 789. https://doi.org/10.3390/min12070789

Academic Editors: Binzhong Zhou, Changchun Yin, Zhengyong Ren, Xuben Wang and Alexey V. Ivanov

Received: 16 April 2022
Accepted: 15 June 2022
Published: 21 June 2022

1. Introduction

Igneous oil and gas reservoirs have become a new field of oil and gas exploration, and they have received a great deal of attention and are highly valued by Chinese and foreign scholars. The Middle-Late Permian Emeishan basalt in the Sichuan Basin and the Yunnan-Guizhou region has a large distribution area and is recognized as one of the major igneous provinces in the world [1–4]. According to recent research on the Permian igneous rocks, the overflow basalt is located in southwestern Sichuan, and the spewed pyroclastic rocks are located in the Jianyang area in the central and western parts of the basin. The natural gas in the pyroclastic rocks in this area mainly comes from the Cambrian Qiongzhusi Formation, and the natural gas accumulation conditions are good, which indicates the great natural gas exploration potential and good exploration prospect of the Permian volcanic rocks [5,6]. Industrial gas flow has been obtained in wells TY1 and TF2 in western Sichuan, which proves that the Permian volcanic oil and gas reservoirs in the Sichuan Basin represent a great breakthrough and have a great exploration potential [7]. Investigation of the characteristics, distribution, and gas-bearing properties of the Permian igneous rocks in the Sichuan Basin has shown that these igneous rocks are mainly distributed in the southwestern part of the basin, in the Jianyang-Santai area in the central and western parts of the basin, and in the Dazhou-Liangping area in the eastern part of Sichuan. Among them, the pyroclastic rocks in the Jianyang-Santai area are medium-high reservoirs with abundant hydrocarbon sources, and they are favorable areas for oil and gas exploration [8]. The Permian rocks in the Sichuan Basin are in unconformable contact with the underlying Cambrian Canglangpu and Qiongzhusi formations, so they have the advantage of a nearby source. Moreover, drilling in the basin has revealed that the Permian volcanic rocks have good reservoir conditions [9]. The rock types of the igneous oil and gas reservoirs that have been identified mainly include basalt, andesite, rhyolite, diabase, and tuff. The logging curves of the igneous reservoirs in various basins show that basalt, andesite, rhyolite, and diabase all have medium-high resistivities and medium-high densities, while tuff has a low resistivity and medium-low density [10]. In the Chengdu-Jianyang research area, the volcanic breccia lava and tuff have medium-low resistivities, and the basalt and diabase have high resistivities. Compared with the surrounding rocks, the volcanic channels have time-frequency electromagnetic response characteristics consistent with relatively high resistivities, which provides an electrical basis for exploring the characteristics and eruption patterns of the volcanic channels in the basin [11]. The lithology of the volcanic rocks in well Yongtan 1 is mainly basalt, tuff lava containing breccia, and breccia lava. Among them, the basalt is characterized by a high density and high resistivity, the tuff lava containing breccia is characterized by a medium-high density and medium-high resistivity, and the breccia lava is characterized by a low density and low resistivity. The volcanic reservoir slogging response is characterized by low gamma, low density, low resistivity, high acoustic time difference, and high neutron, and it has the physical characteristics of high porosity and low permeability [12]. The vertical stratification of the Permian igneous rocks in well Yongtan 1 includes the mudstone of the Longtan Formation, the basalt of the Emeishan Formation, and the limestone of the Maokou Formation, and the corresponding lithology and lithofacies are overflow basalt, explosive volcanic breccia lava and breccia tuff, volcanic channel facies granulite, and diabase porphyrite. The logging data show that the density and resistivity of the igneous rocks in the explosive facies are significantly lower than those of the overflow facies and volcanic channel facies, and these research results provide technical support for evaluating favorable igneous gas reservoir exploration zones [13]. Basalt, pyroclastic lava, and diabase porphyrite were drilled in well Yongtan 1. The basalt has a high resistivity and high density, and the pyroclastic lava has a low resistivity and low density, which are significantly different from those of the basalt. The diabase porphyrite also has a high resistivity and high density. A blowout-facies pyroclastic lava pore-type reservoir is developed, with an average porosity of >10% and a great exploration potential [14]. The research results of the lithofacies and reservoir characteristics of the Permian volcanic rocks in the Sichuan Basin show that the igneous reservoirs are diverse in lithology, but the high-quality reservoirs are mainly developed in the spewing pyroclastic lava, followed by the overflowing basalt, the pore-fracture reservoirs in the Ya'an-Leshan area of southwestern Sichuan, and the pore-type reservoirs in the Chengdu-Jianyang area [15]. Oil and gas were discovered by drilling the Permian volcanic rocks in western Sichuan. The lithofacies are mainly the overflow facies, accompanied by the explosive facies, the lithology is mainly basalt, and the reservoir is mainly porous-fractured basalt. It has been determined that the Permian volcanic rocks in western Sichuan have a good oil and gas exploration potential [16].

Relevant research results have shown that non-seismic exploration technology has an important application prospect in reservoir exploration [17–19]. For example, in the physical property analysis and time-frequency electro-magnetic exploration experiment carried out in the Junlian area in the southern part of the Sichuan Basin based on the research and review of petrophysical characteristics such as the density, polarizability, and resistivity of gas shale, the results shown in this study revealed that the research area has physical properties suitable for conducting electrical exploration [18]. Based on core, thin section, logging, gravity, magnetic, electrical, and seismic data, the lithofacies types and lithology of the Permian volcanic rocks in southwest Sichuan have been delineated, and the physical characteristics such as the density, magnetic susceptibility, and resistivity of the volcanic rocks with different lithologies have been summarized [20]. In the process of igneous oil and gas reservoir exploration, the comprehensive method of gravity, magnetic, electric, and seismic data acquisition has been proposed to predict the target volcanic oil and gas reservoir, and its effect is remarkable. It has also been suggested that time-frequency electromagnetic exploration be carried out and the polarizability information be increased [21]. During the Thirteenth Five-Year Plan period, studies of the physical properties of the Precambrian strata in the Sichuan Basin established the interface of the gravity, magnetic, and electrical properties and analyzed the density, magnetic susceptibility, resistivity, and polarizability characteristics of the different lithologies. However, analysis of Permian igneous rock samples is lacking and needs to be supplemented with samples and further research work [22]. Igneous rocks have distinct density, magnetic susceptibility, and resistivity characteristics [23–26]. Moreover, the results of the non-seismic data and the research on the physical properties of the lithologies have revealed that non-seismic exploration techniques can effectively identify the gravity, magnetic, and electrical anomalies caused by the deep rifts and volcanic rocks in the Sichuan Basin [27].

The volcanic rocks and reservoir space are complex, the reservoir heterogeneity is strong, the comprehensive physical properties vary widely, the formation conductivity mechanism is complex, and evaluation of the reservoirs involves great challenges. In the development of igneous rock exploration techniques, seismic and logging data are still the mainstream exploration methods, but gravity, magnetic, and electrical exploration methods also have obvious advantages and characteristics, and the application space is very large. Therefore, based on previous studies, it is necessary to summarize and analyze the density, magnetic susceptibility, resistivity, and physical properties of the igneous oil and gas reservoirs, to systematically divide the lithologies and lithofacies of the volcanic rocks, to fully understand the density, magnetic susceptibility, resistivity, and other physical properties of the igneous rocks and their conductive mechanisms, and to promote the application of gravity, magnetic, and electrical exploration techniques in the exploration of volcanic reservoirs. In this study, by collecting outcrop specimens of the Permian igneous rocks in the Sichuan Basin and analyzing the geological characteristics of the study area, starting with the density, magnetic susceptibility, and complex resistivity characteristics of the igneous rocks, their mineral compositions, the reservoirs' physical properties, and other parameters, these properties of the igneous rocks were analyzed and the relationship between the comprehensive physical properties of the igneous rocks and the oil and gas was studied to provide a physical basis and technical support for gravity and magnetic exploration of the igneous oil and gas reservoirs in the Sichuan Basin during the 14th Five-Year Plan period.

2. Geology

The Upper Permian igneous rocks in the Sichuan Basin are mafic intrusive rocks and extrusive rocks, mainly gray-green, dark-green, dark-gray, thickly bedded massive, dense, porous, almond-shaped, porphyritic basalts and iron-bearing basalts, with volcanic breccia, tuff, and a small quantity of sandstone, mudstone, copper-bearing layers, and hematite layers. Among them, the lithology of the igneous rocks in southwestern Sichuan is mainly basalt, with a small quantity of pyroclastic rocks, while that in eastern Sichuan is mainly basalt and a small quantity of diabase. The lithology of the igneous rocks in the Jianyang area in central Sichuan is complex, including diabase, basalt, and pyroclastic rocks [8]. The volcanic rock sampling area was mainly distributed in southwestern Sichuan, and the lithology was mainly basalt. Well Gongshen 1 and well Ta 6, from which oil and gas have been produced, are located near the study area [20]. The regional geological survey and sampling distribution are shown in Figure 1.

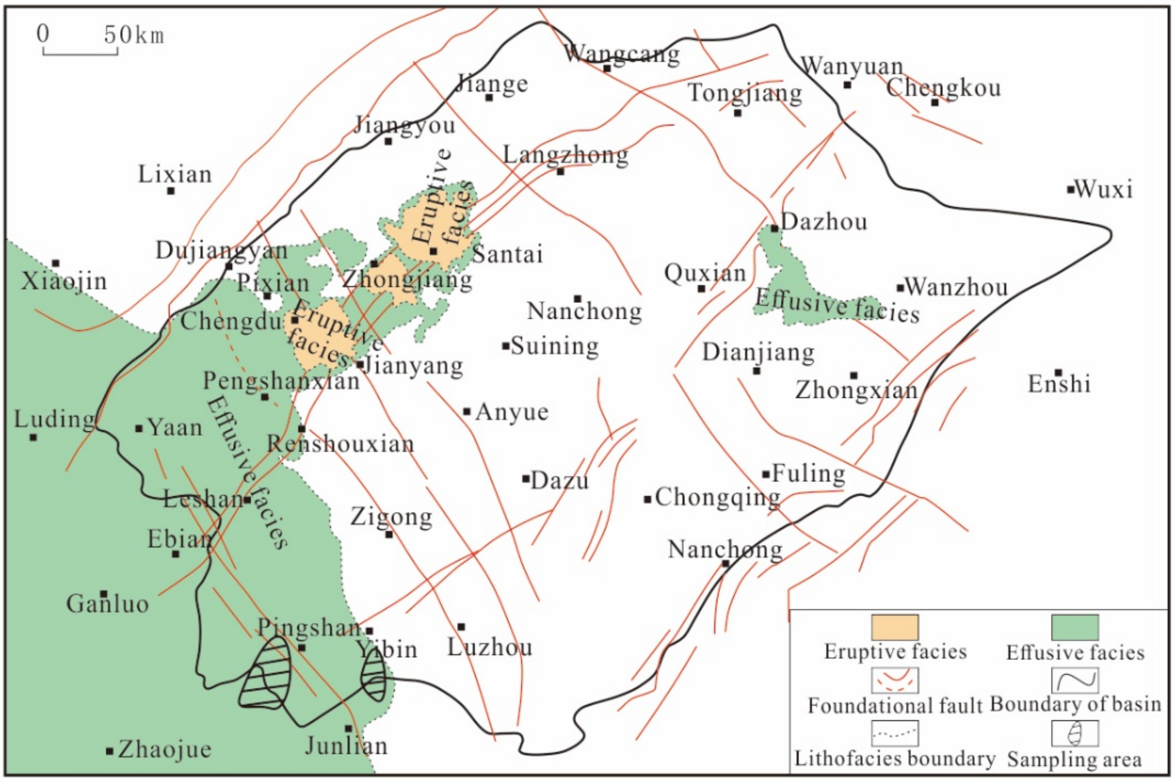

Figure 1. Distribution map of the igneous rock facies and sampling area in the Sichuan Basin (changed from Ma; Li; Ying; Zhagn; Li; Dai; Fan and Zeng [8]).

3. Rock Sample Collection and Physical Property Tests

3.1. Volcanic Outcrop Rock Sample Collection

The locations of the samples collected to test the volcanic rocks' properties were mainly distributed in the southwestern part of the Sichuan Basin, i.e., from Ya'an-Yibin fault zone to the Yibin (D) and Yibin Gongxian County (B). The main lithology was basalt, with a small quantity of tuff and volcanic breccia (Table 1).

3.2. Principles and Methods of Testing the Physical Properties of the Rock Samples

Before the tests, the collected outcrop samples were processed via drilling, cutting, and grinding. The rock samples were 2.5 cm in diameter and 3.0–5.0 cm in length. The density and magnetic susceptibility were measured under dry conditions. Then, the complex resistivity was measured after soaking in saturated brine, and the complex resistivity data were processed and inverted to obtain the Induced Polarization (IP) parameters, such as the resistivity and polarizability. The density and magnetic susceptibility were measured three times and averaged, and after the complex resistivity was measured twice and the curve was smooth without abnormality, the data were saved.

For the density measurements, the drainage method was used and the density of the rock sample was calculated from its mass and volume. For the magnetic susceptibility, a KM-7 high-precision magnetic susceptibility meter was used to measure the magnetic susceptibility of the rocks, with a sensitivity of 1.0×10^{-6} SI, which can directly read the magnetic susceptibility of the samples, and the measurement result is the inductive magnetism.

The complex resistivity of rocks was measured using the quadrupole method (Figure 2). The measuring device used a copper sulfate dough and copper electrode, and the AC power with different frequencies was supplied to both ends of the rock through power supply electrodes A and B. The potential difference between M and N at both ends of the rock was measured using an SI-1260 impedance analyzer.

Table 1. Information about the Permian volcanic rock samples from southwest Sichuan.

Sample Number	Area	Age	Rock Type	Quantity
D2-1 to D2-10	Ya'an-Yibin fault zone to Yibin	$P_2\beta$	gray basalt	10
D3-1 to D3-10	Ya'an-Yibin fault zone to Yibin	$P_2\beta$	gray-green almond basalt	10
D4-1 to D4-6	Ya'an-Yibin fault zone to Yibin	$P_2\beta$	grayish green tuff	6
D5-1 to D5-6	Ya'an-Yibin fault zone to Yibin	$P_2\beta$	grayish green tuff	6
D6-1 to D6-5	Ya'an-Yibin fault zone to Yibin	$P_2\beta$	purple-brown basalt	5
D7-1 to D7-10	Ya'an-Yibin fault zone to Yibin	$P_2\beta$	purple-brown volcanic breccia	10
B-67-1 to B-67-6	Yibin Gongxian County	$P_2\beta$	gray-green dense massive basalt	6
B-68-1 to B-68-3	Yibin Gongxian County	$P_2\beta$	gray-green dense massive basalt	3
B-69-1 to B-69-5	Yibin Gongxian County	$P_2\beta$	gray-green dense massive basalt	5
B-70-1 to B-70-5	Yibin Gongxian County	$P_2\beta$	gray-green dense massive basalt	5
B-71-1 to B-71-5	Yibin Gongxian County	$P_2\beta$	gray-green dense massive basalt	5
B-72-1 to B-72-4	Yibin Gongxian County	$P_2\beta$	gray-green dense massive basalt	4

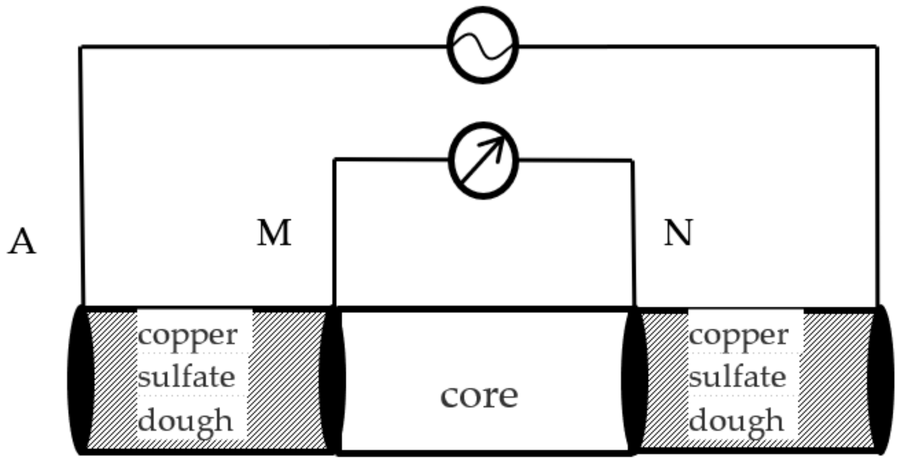

Figure 2. Schematic diagram of the complex resistivity measurement of the rock samples.

For the Complex resistivity model, the Cole–Cole model is a basic model that describes the complex resistivity characteristics of rocks, and it is quantitatively characterized by four parameters: the zero-frequency resistivity, polarizability, time constant, and frequency correlation coefficient [28]. The complex resistivity model is as follows:

$$\rho(i\omega) = \rho_0\left\{1 - m\left[1 - \frac{1}{1+(i\omega\tau)^c}\right]\right\}, \quad (1)$$

where ω is the angular frequency; ρ_0 is the zero-frequency resistivity; m is the polarizability (dimensionless); τ is a time constant; and c is the frequency correlation coefficient (dimensionless). Based on the single Cole–Cole model, many improved models have been developed, such as the Dias model, Debye model, and the multiple and compound Cole–Cole models [29–31]. In this study, the double Cole–Cole model was used for the inversion:

$$\rho(\omega) = \rho_0\left\{1 - m_1\left[1 - \frac{1}{1+(i\omega\tau_1)^{c_1}}\right] - m_2\left[1 - \frac{1}{1+(i\omega\tau_2)^{c_2}}\right]\right\}, \quad (2)$$

where m_1, τ_1, c_1, m_2, τ_2, and c_2 represent the spectral parameters of the IP effect and the electromagnetic effect, i.e., the polarizability, time constant, and frequency correlation coefficient, respectively. According to Equation (2), the spectrum parameters were obtained through inversion. The spectrum parameters caused by the electromagnetic effect cause the electromagnetic coupling interference that needs to be eliminated. This paper mainly analyzes and studies four spectrum parameters (ρ_0, m_1, τ_1, and $c_{1)}$, which reflect the characteristics of the induced polarization of the rocks.

4. Geologic Features

4.1. Petrological Characteristics

The lithology of the rock samples collected from the sampling area was mainly basalt. Eight samples from the Gongxian District, Yibin, were analyzed. These eight samples were classified according to their rock structures, all of which were blocky structures with dense rocks (Figure 3).

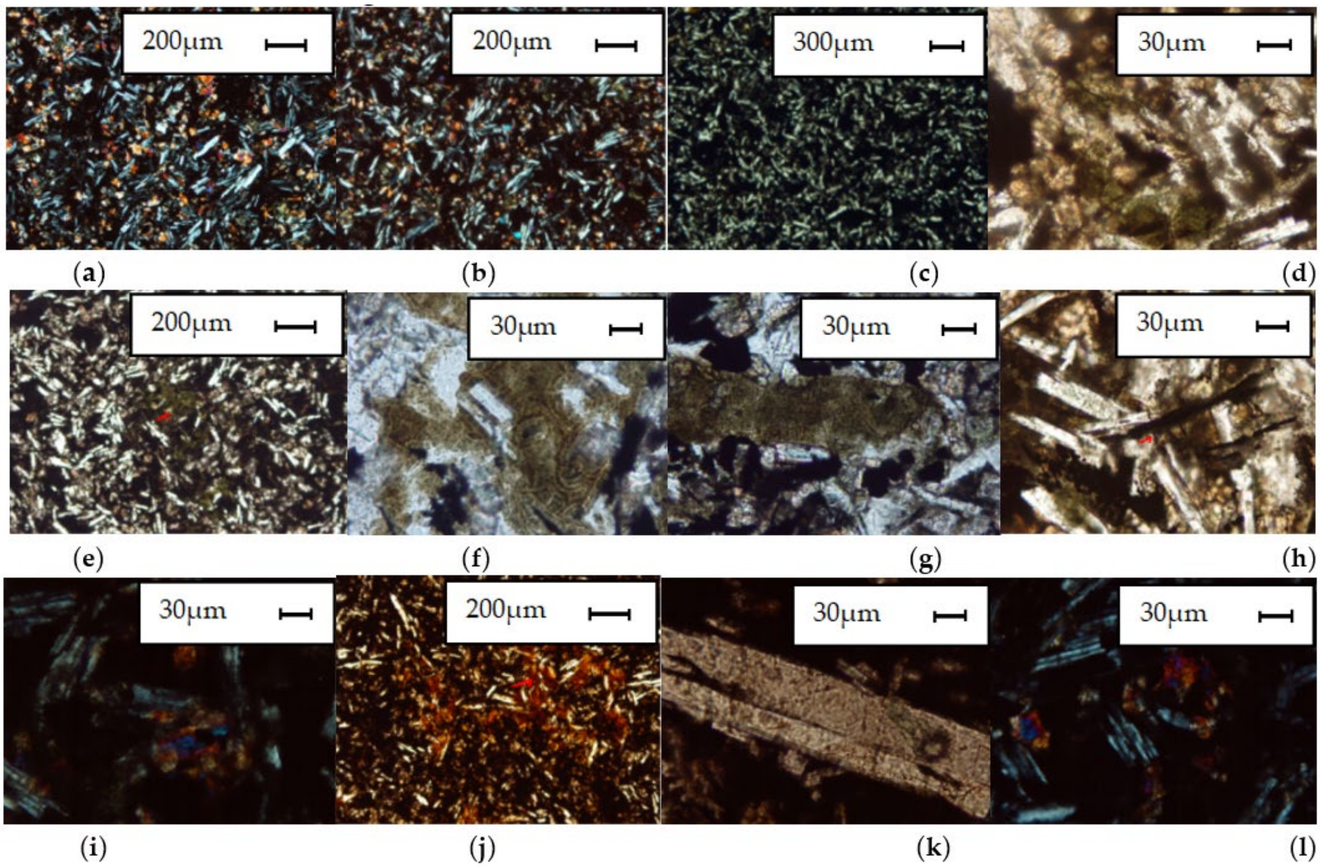

Figure 3. Photos of a basalt sheet from the Gongxian District, Yibin. (**a**) Intergranular structure (orthogonal polarization); (**b**) Intergranular hidden structure (orthogonal polarization); (**c**) Intergranular structure (single polarization); (**d**) Devitrification of volcanic glass (single polarization); (**e**) Chloritization of volcanic glass (single polarization); (**f**) De-vitrification chloritization of volcanic glass (single polarization); (**g**) Pyroxene chloritization (single polarization); (**h**) Ilmenite (single polarization); (**i**) Olivine (orthogonal polarization); (**j**) Iddingsite (single polarization); (**k**) Feldspar porphyry crystal (single polarization); (**l**) Pyroxene with a second-order orange-red interference color (orthogonal polarization).

The main minerals in the rocks from Gongxian County, Yibin, are mafic plagioclase and augite, which have intergranular concealed structures and porphyritic structures. The porphyritic crystals are plagioclase and augite. The long crystal diameters of the rocks in this area are about 0.4–2.3 mm, and they exhibit chloritization and Yiding petrochemical characteristics. The matrix has an intergranular concealed structure, which is composed of microcrystalline plagioclase, devitrified (chloritization) volcanic glass, and clinopyroxene. The tripod made of microcrystalline plagioclase is filled with devitrified volcanic glass, scaly chlorite, clinopyroxene, or ilmenite oxide. In some areas, fibrous pyroxene with low crystallinity occurs in bunches and broom-like aggregates with a spherical structure. It contains sporadic magnetite and ilmenite, and a small quantity of the ilmenite and magnetite is separated from the pyroxene in a needle-like distribution. In addition, under the polarized light microscope, the reservoir rocks from Gongxian County, Yibin, are dense, and there are basically no effective pores and fractures. The physical properties of the reservoirs are generally poor, mainly with ultra-low porosity and ultra-low permeability.

4.2. Physical Characteristics of Reservoirs

The porosity and permeability of 75 rock samples were tested and statistically analyzed according to the lithology. The results are presented in Table 2.

Table 2. Porosity and permeability of rock samples.

Area *	Rock Type	Quantity (Blocks)	Porosity Range (%)	Average Porosity (%)	Permeability Range (mD)	Average Permeability (mD)
D	gray basalt	10	1.03–2.19	1.568	0.003–2.037	0.2074
	gray-green almond basalt	10	1.54–2.17	1.85	0.003–0.026	0.0075
	grayish green tuff	12	0.63–2.65	1.538	0.003–0.006	0.005
	purple-brown basalt	5	1.05–1.67	1.296	0.004–0.007	0.0052
	purple-brown volcanic breccia	10	0.74–3.47	1.672	0.002–0.006	0.0037
B	gray-green dense massive basalt	28	0.313–0.83	0.584	0.003–1.71	0.007

* D—Ya'a-Yibin fault zone to Yibin; B—Gongxian County, Yibin.

The volcanic rocks from the Ya'an-Yibin fault zone to the Yibin area include basalt, tuff, and volcanic breccia, with an average porosity of less than 2%, so they form a low porosity and low permeability reservoir. The volcanic rocks in the Gongxian District, Yibin, are massive basalts, and their average porosity is less than 1%, so they also form low porosity and low permeability reservoirs. The porosity of the volcanic rocks in sampling area D is generally slightly higher than that in sampling area B, but the permeability is poor. The physical parameters of the igneous reservoir are shown in Figure 4. The igneous rocks in southwestern Sichuan are mainly basalt, with a small quantity of pyroclastic rocks. The rock samples are characterized by ultra-low porosity and low permeability reservoir physical properties.

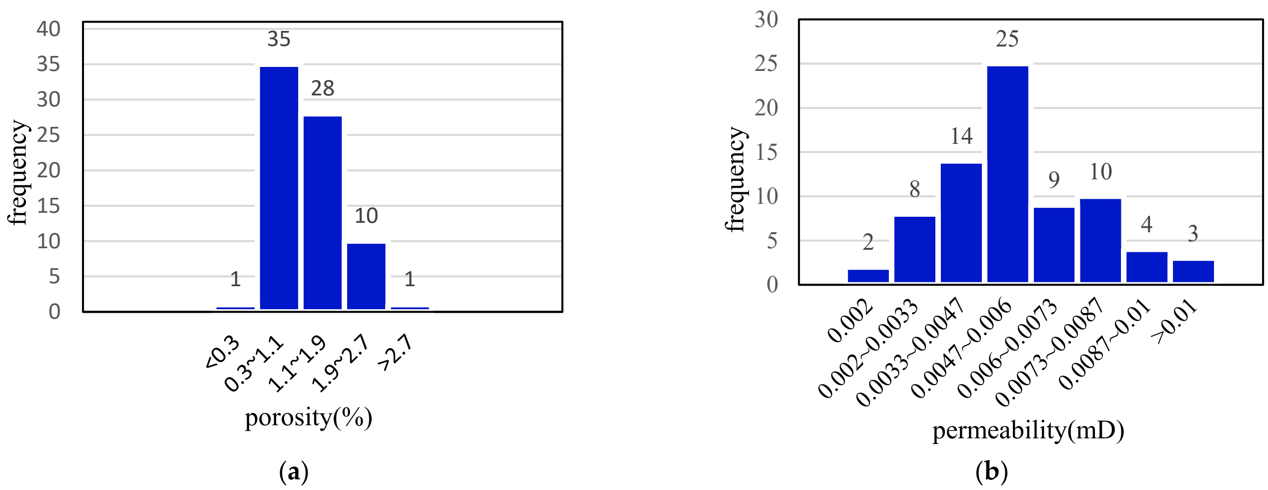

Figure 4. Physical distribution of the porosity and permeability of the igneous rocks in southwestern Sichuan. (**a**) Porosity; and (**b**) Permeability.

4.3. Mineral Composition of Igneous Rocks

The mineral compositions of 75 igneous rock samples were quantitatively analyzed via X-ray diffraction (XRD) whole rock analysis. In the sampling area from the Ya'an-Yibin fault zone to Yibin, the mineral composition of the gray-green basalt and purple-brown basalt is mainly clay, quartz, feldspar, and augite, with a small quantity of magnesite; that of the gray-green almond-shaped basalt is mainly clay, quartz, and feldspar, with a small quantity of hematite; that of the gray-green tuff is mainly clay, quartz, and calcite, with a certain quantity of anatase; and that of the volcanic breccia is mainly clay, quartz, and plagioclase, with a small quantity of hematite and anhydrite. In the sampling area in Gongxian County, Yibin, the gray-green dense massive basalt is mainly composed of clay, quartz, plagioclase, and pyroxene, with a small quantity of magnetite and ilmenite.

For igneous rocks of the same lithology, the average value of the corresponding contents was calculated according to the mineral types, and the distribution maps of the mineral composition and average contents of the samples of different lithologies were created. The results are shown in Figure 5.

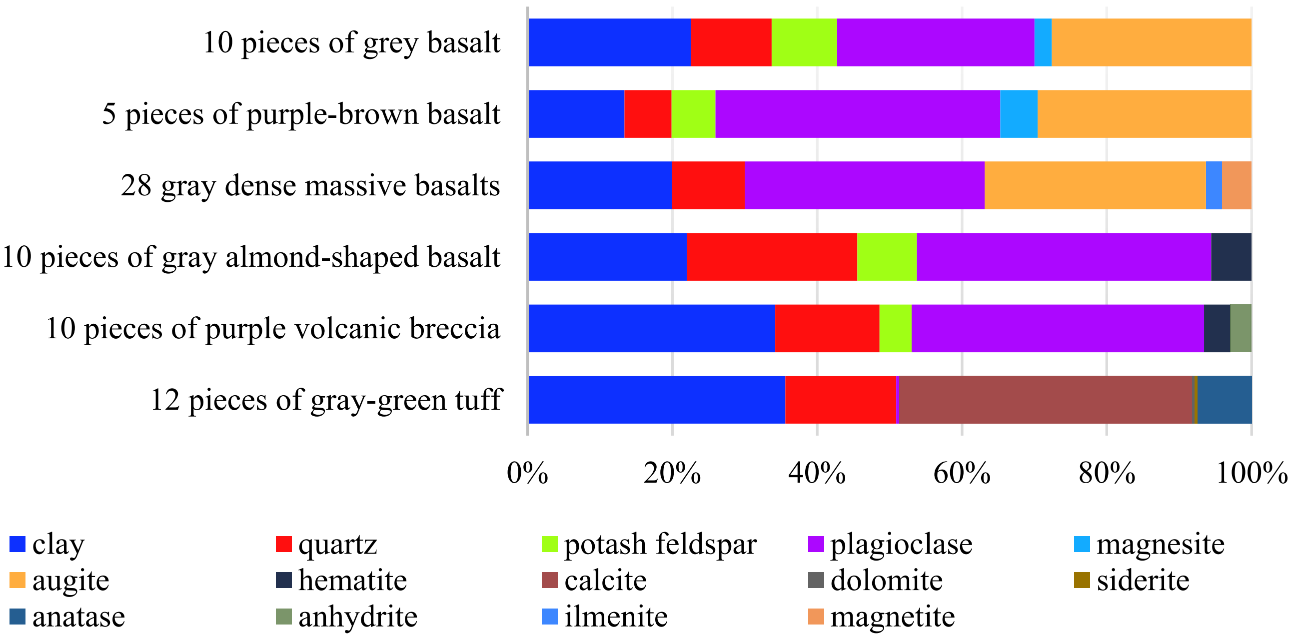

Figure 5. Distributions of mineral types and average contents of the igneous rocks with different lithologies.

4.4. Basalt Reservoir Characteristics

The rocks from the sampling area are mainly basalt. In order to understand the reservoir characteristics of the igneous rocks, the microstructure of the rock samples was scanned. The results of the electron microscopy analysis are shown in Figures 6 and 7.

The whole rock structure is dense, the feldspar crystals are arranged in a disordered manner, and flocculent clay minerals fill the spaces between the feldspar crystals (Figure 6a). Under a magnification of 663, the argillaceous lumps were observed to be distributed in strips (Figure 6b), and under a local magnification of 1851, the argillaceous lumps were observed to be distributed in strips with micro-cracks between the lumps (Figure 6c). Under a magnification of 3066, the feldspar crystals and limonite crystals in the rock were in mosaic contact, with individual intergranular micropores (Figure 6d). Under a magnification of about 3112, the flocculent clay minerals were observed to be attached to the surfaces of the feldspar crystals, with intergranular microcracks (Figure 6e).

Based on the results of the ordinary thin section observations and scanning electron microscope observations, the basalt reservoir space in Gongxian County, Yibin, can be divided into three types: primary pores, secondary pores, and secondary cracks. The primary cracks are undeveloped, and the flocculent clay mineral aggregates fill in the intergranular pores of the feldspar crystals. Most of the feldspar crystals and quartz crystals are in close mosaic contact, some of the tabular feldspar crystals are arranged in a disordered manner, some of the flocculent clay minerals are attached to the surfaces of the feldspar crystals, and some intergranular micro-pores can be seen. The micro-fractures connect the originally unconnected pores, thus greatly improving the physical properties of reservoirs.

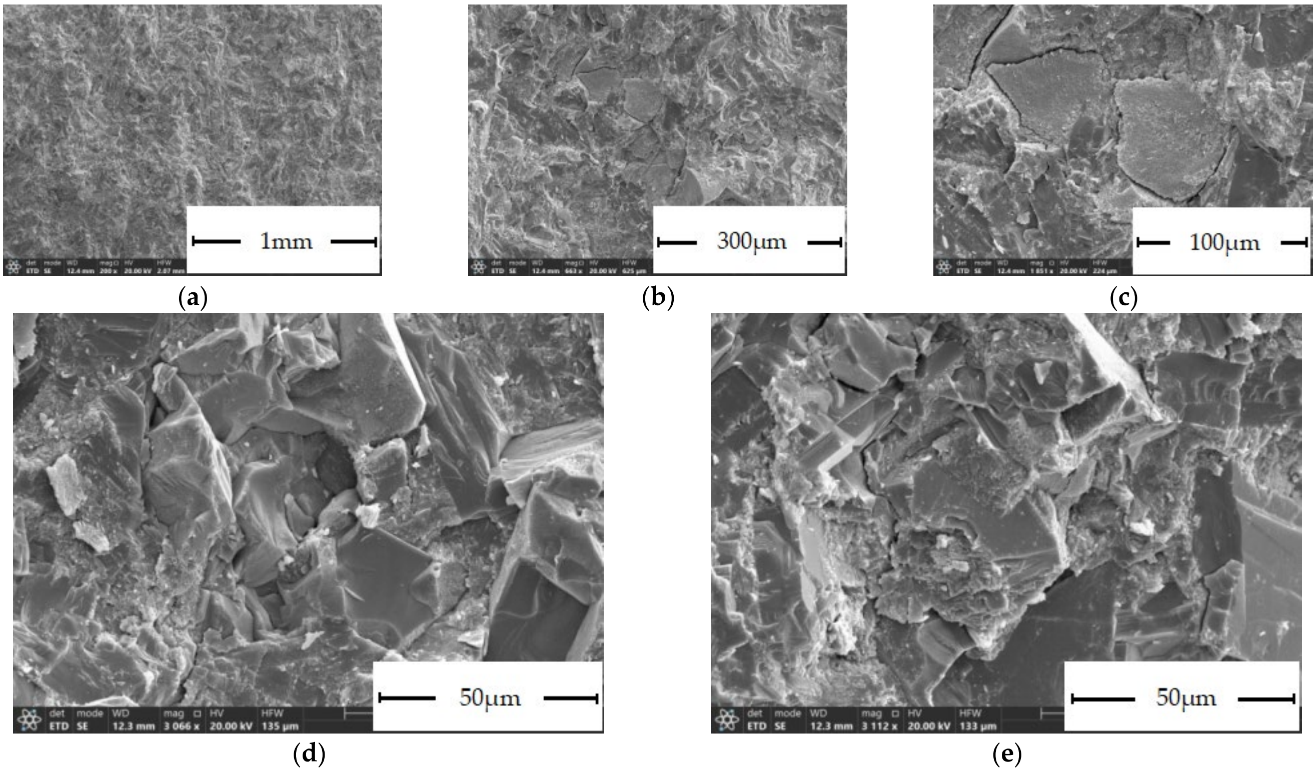

Figure 6. Scanning electron microscopic images of the igneous rocks from Gongxian County, Yibin. (**a**) Magnification of 200×; (**b**) Magnification of 663×; (**c**) Magnification of 1851×; (**d**) Magnification of 3066×; and (**e**) Magnification of 3112×.

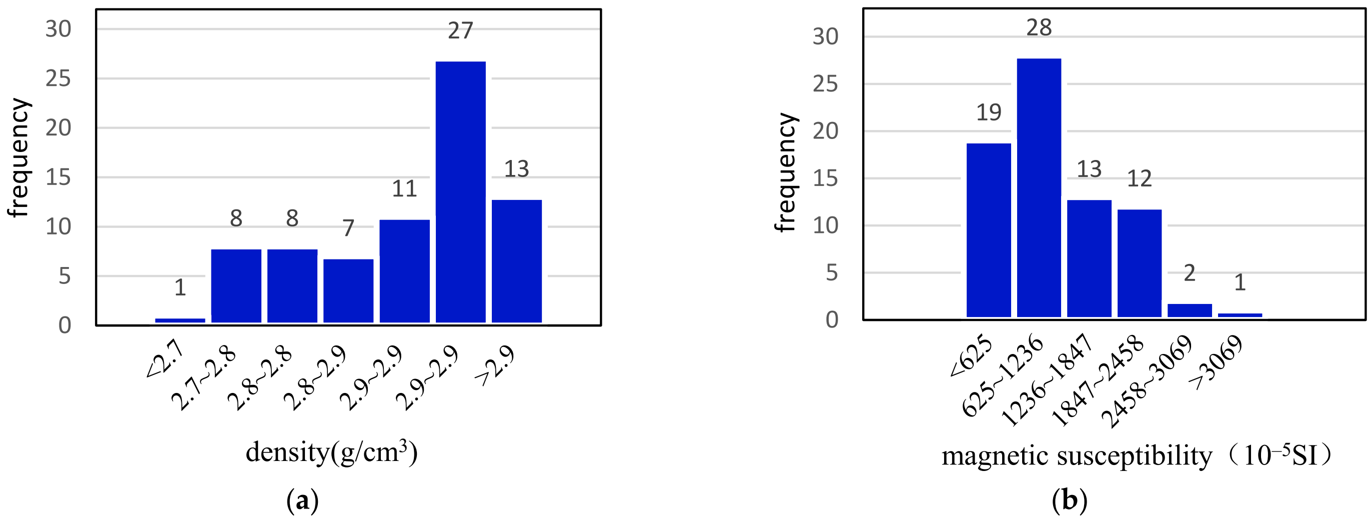

Figure 7. Distributions of the density and magnetic susceptibility of the igneous rock samples in southwestern Sichuan. (**a**) Density; and (**b**) Magnetic susceptibility.

5. Gravity, Magnetic, and Electrical Characteristics and Physical Properties of Igneous Rocks

5.1. Density and Magnetic Susceptibility of Igneous Rocks

In this study, outcrop samples from different strata were collected to directly measure the density changes and magnetic changes in the area in order to determine the changes in the gravity and magnetic anomalies and to understand the changes in the physical properties of the buried strata. The density and magnetic susceptibility of the igneous rock samples were tested and counted, and the results are presented in Table 3.

Table 3. Density and magnetic susceptibility of rock samples.

Area *	Rock Type	Quantity (Block)	Density Range (g/cm^3)	Average Density (g/cm^3)	Magnetic Susceptibility Range (10^{-a} SI)	Average Magnetic Susceptibility (10^{-v} SI)
D	gray basalt	10	2.92–2.99	2.96	1089.5–1749	1410.5
	gray-green almond basalt	10	2.71–2.86	2.79	541.35–3684.5	1544.985
	grayish green tuff	12	2.71–2.83	2.76	14–49.2	31.471
	purple-brown basalt	5	2.91–2.94	2.93	1908.5–2003	1974
	purple-brown volcanic breccia	10	2.79–2.89	2.85	1260.5–963.5	1966.75
B	gray-green dense massive basalt	28	2.88–2.98	2.93	450.05–1212	805.393

* D—Ya'an-Yibin fault zone to Yibin; B—Gongxian County, Yibin.

The statistical results show that the volcanic rocks are characterized by a high density, and the density of the basalt is higher than those of the volcanic breccia and tuff. From the Ya'an-Yibin fault zone to the Yibin area, the average magnetic susceptibility of all of the basalts and volcanic breccias indicate strong magnetic characteristics, while the gray-green tuff has weak magnetism and hardly exhibits any magnetism. In the sampling area in Gongxian County, Yibin, the basalt also exhibits strong magnetism, and the average magnetic susceptibility is slightly less than that of the rocks in sampling area D. Based on the mineral compositions, the rocks generally contain dark iron and magnesium with a high density, and the basalts generally contain metallic minerals, especially ferromagnetic minerals, so their magnetism is generally strong.

According to the above statistical analysis results (Figure 7), the densities of the rock samples are mainly 2.709–2.995 g/cm^3, with an average of 2.879 g/cm^3. The magnetic susceptibilities are 14.2×10^{-5}–3684.5×10^{-5} SI, with an average value of 1057.7×10^{-5} SI, and the magnetic susceptibilities of the samples with different lithologies vary greatly. Therefore, overall, the igneous rocks in southwestern Sichuan have high densities and high magnetism, and the magnetism of the basalts is particularly strong and is higher than those of the other lithologies.

5.2. Complex Resistivity Characteristics of Igneous Rocks

5.2.1. Complex Resistivity of Igneous Rocks

All of the rock samples were 100% saturated with saline solution with a uniform concentration (10,000 ppm) via vacuumizing and pressurizing. The complex resistivity data were measured under normal temperature and pressure conditions, and the measurement frequency range was from 0.01 Hz to 10,000 Hz. The test results of the complex resistivity of the rock samples with different lithologies were plotted in two curves of the amplitude and phase, which reflect the relationship between the complex resistivity and the frequency. The measurement results are shown in Figure 8.

The above complex resistivity measurement results show that as the frequency decreases, the resistivity amplitude gradually increases, and the phase amplitude gradually approaches 0. The resistivity amplitude of the volcanic rocks of the same lithology ranges from several hundred ohm meters to several thousand ohm meters, with a wide range of variation, and the phase amplitude forms and variation trends are basically the same.

5.2.2. Inversion of the Complex Resistivity Parameters of the Volcanic Rocks

According to the measured complex resistivity amplitude and phase results, the complex resistivity model described by Equation (2) was used for the inversion. Figure 9 shows the fitting result for some rock samples, and the effect is good.

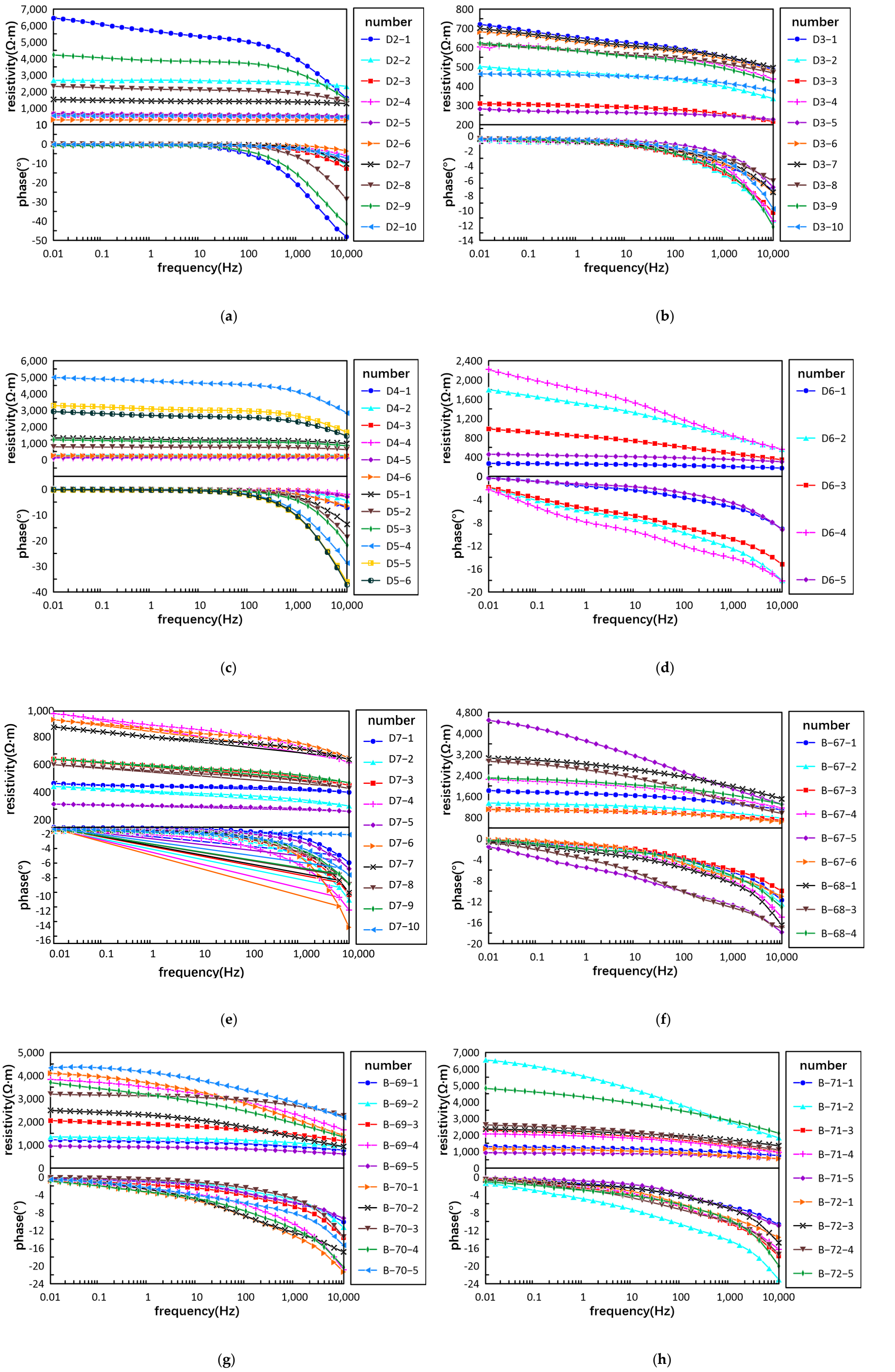

Figure 8. Complex resistivity amplitude and phase curves for the igneous rocks. (**a**) Gray basalt; and (**b**) Gray-green almond basalt; (**c**) Grayish green tuff; (**d**) Purple-brown basalt; (**e**) Purple-brown volcanic breccia; (**f**) Gray-green dense massive basalt; (**g**) Gray-green dense massive basalt; (**h**) Gray-green dense massive basalt.

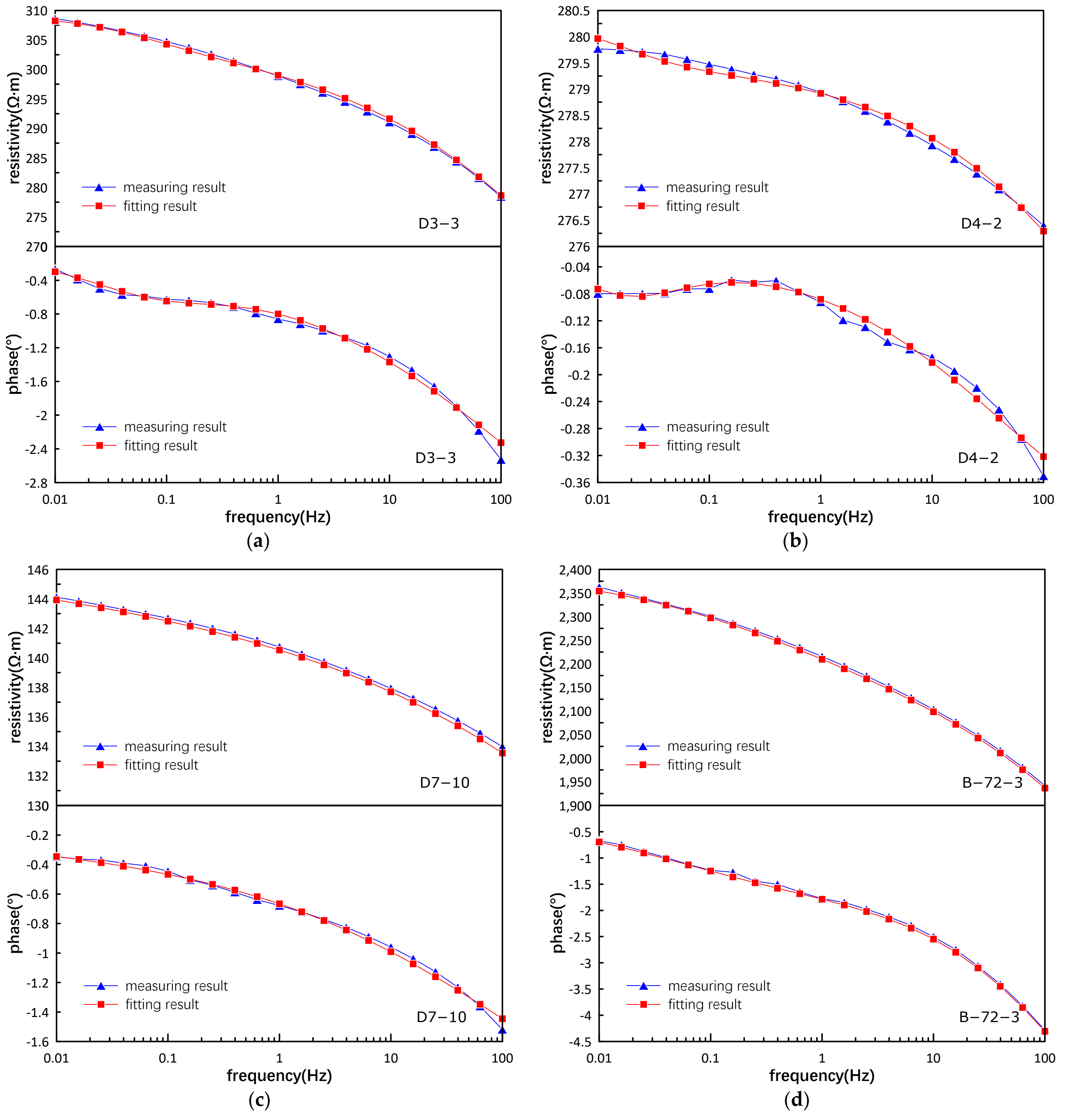

Figure 9. Contrast curves of inversion fitting results. (**a**) Rock sample D3-3; (**b**) Rock sample D4-2; (**c**) Rock sample D7-10; and (**d**) Rock sample B-72-3.

The resistivity and polarizability parameters were mainly analyzed and studied, and the inversion results are shown in Table 4. The inversion and statistical results show that the average resistivity of the gray-green dense massive basalt is 2634.7 Ω·m, which is the highest and classifies it as a high resistivity rock. The average resistivity of the gray basalt is 2033.6 Ω·m, which is high. The average resistivity of the gray-green tuff is 1352.0 Ω·m, and that of the purple-brown basalt is 1213.4 Ω·m, which classifies them as medium-high resistivity rocks. The average resistivity of the purple volcanic breccia is 637.5 Ω·m, and that of the gray green almond basalt is 568.1 Ω·m, which is the lowest, so both of these rocks have medium-low resistivity. The average polarizability is low overall, but the polarizability of some of the rock samples is greater than 20%, among which those of the purple-brown basalt and gray-green dense massive basalt are more obvious.

Table 4. Resistivity and polarizability parameters.

Area *	Rock Type	Quantity (Block)	Resistivity Range (Ω·m)	Average Resistivity (Ω·m)	Polarizability Range (%)	Average Polarizability (%)
D	Gray basalt	10	315.2–6662.1	2033.6	3.00–14.92	9.21
	Gray-green almond basalt	10	293.6–734.4	568.1	2.46–16.34	8.69
	Grayish green tuff	12	116.0–5170.0	1352.0	1.34–15.42	6.98
	Purple-brown basalt	5	278.1–2394.5	1213.4	8.05–22.84	14.59
	Purple-brown volcanic breccia	10	153.7–1012.1	637.5	2.21–13.36	9.28
B	Gray-green dense massive basalt	28	957.0–6814.7	2634.7	3.90–18.98	9.32

* D—Ya'an-Yibin fault zone to Yibin; B—Gongxian County, Yibin.

According to the above statistical analysis results (Figure 10), statistically speaking, the resistivity of the igneous rocks varies widely, ranging from 116.0 Ω·m to 6814.7 Ω·m, with the average of 1712.7 Ω·m. However, the rocks predominantly have high resistivities, and there are great differences within the same lithology, which indicates that the conductive mechanism of the igneous rocks is relatively complex. The polarizability ranges from 1.34% to 22.84%, with an average of 9.19%. However, the results of the polarizability show that the highest polarizability of the purple-brown basalt can reach 22%, indicating that there are highly polarizable rock samples, and the average value is higher than those of other rock types. Although the difference in the polarizability is relatively small, the polarizability of the basalt is higher than that of the other lithologies. Therefore, the comprehensive resistivity value of the polarizability parameter can be used as an important index for determining the igneous rock lithology and lithofacies and for reservoir evaluation.

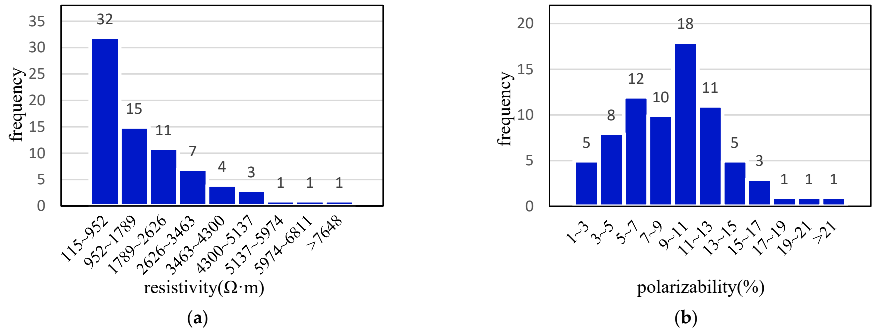

Figure 10. Distributions of resistivity and polarizability of igneous rock samples in southwestern Sichuan. (**a**) Resistivity D3-3; and (**b**) Polarizability.

6. Exploration Potential of Permian Igneous Oil and Gas Reservoirs in Southwestern Sichuan

6.1. Multi-Parameter Comprehensive Analysis of the Igneous Rocks' Physical Properties

6.1.1. Comprehensive Physical Characteristics of the Igneous Rocks, including Density, Magnetic Susceptibility, and Resistivity

According to the related research data for the igneous rocks in the Sichuan Basin, there are four types of lithofacies in southwestern Sichuan, including explosive facies, overflow facies, volcanic sedimentary facies, and volcanic channel facies. The outcrop igneous rock samples collected in this study represent two of these lithofacies. One is the overflow facies, including all of the types of basalt; and the other is the explosive facies, including the volcanic breccia and tuff.

Based on the physical parameters (i.e., the density, magnetic susceptibility, and resistivity) of the igneous rocks of different lithologies in the sampling area, multi-parameter plots of density, magnetic susceptibility, resistivity, and polarizability were created (Figure 11). The tuff is located in the relatively weak magnetic and low-density area, and its resistivity and polarizability are generally low, so it is easier to identify than other lithologies. The distributions of the magnetism and density values of the dense, massive, gray basalt are relatively concentrated, but the distribution ranges of the resistivity and polarizability are large and not concentrated. The resistivity distributions of the gray almond-shaped basalt and volcanic breccia are relatively concentrated in the low resistivity region, which makes them easier to identify than other lithologies of igneous rocks, but their density and magnetic susceptibility are distributed over wide ranges and are not concentrated. Therefore, the 3-D intersection result map of the gravity, magnetic, and electrical properties can be used as an important basis for identifying the igneous rocks of different lithologies.

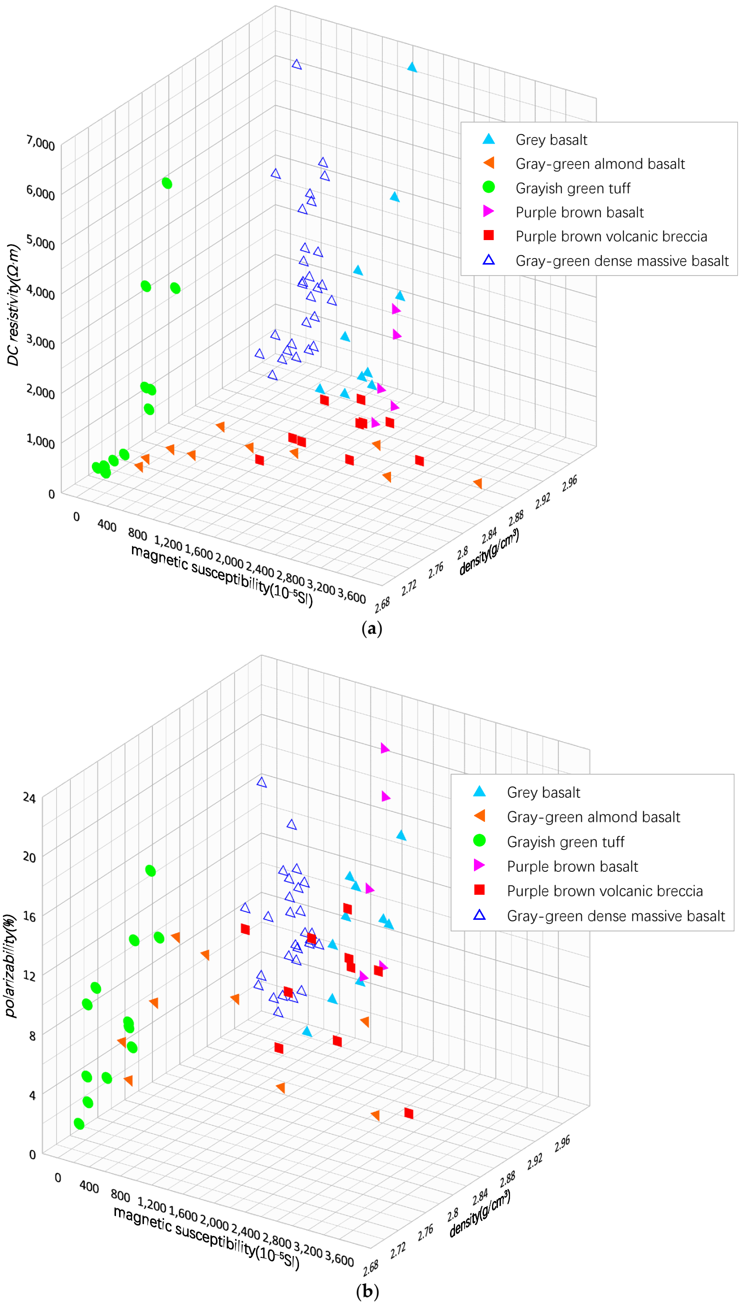

Figure 11. Multi-parameter plots for the igneous rocks with different lithologies. (**a**) Plot of density, magnetic susceptibility, and resistivity; (**b**) Plot of density, magnetic susceptibility, and polarizability.

6.1.2. Multi-Parameter Relationship Model of Physical Properties

According to the different lithologies of the igneous rocks, the relationships between the density, resistivity, and porosity were quantitatively analyzed. There is a logarithmic relationship between the resistivity and porosity, and there is a linear relationship between the density and porosity. No obvious correlations were found between the other physical parameters. Figures 12 and 13 show the relationships model between the density, resistivity, and reservoir porosity.

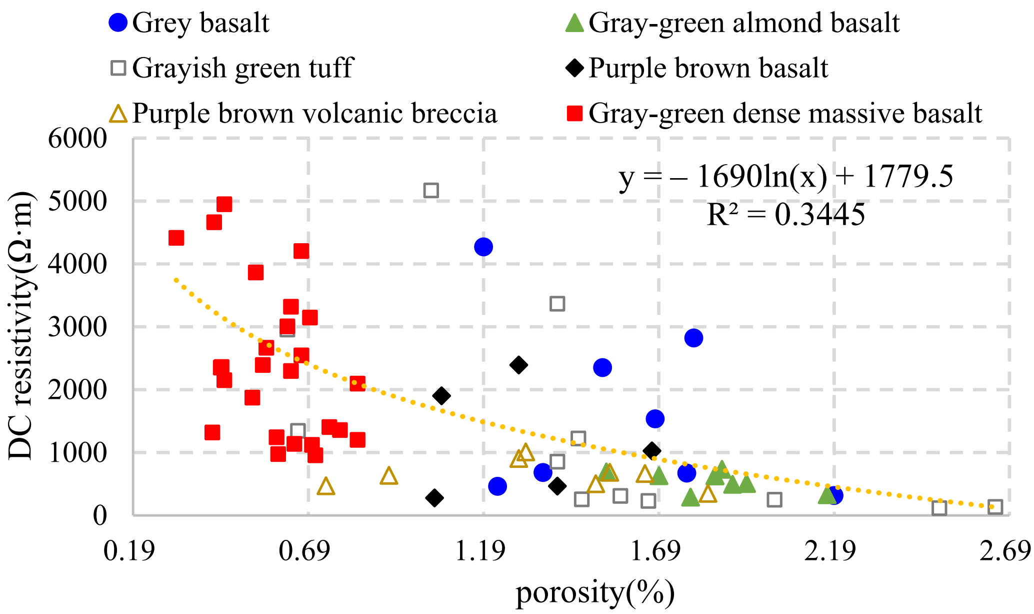

Figure 12. Relationship between the resistivity and porosity of the igneous rock samples from the Sichuan Basin.

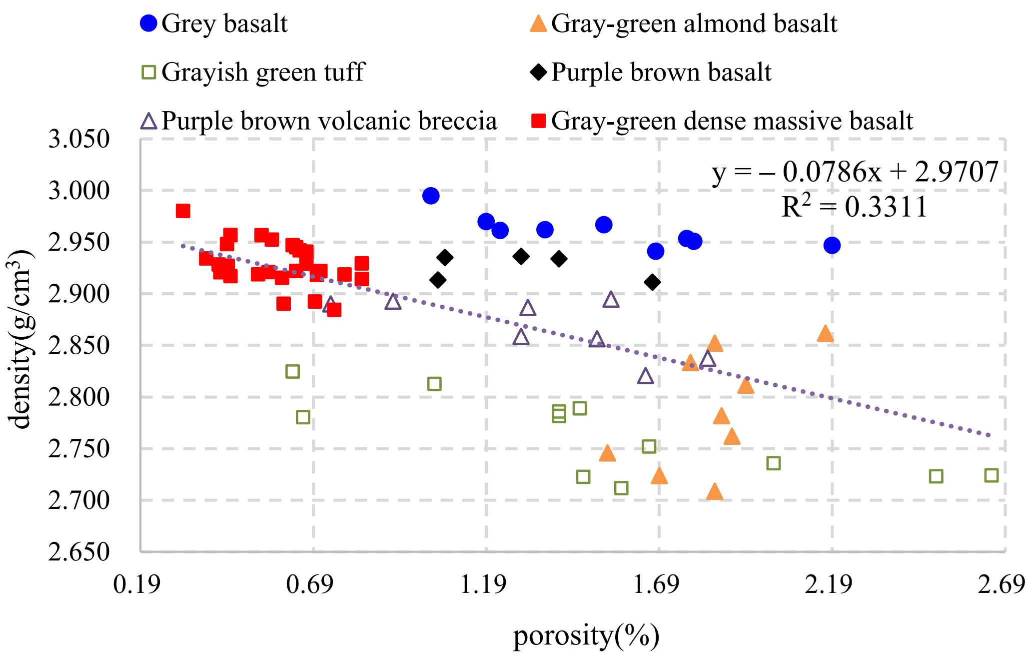

Figure 13. Relationship between the density and porosity of the igneous rock samples from the Sichuan Basin.

6.2. Exploration Potential of Permian Igneous Rocks in Southwestern Sichuan

Three important target strata, i.e., the Qixia Formation, Maokou Formation, and Emeishan basalt, are developed in the Middle Permian section from bottom to top. Under the Permian igneous rocks in western Sichuan, there are several sets of source rock series in the Lower Cambrian, Lower Silurian Longmaxi Formation and Permian strata [32]. After the Caledonian movement, the Permian formed in unconformable contact with the Lower Cambrian Canglangpu and Qiongzhusi formations. This resulted in a source–reservoir relationship with a lower hydrocarbon generation zone and an upper reservoir. In addition, there are many vertical faults between the Permian and Cambrian strata, which connect the igneous rocks with the underlying Cambrian and Permian source rocks, providing favorable conditions for oil and gas migration. Therefore, the Permian igneous rocks in southwestern Sichuan have a good natural gas exploration potential [9,16].

Explosive facies and overflow facies igneous rocks are developed in southwestern Sichuan, and their physical characteristics, including density, magnetic susceptibility, and electrical properties, are significantly different from those of the surrounding rocks. This provides a good basis for using a gravity-magnetic-electric method in igneous oil and gas exploration and identification.

7. Conclusions

Based on measurements of the density, magnetic susceptibility, and resistivity properties of the Permian igneous rocks in the southwestern Sichuan Basin, the density, magnetic susceptibility, and electrical response characteristics of the igneous rocks were studied. Based on the measured physical properties, comprehensive analysis of thin section observations, mineral composition analysis, and scanning electron microscope observations, the following main conclusions were obtained.

(1) The porosity and permeability of the igneous rocks in southwestern Sichuan indicate that the physical properties of these reservoirs are generally poor, and there are basically no effective pores and fractures in the basalt thin sections and electron microscope images. They are mainly ultra-low porosity and ultra-low permeability rocks, and the intergranular micropores were observed in the scanning electron microscope images. Although the primary pores are undeveloped, the microfractures connect the unconnected pores, which greatly improves the physical properties of these reservoirs.

(2) The density, magnetic susceptibility, resistivity, and polarizability measurements show that the igneous rocks in southwestern Sichuan have a high density and high magnetic susceptibility. In particular, the strong magnetism of the basalts is more obvious than those of the other lithologies. The resistivity and polarizability of the igneous rocks vary widely, even within the same lithology, which indicates that the conductive mechanism of the igneous rocks is complex. Overall, the basalt in southwestern Sichuan is characterized by high density, high resistivity, and strong magnetism; the tuff is characterized by medium-high density, medium-high resistivity, and weak magnetism; and the volcanic breccia is characterized by a high density, medium-low resistivity, and strong magnetism. The comprehensive resistivity parameter, i.e., the polarizability, can be used as an important index parameter for determining the lithology and lithofacies of the igneous rocks and for reservoir evaluation.

(3) The three-dimensional plot of the resistivity, density, and magnetic susceptibility, and the three-dimensional plot of the polarizability, density, and magnetic susceptibility show that the distribution characteristics of the physical parameters of the igneous rocks with different lithologies are distinct, and these plots can be used as an important basis for identifying igneous rocks with different lithologies. The relationships between the physical parameters and reservoir parameters established for the study area reflect the porosity distribution range of the different lithologies and provide effective parameters for igneous reservoir evaluation.

(4) The comprehensive physical characteristics of the Permian igneous rocks in southwestern Sichuan are prominent. They provide a physical basis for gravity, magnetic, and electrical exploration, showing that these igneous rocks have a good natural gas exploration potential. Because igneous reservoirs are more complex than conventional sedimentary reservoirs and there are many problems to be solved regarding igneous rock facies, lithologies, and reservoir physical properties, many geological and geophysical techniques still need to be improved for use in igneous oil and gas reservoir identification and reservoir prediction and evaluation. This study provides a physical basis and technical support for gravity-magnetic-electrical exploration of the igneous oil and gas reservoirs in the Sichuan Basin. However, the research on the physical properties of these igneous rocks is still insufficient, and other specimens need to be collected and analyzed, such as the Jianyang-Santai area in the central and western parts of the basin, to further deepen our understanding of the gravity, magnetic, and electrical physical properties of the igneous rocks in this region.

Author Contributions: Conceptualization, K.X. and L.Y.; methodology, K.X.; validation, L.Y., Z.W. and Y.L.; investigation, K.X.; resources, Z.W. and Y.L.; writing—original draft preparation, K.X.; writing—review and editing, L.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (grant numbers 42174083 and 42030805.

Data Availability Statement: Not applicable.

Acknowledgments: We thank the department of geophysical and geochemical prospecting, BGP, CNPC, for supplying rock samples.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Chung, S.L.; Jahn, B.M. Plume-lithosphere interaction in generation of the Emeishan flood basalts at the Permian-Triassic boundary. *Geology* **1995**, *23*, 889. [CrossRef]
2. Wignall, P.B. Large igneous provinces and mass extinctions. *Earth-Sci. Rev.* **2001**, *53*, 1. [CrossRef]
3. Xu, Y.; Chung, S.L.; Jahn, B.M.; Wu, G. Petrologic and geochemical constraints on the petrogenesis of Permian–Triassic Emeishan flood basalts in southwestern China. *Lithos* **2001**, *58*, 145. [CrossRef]
4. Thompson, G.M.; Ali, J.R.; Song, X.; Jolley, D.W. Emeishan Basalts, SW China: Reappraisal of the formation's type area stratigraphy and a discussion of its significance as a large igneous province. *J. Eological Soc.* **2001**, *158*, 593. [CrossRef]
5. Luo, J.; Wang, F.; He, S.; He, Z.; Huang, Y.; Zhang, D.; Zhu, Y.; Sun, Z.; Luo, T. Characteristics of Vein-Forming Fluids in the Sinian Dengying Formation Reservoir and Its Relationship with the Hydrocarbon Accumulation Process in the Southwest and Southeast of the Sichuan Basin. *Minerals* **2022**, *12*, 443. [CrossRef]
6. Ma, X.; Yang, Y.; Zhang, J.; Xie, J. A major discovery in Permian volcanic rock gas reservoir exploration in the Sichuan Basin and its implications. *Nat. Gas Ind.* **2019**, *39*, 1. [CrossRef]
7. Xie, J.; Ya, L.; Yang, Y.; Zhang, B.; Liu, R.; He, Q.; Wang, W.; Wang, Y. Main controlling factors and natural gas exploration potential of Permian scale volcanoclastic reservoirs in the western Sichuan Basin. *Nat. Gas Ind.* **2021**, *41*, 48. [CrossRef]
8. Ma, X.; Li, G.; Ying, D.; Zhagn, B.; Li, Y.; Dai, X.; Fan, Y.; Zeng, Y. Distribution and gas-bearing properties of Permian igneous rocks in Sichuan Basin, SW China. *Pet. Explor. Dev.* **2019**, *46*, 216. [CrossRef]
9. Liu, R.; Luo, B.; Li, Y.; Qiu, N.; Wang, W.; Zhang, Y.; He, Q.; Pei, S. Relationship between Permian volcanic rocks distribution and karst paleogeomorphology of Maokou Formation and its significance for petroleum exploration in western Sichuan Basin, SW China. *Pet. Explor. Dev.* **2021**, *48*, 575. [CrossRef]
10. Zhou, D.; Dong, Q. Characteristics and formation of igneous oil and gas reservoirs. *Lithol. Reserv.* **2010**, *22*, 80.
11. Liu, P.; Chen, K.; He, Q.; Peng, W.; Zebin, L.; Liu, Z. Discussion on fracture eruption mode of Permian volcanic rocks in Sichuan Basin. *Oil Geophys. Prospect.* **2021**, *56*, 389. [CrossRef]
12. Wu, Y.; Xie, B.; Wu, L.; Lai, Q.; Zhao, R. Logging based lithology identification of Permian mafic volcanic rocks in the Sichuan Basin: A case study from the Well Yongtan 1. *Nat. Gas Ind.* **2019**, *39*, 43. [CrossRef]
13. Xia, M.; Wen, L.; Li, Y.; Luo, B.; He, K.; Liu, R.; Qiu, Y.; He, Q.; Chen, K. Permian volcanic eruption cycle, environment and model in the Jianyang area of the Sichuan Basin. *Nat. Gas Ind.* **2020**, *40*, 43. [CrossRef]
14. Liu, X.; Xia, M.; Wu, Y.; He, Q.; Li, Y.; Liu, R. Characteristics of Permian volcaniclastic lava reservoirs in Yongtan 1 well, Sichuan Basin. *Nat. Gas Explor. Dev.* **2019**, *42*, 28. [CrossRef]

15. Wen, L.; Li, Y.; Yi, H.; Liu, X.; Zhang, B.; Qiu, Y.; Zhou, G.; Zhang, X. Lithofacies and reservoir characteristics of Permian volcanic rocks in the Sichuan Basin. *Nat. Gas Ind.* **2019**, *39*, 17. [CrossRef]
16. Lu, J.; Zuo, Z.; Shi, Z.; Dong, X.; Wu, Q.; Song, X. Characteristics of Permian volcanism in the western Sichuan Basin and its natural gas exploration potential. *Nat. Gas Ind.* **2019**, *39*, 46. [CrossRef]
17. He, Z.; Hu, Z.; Wang, Z.; Zhao, Y.; Shen, Y.; Liu, X. Time-frequency electromagnetic (TFEM) technique: Step-by-step constraint inversion based on artificial fish swarm algorithm. *Oil Geophys. Prospect.* **2020**, *55*, 898. [CrossRef]
18. Zhang, C.; Liu, X.; He, L.; He, W.; Zhou, Y.; Zhu, Y.; Cui, Z.; Kuang, X. A study of exploration organic rich shales using Time-Frequency Electromagnetic Method (TFEM). *Chin. J. Geophys.* **2013**, *56*, 3173. [CrossRef]
19. Xu, C.; Xu, Z.; Yang, Z.; Zhang, K. Application effect of complex resistivity (CR) method in detecting oil and gas reservoirs. *Oil Geophys. Prospect.* **2004**, *39*, 31.
20. Zhang, B. *Deep Fault System in Southwest Sichuan and Its Control on Permian Volcanic Rocks*; China University of Geosciences: Beijing, China, 2020.
21. Yang, H.; Wen, B.; Dai, X.; Wang, L.; Zhu, R.; Hou, L.; Mao, Z.; Zhang, L.; Song, X. Comprehensive predication of hydrocarbon deposits in volcanic rock by gravity, magnetic, electrical and seismic data and its application. *Chin. J. Geophys.* **2011**, *54*, 286. [CrossRef]
22. Xiang, K.; Yan, l.; Hu, H.; Hui, Y.; Wen, B. Characteristics and modeling of gravity, magnetism and electricity physical properties of Precambrian in Sichuan Basin. *Oil Geophys. Prospect.* **2020**, *55*, 1160. [CrossRef]
23. Bian, B.; Wang, X.; Gu, S.; Li, Z.; Nueraili, Z. Application of "Five-dimensional Integration" Comprehensive Geophysical Prospecting Technology of Magnetoelectric Seismic Wells in Carboniferous Volcanic Rock Identification in Dabasong Uplift. In Proceedings of the CPS/SEG Beijing 2018 International Geophysical Conference and Exhibition, Beijing, China, 24–27 April 2018; p. 1267.
24. Suo, X.; Zhang, S.; Chen, D. Identification of the Carboniferous Volcanic Lithology with Gravitational-Magnetic-Electric Abnormal Information Pattern—An example from eastern Luliang uplift area in Junggar basin. *Xinjiang Pet. Geol.* **2011**, *32*, 318.
25. Xia, Y.; Li, Y.; Cai, Y.; Huang, Y. Application of "Five-in-One" Volcanic Rock Identification Technology of Gravity, Magnetism, Electric, Well-log, Seismic in Carboniferous Natural Gas Exploration in Dinan Uplift. *Xinjiang Geol.* **2021**, *39*, 448.
26. Zhang, S.; Zhang, P.; Tian, Z.; Yang, Z.; Cui, Z. Description of Deep Volcanic Reservoir in Junggar Basin by Magnetoelectric-Seismic Multi-information Combination. In Proceedings of the CPS/SEG Beijing 2018 International Geophysical Conference & Exposition Electronic papers, Beijing, China, 24–27 April 2018; p. 1282.
27. Guo, H.; Ye, W.; Zenghui, F.; Ming, X.; Yulin, H.; Mingyi, L.; Yi, W. Application of non-seismic exploration technologies to Sichuan Basin. *Nat. Gas Explor. Dev.* **2019**, *42*, 58. [CrossRef]
28. Pelton, W.H.; Ward, S.H.; Hallof, P.G.; Sill, W.R.; Nelson, P.H. Mineral discrimination and removal of inductive coupling with multi-frequency IP. *Geophysics* **1978**, *43*, 588. [CrossRef]
29. Dias, C.A. Developments in a model to describe low-frequency electrical polarization of rocks. *Geophysics* **2000**, *65*, 437. [CrossRef]
30. Luo, Y.; Zhang, G. *Principle of Frequency Domain IP Method*; Geological Publishing House: Beijing, China, 1988.
31. Xiang, K.; Hu, W.; Yan, l.; Zhang, C.; He, W.; Tang, X.; Liu, X. Dispersion characteristics of shale complex resistivity in Sichuan and Guizhou areas. *Oil Geophys. Prospect.* **2014**, *49*, 1013. [CrossRef]
32. Yang, Y.; Yang, Y.; Wen, L.; Zhang, X.; Chen, C.; Chen, K.; Zhang, Y.; Di, G.; Wang, H.; Xie, C. New exploration progress and prospect of Middle Permian natural gas in the Sichuan Basin. *Nat. Gas Ind.* **2020**, *40*, 10. [CrossRef]