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Research Article

Experimental Study on Physical Characteristics of Deep Rocks at Different Depths in Songliao Basin

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Deep earth science is the basic of deep resource exploitation, and the research on the physical and mechanical characteristics of deep rock is a research hotspot at present. In order to study the physical characteristics of deep rock at different depths, based on the cores at different depths of 4900-6830 m in Songke Well 2 (SK-2), Songliao Basin, this paper carried out the study including the rock characteristics of mineral, wave velocity, density, and pore, the variation law of physical characteristics of deep rock with depth is studied, and the relationship between different physical parameters of deep rocks is explored. It is found that the core composition minerals of SK-2 at the depth of 4900-6830 m vary greatly with the depth, in which the quality of hard phase minerals accounts for a large proportion. After entering the basement stratum, the mineral content of different phases tends to be close. With the increase of depth, the wave velocity, density, and dynamic elastic modulus of rocks show a linear increase trend, and there is a positive correlation between density and wave velocity. In the range of 4900-6830 m depth, the porosity generally shows a downward trend with the increase of depth. In the range of 6000-6830 m, the porosity tends to be close to 7% with the increase of depth, indicating that formation compaction has little impact on the development of igneous pores in this formation. There is a negative correlation between wave velocity and porosity, and the empirical formula is fitted. This study can provide a reference for the exploration of deep geoscience and deep engineering practice.

1. Introduction

Songliao Basin is located in northeast China with an area of about 260000 km^2. It is the longest developed continental basin in the world. The Mesozoic-Cenozoic continental strata of the basin are composed of volcanic rocks, pyroclastic rocks and sediments of alluvial fans, rivers, and lakes, and the maximum sedimentary thickness of the basin can reach 10000 m. The basement of the basin is Paleozoic igneous rocks, metamorphic rocks, and volcanic rocks [1–3], as shown in Figure 1. In order to investigate the deep energy of Songliao Basin, establish the deep stratigraphic structure profile of Songliao Basin, seek the geological evidence of Cretaceous climate change, and develop deep exploration technology; the Continental Scientific Drilling Project of Cretaceous Songliao Basin (SK-1 and SK-2) is implemented. As a main phase of the project, SK-2 is the deepest continental scientific drilling in Asia, with a depth of 7018 m, a coring footage of 4279.73 m, and a coring yield of 96.61%, as shown in Figure 1. As an ultradeep coring borehole in continental basin, the project is of great significance to explore the mysteries of the earth and solve major problems such as deep energy environment [4–6].

Deep earth science is the basic of deep resource exploitation [8], and the research on the physical and mechanical characteristics of deep rock is a research hotspot at present [9–14]. Many scholars use rock physical and mechanical tests at different depths to carry out research on multifield coupling, underground excavation, etc. [15–18], but there are some

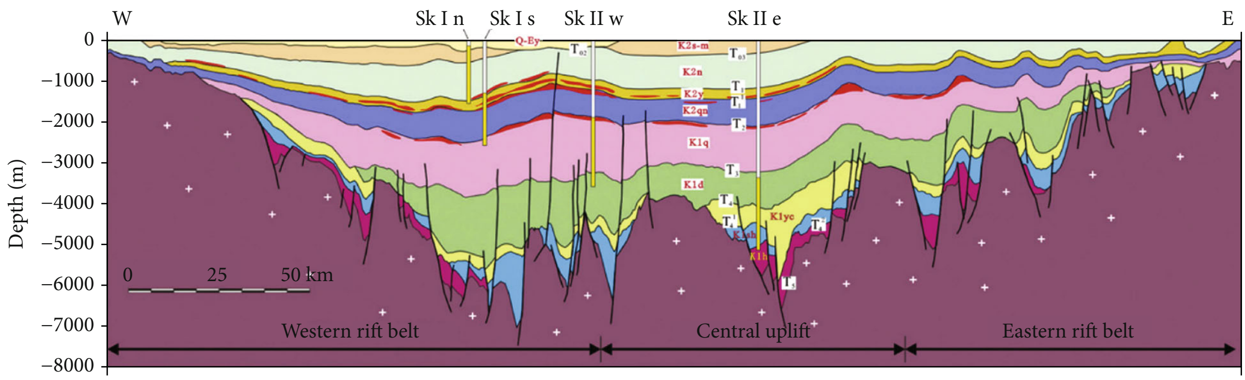


Figure 1: Location of well SK-2 and longitudinal section of Songliao Basin [7]. The yellow interval in SK-2 is the coring interval, the red strip represents the oil layer, and T02-5 represents the seismic reflection horizon.

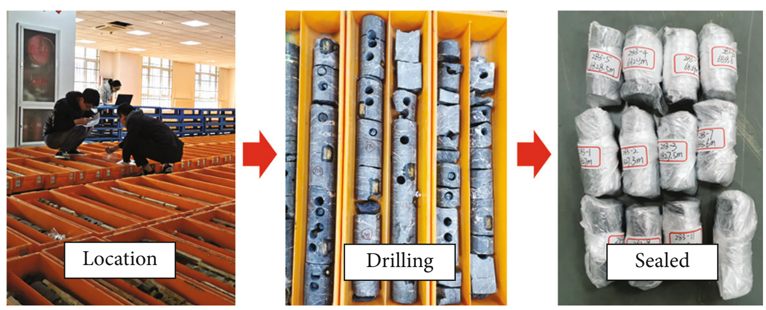


Figure 2: Schematic diagram of the core sampling method of SK-2.

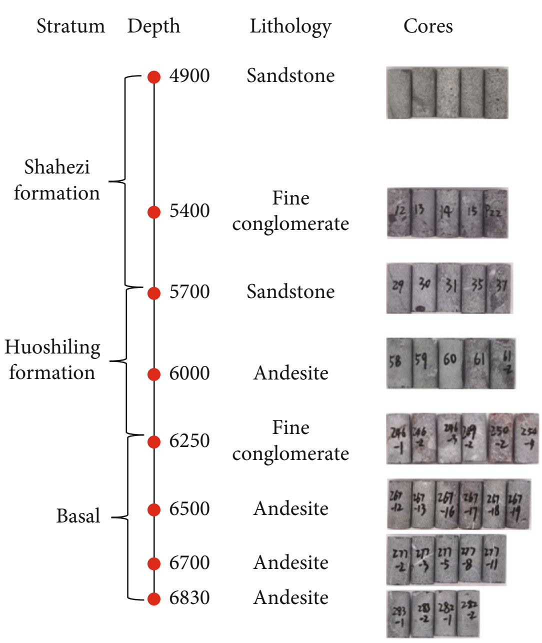


Figure 3: Basic information of deep cores at different depths.

shortcomings, such as shallow depth and nonin situ rock samples, which are difficult to truly reflect the deep rock characteristics [19–24]. At present, there are few tests using deep drilling cores, and most of them are for a certain depth. The obtained physical characteristic parameters are incomplete, which is difficult to reflect the impact of different deep environment on rock properties [25–27]. As the most complete and continuous core drilling in Cretaceous continental strata in the world [28], the deep core obtained by SK-2 is of great research value for studying the physical and mechanical laws of deep rock and guiding deep engineering practice. Some scholars have studied the deep resources, geological evolution, and other information of SK-2 by using logging data [4, 5, 29], but there is little analysis on the physical characteristics of the deep core of SK-2. Lu et al. [30] studied the physical and mechanical laws of rocks at different depths in Songliao Basin, but their rock samples are collected from different wells, and the core depth span is large; so, they did not show a good law in the deep range. Therefore, based on the rocks at different depths of 4900-6830 m in SK-2, this paper carried out the research work including the characteristics of minerals, wave velocity, density, and pores and deeply studied the variation law of rock physical characteristics at different depths of SK-2 with depth, and the relationship characteristics between different physical parameters is explored. Focusing on exploring the laws of deep rock science, this paper provides a reference for deep engineering practice such as deep oil and gas resource development.

2. Deep Core Sampling of SK-2

The SK-2 project provides excellent sample conditions for studying the physical and mechanical characteristics of deep rocks. In order to deeply study the physical characteristics of

Table 1: Mineral composition and relative mass content of rocks at different depths.

Depth (m)	Epidote (%)	Quartz (%)	Potassium feldspar (%)	Plagioclase (%)	Iron dolomite (%)	Calcite (%)	Chlorite (%)	Illite (%)
4900	0.0	19.7	1.8	39.7	0.0	17.1	6.4	15.3
5400	0.0	39.5	0.0	35.1	0.0	0.9	7.9	16.7
5700	0.0	14.2	1.4	61.2	0.0	0.5	8.0	14.7
6000	0.0	23.3	1.1	43.0	0.0	1.8	22.9	7.9
6250	0.0	32.2	0.0	32.5	0.0	7.9	11.9	15.5
6500	11.0	42.9	1.0	19.1	0.0	9.3	11.2	5.5
6700	0.0	24.1	2.2	31.1	0.0	26.9	7.2	8.5
6830	0.0	9.7	6.0	20.1	2.4	19.3	33.3	9.3

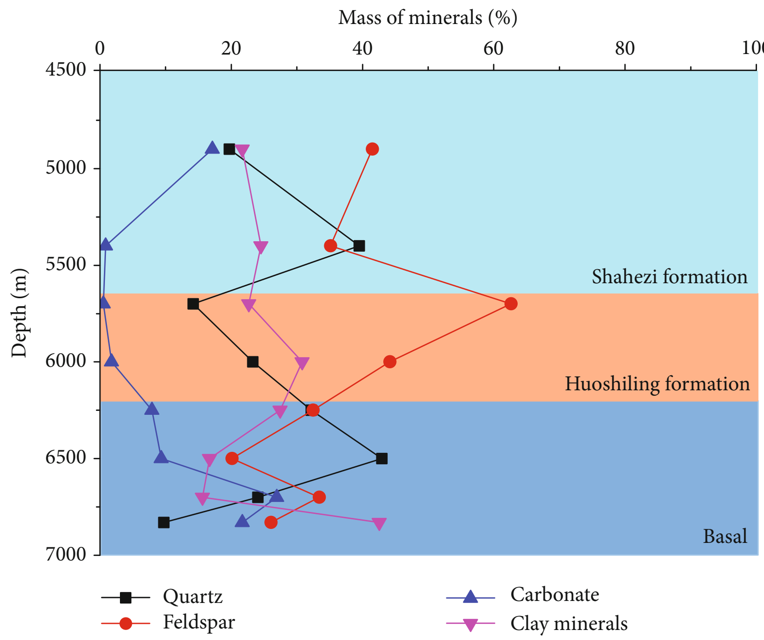


Figure 4: Variation of different minerals with depth.

deep rocks in Songliao Basin, we selected and drilled 8 groups of deep core samples at different depths in the core library of SK-2 for many times based on the lithology histogram, and the buried depths of 8 groups of cores are 4900 m, 5400 m, 5700 m, 6000 m, 6250 m, 6500 m, 6700 m, and 6830 m, respectively. The core drilling direction is perpendicular to the coring rock column. It should be noted that because the coring depth is too deep, the rock column diameter in this depth range is small, and half of the rock column needs to be intercepted in the core warehouse. Therefore, after standardized processing, the core size is ∅20 mm × 40 mm. In order to minimize the damage of weathering to the cores, the cores are quickly wrapped and sealed with fresh-keeping film after drilling from the core string, as shown in Figure 2. Through well logging information and thin section analysis of SK-2, the stratigraphic and lithologic information of cores taken at different depths are obtained, as shown in Figure 3. Within the coring range of 4900-6830 m, the strata include Shahezi Formation, Huoshiling Formation, and Base, and the lithology of core includes sandstone, fine gravel, and andesite.

3. Characteristics of Rock Mineral Composition

3.1. Determination of Mineral Composition. The mineral composition and relative content of rocks are important information for analyzing the physical and mechanical characteristics of rocks. In order to study the mineral composition characteristics of rocks at different depths in SK-2, the mineral composition of deep rocks at different depths in SK-2 is analyzed by X-ray diffraction (XRD). Before the experiment, the rock sample needs to be ground. The experimental instrument is Rigaku Ulima IV X-ray diffractometer, the test voltage is 40 kV, and the current is 40 mA. The test results are shown in Table 1.

3.2. Variation Characteristics of Mineral Composition with Depth. The rocks within the depth range of 4900-6850 m of SK-2 are mainly composed of quartz, potassium feldspar, plagioclase, calcite, chlorite, and illite. In order to deeply analyze the variation characteristics of rock mineral content with depth, the test results are drawn in Figure 4. There are

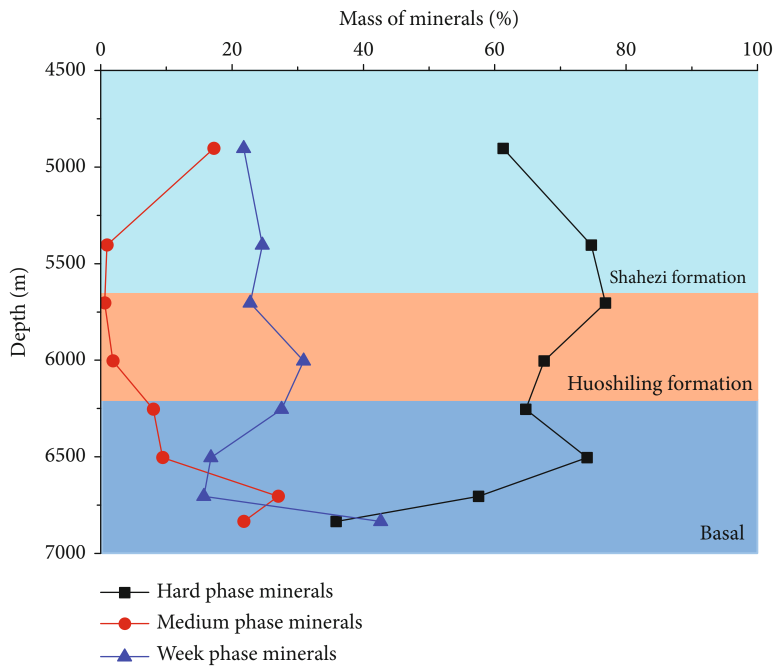


Figure 5: Variation of minerals with different phases with depth.

Table 2: Results of density and wave velocity of rocks at different depths.

Depth (m)	Height (mm)	Diameter (mm)	Quality (g)	Density (kg/m^3)	Average density (kg/m^3)	*P*-wave velocity (m/s)	Average wave velocity (m/s)
	40.20	19.93	32.892	2622.767		4878.05	
4900.00	40.15	20.03	33.395	2639.636	2625.895	5128.21	5089.80
	40.30	20.10	33.44	2615.28		5263.16	
	40.10	20.00	33.15	2631.34		5333.33	
5400.00	40.15	20.06	33.77	2660.91	2644.413	5555.56	5456.11
	40.15	20.05	33.48	2641.00		5479.45	
	40.05	20.05	32.84	2596.98		5000.00	
5700.00	40.00	20.00	32.91	2618.50	2622.634	5194.81	5200.07
	40.20	20.00	33.50	2652.42		5405.41	
	39.95	20.10	34.70	2737.67		5479.45	
6000.0	40.10	20.20	34.84	2711.07	2702.082	5797.10	5691.22
	40.00	20.10	33.73	2657.51		5797.10	
	40.05	20.05	33.74	2668.08		5405.41	
6250.00	40.15	19.90	33.35	2670.79	2668.700	5479.45	5506.22
	40.20	20.00	33.69	2667.23		5633.80	
	40.20	20.00	34.46	2728.76		5882.35	
6500.00	40.05	20.15	34.35	2689.89	2723.566	5633.80	5640.52
	40.00	20.15	35.10	2752.05		5405.41	
	40.20	20.20	34.11	2647.82		5633.80	
6700.00	40.00	20.00	33.50	2665.85	2654.466	5714.29	5687.46
	40.20	20.00	33.46	2649.73		5714.29	
	40.05	20.10	34.37	2704.79		5797.10	
6830.00	40.00	20.10	34.72	2735.74	2707.162	5797.10	5797.10
	40.10	20.20	34.45	2680.96		5797.10	

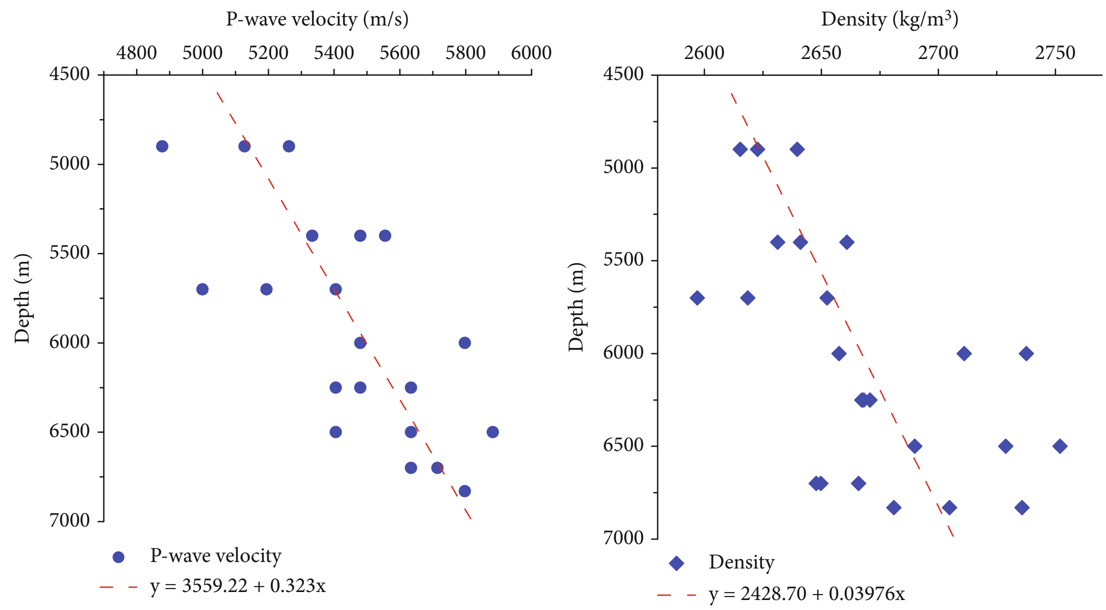


FIGURE 6: Variation of *P*-wave velocity and density with depth of cores at different depths.

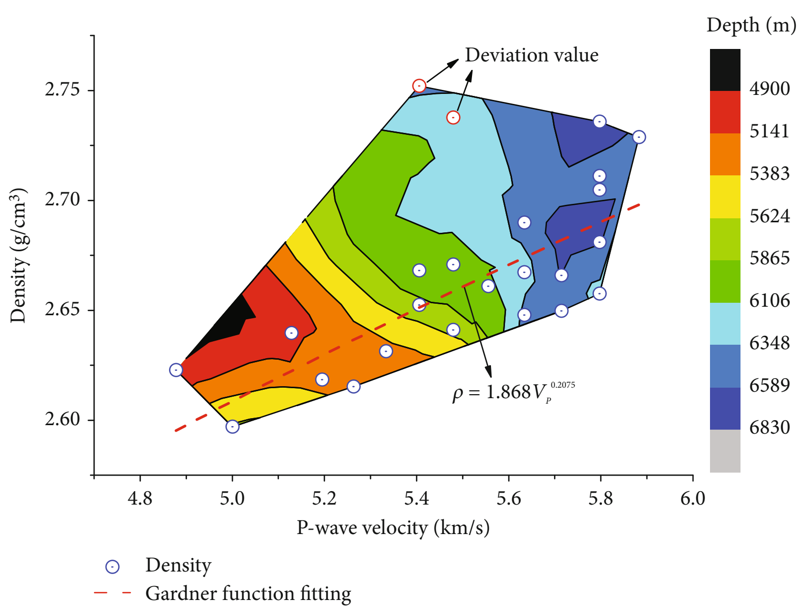


FIGURE 7: Relationship between *P*-wave velocity and density of cores at different depths.

great differences in the relative mineral content of deep rocks in SK-2. With the increase of depth, the content of quartz changes irregularly and discretely. The dispersion of feldspar is also large, but on the whole, it decreases with the increase of depth. The content of carbonate is relatively small, with the increase of depth, and decreases first and then increases. The clay mineral content changes little in the range of 4900-6250 m, basically fluctuating within 20%-30%; after the depth continues to increase, the clay mineral content increases greatly. On the whole, when the depth is less than 6000 m, the content of minerals with different composition varies greatly, the fluctuation range of the curve is also large, and the mass percentage of minerals fluctuates in the range of 0.5%-61.2%. When the depth is more than 6000, the content of minerals with different composition is concentrated in the region, the fluctuation range of the curve is small, and the mass percentage of minerals fluctuates in the range of 7.9%-42.9%. According to the stratigraphic map, the critical depth of 6000 m is very close to the basement of the sedimentary layer in Songliao Basin, and the lithology is mainly igneous rock, which provides some explanations for the variation characteristics of minerals with depth.

Table 3: Dynamic elastic modulus of rock at different depths in SK-2.

Depth/ m	Dynamic elastic modulus/GPa			Average dynamic elastic modulus/ GPa
4900	62.41	69.42	72.45	68.09
5400	74.85	82.13	79.29	78.76
5700	64.92	70.66	77.5	71.03
6000	82.2	91.11	89.31	87.54
6250	77.96	80.19	84.66	80.94
6500	94.42	85.38	80.41	86.74
6700	84.04	87.05	86.52	85.87
6830	90.9	91.94	90.1	90.98

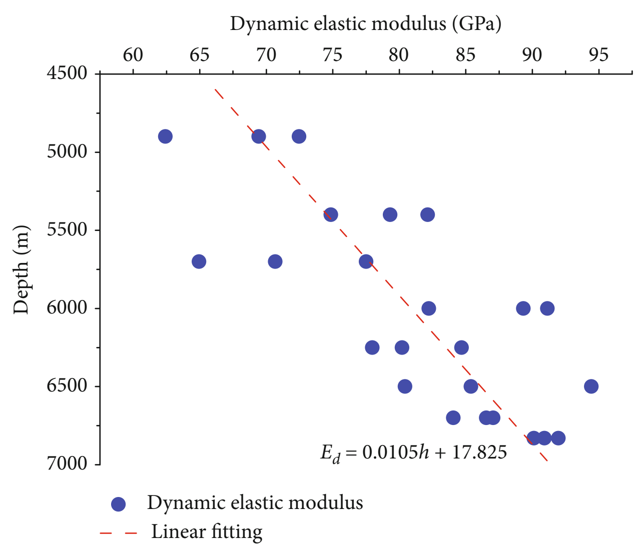


Figure 8: Relation curve between dynamic elastic modulus and depth.

In order to more clearly present the mineral characteristics of rocks at different depths, the constituent minerals of the rocks are further classified, and the constituent minerals are divided into hard phase minerals, medium phase minerals, and weak phase minerals according to the difference of hardness [30]. Hard phase minerals mainly include quartz, feldspar, and pyrite. Medium phase minerals mainly include carbonate minerals, mainly calcite. Weak phase minerals mainly include mica and clay minerals, as shown in Figure 5. On the whole, the content of hard phase minerals in the core of well SK-2 at the depth of 4900-6830 m is the most, and its quality accounts for a large proportion, indicating that the core of SK-2 is hard. The content of medium phase minerals is the least, especially in the range of 5400-6000 m; in the strata of Huoshiling Formation and Shahezi Formation, the mineral content of the three phases remains relatively stable, but after entering the basement, the mineral content of different facies changes obviously, and the mineral content of the three phases tends to be close, which is more consistent with the characteristics of formation lithology. Above the basement is the sedimentary layer of Songliao Basin, and after entering the basement, the lithology becomes igneous rock; so, there is an obvious change in mineral content.

4. Characteristics of Wave Velocity and Density of Rock

4.1. Determination of Wave Velocity and Density. As an important physical property of rock, the acoustic characteristics of rock play an important role in the study of pores, structure, and main mineral types in rock [31, 32]. Among them, the wave velocity of rock elastic wave plays a certain role in the study of physical properties, mechanical properties, and damage degree of samples and is the basic factor to describe rock properties [33, 34]. At present, the measurement methods of elastic wave velocity of rock can be divided into three categories: resonance method, pulse method, and interference method [35]. In order to study the wave velocity characteristics of rock cores at different depths in SK-2, the pulse method is used to study the elastic wave P-wave velocity of rock. The calculation formula of P -wave velocity is shown as Equation (1).

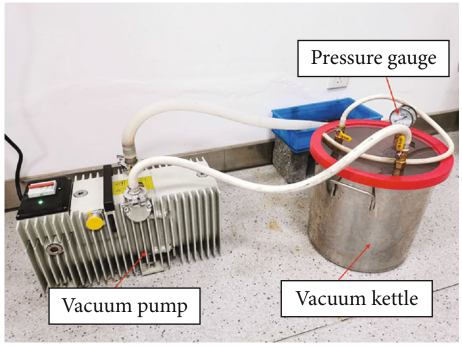
$$V_P = \frac{L}{t}, \tag{1}$$

where V_P is the longitudinal wave velocity, m/s, L is the core length, m, and t is the propagation time of elastic wave in medium, s. The experimental instrument is JAMES ultrasonic testing system of Sichuan University. In order to fully consider the discreteness of the test, three cores are selected for each depth, and vaseline is selected as the coupling agent. The experimental results are shown in Table 2.

It can be seen that the P-wave velocity of rock ranges from 4878.05 to 5882.35 m/s, and the variation range of P-wave velocity of rock core at the same depth is small. The rock density in this depth range ranges from 2596.98 to 2752.05 kg/m^3, and the variation range of the results is relatively large.

4.2. Variation of Wave Velocity and Density with Depth. According to the test results in Table 2, the variation law of P -wave velocity and density with depth is drawn, as shown in Figure 6. In the depth range of 4900-6830 m of SK-2, with the increase of depth, the wave velocity and density of rocks show an increasing trend, which shows that the sedimentary environment of Songliao Basin for hundreds of millions of years has a profound impact on the integrity, compactness, and other overall properties of rocks at different depths. The greater the depth, the denser the rocks are.

The relationship between wave velocity and density of rocks at different depths is shown in Figure 7. It can be seen that there is an obvious positive correlation between wave velocity and density of rocks at different depths, which is consistent with the research results of other scholars [36–38]. In order to further summarize the relationship between rock density and wave velocity at different depths of SK-2, according to the function form of average P-wave velocity and density of various rocks $\rho = \mathrm{A}V_P^B$ (where A and B are fitting coefficients, ρ is the rock density) proposed by Gardner et al. [39], the relationship between rock density



(a) Vacuum saturation device


(b) GeoSpec2 NMR core analysis system

Figure 9: Instruments for measuring porosity by NMR.

Table 4: Porosity measured by the NMR method.

Depth/m	Porosity (%)				Average porosity (%)
4900	2.5	2.5	3	1.3	2.325
5400	2.5	1.7	1	/	1.733
5700	2.2	0.9	1.7	/	1.6
6000	1	1.4	0.4	1	0.95
6250	0.75	0.67	1.1	/	0.84
6500	0.34	0.95	0.93	/	0.74
6700	0.82	0.75	1.2	0.43	0.8
6830	0.52	1.2	0.4	/	0.707

Table 5: Porosity measured by the water saturated drying method.

Depth/m	Porosity (%)			Average porosity (%)
4900	1.98	1.78	1.07	1.61
5400	1.44	0.91	1.11	1.15
5700	1.75	0.76	0.89	1.13
6000	0.92	0.62	0.55	0.7
6250	0.89	0.54	0.51	0.65
6500	0.54	0.75	0.67	0.65
6700	0.61	0.64	0.68	0.64
6830	0.76	0.61	0.52	0.63

and wave velocity at different depths of SK-2 is statistically fitted. The fitting results are shown in Figure 7 and Equation (2).

$$\rho = 1.868 V_P^{0.2075}. \tag{2}$$

The unit of longitudinal wave velocity is km/s, and the unit of density is g/cm^3.

4.3. Dynamic Elastic Modulus Analysis. Dynamic elastic modulus is also one of the basic mechanical parameters to describe rock strength [40], which can be obtained by measuring the propagation velocity of ultrasonic in rock samples in the laboratory. Dynamic elastic modulus refers to the ratio of stress and strain of rock under dynamic load. It is equivalent to the elastic modulus when the stress is close to zero on the stress-strain curve. Therefore, dynamic elastic modulus is also called "initial tangent modulus." The dynamic elastic modulus can be approximately solved by the dry density and longitudinal wave velocity of rock [41]. In this method, the dynamic elastic modulus is used to replace the bulk modulus in Gassmann equation, and the obtained dynamic elastic modulus is approximately equal to the product of the square of rock dry density and longitudinal wave velocity. The specific calculation formula is shown in Equation (3).

$$E_d = \rho V_P^2, \tag{3}$$

where E_d is the dynamic elastic modulus, Pa, ρ is the dry density, kg/m^3, and V_P is the longitudinal wave velocity, m/s. The dynamic elastic modulus is directly proportional to the dry density and the square of the longitudinal wave velocity. The calculation results of the dynamic elastic modulus of cores at different depths are shown in Table 3.

The dynamic elastic modulus of rocks within 4900-6830 m of SK-2 is 62.41-94.42 GPa. The relationship between dynamic elastic modulus and depth is drawn in Figure 8. The dynamic elastic modulus of rocks in the deep part of SK-2 has a good linear relationship with depth, and the deeper the buried depth of rocks, the greater the dynamic elastic modulus.

5. Pore Characteristics of Rock

As a natural porous material, there are a large number of irregular and multiscale pores in rock, which will directly affect the macrophysical, mechanical, and chemical properties of rock, and have important reference value for the research of deep scientific laws and the development of deep resources [42–44]. In order to study the pore characteristics of cores at different depths in SK-2, the pore characteristics of cores at different depths are measured by the nuclear magnetic resonance (NMR) method and saturated drying method, respectively, and the variation law of pores with depth is analyzed.

5.1. Determination of Porosity. The principle of determining porosity by NMR is to measure the relaxation characteristics of hydrogen containing fluid in pores; therefore, the core needs to be saturated before NMR test. The specific

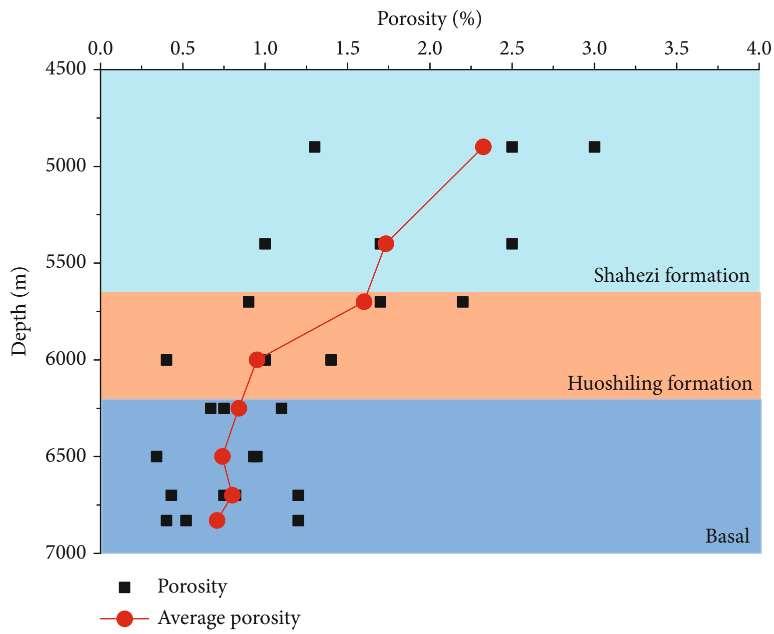


Figure 10: The porosity measured by NMR varies with depth.

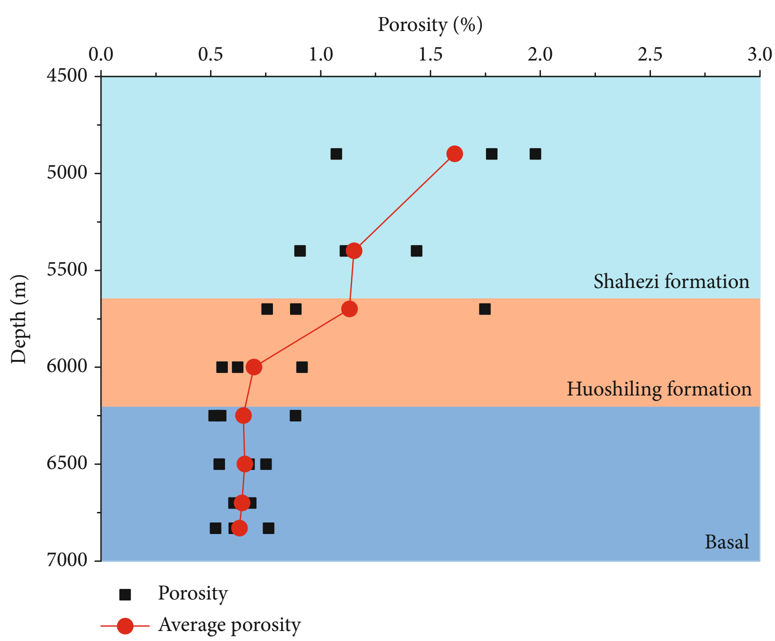


Figure 11: The porosity measured by the saturated drying method changes with depth.

operations are as follows: put the core into the vacuum kettle, vacuum it for 4 hours, inject water into the vacuum kettle, continue to vacuum for 4 hours, and finally stand for 6 hours to make the core gap full of water. During the experiment, take out the core to be tested one by one, quickly wipe the water droplets on the surface with absorbent paper, and put the core into the test chamber for testing. In order to fully consider the discreteness of core test results at different depths, 3-4 cores are selected for NMR at each depth. The NMR instrument in this study is GeoSpec2 NMR core analysis system of Sichuan University, using a probe with a diameter of 53 mm, as shown in Figure 9.

The test results are shown in Table 4, and the test results are averaged.

In order to further compare and verify the porosity measured by NMR, the porosity is measured again by using the above water saturated core. After the water saturation is completed, take out the core one by one, quickly wipe off the water droplets on the surface with absorbent paper and weigh to obtain the mass of the water saturated core m_s, then

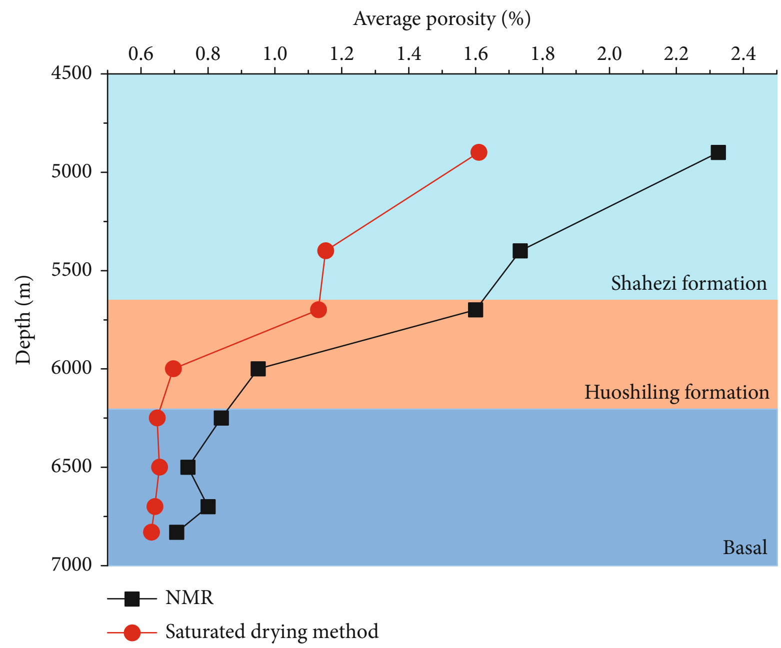


Figure 12: Comparison of porosity curves measured by NMR and saturated drying method.

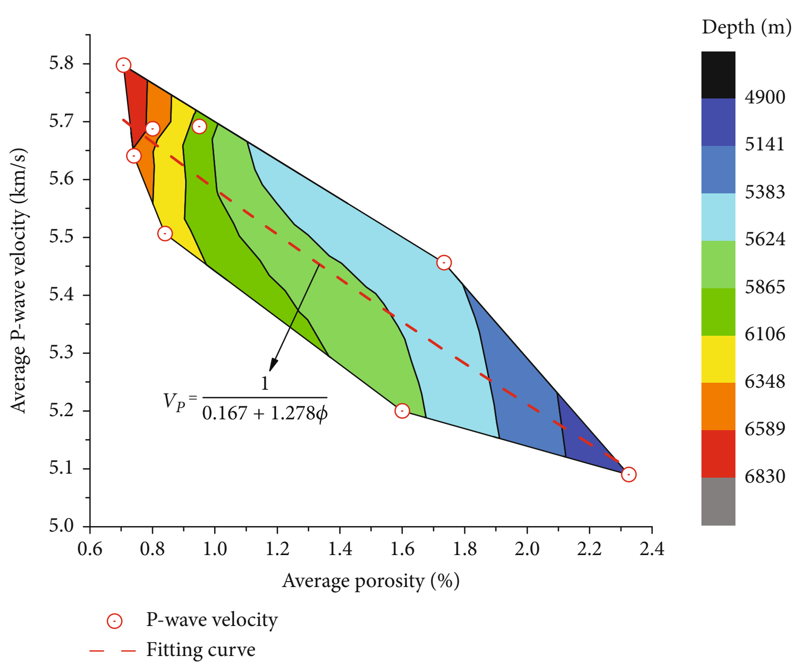


Figure 13: Fitting curve between wave velocity and porosity.

put the water saturated core into the dryer, dry it at 105°C for 12 h and cool it naturally according to the procedures, and weigh again to obtain the mass m_d of the dried core. Combined with the volume of the core v and the density of water ρ_w, the water saturated drying porosity of the core ϕ_{sd} can be obtained as Equation (4):

$$\phi_{sd} = \frac{m_s - m_d}{\rho_w v}. \tag{4}$$

The test results are shown in Table 5, and the core test results at each depth are averaged.

5.2. Variation Characteristics of Porosity with Depth. In order to analyze the variation characteristics of core porosity with depth in SK-2, the porosity test results in Tables 4 and 5 are plotted, as shown in Figures 10–12. Although the test results of the two methods have some differences, the porosity measured by the two methods has the same change trend with the change of depth. In the depth range of 4900-

6830 m, the porosity of SK-2 generally decreases with the increase of buried depth. In the range of 4900-6000 m, with the increase of depth, the gradient of core porosity decreases greatly, and the measured values of porosity at the same depth are discrete. In the range of 6000-6830 m, with the increase of depth, the change gradient of core porosity is small, the porosity in this range tends to be close to a constant value of 7%, and the dispersion of measured rock porosity at this depth is small. Quantitatively compare the results of nuclear magnetic resonance and water saturated drying. As shown in Figure 12, it is found that the porosity measured by NMR is greater than that measured by the water saturated drying method, which shows that the nuclear magnetic resonance method has better accuracy in porosity measurement.

It can be seen that the change of rock porosity at the buried depth of 6000 meters is a critical depth, and the reason can be analyzed from the perspective of stratum and lithology. As shown in Figure 3, the shallow part of 6000 m is mainly Shahezi Formation and Huoshiling Formation, the lithology of the core is mainly clastic rock, and there are many multiscale pores between mineral particles, which lead to the large dispersion of measured porosity in different cores at the same depth. The porosity of clastic rock in this depth range is mainly controlled by the depth, and the deeper the depth, the more serious the compaction effect caused by geological deposition, the denser the rock, and the smaller the porosity. The rock stratum with a depth of more than 6000 m is mainly the Base Formation, and the lithology of the core is mainly andesite, belonging to the category of igneous rock. The rocks in this range are less affected by sedimentation, and the rock itself is relatively dense, which leads to small core porosity at this depth, little change with depth, and small dispersion of core porosity at the same depth.

5.3. Relationship between Porosity and Wave Velocity. In order to analyze the relationship between porosity and wave velocity of rocks at different depths in SK-2, the data of porosity and wave velocity are drawn in the figure. Since the porosity obtained by NMR is more accurate in the above analysis, the porosity obtained by NMR is used for analysis and research.

Wyllie et al. [45] give the time average equation of wave velocity and porosity by measuring water saturated rock and consolidated rock as Equation (5):

$$\frac{1}{V_P} = \frac{\phi}{V_F} + \frac{1-\phi}{V_R}, \tag{5}$$

where V_P, V_F, and V_R represent the P-wave of rock, pore fluid, and minerals of rock, respectively. On this basis, Domenico [46] proposed a regression formula between velocity and porosity according to the laboratory measurement results: $1/V_P = A + B\phi$, where A and B are constants, and the unit of longitudinal wave velocity is km/s. Based on the empirical formula, the data of wave velocity and porosity are empirically fitted, and the depth information of the core is reflected by the original drawing, as shown in Figure 13. It can be seen that the wave velocity of rocks at different depths of SK-2 is inversely proportional to the porosity, and the specific fitting formula is as Equation (6):

$$V_P = \frac{1}{0.167 + 1.278\phi}. \tag{6}$$

With the increase of buried depth, the porosity of deep core of SK-2 well decreases, and the corresponding P-wave velocity increases significantly. Due to the geological sedimentation and other tectonic processes in Songliao Basin, in general, the deeper the rock is buried, the better the rock integrity, the fewer the internal joint pores, and the smaller the pore reduction effect received when the elastic wave propagates in the rock. Therefore, the faster the P-wave velocity propagates in the deeper rock.

6. Conclusions

Based on the deep rocks at different depths of 4900-6830 m in SK-2, this paper carried out the research work on the characteristics of deep rocks including mineral, wave velocity, density, and pore, the variation law of deep rock physical characteristics with depth is studied, and the relationship characteristics between different physical parameters are explored. The conclusions are as follows.

(1) In the cores of SK-2 at the depth of 4900-6830 m, the content of hard phase minerals is the most, and the quality accounts for a large proportion, which indicates that the cores of SK-2 are hard. The content of medium phase minerals is the least. In Huoshiling Formation and Shahezi Formation, the mineral contents of the three phases maintain relatively stable, but after entering the basement igneous rock formation, the mineral contents of different phases change obviously, and the mineral contents of the three phases tend to be close

(2) In the depth range of 4900-6830 m of SK-2, the wave velocity and density of rock increase linearly with the increase of depth. The relationship between density and wave velocity is fitted based on Gardner empirical formula, and the fitting formula is $\rho = 1.868\ V_P^{0.2075}$. The dynamic elastic modulus of deep rock in SK-2 has a good linear relationship with depth, and the deeper the rock is buried, the greater the dynamic elastic modulus is

(3) The NMR method and saturated drying method are used to determine the porosity of rocks at different depths of SK-2. It is found that the porosity generally decreases with the increase of buried depth in the depth range of 4900-6830 m. In the range of 6000-6830 m, the change gradient of core porosity is small with the increase of depth, the porosity in this range tends to a constant value of 7%, and it shows that formation compaction has little effect on the pore development of igneous rock in this formation

(4) With the increase of buried depth, the porosity of the deep core of SK-2 decreases, and the corresponding P-wave velocity increases significantly. The inverse proportional function relationship between the wave velocity and porosity of rocks at different depths of SK-2 is fitted by using the empirical formula. The specific fitting formula is $V_P = 1/0.167 + 1.278\phi$

Data Availability

The test data used to support the findings of this study are included within the article. Readers can obtain data supporting the research results from the test data table in the paper.

Conflicts of Interest

The authors declare no conflict of interest.

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