Analysis of Cuttings’ Minerals for Multistage Hydraulic Fracturing Optimization in Volcanic Rocks

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ABSTRACT: The fracturing of naturally fractured volcanic rocks has a significant impact on the logging due to the high degree of volcanic fracture development and the complex distribution of fractures. Such impact ultimately leads to the difficulty in determining the location of fracturing perforations and the increase in engineering costs. This article proposed a method of analyzing cuttings for geologging that return to the ground when drilling. After cleaning and further processing of the cuttings, samples at every depth are formed. Then, an electron microscope and supporting processing software are used to calculate the parameters of the sample at each depth and the rock mechanical parameters in the target well section based on the mineral content. Compared with mud logging data, the mineral analysis method of rock cuttings costs less time, and the materials are easier to obtain, thereby providing richer data. This method has an important guiding role for the selection of perforation positions in large-scale hydraulic fracturing.

1. INTRODUCTION

Since the discovery of the world’s first volcanic reservoir in the United States in 1887, the extreme properties of volcanic reservoirs have attracted countless researchers. The Interior Coastal Plain reservoir and Thrall field in the United States; Bacuranao and Motembo fields in Cuba; Furfaro Gabbron reservoir in Mexico; Minami Nagaoka gas field in Japan; Akita, Niigata, and Neuquén basins in Argentina’s Austral; and Browse basin in Australia are early discovered volcanic reservoirs that have been adequately studied by scientists around the world.

Volcanic reservoirs were discovered by chance in their early stages of development. China has been exploring volcanic reservoirs for more than 50 years. In 1957, China obtained industrial oil flow for the first time from volcanic rocks in the Junggar Basin. However, due to the limitations of mining technology, global volcanic rock research has entered a period of calm. After the 1980s, volcanic reservoirs were not limited to accidental discoveries. People began to explore volcanic reservoirs on purpose. In the 21st century, with the gradual improvement of unconventional oil and gas resource development technology, volcanic reservoirs have entered their maturity stage in terms of development.

The distribution of the pores in volcanic reservoirs is extraordinarily complicated and usually irregular. The change of rock mechanical parameters is generally related to the components of volcanic materials. Lithology has a much more significant impact on physical parameters than the reservoir environment. The fracture environment of volcanic rocks is also complicated. The main natural fractures formed by diagenesis are generally filled with minerals, and the component of the secondary fractures’ minerals is the critical factor that determines whether the interval can become a reservoir. Therefore, it is essential to analyze the mineral components of volcanic rocks.

The identification and evaluation of fractures in volcanic reservoirs rely heavily on logging data. At the same time, due to the heterogeneity of volcanic rock fractures, volcanic reservoirs cannot be dynamically interpreted by a single log data. Volcanic reservoir prediction is carried out in combination with wave impedance inversion. The distribution law of the target layer has been studied using three-dimensional (3D) seismic data. The principle of resonance oil and gas monitoring has been analyzed. The acoustic curve has been reconstructed. Many calculation methods using seismic feature modeling and inversion have been studied.

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determine the need for more studies on the identification and evaluation of rock mechanical parameters.

In the related research of hydraulic fracture initiation and expansion models, many scholars have carried out physical experiments and numerical simulation studies, including the use of large-scale triaxial experiments for the simulation of crack propagation during multistage fracturing to study the various types of fractures that may exist in sandstone reservoirs. Large-scale physical simulation experiments can consider the influence of various engineering factors on fracture morphology, but there are many problems in physical simulation experiments to study the influence of geological conditions on fractures. The study of numerical simulation can analyze the difference in fracture morphology such as fracture length and fracture height under different geological conditions, such as the law of expansion and the formation conditions of fracture network. These physical simulation experiments and numerical simulation models have very strict requirements on basic rock parameters. In rock foundation properties, brittleness is an important feature, which is related to many mechanical properties of rock. To provide a theoretical basis for hydraulic fracturing design and perforation location selection, there are many evaluation methods for rock brittleness. \( L. \)\(^{28} \) conducted brittleness evaluation experiments for various rocks. He conducted a series of uniaxial compression tests using coal rock, shale, and tight sandstone to evaluate the brittleness evaluation methods of different rocks. Combined with physical simulation experiments and numerical simulation models, it enriches the research methods of rock brittleness.

In the past few years, the multistage fracturing technique of horizontal wells has made a series of significant breakthroughs in fracturing tools, operational efficiency, and monitoring methods. Still, some problems, such as the selection of preferred fracturing intervals, tracking of pressure sweet spot, and optimization of fracturing design, were present.\(^{29} \) The multistage fracturing technique of horizontal wells aims to fracture more sections accurately. If every stage of fracturing affects the production zone, this technique will be revolutionary. It will considerably reduce costs and improve efficiency. Mud logging and well logging data are critical for oil and gas exploration and development. However, wireline logging tools are expensive and can be damaged or fall into wells.

The application of elemental-mineral transformation analysis is a comprehensive technology used in geology.\(^{30−34} \) The rock cutting analysis technology (RoqScan cuttings’ analysis system)\(^{29,30} \) that is based on elemental-mineral transformation has been proposed by the CGG company from the United States. This technology provides the possibility of analysis while drilling.\(^{35−37} \) Using this technology, field tests have been successfully implemented in various oil fields around the world, such as Bakken Shale, Barnett Shale, Haynesville Shale in Northwest Louisiana, Southern Powder River Basin in Wyoming, Marcellus Shale, and Cauvery Basin in Southern India.\(^{34} \)

The proposed method can scan and analyze a batch of samples (up to 9) every 6 h on average or 2 h for the analysis of a single sample. The data of the corresponding depth of the sample are obtained. Compared with the traditional electron microscope scanning sample processing process, the time is greatly shortened. Rock mechanical parameters at the latest depth can help drilling control. For example, they help determine the wellbore trajectory and drilling speed. The proposed method can provide an efficient and fast auxiliary judgment when it encounters complex drilling conditions (such as drilling stuck). Moreover, not all old wells have electrical measurements. Therefore, an alternative method is needed to obtain the necessary data for the petrophysical model. Lithology can be rapidly and accurately identified by analyzing the elemental-mineral components of cuttings. In this article, a method for mineral content analyses based on cutting scanning was used. The basic rock mechanical parameters of the target zones were calculated based on mineral volume content, which provided a new method for selecting perforation intervals in volcanic rocks. Compared with mud and well logging data, the results were better.

This article adopted a new method, the rock cutting mineral analysis onsite evaluation technology, for real-time evaluation of reservoir fundamental physical parameters. This method can be directly used in the field drilling process to achieve real-time testing and to evaluate formation physical parameters.

The rock mechanical parameters measured in the laboratory have weak continuity. Obtaining continuous rock mechanical parameters is difficult in the reservoir. Logging calculation of the rock mechanical parameters relies too much on the acoustic time difference data of the reservoir. At present, the general practice of horizontal wells in oil fields is only to measure P-wave data, after which S-wave data are inverted according to empirical formulas. Then, rock mechanical calculations are performed. The use of empirical formulas has great limitations due to block differences, resulting in large errors in logging the interpretation of rock mechanical performance data.

The cutting mineral analysis technology is composed of scanning electron microscopy (SEM), energy-dispersive spectroscopy (EDS), and evaluation software, by which the formation cuttings recorded on the surface during drilling are scanned, tested, and analyzed, respectively.

Then, quantitative rock mechanical data, such as mineral content, P-wave velocity, bulk density, and Young’s modulus, can be obtained. The following models can be established: wellbore rock mechanical, micropore structure, and mineral content models. The premise is that the model will be corrected by the wells adjacent to the target well, which makes the model suitable for the geological characteristics of the block and the output data reliable. The cuttings were collected while drilling, and the mineral element composition and content were obtained by scanning. They were input into the wellbore rock mechanical model, and the P-wave velocity and the rock mechanical data, such as brittleness index, Poisson’s ratio, and Young’s modulus, were inverted. The inversion curve can be simulated in real time, and the data curve can be provided at any time needed. The accuracy depends on the sampling interval of cuttings, which can be intensively analyzed at any time to improve the accuracy of the curve.

2. RESULTS AND DISCUSSION

2.1. Results. Cuttings’ mineral analysis technique can obtain the mineral and geological information of wells in a short time. Through the quantitative analysis of cuttings’ components, the elemental parameters of the target zone, such as pore size, pore throat ratio, petrophysical properties, and chemical properties, can be better understood. Through continuous sampling of the target zone, a total of 484 groups of cutting samples were collected and analyzed. Six groups of samples scanned by an electron microscope were taken as examples and are shown in Figure 1. The picture on the left is a basic scan of cuttings in the scanning electron microscope. The areas marked in purple are automatically identified fractures and pores. The
picture on the right is a picture of the result of the mineral distribution identified by backscattered electron scanning. The mineral composition is identified by different colors.

The obtained mineral data was compared and corrected with the data collected by the logging while drilling equipment, and the mineral and geological components were analyzed by the CGG RoqScan analysis system (Figure 2). According to the weakness index (WI) and other mineral properties, including Young’s modulus (YM) and Poisson’s ratio (PR), the perforated interval was recommended.

In terms of metal element content, the contents of aluminum and iron are higher than other elements. Among the minerals, the content of quartz is higher (approximately 45%) than other minerals. The content of plagioclase is between 20 and 30%. The content of montmorillonite fluctuates greatly in the range from 16.8 to 60%.

The percentage of mineral content is of great significance for judging formation lithology, rock mechanical properties of the whole well section, and the subsequent hydraulic fracturing design. In experimental wells, higher brittle mineral content indicates stronger brittleness and higher clay mineral content increases the plasticity.

Therefore, the percentage stacking chart of the mineral composition of the whole well section can intuitively show the high brittleness section and the high plasticity section of the well. The average content of brittle minerals in the whole section is 51.61%, and the average content of clay minerals is 40.69%. The difference in plasticity indicates that even for the same type of volcanic lithology, the mineral content changes in the same well are complex, the brittleness fluctuation is relatively strong, and the reservoir has great heterogeneity (Table 1).

| category       | name              | range   | avg   |
|----------------|-------------------|---------|-------|
| brittle mineral| quartz            | 5.92−51.18 | 25.04 |
|                | potash feldspar   | 0−4.34  | 0.28  |
|                | plagioclase       | 2.11−41.72 | 19.78 |
|                | calcite           | 1.78−13.79 | 6.79  |
| clay mineral   | mixed clay        | 4.75−60.65 | 29.34 |
|                | calcium clay      | 0.90−9.93  | 4.87  |
|                | kaolinite         | 0.81−21.65  | 6.48  |

WI expresses the probability of rock crushing and is an indicator that characterizes the perforation interval in fracturing. A low WI leads to low energy required for rock fracturing. Thus, rocks are more likely to be fractured. Different from the brittleness index (BI), YM, and PR, WI takes the characteristics of most minerals into consideration rather than those of a single mineral. At the same time, according to the comprehensive calculation of YM and PR of different minerals, combined with pores and fractures obtained, the values obtained can adequately describe the strength, elastoplasticity, and other rock mechanical parameters. Therefore, WI as a critical parameter of the cuttings’ mineral analysis technique is superior to other parameters that characterize rock fracture capability.

The calculation of rock mechanical parameters is based on the mineral content, and the weighted calculation is based on the influence of different mineral contents on the rock mechanical parameters, and then through the iterative correction of other similar wells in the area, using the algorithm to modify the rock mechanical parameters. The calculated rock mechanical parameters calculated by inversion are shown in Figure 3a. The calculation of the BI is shown in Figure 3b.

The curve in Figure 3 shows that the YM of the horizontal section of this well is between 30 and 70 GPa. There are obvious changes at depths such as 1560, 1740, 1800, 1980, 2040, 2160,
2280, and 2370 m, indicating the great variation of the surrounding hardness of these sections. The variation of PR is small (approximately 0.2–0.25).

Conventional logging is a method often used in processing development wells. Generally, nine curves are measured. Three lithological curves, natural $\gamma$, natural potential, and well diameter curves. The method of measuring the natural potential difference that exists naturally in the formation is called natural potential logging. The method of measuring the radioactive intensity of the formation is called natural $\gamma$ logging. Three resistivity curves are shallow, medium, and deep resistivity curves. Resistivity logging is to put a common electrode system (composed of three electrodes) into the well and measure the curve of rock resistivity change in the well. Three pore characteristic curves are acoustic wave, neutron, and density curves. Acoustic logging is to put a controlled acoustic vibration source into the well. The acoustic wave emitted by the acoustic source causes the vibration of the surrounding particles and generates acoustic waves in the formation. When the nature of the rock changes, the acoustic curve also changes. Neutron logging is the direct measurement of the density of thermal neutrons and superthermal neutrons in underground formations with neutron detectors. It can record the curve of porosity with depth. Density logging is a method for detecting lithology and rock density through the absorption of $\gamma$ rays by different strata. Through technical analysis and application of cuttings in the horizontal section of the well, a geological model suitable for the

Figure 3. (a) YM and PR according to depth and (b) BI to depth.

Figure 4. Two ways to interpret the formation.
mainly include two aspects as follows:

1. Data obtained from the elemental minerals of rock debris reflect the characteristics of rocks at several consecutive points, and logging is a comprehensive analysis of the characteristics of rocks and fractures within a certain depth near the wellbore.
2. The influence of fluids in rock pores is particularly sensitive to formation gas. Even if the formation gas content is only 5%, a significant change in the P-wave velocity curve occurs.

The BI is calculated as 43.22. The change of the BI with well depth is shown in Figure 5a. The red part is high, and the blue part is low.

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The inversion calculation can obtain the wave longitudinal and transverse wave velocity of the rock, which are converted into the acoustic time difference and compared with the logging acoustic time difference. The secondary rock-crack number is compared in Figure 5b.

According to Yin Shuai’s research in the western Sichuan region, the wave velocity ratio can effectively distinguish the strength of fractures. With the generation of microfractures, the wave velocity ratio increases abnormally. Moreover, either an increase in the wave velocity ratio or a decrease in the shear wave velocity can provide a certain indicator for the development of microfractures.

The P-wave velocities are converted into sonic time difference, and the results are consistent with the sonic time difference obtained from well logging. The reasons for the high difference between the two positions at 2226 m and other places mainly include two aspects as follows:

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If the value in the logging curve is significantly larger than that in the mineral analysis curve, then the main crack develops. If the microcrack development is good at the same time, then the secondary crack easily forms a large-scale seam network. If the overlogging curve approximates the mineral analysis curve, then the main crack in this section is similar to the development of the secondary crack. It is necessary to induce communication as possible between the main crack and the secondary crack. If the value in the log curve is smaller than that of the mineral analysis curve, then only the secondary crack develops in this section, and no induced channel is present. In the fracturing, if the fracture network wants to develop fully, dense perforation is required.

With the support of gas and oil logging data and pore and fracture data, 32 recommended perforation intervals (fracturing layer) are selected in the target zones, and two schemes are proposed as follows:

1. 60−70 m spacing: it is recommended to perforate 13 intervals.
2. 20−30 m spacing: it is recommended to perforate 32 intervals.

Finally, through comparison, the second scheme was selected. Mud logging data also matches the second scheme. Then, considering adjacent wells, 32 intervals were proposed to be perforated. Figure 6 shows the results.

2.2. Discussion. In this part, we focus on how the recommended perforation points are chosen. RoqScan technology establishes the rock mechanics model of the wellbore and corrects the model by the adjacent well to make it suitable for the geological characteristics of the block. After entering the necessary data, a complete system that reflects the microscopic pore structure can be obtained, which is conducive in optimizing the horizontal well. The optimization of the clustered perforation position of the segment means that the perforation is considered comprehensively at the position where the porosity is high, the fracture is developed, the brittleness index is high, and the oil and gas display effect is good.

With the support of RoqScan analysis technology, the mineral content, microscopic pore structure, and rock mechanical parameters of the reservoir can be more comprehensively understood, so that more geological characteristics of the target layer can be mastered during the fracturing design process.
According to this technology, the fracturing points provided can effectively communicate the natural fractures, improve the permeability in the near-well zone, and effectively improve the irrationality of the average segmentation due to the heterogeneity of the formation in the horizontal well section. The problem of partial fracturing caused by the average fracturing of horizontal wells is solved. According to the data provided by the cutting analysis technology, this well uses slickwater as the fracturing construction fluid, it reduces the damage to the formation, and solves the problem of construction fluid backflow. At the same time, a small amount or no proppant fracturing also saves cost, which is in line with cost reduction and efficiency increase.

2.2.1. Well Depth from 1500 to 1920 m. From 1500 to 1920 m, the YM of the formation fluctuates greatly, but the value over this part is low.

Comparing the two AC curves, the abnormal section is from 1600 to 1700 m. The value in the logging AC curve is smaller than that from the mineral analysis. AC logging has a strong response to the main fractures. Thus, AC logging has great limitations in a complicated fractured reservoir. Correct identification of the specific development of the fracture is impossible. The cuttings’ mineral analysis makes up for the shortcomings of AC logging in fractured reservoirs. By combining them, the secondary fractures from 1600 to 1700 m are well distributed. YM fluctuates drastically, indicating that the heterogeneity is intense. At the same time, the YM is generally small, indicating that the section is affected by secondary fractures and that the rock is more plastic. Communication between the main fracture and natural fractures is easy in hydraulic fracturing. The compound fracture network cannot be opened due to the strong plasticity of the reservoir and the microcracks, thereby forming a main fracture to communicate multiple natural fractures. Controlling the height is not easy. Therefore, in this section, the perforations should be as few as possible. In the final design, the maximum spacing of 30 m is used from 1600 m. The perforation is in three sections, namely, 1600, 1631, and 1663 m, to avoid wasting fracturing energy here.

From 1670 to 1750 m, the YM and the BI of the reservoir increase, indicating that the reservoir fragility is good. At the same time, the two AC curves are highly coincident. Considering the number of secondary fractures, the development of main and secondary fractures can form a complex joint net through an intelligent design, increase the scale of fracturing on a large scale, and improve the efficiency. Therefore, at 1663, 1685, 1705, 1729, and 1753 m, the minimum perforation space of 20 m is selected.

From 1750 to 1920 m, similar to the case from 1600 to 1700 m, the secondary fractures are well developed, and the perforation distance is supposed to be 30 m. Perforation is at five depths, namely, 1786, 1820, 1848, 1885, and 1922 m.

2.2.2. Well Depth from 1920 to 2464 m. Between 1920 and 2050 m, the two-stage fractures of the reservoir are widely developed, making it easy to form complex fracture networks. After 2050 m, the secondary fractures in the reservoir are significantly reduced, and the YM is increased. However, after analyzing the BI curve, the BI curve will not be increased because it is derived from the cuttings’ analysis. However, the logging curve is affected by the main fracture. Thus, the BI of the cuttings’ mineral analysis is closer to the brittleness of the bedrock itself, rather than the brittleness of the whole reservoir.

For the fractured reservoir, the study of the natural fracture distribution pattern is more important. The critical point is that two different ways for comparison are present, thereby possibly improving the awareness of the reservoir.

From 2150 m, the value in the logging AC curve is larger than the mineral analysis AC curve, indicating that the main fracture is developed in the last 300 m section. When fracturing started, the high-permeability main fracture continues to lose fluid. Forming a sand block is easy in the early stage of fracturing. The liquid in the artificial fracture flows to the natural fractures. Thus, the proppant remains in the slit, and this phenomenon has a negative effect on the fracturing treatment. Therefore, the fracturing scheme’s design needs to be fully prepared. Water slug injection and temporary blocking fracturing are good choices.

3. CONCLUSIONS

A cost-effective and convenient method is proposed to design a fracturing treatment using cuttings’ mineral analysis techniques. This approach is applicable for almost all geological conditions and can provide complete data, thereby providing tremendous data support for follow-up work. From the construction of this well, cuttings’ mineral analysis technique matches well with mud and well logging techniques. Cuttings’ mineral analysis technique is also a useful supplement for future oil field development strategies.

The construction of the well demonstrates the feasibility and effectiveness of using elemental-mineral formation evaluation techniques to optimize the perforation interval during fracturing. The optimized fracturing scheme is feasible and reliable. Based on the geological and mineral analyses of the target well and its adjacent wells and combined with logging data, the critical parameters and fracturing optimization of each horizon could be determined, thereby meeting the requirements of formation heterogeneity and conforming to the integration principle of fracturing design. Thus, the value of fracturing operations is maximized.

Based on the analyses of the 484 samples collected in horizontal sections, 32 perforation intervals are determined according to the mineral analyses. The reliability of the elemental-mineral formation evaluation technique is verified by comparing logging data.

The fracturing characteristics of rocks are related to their WI. Therefore, the selection of the perforation interval is based on the BI or WI. WI has particular guiding significance for fracturing construction, which can be verified in practice.
Through the actual evaluation of the studied well, the mineral properties can be more intuitively analyzed using the cuttings’ mineral analysis technique, including the content of different clay minerals. This approach is much more meaningful to drilling construction and subsequent construction than well and mud logging.

Elemental-mineral analysis technology is very effective as a supplement to logging. However, the technology itself has a lot of interference. For example, cuttings analysis cannot reflect the effects of natural cracks and impurities in cuttings on the analysis results. In general, the elemental-mineral analysis provides a more accurate trend of variation across the entire well. The approach can provide technical support for onsite construction from a microlevel. This technology provides exceptionally comprehensive data, but accuracy needs to be improved.

Based on the logging debris analysis and RoqScan technology, wellbore rock mechanical, micropore structure, and rock mineral composition models are established. The rock brittleness and pore and microfracture development area are preferred as the initiation point that guides the horizontal well fracturing segmentation to achieve precise point fracturing and achieve good results.

1. Establish the rock mechanics model of the well. Data inversion results show that the elastic modulus of the well is 51.9 GPa on average, and the Poisson’s ratio is 0.22 on average. The micropore structure model is established with an average face ratio of 0.71 and an average porosity of 2.59%. In the establishment of a model of rock mineral composition, the quartz content in the horizontal well section is relatively high (approximately 45%). The content of plagioclase is between 20 and 30%. The content of Yili/montmorillonite fluctuates greatly in the range of 16.8–60%.

2. RoqScan analysis time is 7.5 min per m section, and the average drilling time per m of this well is 10.5 min. This technology has high construction efficiency. In the field implementation, the cuttings are collected and analyzed while drilling. The analysis results are obtained synchronously while drilling to ensure the timeliness of fracturing design in the later stage. Back-to-back comparisons of P-wave data from cuttings’ inversion with well logging P-wave data show that the trends are the same. RoqScan technology has high P-wave data credibility.

3. By analyzing the scanning results and inversion parameters of the experimental wells, the lithology and physical property change rules of the horizontal section of the experimental wells are obtained. The fractured volcanic bedrock has strong heterogeneity, which is mainly caused by changes in mineral content and reservoir heterogeneity. The properties are controlled by the bedrock and the fracture, and the YM and brittleness fluctuate greatly. The logging interpretation and mineral analysis are affected by natural fractures, considerably affecting the effectiveness of the hydraulic fracturing design. The fracture propagation model needs to be developed along with crack morphology research.

4. The matrix mineral content, fracture density, YM, PR, and BI of experimental wells were obtained.

### 4. MATERIALS AND METHODS

#### 4.1. Analytical Experiment of Cuttings’ Minerals

The cuttings were collected during drilling, and they were quantitatively analyzed using backscatter imaging and X-ray diffraction spectroscopy to obtain the reservoir characteristics of target zones. More than 50 elements were recognized, including elemental-mineral composition, particle size, size distribution, morphology, and porosity. Inverted GR, S-wave, P-wave, and density curves of horizontal sections can be derived. The accuracy of backscatter imaging is 1 µm. A calculation process of cuttings’ analysis steps is shown in Figure 7.

Based on the rock elastic curve data obtained by inversion, the distributions of rock mechanical parameters, such as YM, PR, and BI, were obtained. According to the mineral components, pore characteristics, and rock mechanical properties of horizontal sections, the wellbore rock mechanical model was established, and the position with large brittleness was proposed to be perforated to ensure fracturing effect. Also, quantitative analysis was needed to characterize the formation characteristics of vertical and horizontal wells.

Cuttings’ mineral analysis formation evaluation and fracturing optimization technique is an electron microscopy scanning technique widely used in petroleum exploration and develop-
4.1.1. Sampling. Rock samples were collected by a vibrating screen. Samples were first cleaned in a mud tank before being brought back to the workroom to be cleaned for the second time using a degreaser and water. Then, they were placed in ethyl alcohol (75% concentration) to remove the residual degreaser. The cleaned rock samples were placed on dry sample equipment to swab off the water. A 10-mesh screen was used to remove the falling pieces from the rock samples. The sieved rock samples were poured into a sample preparation mold. The acrylic powder and curing agent at appropriate proportions were poured into the mold containing the rock samples and stirred rapidly. After stirring, the mold was tapped with a stirring stick to remove the bubbles. After the samples solidified, a new surface was ground using 180-mesh sandpaper and then polished using 1200-mesh abrasive paper. The polished samples were placed in a carbon plating machine to reduce the charge effect of charge accumulation. The carbon-coated samples were placed in the cuttings’ mineral analysis instrument to perform elemental and mineral analyses.

4.1.2. Test Method. The technology is mainly composed of a SEM and EDS. It includes a surface logging tool that quantifies mineralogical and compositional data by analyzing cuttings.

1. Every cutting sample was divided into a series of regions, which were then analyzed sequentially. Initially, back-scattered electrons were used to detect the atomic weight of the surface. The brightness of the image reflected the chemical composition. The backscattered electronic data can also be used to identify the effective porosity, diagenesis, and mineral transition phases of the particles.

2. Cutting partials were further analyzed by EDS detector (about 6000–10,000 X-rays per step; the entire sample comprised approximately 4–5 million). Each sample had approximately 250,000 mineral points.

3. After the elemental component was combined with the BSE image, mineral facies were converted. This technique could be used to distinguish transparent and opaque mineral phases. More than 100 minerals, including clay, could be identified.

4.2. Data Processing. For reservoirs, especially unconventional reservoirs, oil, and gas potentials were accurately evaluated, and fracturing sections were optimized to support drilling and production by quantifying the mechanical and elastic properties of underground rocks. Currently, oil and gas operators use cable tools to obtain the physical properties of rocks in a wellbore. These petrophysical properties include density, acoustic wave propagation time, and porosity.

The data output by the petrophysical model is usually bulk density, P-wave, and S-wave velocity. These three elastic data, i.e., bulk density, P-wave, and S-wave velocity, are used to...
directly derive the elastic mechanical properties of underground rocks, such as YM and PR.

In general, the petrophysical model requires three steps from the input of rock properties to the generation of the needed elastic mechanical properties.

In the first step, the active mineral properties of rocks, such as density, bulk modulus, and shear modulus, are calculated based on the weighted average of different mineral components. In the second step, the dry rock properties of subsurface rocks, i.e., the dry rock volume and shear modulus, are calculated by pore geometry and the contact between different rock components. The following calculation uses two types of models, namely, particle-based and pore-based models

\[
K_{\text{dry}} = \left[ \frac{C^2(1 - \varnothing)^2 \mu_m^2}{18\pi^2(1 - v_m)^3 P_{\text{eff}}} \right]^{1/3}
\]

(1)

\[
\mu_{\text{dry}} = \frac{5 - 4v_m}{2(2 - v_m)} \left[ \frac{3C^2(1 - \varnothing)^2 \mu_m^2}{2\pi^2(1 - v_m)^3 P_{\text{eff}}} \right]^{1/3}
\]

(2)

The particle-based model was derived from the Hertz–Mindlin model. In the above formula, \(K\) is the bulk modulus, \(P_{\text{eff}}\) is effective pressure, \(\varnothing\) is effective porosity, \(v\) is PR, and \(\mu\) is the viscosity coefficient. Dry represents dry rock properties and sat represents saturated rock properties. The model was used to calculate the elastic data of rock skeleton based on sufficient pressure, porosity, number of contacts between particles, and the elastic properties of particles

\[
(K_{\text{dry}} - K_m) \left( \frac{K_m + \frac{1}{2} \mu_m}{K_{\text{dry}} + \frac{1}{2} \mu_m} \right) = \sum_i f_i (K_i - K_m) P(\alpha)_i^y
\]

(3)

\[
(\mu_{\text{dry}} - \mu_h) \left( \frac{\mu_h + \frac{1}{2} \epsilon_m}{\mu_{\text{dry}} + \frac{1}{2} \epsilon_m} \right) = \sum_i f_i (\mu_i - \mu_h) Q(\alpha)_i^y
\]

(4)

\[
\epsilon_m = \frac{\mu(9K_m + 8\mu_m)}{6(K_m + 2\mu_m)}
\]

(5)

The pore-based model was derived from the Kuster–Toksoz model. In the above formula, \(f_i\) is the mineral volume fraction. \(P\) and \(Q\) represent pore shape factor, depending on the aspect ratio of the pore.

The model was used to calculate the elastic data of rock skeleton based on the geometry of ideal ellipsoidal pores for a given aspect ratio

\[
K_{\text{sat}} = K_{\text{dry}} + \frac{(1 - K_{\text{dry}}/K_m)^2}{\varnothing/K_{\text{fl}} + (1 - \varnothing)/K_m - K_{\text{dry}}/K_m}
\]

\[
m_{\text{sat}} = m_{\text{dry}}
\]

(6)

(7)

In the third step, the saturated rock properties were calculated by performing a fluid replacement, i.e., adding a given fluid to the pores. The most commonly used model was developed by Gassmann. In the above formula, \(m\) is shear modulus. The subscript \(m\) used in the equation represents mineral properties. However, the abovementioned calculation is only useful when the pore-filling material is a fluid with zero shear modulus. Ciz and Shapiro later improved these equations to explain solid filler materials. The fluid properties required for displacement can be measured in the laboratory or based on empirical formulas, such as Batzle and the FLAG joint model.

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Conceptualization, G.Y. and S.Z.; data curation, G.Y.; formal analysis, G.Y.; funding acquisition, S.Z. and G.T.; investigation, G.Y.; methodology, G.Y.; project administration, S.Z. and G.T.; resources, S.Z., G.T., and H.Z.; software, G.Y., S.Z., and G.T.; supervision, S.Z. and G.T.; validation, G.Y. and H.Z.; visualization, G.Y.; writing—original draft, G.Y.; writing—review and editing, G.Y. and S.Z.

**Notes**

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