Application of Magnetic Susceptibility Parameters in Research of Igneous Rock in Chepaizi

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Abstract: The Carboniferous reservoir of the Chepaizi High in the Junggar Basin is mainly composed of igneous rocks, with complex lithology and low exploration degree. The reservoir is highly heterogeneous and the development characteristics are not clear. The heterogeneity of the Carboniferous reservoir was studied by using the magnetic susceptibility measured in the field or by coring as well as the logging data, thereby, the reservoir space, physical characteristics, distribution characteristics and lithofacies development characteristics and hydrocarbon content of the Carboniferous igneous reservoir were analyzed. The results show that the Carboniferous rocks with high magnetic susceptibility are prone to be weathered into a favorable reservoir with good physical properties, while the Carboniferous rocks with low magnetic susceptibility are difficult to develop into a favorable reservoir, and only occurs near the fault zone. This provides an important basis for the exploration of igneous oil and gas in the study area.

1. Introduction
In recent years, China Petroleum & Chemical Corporation Shengli Oilfield Branch (SINOPEC Shengli Oilfield) has made gratifying progress in the oil and gas exploration of the Carboniferous igneous rocks in the Chepaizi area along the western margin of the Junggar Basin. Welss Pai 66, Pai 667, Pai 665 and so on have obtained industrial oil flow in the Carboniferous system. All these have proved that the Carboniferous igneous rock reservoir contains rich oil and gas resources [1]. The predecessors have carried out a lot of research on the igneous rocks east of the Hongche Fault Zone in the Chepaizi area, and they believed that the Carboniferous igneous rocks have the characteristics like multi-stage diagenesis, various rock and reservoir space types, high heterogeneity and variable control factors and complex oil-gas reservoir formation [2-3]. The research based on coring by drilling, logging data, oil test, seismic data, etc. has also made certain progress [4]. However, the magnetic susceptibility was rarely involved in previous research, though it is an important physical property to distinguish and identify igneous rock lithology and lithofacies. Therefore, the author conducted magnetic susceptibility measurement on the field outcrops and cores by drilling in Chepaizi area and studied the heterogeneity of Carboniferous igneous reservoir combining the logging, oil test, seismic and other achievements; analyzed the oil-gas bearing laws of igneous rocks and established the magnetic susceptibility-natural gamma intersection map to identify lithology, and then carry out magnetic shock joint inversion to identify the igneous rock development area, in order to provide reference for the exploration of igneous oil and gas.
2. Geological Overview of the Region

The Chepaizi High is located at the western margin of the Junggar Basin (Fig. 1), and it is a sub-tectonic unit of the uplift in the western Junggar Basin, located in front of the Zaire Mountains and connected to the Changji Sag eastward through the Hongche Fault Zone. The High has long been in the hydrocarbon migration direction zone of Changji and Sikeshu Hydrocarbon-generating Sags\textsuperscript{[5-6]}, which is a favorable oil and gas enrichment zone.

There are less boreholes with the Carboniferous formation as the target in the work area, and the boreholes are mainly located in the northeast of the work area. The drilling data reveals that the lithology mainly involves igneous rocks and sedimentary rocks, of which, the igneous rocks include tuff, andesite, volcanic breccia, basalt, granite, etc. and the sedimentary rocks include tuff mudstone, tuff sandstone, carbonaceous mudstone, mudstone, etc.

![Fig. 1 Location of Chepaizi High Area](image)

3. Magnetic Susceptibility Characteristics of Rocks and Ores

3.1. Magnetic Susceptibility Measurement Method

The magnetic property of matters is caused by the spin magnetic moment and the orbital magnetic moment of the outer electrons of the atom. Different minerals have varying magnetic properties, and different rocks contain different radioactive elements as well. For igneous rocks, the more acidic they are, the lower their magnetic susceptibility will be, and the higher their radioactivity will be, and in this case, their natural Gamma logging value is larger naturally\textsuperscript{[7]}. The measurement of the magnetic susceptibility of the field and cored rock was done by using the Czech SM-30 magnetic susceptibility meter with a resolution of $1 \times 10^{-7}$SI, which has the advantages of high accuracy, high precision, compactness and light weight. During the measurement, the same measuring point was measured six times from different angles, and finally, the average of the six measurements was taken as the result, which provide a guarantee to obtain accurate data.

3.2. Magnetic Susceptibility Characteristics of Formations

In recent years, more than 10 measurement profiles have been made for the Carboniferous outcrops west of Karamay in the neighboring area of Chepaizi, involving the cumulative length of 500km. A total of 1664 physical property points have been measured, and 8010 items of effective magnetic susceptibility data have been obtained, of which, there were 3,500 items for the Tailegula Formation,
1510 items for the Baogutu Formation, and 3000 items for the Shibekulas Formation. The data clearly reflects the magnetic susceptibility characteristics of the three sets of Carboniferous formations and the types of igneous rocks in the formation. The magnetic susceptibility values are varying, as shown in Table 1.

The statistics show that igneous rocks develop in the Carboniferous Xibeikulas Formation and the Tailegula Formation, with high magnetic susceptibility. Tuffaceous sandstones with high magnetic susceptibility occur in the Tailegula Formation. The Baogutu Formation mainly consists of mudstone and silty mudstone, and the diorite porphyry vein is found. For them, the percentage of high magnetic susceptibility data in total is: Xibeikulas Formation 5%, Baogutu Formation 3%, and Tailegula Formation 8%, which provides a basis for processing and identification of igneous rocks by using high-precision magnetic force.

Table 1 Summary of Magnetic Susceptibilities of the Carboniferous Rocks in the Karamay Area in the Western Junggar Basin

| Formation       | Lithology                                                                 | Number of Measured Points | Number of Magnetic Susceptibilities | Magnetic Susceptibility/ $10^{-5}$SI |
|-----------------|---------------------------------------------------------------------------|---------------------------|-----------------------------------|-------------------------------------|
| Xibeikulas      | Gravel-bearing coarse sandstone, pebbly sandstone, tuffaceous sandstone,  | 533                       | 2832                              | 8                                   |
|                 | mudstone, siltstone, tuff and argillaceous siltstone                        |                           | 45                                | 23                                  |
|                 | Granodiorite, diorite, and andesitic tuff                                  | 20                       | 100                               | 100                                 |
|                 | Andesite and diabase                                                       | 10                       | 50                                | 350                                 |
|                 | Gemstone                                                                   | 3                        | 18                                | 700                                 |
|                 |                                                                           |                           | 3040                              | 2330                                |
| Baogutu         | Mudstone, silty mudstone, siltstone and tuffaceous siltstone               | 360                       | 1480                              | 7                                   |
|                 | Diorite porphyrite, diorite and tuffaceous sandstone                        | 12                       | 45                                | 259                                 |
|                 |                                                                           |                           | 491                               | 350                                 |
| Tailegula       | Silty mudstone, argillaceous siltstone, fine sandstone, siltstone,         | 690                       | 2760                              | 8                                   |
|                 | silicalite and tuffaceous sandstone                                         |                           | 400                               | 23                                  |
|                 | Tuff                                                                       | 20                       | 116                               | 50                                  |
|                 | Andesite, andesitic tuff, granite, granodiorite                            | 18                       | 100                               | 541                                 |
|                 | Basalt                                                                     | 4                        | 24                                | 919                                 |
|                 |                                                                           |                           | 2350                              | 1850                                |

3.3. Characteristics of Lithology Magnetic Susceptibility

The magnetic susceptibility measurement on the lithology of 28 Carboniferous coring wells in the Chepaizi area, involves the cumulative length of more than 460 meters, and 1648 items of measured magnetic susceptibility data. The analysis shows (Fig.2), the magnetic susceptibilities of basalt, andesite, volcanic breccia and granite are larger than 500×10^{-5}SI, and the averaged magnetic susceptibilities of volcanic breccia, granite, andesite, and basalt are 566×10^{-5}SI, 969×10^{-5}SI, 1670×10^{-5}SI and 1721×10^{-5}SI, respectively. The magnetic susceptibility of tuff is mainly distributed in two areas. In one area, the magnetic susceptibility is larger than 600×10^{-5}SI. According to the analysis
combining with the logging and slice data, the volcanic fragments in that area are mainly intermediate-basic andesite (Pai 66 and Pai 61 wells). In the other area, the magnetic susceptibility is less than $80 \times 10^{-5}$SI, indicating the rock in that area is typical tuff (Pai 665 and Pai 624 wells). The magnetic susceptibilities of mudstone and sandstone are both less than $50 \times 10^{-5}$SI. The magnetic susceptibility effectively reflects the heterogeneity of the Carboniferous igneous rocks. The basalt and andesite have the highest magnetic susceptibility, followed by andesitic tuff; and then granite. The volcanic breccia has medium-high magnetic susceptibility. The tuff, sandstone and mudstone are basically non-magnetic.

**Fig. 2** Meteorogram of the Magnetic Susceptibility of the Carboniferous Cores

**4. Magnetic Susceptibility Analysis and Application**

**4.1. Characteristics of Reservoir Magnetic Susceptibility**

The statistical analysis of the test oil well section (Fig. 3) shows that more than 90% of the favorable reservoirs have high magnetic susceptibility ($>250 \times 10^{-5}$SI) characteristics, and the lithologies mainly include andesite, andesitic tuff, volcanic breccia and basalt. In the lithologies with low magnetic susceptibility, only the tuff of a few wells contain hydrocarbons. Combined with drilling data, it is found that the typical characteristics of this type of reservoirs are serious leakage of drilling fluid (for example, leakage occurred in the 811-988m section of Pai 665 Well, and leaked mud was up to 303.39m$^3$, the leakage involved gray-black tuff, belonging to cracking loss).

**Fig. 3** Relationship between Oil Content and Magnetic Susceptibility of Carboniferous Coring Section
4.2. Application of Magnetic Susceptibility in Identification of Reservoir Heterogeneity

Previous studies have shown that the physical properties of the Carboniferous igneous reservoir are controlled by lithology and weathering and erosion time. Under the same surface environment, the differences in rock strength, brittleness and soluble minerals lead to large difference in reservoir heterogeneity. The unweathered volcanic breccia can form effective reservoirs, and the weakly-weathered intermediate-basic rocks like volcanic breccia, andesite and basalt can form effective reservoirs, while the tuff has the most rigorous requirements for the formation of effective reservoirs. The sedimentary rocks basically do not develop reservoirs [8]. We carried out an analysis on the igneous rock core of 10 wells, combining with the logging and nuclear magnetic interpretation results, and obtained the parameters like igneous rock porosity, permeability and magnetic susceptibility of the study area (Table 2). The results show that the igneous breccia and altered andesite are the best reservoirs with the medium-high magnetic susceptibility; the secondary one is basalt, which has a high magnetic susceptibility; the andesite and andesitic tuff rank the third, with a high magnetic susceptibility. The tuff and basaltic andesite reservoirs have the worst reservoir property.

Table 2 Relationship between Lithology and Physical Properties of Igneous Rocks In Chepaizi

| Lithology       | Porosity Φ/% | Permeability K/mD | Magnetic Susceptibility/10^-5SI |
|-----------------|--------------|-------------------|-------------------------------|
|                 | Minimu m     | Maximu m          | Avera ge                      | Minimu m | Maximu m | Avera ge | Minimu m | Maximu m | Avera ge |
| Volcanic breccia| 3.59         | 17.89             | 11.12                         | 0.12      | 33.41     | 10.78    | 40        | 689      | 566      |
| Basalt          | 2.78         | 10.04             | 4.92                          | 0.01      | 225.5     | 6.42     | 1200      | 5280     | 1721     |
| Andesite        | 2.54         | 14.61             | 6.815                         | 0.08      | 13.82     | 2.343    | 147       | 4900     | 1670     |
| Basaltic andesite| 2.54       | 6.85              | 5.93                          | 0.05      | 3.82      | 0.44     | 689       | 2400     | 1600     |
| Altered andesite| 3.51         | 18.6              | 10.3                          | 0.06      | 45.8      | 11.6     | 150       | 3600     | 1280     |
| Tuff            | 1.42         | 28.1              | 6.49                          | 0.01      | 35.51     | 3.447    | 12        | 65       | 30       |
| Andesitic tuff  | 3.43         | 15.6              | 8.21                          | 0.06      | 14.6      | 4.01     | 180       | 3780     | 1031     |

The analysis on the logging data of 24 Coring Well Sections shows that the core magnetic susceptibility and natural Gamma intersection can better reflect the heterogeneity of reservoirs (Fig. 4). The basalt, andesite, andesitic tuff and breccia reservoirs have low natural Gamma (<40API) and high magnetic susceptibility (>250×10^-5SI); The altered andesite reservoirs have medium natural Gamma (>40API, <75API), and high magnetic susceptibility (>350×10^-5SI); and the tuff and mudstone reservoirs have high natural Gamma (>40API) and low magnetic susceptibility (<100×10^-5SI).

Fig.4 Chepaizi Carboniferous Igneous Core Natural Gamma - Magnetic Susceptibility Intersection
5. Conclusion

(1) Igneous rocks are relatively developed in the Carboniferous Xibekulas Formation and Tailigula Formation of the Chepaizi area in the western Junggar Basin; and basically not developed in the Baogutu Formation. Among the igneous rocks, the basalt, andesite and Andesitic tuff have high magnetic susceptibility; the volcanic breccia and granite have medium magnetic susceptibility; and the tuff and sedimentary rocks have extremely-low magnetic susceptibility.

(2) The magnetic susceptibility can well indicate the development of favorable carbonate reservoirs, and more than 90% of the oil and gas reservoirs have medium and high magnetic susceptibility. Establishing a magnetic susceptibility and natural gamma intersection map can well identify lithology and reservoir’s heterogeneity. Through the study of the magnetization pattern of the magnetization formations and the coring lithology in the western Junggar Basin, the corresponding parameter relationship between the magnetic susceptibility and the natural Gamma was established, which provides the technical support to further carry out the identification of igneous rock development area by the magnetic susceptibility-constrained seismic inversion of the full well section.

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