Mapping complex reservoir targets by electromagnetic multi-attributes

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Abstract. In development of oil and gas exploration, complex reservoirs have become a key problem for increasing production capacity. It is of great significance to develop novel technologies for reservoir prediction and evaluation. Non-seismic methods such as time-frequency electromagnetics and well-ground electromagnetics have been applied to the study of complex reservoirs, oil and gas detection methods of electromagnetic properties based on the analysis of dispersion characteristics and a method of oil and gas target identification based on complex resistivity equivalent models have been proposed and the method of inversion of electromagnetic properties of complex reservoirs using the well-ground multi-scale sequential constraint inversion method, etc., introduces the actual profiles applied to the development of exploration of igneous rocks and complicated fault-block lithological reservoirs. It provides an effective method for oil and gas detection of knew hydrocarbon traps in complex targets of oil and gas.

1. Introduction
Complex reservoirs have always been the most difficult problems for development of oil and gas exploration. Among them, volcanic rocks and complicated fault-block lithological reservoirs are the two main types. Such complex oil and gas reservoirs are common in major basins in the east and west of China and are widely noticed and concerned by experts of oil and gas exploration. Although many complex reservoir trap seismic prediction methods have been developed, such complex oil and gas reservoirs are complicated by fault lithology or igneous rocks, making it difficult for seismic exploration to locate(delineate) targets of oil and gas effectively. Therefore, we need to find other new geophysical methods. The time-frequency electromagnetic exploration technology independently researched and developed by China, this technology uses optimization measures such as high-power excitation, time-domain magnetic induction and frequency-domain electric field complementation, and multi-parameter integrated processing and interpretation. It has been widely used in oil and gas exploration, and has achieved good results as an assist to seismic exploration. Especially in recent years, time-frequency electromagnetic technology has been further developed and improved, proposing a multi-parameter combined prediction method of electromagnetic attributes and seismic traps, which play an important role in the evaluation and optimization of targets of complex reservoir. It has been extensively used at domestic and overseas with significant effects. Time-frequency electromagnetic method of well-ground developed with the method of twice-up and down-excitation
in the well and receiving electromagnetic fields on the ground can further improve the accuracy of delineating the oil range of the reservoir, and has been applied to the development of multiple oil fields. Obviously, the ground method is utilized for ground power supply and ground reception, and the detection object is far away from the excitation receiving device. The detection accuracy is both affected by the target depth and ground noise. It is difficult to guarantee the accuracy of the data, and it is difficult to improve the description of detail of the reservoir; However, the time-frequency electromagnetic method of well-ground focus on the target of the reservoir to stimulate and then adopts differential processing. The collected data contain more information about the target of reservoir, which becomes an effective method for delineating the boundaries of reservoirs of oil and gas after drilling, and it has been popularized and applied. Therefore, on the basis of existing seismic exploration data, it is an essential choice for complex reservoirs to improve the efficiency of exploration and development by further using surface and well-ground electromagnetic methods or a combination of both and multiple types of electromagnetic properties.

2. The detection of oil and gas based on electromagnetic properties of dispersion characteristics

Predecessors used high-pressure flooding on pore rocks of oil-bearing reservoirs to obtain rocks of different saturation. Characteristics of electromagnetic of amplitude-frequency of the rocks at different frequencies were measured, and the positive correlation between the dispersion rate of electromagnetic amplitude and phase of oil-bearing cores and oil saturation was determined [1,2,3,4,5]. Therefore, the dual-frequency amplitude and dual-frequency phase can be used to characterize the induced polarization effect on the measured data. However, these two parameters are only a qualitative description of the dispersion effect of a certain frequency. The effect of the two applications in actual work is not satisfactory, and sometimes they contradict each other. This is caused by the inevitable existence of various geological and human disturbances in the measured data. The influence of these disturbances on the amplitude and phase components results in poor application effects. We know that if the noise is from diverse sources, relevant processing can be carried out to suppress the interference and enhance the effect of excitation polarization anomaly. Take into account this, we propose a dual-frequency correlation attribute for a specific reservoir to predict the oil range of the reservoir, the method is as follows:

According to the target depth $H$ to be detected and the average resistivity $ρ$ of the target reservoir and the overlying strata in the exploration area, we can figure out the excitation frequency needed to detect the target. Then the target frequency can be obtained from the following formula:

$$F_A = \frac{ρ}{πµH^2}$$

According to the frequency $F_A$ of the detection target, in the construction design, a series of dense excitation frequency points need to be designed near this frequency. In data processing, two actual excitation frequencies, $F_H$ and $F_L$ are selected and satisfied: $F_L > F_A > F_H$, that is, High frequency ($F_H$) detection depth has not reached the reservoir target, while low frequency ($F_L$) has detected the bottom of the reservoir target.

At this time we calculate the dual-frequency amplitude, the formula is as follows:

$$\Delta A = \frac{A_L - A_H}{A_L} \times 100\%$$

(2)

Where $A_L$ and $A_H$ are the low-frequency amplitude and high-frequency amplitude, respectively. The calculation formula of the dual-frequency phase is as follows:

$$\Delta \phi = \frac{\phi(F_L) - \phi(F_H)}{F_L - F_A}$$

(3)
Where $\varphi(F_A)$ and $\varphi(F_L)$ are phase shifts when the frequencies are $F_A$ and $F_L$ respectively. Dual-frequency correlation attribute is to normalize dual-frequency amplitude and phase of dual-frequency, and then do correlation processing. The calculation formula is as follows:

$$R_{A\varphi} = Q \sum_{dx=0}^{n} \Delta A^g(x) \Delta \varphi^g(x + dx)$$

(4)

In the formula, $\Delta A^g$ and $\Delta \varphi^g$ are the normalized dispersion rates of the amplitude and phase components, respectively, $dx$ is the corresponding measurement point distance, $n$ is the number of measurement points, and the $Q$ symbol coefficient. The $Q$ value is determined by the sign of the normalized amplitude and phase. Both are positive, then $Q$ is positive, both are negative, then $Q$ is negative. One is positive, and other is negative, then $Q$ is negative.

Figure 1. Normalized correlation profile of dispersion rate: a Dispersion Rate of Amplitude. B Dispersion Rate of Phase. c Related attributes.

3. Extraction the IP Effect of Reservoir Based on Equivalent Model of Complex Resistivity

Because the underground medium is a multiphase medium, especially the medium of pore of reservoir is rich in free ions, it is easy to produce ion-induced polarization effects. The core test shows that the dispersion effect of the reservoir rock is obvious, and the dispersion rate is proportional to the oil saturation. Therefore, DC resistivity cannot be used to describe multiphase porous media such as reservoirs, complex resistivity must be used. There are many mathematical models to express frequency characteristics of complex resistivity. Here we use the parallel connection of Wait equivalent circuit model and Warburg equivalent circuit model as equivalent resistivity model of underground medium is used for inversion to extract the IP anomaly of the reservoir:

$$\rho(\omega) = \rho_0 \left(1 - m \left(1 - \frac{1}{1 + (i\omega\tau)^m}\right) \right) \left(1 - \frac{1}{m + \frac{2}{3}}\right)$$

(5)

In the above formula, $m$ is the polarizability and $\omega$ is the angular frequency, $\tau$ is time constant, $\rho_0$ is the DC resistivity. It can be observed in Equation (5). Resistivity and polarizability are product relations. If they are used as unknown variables at the same time, the inversion is sometimes difficult to fit at the same time and not accurate to determine any of these unknowns.

Because the resistivity is under a greater impact, the DC resistivity is generally inverted as usual. After getting the resistivity model, then fix to the resistivity of the Warburg-Wait model to invert the polarizability. Other parameters $\tau$ can also be fixed first and then inverted one by one, the specific method can see literature. In this way, the results of resistivity model reflect the electrical
characteristics of the basic geological model, while results of the polarizability inversion model are the residual electromagnetic anomalies excepting the basic electrical characteristics. A large amount of data from oil and gas field indicates that oil and gas fields are mainly induced polarization effect of the oil reservoir. Similarly, the variation range of the maximum and minimum polarizability of each layer is indicated by test data of the induced polarization logging or rock polarizability, and the initial polarizability are averaged between the maximum and minimum values. For example, in a certain exploration area, polarization logging statistics of a group of sand and mudstone formations in the Tertiary is between 2%-15%, the minimum value is 2% and the maximum value is 15%, the average value of initial model is 8.5%.

Take inversion of frontal-induced polarization effects of time-frequency electromagnetic data in TG basin as an example. 2D and 3D seismic exploration has been completed in this area, and there are still a large number of exploration wells. The geological structure is basically clear, and the vertical electrical properties of the stratum are significantly different. The bury depth of target layer of oil storage is approximately 2km, which is a complex reservoir controlled by dual factors of structure and lithology (sand body). The success rate of exploration wells based on 3D seismic exploration deployment is only 25%. Therefore, new technologies for predicting lithologic reservoirs are needed. Figure 2a shows the inversion profile of resistivity under the constraint of seismic data and the polarizability profile of constraint inversion based on the complex resistivity equivalent model (Figure 2b). It can be seen that the polarizability profile clearly reveals favorable reservoir distribution and provides an important basis for drilling deployment in this area. Exploratory wells deploy next to measurement point 1221 and obtain high oil-producing gas flows.

4. Extraction of Well-Ground Multi-scale Electromagnetic Attribute Anomalies for Complex Reservoirs

The difference between the received data excited by the two electrodes the upper and lower the target layer, according to the well-ground electricity method, is mainly a reflection of the electrical changes in the target layer. Using the difference between the electromagnetic field data of the upper and lower electrodes to invert the resistivity distribution in the target layer. And then inferring the oil-bearing property in the target layer. Therefore, the background model for the target layer can be formed based on the resistivity and polarizability profiles of known constraints inversion of time-frequency electromagnetic. Fine mesh generation is carried out in the target layer, and fixes the electrical parameters of the upper and lower layers of the target layer. Inverting only the internal details of the target layer, it can reduce the impact of the inversion of the upper and lower layers for the target layer and improve the resolution of the target layer inside.

Taking the inversion of oil and gas reservoirs of complex igneous, in the HX exploration area, as an example. The reservoirs in this area have large burial depths. Lateral variation is complex, and have been severely complicated by igneous rocks that have erupted in multiple, which has become a problem for oil and gas exploration and development in this area. Physical property analysis shows that the resistivity value of igneous rocks in this area is more than 100 $\Omega \cdot m$, and higher resistivity
when containing oil and gas, while the resistivity value of the sedimentary layer between igneous rocks varies between 1-10 Ω.m, such a large resistivity comparison provides a good physical basis for electromagnetic exploration.

Figure 3a shows the surface inversion profile of time-frequency electromagnetic. In order to further improve the internal details of the reservoir, a well-ground electromagnetic method is deployed. Figure 3b shows the inversion profile of the well-ground electromagnetic method for the reservoir inside. It is obvious that the vertical and horizontal resolutions of the target layer inside are significantly improved. Igneous reservoir is characterized by multi-periods and controlled by faults.

5. Conclusions
For complex reservoirs such as lithological reservoirs and igneous rocks, conventional exploration methods have not been very effective in identifying oil-bearing targets. Here are three research schemes from qualitative to quantitative to internal details: (1)Analysis based on dispersion characteristics of oil and gas detection method for electromagnetic property profile; (2)Inversion method of polarizability profile based on complex resistivity equivalent model; (3)Well-ground multi-scale sequential constraint inversion method for extracting electromagnetic property anomalies of complex reservoirs, which can obtain many kinds of electromagnetic properties with different scales, and the combination of the three can improve the exploration accuracy. These methods have many application examples and have been corroborated by later deployed drilling. Therefore, the method proposed in this paper can be used in areas with poor performance of conventional seismic exploration for such complex oil and gas reservoir targets, which are bound to have unexpected effects.

6. Acknowledgments
This research was supported by the National Natural Science Foundation of China (41874085) and Shenzhen Science and Technology Program (KQTD20170810111725321).

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