Evaluation of reservoir flooding by 2 MHz and 60 MHz electromagnetic wave logging data

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Abstract. Electromagnetic wave logging data provide two aspects of phase difference and amplitude ratio information, which can comprehensively reflect the changes of formation conductivity and dielectric constant. According to the characteristic that the dielectric constant is basically independent of the salinity of formation water and only related to the water content, through the phase difference of 60MHz reflects the water saturation at a certain water content or porosity of the flush zone, the phase resistivity log of 2MHz reflects the oil-bearing property of the unfractured formation and determines the fluid properties or water flooding degree through the radial comparison of different detection depth curves. Based on the analysis of actual well data, the response of electromagnetic wave logging to water flooding degree of pure sandstone reservoir above 0.4 m is more obvious than that of conventional resistivity logging. The reservoirs with heavy argillaceous and calcium and small bed thickness must be corrected before the evaluation of water flooding layer of thin and poor oil reservoir can be applied.

Key words: Electromagnetic wave logging data; Water flooded layer; 60 MHz; 2 MHz.

1. Introduction

Electromagnetic wave logging, as one of the important means of geophysical logging, can simultaneously measure the conductivity and dielectric constant of the formation around the well, and these constants are crucial for the evaluation of formation oil-bearing property[1,2]. For the oilfield developed by water injection, the formation water resistivity is constantly changing and always in a dynamic process due to the long-term fresh water injection or sewage reinjection, which makes it extremely difficult to calculate the formation water resistivity, and thus greatly limits the evaluation effect of the water-flooded layer with the general resistivity and the focused resistivity logging. Electromagnetic wave logging is based on the theory of dielectric polarization, and reflects the oil-bearing property of flush zone and unshaped formation through phase difference measurement of different frequencies. Theoretically, electromagnetic wave logging has the advantage of being less affected by formation water resistivity[3].
The dielectric constant of the formation rock skeleton is relatively stable, and the dielectric constant of the fluid contained in the reservoir varies greatly, so the electromagnetic wave data can be used to better distinguish the oil and water layers. Application: Determine the water saturation of the formation; Judge the oil and water layer; Determine the flooded layer and divide the flooded grade [4]. Dielectric logging is more effective than electromagnetic resistivity logging in distinguishing between oil and water layers. The disadvantage is that the depth of exploration is shallower. Therefore, based on the actual requirements of water-flooded layer interpretation in old areas, electromagnetic wave logging tests are carried out, and the main factors affecting electromagnetic wave logging are analyzed through rock physics experimental data of closed coring Wells, and then the feasibility of application of electromagnetic wave technology in water-flooded layer interpretation is made, and the further improvement and development direction are proposed.

2. Analysis of the influence of clay content on phase difference curve

Electromagnetic wave logging is a method to detect the physical properties of formation based on the theory of dielectric polarization, and to reflect the oil-bearing property of reservoir based on the difference of oil and water polarization ability. Like other logging methods, it is inevitably affected by lithology and layer thickness. At present, the electromagnetic logging tools of Daqing Logging Company are divided into 2 MHz phase resistivity logging with lower frequency and 60MHz phase dielectric logging with higher frequency. The structural parameters and performance indexes are shown in Table 1.

| The instrument | Distance of source (m) | Spacing (m) | Detection depth (m) | Resolution (m) |
|----------------|-----------------------|-------------|---------------------|---------------|
| Phase resistivity | 1.4                   | 0.35        | 1.2-1.4             | 0.8           |
| Phase dielectric | 0.35                  | 0.12        | 0.3-0.4             | 0.4           |

3. Lithology influence analysis:

According to the relationship between the shale content in the core analysis and the measured phase difference in Fig.1, The phase difference of 2MHz has a linear relationship with the content of mud, while the phase difference of 60MHz phase difference is clearly linear. It is shown that the mudstone has a more significant influence on the high frequency electromagnetic logging, which not only reflects the great difference between the polarization characteristics of mudstone and the rock skeleton, but also reflects the 2MHz signal contribution of phase difference is mainly the conductivity, and the dielectric constant is weak, on the contrary, 60MHz signal contribution of phase difference is mainly the dielectric constant and the electrical conductivity is weak. The effect of mud must be taken into account in the interpretation process.

Fig. 1 Relationship between phase difference and mud content
4. **Analysis of the influence of layer thickness on phase difference curve**

According to the relationship between phase difference and formation thickness as shown in Fig. 2, with the increase of formation thickness, 2MHz and 60MHz phase difference showed an obvious decreasing trend, and the decreasing rate of the latter was obviously smaller than that of the former. It shows that the phase difference curve reflecting the polarization ability of the medium is obviously affected by the thickness of the formation, and 2MHz phase difference is seriously affected by the layer thickness. Therefore, the post-layer factor is another factor that must be considered in the interpretation of electromagnetic logging.

![Fig. 2 2MHz and 60 MHz phase difference and layer thickness diagram](image)

5. **Influence of moisture content on phase difference curve**

Theoretically speaking, the phase difference reflects the polarization ability of the medium, that is, the greater the water content, the greater the phase difference, and the higher the water saturation of the formation, the lower the resistivity. In Fig. 3, except for a few layers specified by the curve, the radial difference of the discriminant factor curve has a good nonlinear relationship with the water content, while the relationship between the conventional resistivity logging is rather weak, indicating that the electromagnetic wave logging has an obvious response to the formation water content, which is more conducive to indicating the extent of water flooding.

The few sample points circled by the curve all have the characteristics of small radial difference of discriminant factors, pure lithology and heavy water flooding. The main reason for deviating from the normal trend line may be that the oil saturation is high, resulting in low phase difference at 2MHz, or it may be related to the distribution form of oil and water.
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6. Influence of water flooding degree on phase difference curve

After standardization, the two discriminant factor curves not only carry all the information of the original curve, but also have radial comparability. The consistency of logging response is described by four conditions: good, medium, poor and no display. If the core shows level 1 or 2 flooding, the logging shows obvious flooding as "good"; if the logging shows obvious but not obvious flooding as "medium"; if the phenomenon of no water flooding is "poor"; and if the reservoir is not shown as "no show". Classified statistics from layer 235 data are described as follows. Table 2 shows the extent of water flooding in layer 235 by electromagnetic logging and its comparison with resistivity and spontaneous potential logging. Among the 21 undisplayed electromagnetic waves, 86% have a thickness of less than 0.4m, and the layers greater than 0.4m are all high-mud reservoirs. Among the 35 differential display layers, 14 layers are less than 0.4m thick, and 16 layers are high mud or high calcium. The good electromagnetic wave display layer accounted for 44.3% of the total layer, which was 16.6 percentage points higher than the conventional resistivity. It shows that the electromagnetic wave of the formation with thickness greater than 0.4m is more sensitive to water flooding than resistivity logging.

![Fig. 3 Relationship between radial difference of discriminant factor and water content](image)

Table 2. Comparison of water flooding degree response between electromagnetic wave and resistivity logging

| According to situation | Electromagnetic Display (Layer) | Comparison (%) | Conventional display | Comparison (%) | Synthetical interpretation coincidence | Conformity rate (%) |
|------------------------|---------------------------------|----------------|----------------------|----------------|-----------------------------------------|-------------------|
| good                   | 104                             | 44.3           | 65                   | 27.7           | 38/52                                   | 73.1              |
| medium                 | 75                              | 31.9           | 125                  | 53.5           | 59/82                                   | 71.9              |
| poor                   | 35                              | 14.9           | 44                   | 18.8           | 15/24                                   | 62.5              |
| no show                | 21                              | 8.9            | 0                    | 0              | 0                                       | 0                 |
| Coincidence rate       |                                 |                |                      |                | 112/158                                 | 68.7              |

7. Application examples

The analysis of the influencing factors of the phase difference curve above shows that electromagnetic logging is not suitable for the evaluation of thin layers below 0.4m, and lithology correction must be carried out for the reservoirs with high mud and high calcium content. The following examples further illustrate by lithology, although electromagnetic log resistivity, layer thickness and other factors, but for pure lithology and thickness of reservoir, water flooded degree display is better, to improve the effect of water flooded layer interpretation still has its special meaning, especially the formation water resistivity is not clear and resistivity increase after oil layer being water flooding.

Fig. 4 shows an application example of electromagnetic wave logging in 50m thick formation of Well Gao # - Jian *1.
Fig. 4 Application example of electromagnetic wave logging in the first section of well gao 168-jian

In Fig. 4, the core analysis of layers ① to ⑥ are all water-flooded layers. The upper and lower permeability of layer 1 are 420 and 740 mD, the oil saturation is 54.7% and 51%, and the oil displacement efficiency is 0.363 and 0.333. It is a level 2 water-flooded layer with relatively light upper water and heavy water-flooded lower water. The resistivity logging shows that the upper and lower layers are 30Ω·m and 50Ω·m, and there is no obvious baseline shift of spontaneous potential. However, the electromagnetic discriminant factor curve shows that the reservoir has good oil content, the upper layer is lightly flooded, and the lower layer is significantly flooded, which is interpreted as low flooded upper layer and medium flooded lower layer.

No.3 and No.6 layers are two medium-flooded and high-flooded layers with relatively pure lithology and large thickness, with permeability of 895mD and 623mD respectively, oil saturation of 50% and 36%, oil displacement efficiency of 0.357 and 0.497. Conventional logging shows that the resistance is greater than 30Ω·m, and the natural potential has a baseline shift phenomenon, indicating the water flooding phenomenon correctly. In the electromagnetic wave logging, the phase difference of 2MHz reflected the worsening trend of waterlogging with the increase of depth, and the discriminant factor curve showed obvious radial difference, indicating that the waterlogging was more serious, which was completely consistent with the experimental conclusion.

8. Conclusion
(1) Because the resistivity of formation water is difficult to determine, the waterout is often not obvious in conventional logging, while the radial difference of electromagnetic wave logging can often give a direct and correct waterout indication to the response of waterout degree.
(2) At present, electromagnetic wave logging only measures the phase difference but does not provide the electromagnetic wave amplitude curve, which cannot effectively calculate the phase resistivity and dielectric constant, so quantitative interpretation must be established on the basis of phase difference.

(3) Because of the limitation of vertical resolution, electromagnetic logging is not suitable for thin layer evaluation below 0.4 m. The content of argillaceous and calcium has a great influence on the response of waterout characteristics. Therefore, the lithologic influence correction for phase difference should be carried out in the future interpretation methods to meet the needs of surface and outer interpretation.

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