A feasibility study of hydrocarbon detection in carbonate reservoir using electromagnetic sounding

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Summary

The frequency dependence of the amplitude of electromagnetic field in marine carbonate reservoir has been studied through experimental measurements of the carbonate samples with different oil saturations to explore the variation of frequency dependence in amplitude and phase of the electromagnetic fields. Our experimental results show that the percent frequency effect (PFE) of the amplitude and phase of the electromagnetic field can be related to the hydrocarbon saturation in samples and the higher the hydrocarbon saturation, the stronger the percent frequency effect is. The percent frequency effect has been analyzed by using two field survey lines acquired from a known carbonate hydrocarbon reservoir in North-wet China and the high PFE anomaly has been used to map the boundary of the hydrocarbon reservoir. The anomalous polarizability can distinguish hydrocarbon bearing zones from those that have high resistivity from special lithology. Through experimental results and field data sets, it is shown that electromagnetic sounding can be applied to detect the hydrocarbon under favorable reservoir conditions and also PFE anomaly may be a very important method of quantitative assessment of hydrocarbon saturation.

Introduction

Hydrocarbon resources stored in marine carbonate formations have gained attention for several decades for their high quality, large quantity, and wide distribution. (Zhou and Xu, 2009). The effects of the diageneses of the dolomitization and of the structural and stratigraphic stress on the carbonate formation have resulted in abundant of heterogeneously distributed vuggs and fractures in the carbonate reservoirs. The heterogeneity of the secondary porosity causes the complexity and the peculiarity of marine carbonate reservoirs that limit the expedient development of exploration and exploitation. As an effective tool, seismic exploration is widely accepted and applied in carboniferous oilfields all around the world. Sometimes, however the information shown on the seismic profile are difficult to interpret in many carbonate targets. For example, some strong reflections, disordered reflections, or weak reflection of scattered waves that occur within the carbonate section are difficult to correlate with the porosity or hydrocarbon saturation (Jin, 2005).

Carbonate formations with few fractures present characteristics of high density and resistivity, and if it is developed of vuggs and fractures, it always presents low resistance because of the connected water filling pores. The electromagnetic survey takes advantage of this discrepancy to detect fluid-filled fractured carbonate sections. Therefore, as a complementary mean to seismic method, electromagnetic surveying is a suitable method of mapping and evaluating the hydrocarbon bearing formation with very high precision (Gu et al., 2012; Xiao et al., 2005).

In recent years, great progress has been made in the study of characteristics of complex frequency dependency of electromagnetic fields in sandstone (Xiao et al., 2005). Several authors (Zhdanov, 2008) have achieved insights in frequency dispersion and its measurement methods in clastic rocks, they found that multiple factors, such as frequency of measurement, properties of pore fluids, electrical characteristics of frame particles' surface, exert effects on the amplitude and phase of the frequency dispersion in rocks. And they have shown that there is a close relation between frequency dispersion and hydrocarbon saturation. The higher the hydrocarbon saturation in rocks is, the stronger the frequency dispersion occurs that hints the hydrocarbon related induced polarization. This paper focuses on topics of the frequency dispersion of the EM field in the marine carbonate reservoirs which are rarely discussed before, to the best of our knowledge. Through the experimental results of carbonate rock samples with various hydrocarbon saturation, we have analyzed the relationship between frequency dispersion of the EM fields and the types of fluid, hydrocarbon saturations within carbonate rocks. It is found that there is quantitative relationship between magnitude of frequency dispersion and hydrocarbon saturation. We provide evidence from experimental data that electromagnetic exploration can be an effective tool for exploration of carbonate hydrocarbon reservoirs.

Frequency dispersion of the EM fields in carbonate formations

Theoretical basis of rocks' frequency dispersion

Induced polarization (IP) is a physiochemical phenomenon that is initiated by charge separation in geologic media exposed to external current induction. In an electromagnetic survey, the variation of potential difference caused by IP is expressed in percent of frequency dependent dispersion. It can be estimated by two characteristic parameters of frequency-dependent amplitude and frequency-dependent phase in frequency domain of IP. Different geology media show discrepancies in frequency-dependent amplitude and frequency-dependent phase, which are the basis of solving the geological problems.

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In resistivity method, apparent resistivity can be calculated by:

$$\rho_s = K\frac{\Delta V}{I} \qquad (1)$$

where, I is current, ΔV is potential difference between measuring electrodes M and N, K is array factor. In complex domain, we note:

$$\Delta V = \Delta V(f)e^{i\varphi(f)} \qquad (2)$$

Therefore, apparent resistivity is also a function of frequency dependent and a complex function in frequency domain.

$$\rho_s(f) = \frac{K}{I}\left|\Delta V(f)\right|e^{i\varphi(f)} = \left|\rho_s(f)\right|e^{i\varphi(f)} \qquad (3)$$

where $\rho_s(f)$ is complex resistivity, $|\rho_s(f)|$ is amplitude, and $\varphi(f)$ is phase.

In frequency domain, the magnitude of the IP is usually expressed in percent frequency effect (PFE). In this paper, we adopt the concepts of dual-frequency amplitude and dual-frequency phase (Xiao et al, 2006). The dual-frequency amplitude anomaly can be written as:

$$\Delta A = \frac{A_L - A_H}{A_L}\times 100\% \qquad (4)$$

where, A_L and A_H are low-frequency amplitude and high-frequency amplitude respectively. The anomaly of dual-frequency phase may read:

$$\Delta\varphi = \frac{\omega_2\varphi(\omega_1) - \omega_1\varphi(\omega_2)}{\omega_2 - \omega_1} \qquad (5)$$

Here, $\varphi(\omega_1)$ and $\varphi(\omega_2)$ are absolute phases of field source when frequency is ω_1 or ω_2 (Liu, et al, 2001; Liu et al, 2007).

Experimental measurement of frequency dispersion's in marine carbonate rocks

In order to understand the frequency dependent characteristics of resistivity and polarizability in carbonate reservoirs, we take 10 core samples from 6 boreholes that were saturated with different fluid types and various hydrocarbon saturations, the tested cores consist of four dolomite blocks and six limestone ones, and then we measure the frequency dispersion.

Some conventional experimental procedures including washing oil and immersion in salt water, drying and weighing are needed in the preparing steps. (1) Weighing the core after drying. (2) Adjust the simulation formation water of 4000 mg/L in salinity, let cores to be 100% water saturated and measure the wet weight. (3) Putting core above into core clipper at 50°C, adding pressure to 10 Mpa and measuring its electrical parameters and dispersion's characteristics in different frequency. (4) Altering water saturation by evaporation method, then let it to be oil saturated.

We chose 5 cores of dolomite in Su No.22 well for the first test. And as a comparison, several cores in Niu No.19 well were also taken and we did similar experiments. The results of two groups show sound consistency in fluctuations of frequency dispersion.

Characteristics of the frequency dispersion acquired from experimental samples

Having obtained the experimental results of the frequency dependent amplitude data of all the tested samples described above, we analyzed them for five different saturations as follows. Figure 1 and figure 3 indicate measured amplitudes as a function of the excited frequencies. It is shown that the amplitudes decline as the frequency increases, whereas the phases and reactance rates (imaginary part) shown in Figures 2 and 4 present decline trends at first and then creep up as the frequency increases. The reason for this variation in trend is that the IP effect is getting weaker and EM effect is getting stronger as the frequency increases. Compared with the results of the water-bearing cores, it is suggested that the resistivities of the oil bearing cores are higher and the magnitude of their frequency dispersions are more significant. Also, with the same frequency, amplitudes of PFE and phases increase with the hydrocarbon saturation.

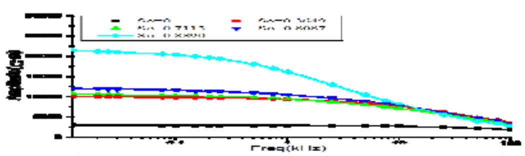

Figure 1. Variations of the amplitudes of complex resistivity with frequencies acquired from limestone cores.

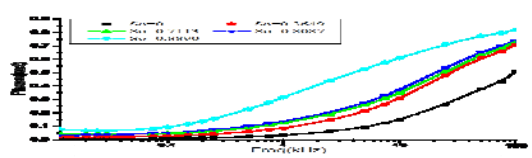

Figure 2. Variations of the phases of complex resistivity witch frequencies measured in limestone cores.

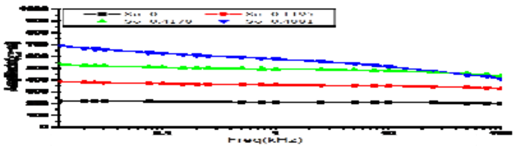

Figure 3. Variations of amplitudes of complex resistivity asa function of frequencies acquired in dolomite cores.

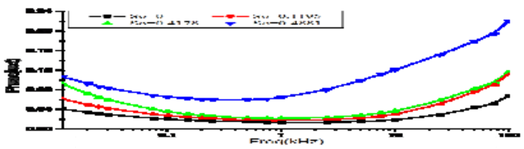

Figure 4. Variation of phases of complex resistivity as a function of frequencies measured in dolomite cores.

Extraction of the polarization anomaly from frequency dependent dispersion curves

It is known from Figure 1 to Figure 4, that if the frequency is decreased to below 1Hz, IP effect is dominating over the EM effect, and the IP effect is getting weaker than that of the EM when frequency grows from 1Hz. Therefore, we have to extract the IP anomalies by calculating percent frequency effect (PFE) within the frequency spectrum of 0Hz-0.1Hz. It can be suggested that cores bearing higher oil saturation show higher dual-frequency amplitude, higher resistivity and higher dual-frequency phase. These response characteristics provide reasonable hints for electromagnetic sounding survey for the hydrocarbon detection in carbonate formations.

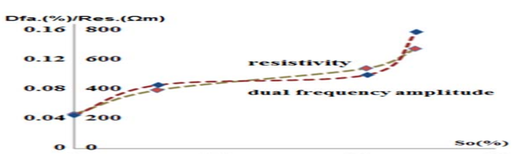

Figure 5. The relationship among oil saturation, resistivity and dual-frequency amplitude acquired in dolomite cores.

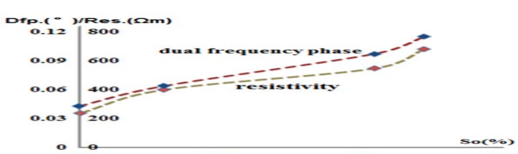

Figure 6. The relationship among oil saturation, resistivity and dual-frequency phase measured in dolomite core.

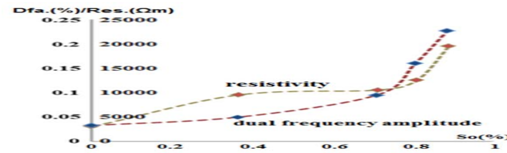

Figure 7. The relationship among oil saturation, resistivity and dual-frequency amplitude acquired in limestone cores.

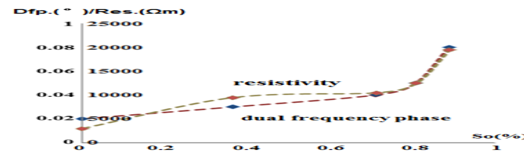

Figure 8. Relationship among oil saturation and dual-frequency phase measured in limestone cores.

Field data analysis and application

Figure 9. Map of test line location.

In order to verify our experimental insight by field survey data, we have carried out a powerful TFEM test line in a known oil field and hoped to derive any relations between the boundary of hydrocarbon and the PFE anomaly. The selected test site is in Suqiao region in north central China, where the buried hill carbonate reservoir formed large hydrocarbon trap. The test line extends 6 km and includes 30 survey points. The test line is perpendicular to the structural trend and stretches across the oil field shown in Figure 9.

Figure 10 and 11 indicate the frequency spectrum of the amplitude acquired in point A at a location outside the oil field and that of point B which rests inside the oil field. The calculated dual-frequency amplitude is shown in Figure 10 and dual-frequency phase is in Figure 11. For comparison sake, the measured anomaly from point within oil field and that outside of the oil field have been drawn in the same figure.

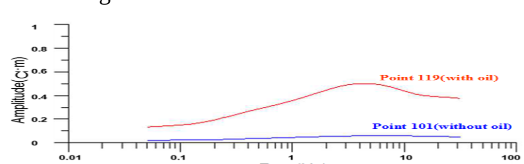

Figure 10. Extracted amplitude anomalies of point A and B from field survey data.

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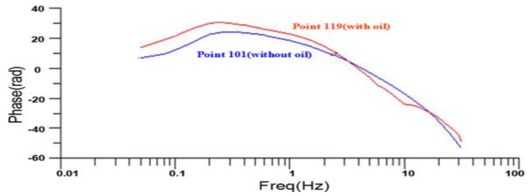

Figure 11. Phase anomalies derived from field data of points A and B.

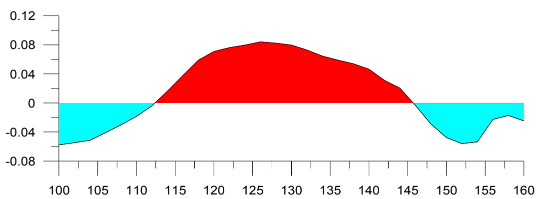

Figure 12. Dual-frequency amplitude anomaly extracted from the field data of the test line.

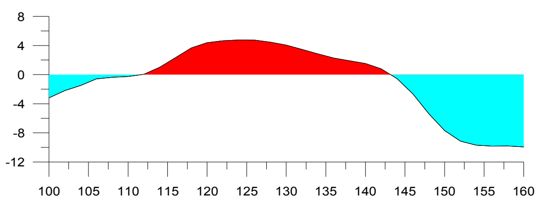

Figure 13. Dual-frequency phase anomaly extracted from field data of the test line.

As shown in the Figures 11, 12, 13, above, it is suggested that the extracted amplitude of the PFE in point A is several times that in point B in terms of magnitude of PFE. The phase frequency dispersion in point B is stronger than that in point A when the frequency decreases to below 3 Hz. For all of the survey points, we found that the amplitude and the phase anomalies were higher in oil-bearing sites than that in water bearing points below a specific low frequency. To extract the anomaly of IP effect, we derive the dual-frequency amplitude in every point of the test line, and obtain the anomaly according to equation (4). Adopt the average of the anomaly as a relative criterion, the anomaly above it is set to be positive and filled with red color to indicate the oil favorable area, whereas the anomaly below it is set to be negative and light blue colored to show the water region. From result in Figure 12, we find that the anomaly is between points 114-145. The result in Figure 13 has been processed in a similar way and acquires the dual-frequency phase anomaly. In Figure 13, it is shown that the anomaly is between points 114-144. Examining the location and point numbering in the test line, it is suggested that the oil field boundary corresponds well to the high amplitudes and phases anomalies.

Conclusions

The experimental results of carbonate reservoir core samples show that the resistivity, PFE amplitude and phase grow as the increase of oil saturation, as does the dual-frequency amplitude/phase. Dry or water bearing samples are extremely weak in frequency dispersion, and nearly non-existent in dual-frequency amplitude and dual-frequency phase anomalies. The field survey data of known carbonate hydrocarbon reservoir shows that the boundary of the reservoir can be mapped by examining the strong amplitude and the high phase anomalies in low frequency spectrum of the frequency dispersion curves. Though initial results in this paper show perspective of the powerful TFEM in hydrocarbon detection in carbonate reservoirs, there are still open problems of physical mechanism needed to be studied in further.

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