New Approaches in the Interpretation of Magnetic Survey Data during Prospecting and Exploration of Hydrocarbon Deposits

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Abstract

The presence of hydrocarbons in the basement and sedimentary cover triggers the epigenetic processes that make the formation of iron minerals possible. At that, there is a fairly clear zoning: the center of flow migration is presented by paramagnetic minerals, the borders are presented by ferromagnetic minerals. This fact makes it possible to use magnetic survey during the prediction and the search for oil and gas deposits. The main problem is the interpretation method of the data obtained through the data magnetic survey. The authors of the article suggest the use of multiple approaches to the analysis and interpretation of the obtained data. The first approach is the lineament analysis, the peculiarity of which in this case is the design of maps on the basis of linear objects expressed in a magnetic field. This map will reflect the borders of objects contrasting by magnetic properties, including the deposit borders. The comparison of magnetic field lineaments and the lineaments of relief helps to identify the fault zones in which the migration of hydrocarbons takes place. Another approach in the interpretation of magnetic survey data is the calculation of the magnetic field fractal characteristics. An indication of hydrocarbon migration in this case is the fractal dimension, the high values of which are characterized for the areas where the migration of hydrocarbons took or takes place. The basic wavelets developed on the basis of point source potential derivatives were used for the quantitative analysis of the magnetic field.

Keywords: Fractal Analysis, Hydrocarbons, Lineament Analysis, Magnetic Survey, Wavelet Transformation

1. Introduction

There is quite a number of service geophysical companies providing a wide range of services for the operations by the methods of aerial and ground-based magnetic survey in Russian Federation and abroad. The services include the qualitative and quantitative interpretation of data, the spectral analysis of magnetic field, etc. Dozens of original algorithms are developed solving various problems of magnetometry. At the same time, for the most part, all of the obtained solutions are reduced the allocation of anomalies such as “deposit”*. Some features of the magnetic field are explained quite often by epigenetic changes of the sedimentary rock cover under the influence of hydrocarbons, but the analysis of the change nature was performed very rarely. The detailed study of local magnetic field fine structure was performed even more rarely. The proposed methods use, as a rule, the traditional approaches in the interpretation of ground magnetic survey results*.

The active epigenetic processes initiated by hydrocarbons, lead to the change in the formation of new iron minerals. At that magnetic properties are altered in large volumes of rocks. The penetration of hydrocarbons leads to the restoration of iron and to the formation of iron sulfides (pyrite, pyrrhotite) at a sufficient partial pressure of sulfur. Within the weak recovery areas at the front of a hydrocarbon stream the mobility of iron is substantially increased and an intensive removal of iron takes place. Finally, the sections with a high content of magnetic iron minerals (greigite, magnetite - depending on geochemical environment) are developed at the border of reducing and oxidizing environments (the depths make 600-800 m and 100-200 m)*.
Obviously, the essential factor of an active fluid dynamics is the presence of weakened, permeable areas in the sedimentary cover, which may perform the migration of fluids, both vertically and laterally. In this case, the "attenuated permeable" areas are the faults and structures related to them. A limited lateral migration may partially pass through the permeable formations and cracks. In addition, the magnetic properties of rocks may be influenced significantly by biological and diffusion processes (the activity of sulfate-reducing bacteria).

2. Lineament Analysis of Magnetic Survey Data

The basis for the calculation of the lineament maps and the maps of lineament density using a digital model of the magnetic field, is the map of strokes - primary linear objects expressed in a magnetic field. The calculation of stroke field and all derivative fields was carried out by A. Zlatopolsky method. In order to determine the strokes in the digital model of a magnetic field the straightened parts of positive and negative anomalies are detected. The next step in the analysis of strokes is the formation of straight extended lineaments on their basis. Here you can set a filter, selecting lineaments according to their severity. In addition to the calculation of lineaments and their trends the map of primary strokes is used to calculate the density of lineaments (stroke density). The value of each cell in a density raster demonstrates the ratio of all strokes total length to the area of this cell vicinity.

The structure of the magnetic field lineaments reflected linear contrasting objects and their boundaries in a magnetic respect (Figure 1). Such objects may be located in a crystal base, and in a sediment cover. The separation of anomalous magnetic field sources by depths allows you to split these objects. The particular interest is presented by the objects in a sedimentary cover, where the sources of linear structures in an anomalous magnetic field are the lithological borders, the zones of facial replacement and epigenetic changes. The most contrasting structures are formed along the fractured zones. The reasons for high or low rock magnetization in these areas are precisely epigenetic changes of ferrous minerals due to the effect of hydrocarbons.

From the point of view of hydrocarbon migration study in the sedimentary cover, the maps of lineament comparison identified along the digital relief model and the magnetic field are very interesting and informative ones. The nature of coinciding lineaments is quite simple: these are the zones of fracturing, which involves the migration of fluids containing hydrocarbons.

For example, this is presented by the dissolution of magnetic iron minerals and the takeaway of iron near the deposits and the deposition of magnetic minerals in fractured zones on the border of oxidizing restoration zones.

Figure 1. The example of the magnetic field lineament analysis (blue color corresponds to the axes of positive magnetic anomalies).

3. Fractal Analysis of Magnetic Field

Despite the great interest to the fractal properties of geophysical fields, their value is significantly undervalued. We showed earlier that the energy spectra of magnetic anomalies with a good degree of approximation can be approximated by the following function

\[ S(\omega) \propto \omega^{-\alpha} e^{-\beta \omega}. \]  

(1)

On the territory of the Republic of Tatarstan the values \( \alpha = 0.71, \beta = 1.92 \) were obtained for \( \alpha \) and \( \beta \) parameters.
This empirical result is explained by a horizontally layered model of the magnetically active medium with a vertical statistically fractal distribution of magnetization. Under this model, the parameter $\alpha$ is related to the fractal dimension of the magnetization by the following ratio

$$\alpha = 5/2 - D_f,$$  \hspace{1cm} (2)

and the parameter $\beta$ is the depth of the model upper edge for magnetically active medium. On the territory of RT the following estimates of the fractal dimension mean values and the depths of the model upper edge were obtained: $D_f = 1.7 +/- 0.07$, $h = 1.85 +/- 0.2$ km.

According to the fractal analysis of the magnetic field (the method of absolute increments) the graph of the specified dependence in bilogarithmical scale experiences the inflection that also fits well into the provided environment model. At the same time on a small scale the dependence curve is approximated by a straight line, the incline of which depends on the parameter $h$, and within large scales by a straight line, the incline of which depends on the parameter $D_f$.9,10

The intersection point of these two lines provides a certain interest. Its situation is extremely sensitive to the angle between the lines and becomes unstable at low angles. In its turn, this situation can only be if the surface boundary is not clearly expressed and has a fractal character.

In order to study the spatial arrangement of these areas we use the calculation method of the local fractal dimension for mobile fractional sets.

The maps of fractal characteristics concerning an anomalous magnetic field reflect the complexity of the magnetic field and provide a summary information on the extent of geological environment secondary transformation (Figure 2). The zones of high fractal dimension are observed in the areas of intense destruction of hydrocarbon deposits in the upper part of the sedimentary cover. In these areas the migration of hydrocarbons took place, of course. In the lower part of the section (including the basement), the origin of these anomalies may be associated with the processes of low-temperature metamorphism associated with the rising migration of fluids and energy (heat), which may be an indirect sign of hydrocarbon fluids formation and migration in the bottom of the sedimentary cover.

4. “Natural” Wavelets

A very important issue is the quantitative interpretation of magnetic survey data. The detailed three-dimensional petromagnet models allow us to trace the zones of possible epigenetic change of rocks under the influence of hydrocarbons on different structural floors of a sedimentary cover (Figure 3).

For the analysis of potential geophysical field anomalies, we used the basic wavelets constructed on the basis of higher potential derivatives of the point source corresponding field. Such wavelets were called “natural”
ones. We showed previously that the choice of this class of basic functions was successful for several reasons:

1. It is proved that at the decomposition of anomalies with the help of the “natural” basis, the wavelet spectrum is also an exact solution of the corresponding inverse problem.
2. It was proved that according to “natural” wavelet spectra of a point source its parameters are determined clearly (position, weight/magnetization).
3. It was proved that in order to obtain the spectrum for “natural” continuous wavelet transformation one may use the results of the fast discrete wavelet transformation.

5. Conclusions

The proposed approaches to the interpretation of magnetic survey data, will surely have the right to exist. Lineament analysis allows you to outline the boundaries of hydrocarbon deposits within limited periods. One can’t talk on the calculation of the quantitative characteristics in this procedure, but oil and gas availability of the area may be indicated with a high confidence. The use of fractal analysis and the use of “natural” wavelets is possible at the quantitative interpretation necessity. The sources of magnetic anomalies at this decision are the point objects, and the solution of an inverse problem in practical issues as the point source system cannot be final for obvious reasons. Therefore, you should continue to carry out the procedure for the equivalent redistribution of sources taking into account a priori geological and geophysical data.

6. Summary

The problem of magnetic field fine structure study is an extremely important task in terms of geological history of hydrocarbon fields reconstruction concerning the deposits of hydrocarbons, their prospecting and exploration. From this perspective, the compounds of iron are very effective indicators of changing geochemical conditions. They are widespread in the sedimentary rocks which allow to perform studies almost everywhere.

The importance of this area is the ability of a field study at all stages of development, i.e., the monitoring of hydrocarbon migration during the operation process. The improvement of techniques at all phases of works is the most important problem, the solution of which will provide high-quality data and respectively the qualitative scientific results. Another set of problems in this scientific trend is connected with the improvement of research tools: the creation of absolutely new tools which allow to obtain previously unavailable information, the increase of sensitization and the immunity of traditional instruments.

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8. References

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