Simultaneous EM and IP inversion using relaxation time constraints

S. Garina,[1] S. Ivanov,[1] E. Kudryavceva,[1] P. Legeydo,[1] P. Veeken[2*] and V. Vladimirov,[1] **discuss geochemical alteration zones above hydrocarbon accumulations, identified by differentially normalized electromagnetic surveying, and how they may give rise to induced polarization (IP) anomalies.**

Forecasting the presence of hydrocarbon accumulations, by means of differentially normalized electromagnetic surveying (DNME), depends on the distribution and interaction of polarization parameters. It is common practice to determine the geoelectric parameters by a simple Cole-Cole inversion procedure, based on subsurface modelling with an iterative update procedure (e.g., Veeken et al., 2009a). The drawback is that inversion does not generate a unique solution, i.e., usually a preferred model out of a wider range of possibilities (equi-probable solutions) is selected. Additional subsurface knowledge puts constraints on the outcome of the inversion exercise, e.g., only geologically meaningful scenarios are accepted as available solutions. In geoelectric surveying not only one parameter (resistivity ρ) is determined in the analysis of the IP field response, but three other parameters are considered as well. In the case of Cole-Cole modelling these parameters are: η, τ and c (cf. Legeydo et al 2011). Tau is the relaxation time and c is the Cole-Cole coefficient. Unfortunately the equivalence range of the outcome frequently remains quite large and sometimes additional problems appear, hampering adequate subsurface modelling.

One uncertainty in geoelectric surveying is the exact nature of the registered electrical signals. The total field response is always recorded in electrical experiments. The measured field is composed of IP and EM components, which are basically not additive (Veeken et al., 2010). Another constraining factor is the relative weakness of IP response in highly conductive rocks. At the same time, there is often a lack in a prior information on the distribution of the polarization parameters in the subsurface model. Under those circumstances, the solutions to the inversion problem will be distributed randomly within the equi-probable solution range. Repeatability of the inversion solution is not sufficient to guarantee its credibility. A further uncertainty is caused by possible 3D distortions and the special relationship between the polarization parameters. Obviously, it will be beneficial to fix parameters τ and c in order to calculate parameter η. It should be realized that in such a case the resulting values of η definitely depend on the choice of the starting values for τ and c. Other modelling issues are:

- The number of polarizable layers (in 2D sense)
- The number of objects (in 3D sense)
- Their position in the subsurface model.

Sensitivity to the polarization in the lower part of the model is usually insufficient and thus can be assumed to be zero.

Due to the non-uniqueness of the inversion problem, an earth model can be generated with the same accuracy and degree of confidence by varying the resistance in the upper layers. To take care of the ambiguity problem, first a quantitative separation of IP and EM fields is needed (Veeken et al., 2009b). It is necessary to establish stable polarization parameters, on which the interpretative model can be based. In the DNME method the IP field (induced polarization of galvanic origin) has just such properties. The IP component is determined by applying appropriate procedures in data acquisition and processing in the lab. After proper data preconditioning, an algorithm for 2.5D inversion is used and the results of inversion are further optimized with 3D modelling constraints. The DNME approach to EM inversion is robust, as shown by many successful IP studies over the last 10 years. It allows discrimination and avoidance of false IP anomalies that are not caused by the presence of hydrocarbon filled traps.

Distinctive features of DNME

A distinction between DNME and other electrical methods is formed by the way IP processes are analyzed. Veeken et al. (2009b) have shown that DNME allows quantitative separation of electromagnetic induction (EM) and IP field components in a wide time range (patent 2399931). EM and IP processes overlap each other in sedimentary rocks with media of relatively high conductivity. This condition

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is typical for most oil- and gas-bearing regions. An extra uncertainty in the inversion is introduced when no proper separation of the field components is achieved.

The IP processes are screened and filtered to better discriminate the potential HC response. This crucial step in the DNME workflow is obligatory because IP depends on many lithological factors: such as mineral composition, clay content, porosity, formation water salinity, and so on. Not every IP anomaly measured at the surface is connected with HC occurrences at greater depth. It is important to separate the anomaly from the normal background value in an optimized way. Therefore every survey is carefully processed with specially selected and adapted parameters.

Generation of the polarization parameters

In practice the possible inversion solutions are controlled by geological and geophysical information from other prospecting methods, like seismic reflection profiling, deep hole drilling, and well logging.

For example, in a test area of the Sakhalin shelf (Okhotsk Sea) the background average resistivity r according to the electric logging, varies from 1 to 3 Ohm * m from the bottom of the well to a depth of 2–2.5 km. Increase of ρ is observed at certain intervals, or through increase in hydrocarbon saturation, or by the appearance of carbonate or siliceous layers (cementation). The structural configuration of the marker horizons is known from interpreted seismic data and provides constraints on the inversion to determine the resisitivity distribution.

The next step is quantitative separation of electromagnetic coupling (EM) and induced polarization (IP) field components. It requires analysis of particular transforms of the measured transient field response that can be assigned to one point and have different functional dependence on IP and the inductive fields. These transforms are normalized spatial derivatives (more precisely, the final potential difference), because the space-time structure of the EM and IP fields is different (Veeken et al., 2009b). The IP field component, obtained after its separation from the total field, represents a stable polarization characteristic in DNME. It forms a solid basis to select input parameters for the inversion and the interpretative model.

In addition to the resistivity (ρ), three more parameters – η, τ, and c – are used to model the IP response. But these parameters also have the undesirable effect of increasing the equivalence solution range of the inversion. Fixation of parameters τ and c is required to augment the reliability of the determined η value in the polarizable media. Since η depends explicitly on the chosen values of τ and c, it is necessary to have ways to estimate these parameters in a realistic manner, or at least one of them should be assumed known as part of the input. At this stage there are two ways to estimate possible values of relaxation time τ.

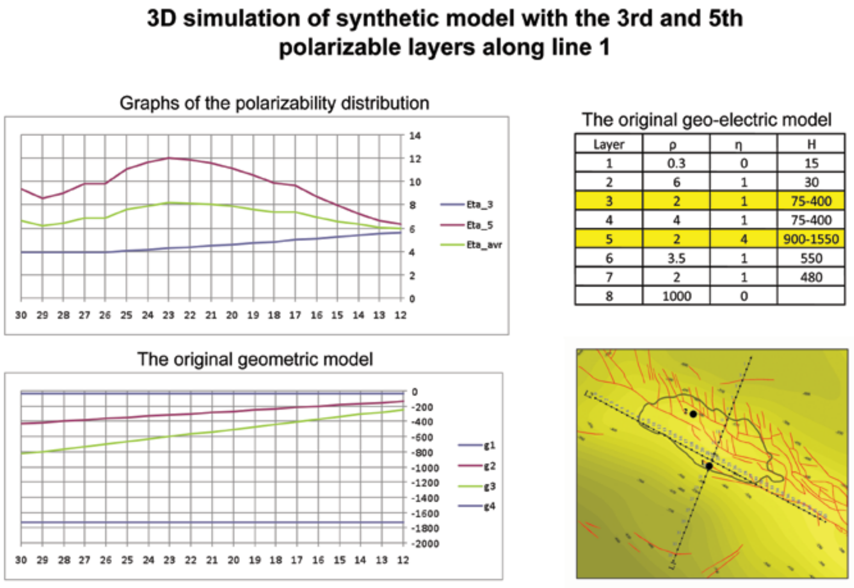
Initially, possible values of τ (of course, integral, but not in layers or objects) can be estimated from the IP field analysis. Then these values are transcribed to one of the layers by way of inversion. For these purpose special coefficients are calculated by a formula as sum of two or three exponents.

$$IPg(t) = \sum_{i=1}^{n} a_i e^{-\frac{t}{\tau_i}}$$

Where: IPg(t) – time function of IP field, α – amplitude factor for each layer (object), t – time of decay, τ – time constant (relaxation time) for each layer (object), n – number of polarizable layers (objects). Parameters α, τ, and R2 are calculated, where R2 is a measure of the reliability of the approximation. It is clear that values of τ are only approximated, but due to low sensitivity to this parameter, they may serve as a reasonable starting point for the inversion.

The second strategy is a method whereby τ values are empirically determined via reference objects (productive and non-productive wells). Filtering of IP field response by means of relaxation time τ is carried out. The approach is based on the following factors: IP response over hydrocarbon fields is predominantly due to the presence of epigenetic pyrite (electrical conductive mineral) in the area where there is a geochemical mobility barrier in the overburden (Kudryavceva et al., 2010). The IP process of electrical conductors is related to different kinds of over-voltage, caused by discharge, adsorption, and/or diffusion. Values of the relaxation time for pyrite samples have been empirically determined: 0.002–0.01 second for over-voltage of discharge, 0.1–0.2 second for over-voltage of adsorption, from a few seconds to several minutes for over-voltage of diffusion (Komarov, 1980). Since time of decay for measurement of DU values in the DNME methodology varies from 2–8 seconds, only the first two over-voltage types are of interest.

Komarov (1980) also observed that for small electron-conductive spheres it is proportional to the sphere's radius and will be typically less than τ for larger mineral crystals. Epigenetic pyrite is fine-grained (less than 0.1 mm). Therefore, it is expected that the relaxation time associated with a transient process in the deposits above a hydrocarbon field, containing epigenetic pyrite, will not be higher than the one determined experimentally for samples of pyrite (i.e., tenths of milli-seconds or less). Thus, the range of τ values for selection significantly contracts. It is hence convenient to carry out IP field filtering, separating components associated with a narrow range of small τ values, through the support of the response measured in reference objects.



Layer	ρ	η	H
1	0.3	0	15
2	6	1	30
3	2	1	75-400
4	4	1	75-400
5	2	4	900-1550
6	3.5	1	550
7	2	1	480
8	1000	0	

Figure 1 *Influence on the IP response distribution of inclined geoelectric layer boundaries and wedging interfaces located on the flank of a geologic structure. a) Graph with curves of computed polarization coefficient distribution for differently inclined interfaces as shown in depth section; b) Depth section with interfaces of the various geometric configurations.*

IP anomalies sorting

The modelling and IP filtering based on τ allows the optimization of the geoelectrical model and discrimination of IP anomalies associated with hydrocarbon fields. This approach ensures that under certain conditions (absence of sharp lithological changes in area, or a sufficient number of known productive and non-productive wells in the presence of such changes), objects are not missed that are of interest for hydrocarbon prospecting.

The intensity of the IP response depends not only on the presence of hydrocarbon filled traps, but it is also related to lithological factors like: porosity, clay, salinity of formation, wood fragments, and abrupt gradient changes of the bedding of rocks with different geoelectric properties. Simultaneous analysis of ρ and η distribution is required for identifying IP anomalies triggered by lithological and/or porefill changes. Polarization coefficient values are normalized in respect to its correlation index with resistivity values, in order to remove the influence of these factors on the IP response. Complex parameters, based on the polarization and the conducting properties of the media, can be exploited too. Classification of the IP anomalies can be done (Veeken et al., 2010).

Detailed 3D modelling helps to identify IP anomalies related to 3D objects that are not connected to any hydrocarbon trap. DNME investigations in the Caspian Sea region have shown the benefits of this type of 3D modelling. The seismic data illustrate a large anticlinal structure with dipping flanks, affected by some tectonic dislocations. Taking into account that the seismic layering may not coincide with the electric boundaries, additional calculations were performed with help of a computer program, simulating the analytic continuation of the IP response. The spatial position of 3D objects is computed and, in conjunction with seismic constructions, the geometrical shape of objects with different electrical properties is determined. The results then form the input for geometric parameterization of the modelled geoelectric section in the Cole-Cole inversion exercise.

During the study of the influence of the complex shape of the 3D object associated with the structure in the Cretaceous and Paleozoic sediments on the IP response, it was found that a false IP anomaly appeared. This was due to a very rigid parameterization of the non-adjacent layers (Figure 1). Subsequent 3D modelling was carried out for different types of synthetic models. These were constructed from a number of known structures. The modelling showed high stability of the rigid parameterized model, with the adjacent polarizable layers having distortions. The latter occur under the influence of 3D irregularities of the medium in the time of IP response calculation. Prediction accuracy is increased when the modelling takes into account the polarization and complex parameters, as well as the variations in the conductive properties of the media.

Computation of maximum possible limits of relaxation time τ in the target layer (for IP response determination) enables identification of IP anomalies connected with special electric conductive minerals located in an oxidizing or neutral environment (e.g., breached HC accumulation in a strat trap configuration). Obtaining accurate values of τ by inversion stays problematic, because of low sensitivity and range in solutions due to model equivalence. However, the maximum and minimum limit for each observation point can be estimated. Theoretically it can be shown, confirmed by experimental measurements in the laboratory and tested in field practice (e.g., Caspian Sea), that under neutral and/or oxidative conditions relaxation times (τ) values are increased several times. This is due to appearance of an oxidized rim on the boundary of electrical conductive pyrite grains.

Conclusions

DNME provides a reliability measure for the identification of IP anomalies associated with hydrocarbon deposits, despite the dependence of the recorded IP response on other factors like lithology, petrochemistry, and different 3D interferences. The validation of the HC-related IP anomalies are achieved by: 1) Quantitative separation of electromagnetic induction (EM) and IP processes; 2) IP anomalies filtering via a number of algorithms, among which are IP filtering with aid of τ, simultaneous analysis of ρ and η distribution, and computation of maximum possible limits of relaxation time τ in target layer; and 3) Usage of 3D modelling for recognition of possible distorting effects of the available three-dimensional objects to the IP response.

Acknowledgements

Authors express their gratitude to Lukoil, Gazprom, and Rosneft for permission to present some of their DNME study results.

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