An advanced deep penetrating EM technique for hydrocarbon and mineral exploration: mVECS

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Summary

We present a new electromagnetic method, the vertical electric current sounding (VECS). VECS uses a circular electric dipole (CED) as source and is useful for hydrocarbon and mineral exploration. CED is a purely galvanic source generating a non-stationary transverse magnetic (TM) field that differs from a loop or a line source that respectively are pure inductive and galvanic sources. For the source installation in CED, one of the transmitter poles is grounded in the central point and the other poles are uniformly grounded around the central pole with a radius determined by the desired depth of investigation. Within the limits of quasi-static approximation, the normal magnetic field on the earth's surface and above it for a horizontally layered medium is vanishes and only a radial electric component exists. A CED field is at right angle to the loop field and is azimuthally symmetric that is always governed by a vertical structure rather than longitudinal conductivity both at early and later stages. Besides, CED is a pure galvanic source that does not excite a long-term transient field, and consequently it allows a new and useful means of studying induced polarization (IP) processes. CED has been applied for both mineral and hydrocarbon explorations. In this paper, we present field results using CED and investigate ways of combining these data with seismic data for developing a new interpretation technique for hydrocarbon and mineral exploration.

Introduction

Seismic methods have been extensively used in hydrocarbon exploration for many years. Seismic data are sensitive to the contrasts of subsurface acoustic properties. Hydrocarbons and minerals on the other hand have a large conductivity contrast compared to the surrounding rock formations. Electromagnetic (EM) methods, sensitive to such contrasts, have been used in the mineral industry for many years and it is a proven technology for mineral exploration. With recent advances in the acquisition, processing and inversion, EM is rapidly emerging as a valuable tool for hydrocarbon exploration. The primary disadvantage of EM for hydrocarbon exploration is its lack of resolution at the depths that are of interest. Conventional dipole EM source is known to have a very low depth of penetration. CED, originally introduced by Mogilatov (1992) and Mogilatov and Balashov (1996) on the other hand is reported to have a maximum penetration of about 2500-3000 meters into the subsurface.

The efficiency of any electrical prospecting method depends upon several factors, out of which the choice of the EM field source is the key factor. A correct choice of source field creates an optimal space-time structure for the EM field that best interacts with target objects, providing real physical preconditions for solving the geophysical problem in hand.

We propose CED as an alternative to the classical sources: the loop and the horizontal electrical line source. It is reasonable to classify CED as a source with no magnetic field of its own. This, in other words, means that we put forward a geometry of array on the earth's surface that allows a considerable attenuation of the magnetic field of each of the conductors making up the transmitter as a whole. CED is a pure galvanic source and it can also be described as a focusing source. The source field is always governed by the vertical structure of the medium, even at the late stage of the transient, and is not governed by total longitudinal conduction. Therefore, CED allows a new and useful way of studying IP processes. Considering the pronounced vertical character of the currents under the central electrode and current circulation in the vertical planes, the electrical prospecting technique using CED is termed as the vertical electric current sounding or VECS method.

In this paper, we present some field examples of VECS method for hydrocarbon and mineral exploration and discuss the possibility of further development of this method for interpreting subsurface geological formations by combining EM with surface seismic data.

Outline of the methodology and field survey

VECS uses a centrally placed current array with eight radial electrodes at 45° angle. The lines are distributed with equal currents uniformly in radial directions and pulsed at the same instant of time.

A variety of transmitter systems located at the Earth's surface or at any other boundary that is formed by wire and grounding segments can be described with the use of the surface density of synchronously varying excitation current. In general, the field components are represented by inductive and galvanic modes (TE and TM modes). An underground loop is the purely inductive source generating only a transverse electric field (TE mode). The behavior of an inductive source (loop) and the TE process is well known in the geophysical community. The properties of the TM transient process and its application have not been studied in its full potential. The most remarkable property of the TM field include the absence of normal (quasi-static) magnetic field at the outer surface of a layered medium, and the dependence of the process on the vertical geoelectric structure.

Being a purely galvanic source with a non-stationary transverse magnetic (TM) field (Mogilatov et al., 1992, 1996), it is possible to realize CED by a set of radial current lines grounded in the center and on a circle with a radius determined by the desired depth of investigation. A detailed theoretical description of the CED can be found in Mogilatov (1992) and Mogilatov and Balashov (1996).

The field setup and the CED source field radiation are

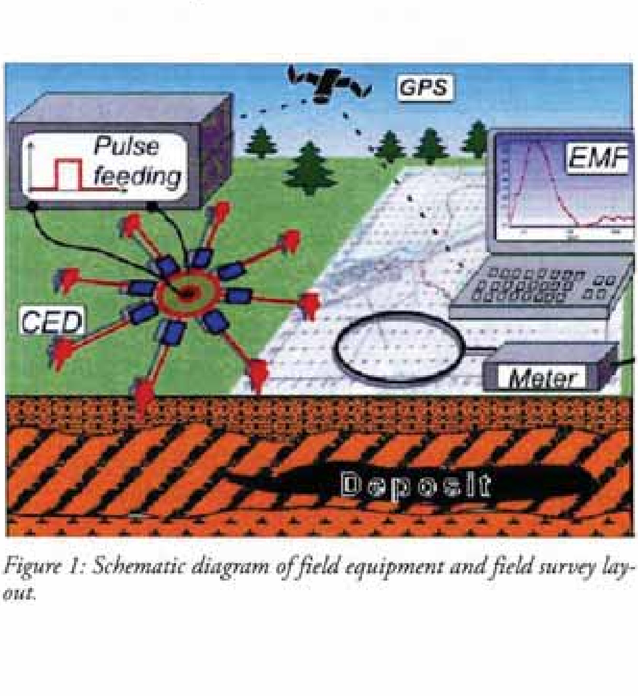

Figure 1: Schematic diagram of field equipment and field survey layout.

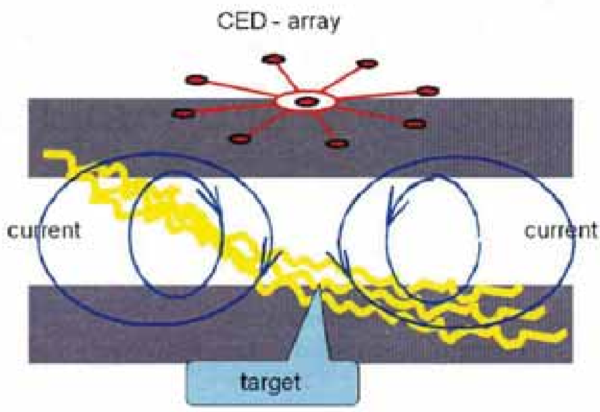

Figure 2: CED field radiation into the subsurface and interaction of the field component with the subsurface.

illustrated in Figures 1 and 2. The CED-array is placed on the surface and equal currents are aligned in radial lines by special devices. The receiver system, an inductive sensor is moved along a square grid. The receiving equipment, composed of an EM receiving unit, is linked for position and timing of pulse reading through a real-time GPS link. The EM receiver uses a PDA device, radio-linked to initiate readings and record the sampled channel values from the receiver as they are acquired. A multi-turn loop of 1m sides is laid on the ground and connected to the receiver. Multiple turns of fine copper wire ensure a high turns-moment to increase sensitivity and signal-to-noise ratio (SNR) of the recorded signal. Each decay reading is sampled over a number of definable windows and the readings are repeated to ensure repeatability. Once data are read and a repeat reading is made at each sample location, they are stored on a field computer. A normalizing correction is made on the field recording before plotting the results to account for the radial distance of the recording point from the location of the current electrode dipole. Each window reading is considered as a transient reading for time-depth and an area map of the signal intensity is formed for each temporal reference. On a contour of the received signal, it is possible to delineate location of a spatial heterogeneity. For hydrocarbon exploration, CED uses a radius of 500-800m with the current in each line up to 10A. The receiving system has a maximum depth of penetration of 5 times the radius of CED.

Results and Discussion

Figure 3 is a survey layout showing receiver locations and CED array on a known oilfield in Tatarstan, Russia. The VECS signal in a 2D time slice and in a vertical section is shown in Figure 4. The dotted contour is the area marked by a 3D seismic survey as a potential oil reserve. The VECS survey has confirmed some additional area beyond the closed seismic contour where the presence of hydrocarbon was found. This result also confirmed that

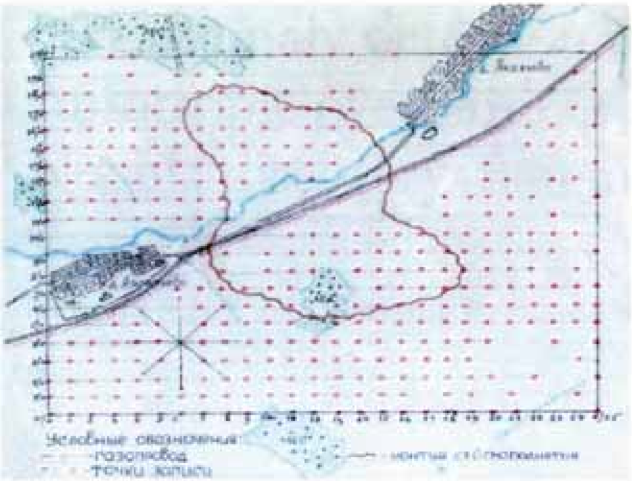

Figure 3: Map of the receiver location and CED array for hydrocarbon detection in Tatarstan, Russia, a known location of hydrocarbon.

the subsurface heterogeneity can be mapped in great detail using VECS survey. Figure 5 is a similar survey layout map with receiver and CED array locations for exploring a copper ore-body in Australia. The VECS signal in a 2D time slice and in a vertical section in this case is shown in Figure 6, and Figure 7 is a 3D image of the copper body. Figures 3-7 clearly demonstrate the usefulness of VECS for hydrocarbon and mineral exploration.

Although VECS sounds promising, it must be noted that no single geophysical method is, by itself is self-sufficient, and to accurately delineate the subsurface geology, it is necessary to couple EM with other available geophysical methods. Recent work by Mukerji et al., 2009 shows relationship between seismic velocity and conductivity. Relations such as this are promising as they could be effectively used in combining EM data with seismic in a joint

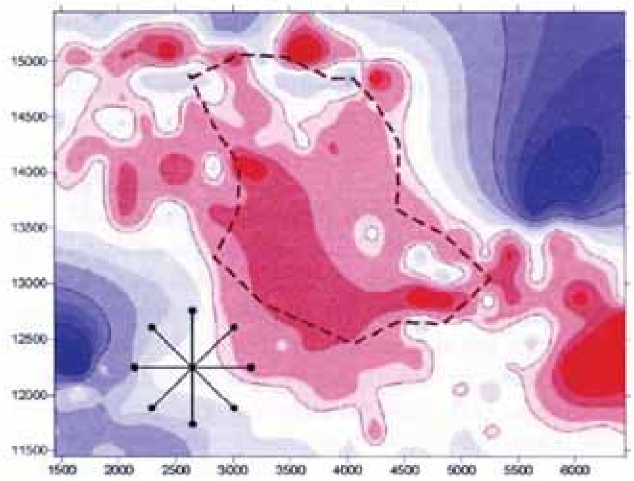

Figure 4: Horizontal section of the received VECS signal and CED array. Dotted contour shows the area where seismic survey has delineated the prospecting oil reserve.

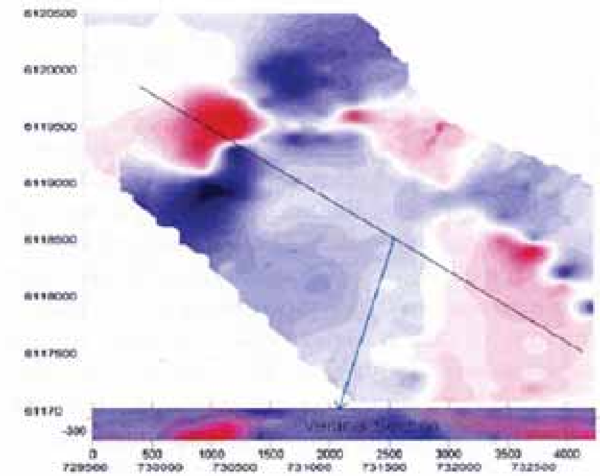

Figure 6: Horizontal section of the received VECS signal at 0.34 ms and a vertical cross-section. The red zones are the area of copper deposit.

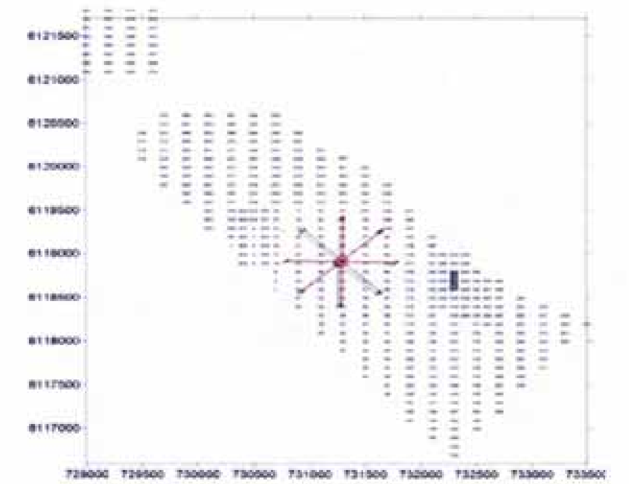

Figure 5: Map of the receiver location and CED array for copper ore-body detection in Australia.

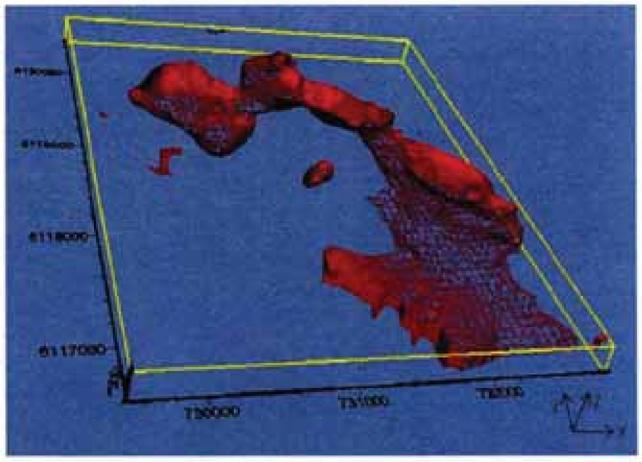

Figure 7: 3D image of the copper ore-body deposit.

seismic and EM inversion scheme. As seismic is sensitive to the changes in acoustic properties while EM is sensitive to conductivity, combining EM with seismic in a joint inversion could be an extremely valuable exploration tool. Primary limitation of EM, even for VECS, is the depth of penetration. It is however possible to run modeling studies with different parameterizations of the CED source and achieve optimum parameterizations for greater depths of penetration. This will allow EM to explore for deep targets, in excess of 3000m that is currently achievable. To stop global warming caused by greenhouse gas emissions, there are now initiatives of sequestrating CO_2 into deep saline aquifers. To avoid possible contamination of the injected CO_2 with freshwater, these sequestration sites are always likely to be deep (more than 4000m). If modeling studies could allow VECS to achieve such penetration, EM in conjunction with seismic could be effective used to monitor such carbon sequestrated saline aquifers.

Conclusions

VECS is useful for mapping subsurface heterogeneity for hydrocarbon and mineral exploration. Although maximum achievable depth of penetration for VECS is currently limited to about 3000m, it is possible to run modeling studies and optimize CED for greater penetration depths. This will allow VECS to be effectively used where depths in excess of 3000m is desired such as geophysical monitoring of carbon sequestrated deep saline aquifers. Combining seismic with VECS EM data in a joint inversion scheme has a tremendous potential as a future interpretation tool for delineating subsurface geology.

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