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Advances in Electromagnetic Survey Instrumentation and the Use of a Cased Borehole for Imaging a Deep Formations

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SUMMARY

Electromagnetic (EM) resistivity imaging methods have the potential to map subsurface fluid distribution in applications ranging from derisking potential prospects to quantifying the propagation of hydrofractures in unconventional reservoirs. However, to date EM surveys have been limited to reservoirs too shallow or too large to be of general applicability in the oil industry. The critical technology issues in extending EM methods are: a) generating an adequate subsurface electrical current, and b) the sensitivity and stability of the EM resistivity measurement apparatus.

A borehole provides a physical means to contact to deep hydrocarbon formations. To date boreholes have been exploited by lowering a current injection electrode to the depth of interest and completing the electrical circuit with a counter electrode at the surface. This borehole to surface EM method has been successfully used to image oil-to-water contact in an oil reservoir but has the disadvantage that the well must be opened, and, for a producing reservoir, taken off-line. We have now demonstrated a new approach that uses the borehole casing as a current injection electrode. In addition, we have developed the first capacitive sensors for geophysical use and have adapted them for use with commercial seismic data recorders.

Introduction

Electromagnetic (EM) resistivity imaging methods have the potential to map subsurface fluid distribution in applications ranging from derisking potential prospects (Constable and Srnka, 2007) to quantifying the propagation of hydrofractures in unconventional reservoirs (Wilt, 2014). However, to date EM surveys have been limited to reservoirs too shallow or too large to be of general applicability in the oil industry. The critical technology issues in extending EM methods are: a) generating a subsurface electrical current adequate to illuminate formation features of interest, and b) the sensitivity and stability of the EM resistivity measurement apparatus.

Generally, electric dipole sources and electric dipole receivers are used in EM hydrocarbon surveys. For marine applications the high conductivity fluid environment is ideal for coupling both an electric source and electric sensors to the target geology. On shore, the source electric current is 50 to 100 times less owing to high contact resistance to the earth, and the sensor internal voltage noise is 100 times higher. Further, neither the source nor the sensors can be easily moved onshore, reducing the capability to acquire multiple views of a target. As a result, applying EM methods to onshore hydrocarbons requires new approaches to implementing electric sources and sensors.

A borehole provides a physical means to contact to deep hydrocarbon formations. To date boreholes have been exploited by lowering a current injection electrode to the depth of interest and completing the electrical circuit with a counter electrode at the surface (He et al, 2005). This borehole to surface EM (BSEM) method has been successfully used to image oil-to-water contact in an oil reservoir (Marsala et al, 2013) but has the significant disadvantage that the well must be opened, and, for a producing reservoir, taken off-line. We have now demonstrated a new approach that uses the borehole casing as a current injection electrode. Electrical contact is made to the outside of the casing at the surface, as shown in Figure 1A. Current is injected into the earth using one or more surface electrodes and flows into the earth at varying depths, flowing back up the casing to the surface connection. In uniform earth the current distribution along the casing varies exponentially away from the contact point with a characteristic length given by $(\text{casing conductance} \times \text{the formation resistance})^{1/2}$. For example, for a standard casing in 20 Ωm earth, the characteristic length is 1350 m. This means that for a casing 2000 m deep, 23% of the current is flowing at formation depth.

Examples

Figure 1B shows a comparison between measured data and a uniform earth model for a casing 6914 ft (2107 m) deep. The field at 3 km is 100 nV/m/A, corresponding to a 2 $\mu\text{V/m}$ electric (E-) field for a 20 A transmitter. On many fields well spacing is 1500 m and the gradual reduction in surface field allows a formation to be imaged via multiple wells by a simple change of surface connection.

Figure 1. A) Electrical connection to implement a casing source. B) Comparison of measured data (V/m/A) (blue circles) with model predictions (brown circles) as a function of radial distance

To date, all E-field sensors have required a galvanic electrical connection to the earth. Capacitive E-field sensors couple to the earth potential via the electric displacement field, which is continuous across a conducting boundary. The first capacitive sensors for geophysical use were introduced in 2011 (Hibbs, 2012) and have now been adapted for use with commercial seismic data recorders. An example of a capacitive sensor (the "eQube") used to record the data of Figure 1B is shown in Figure 2A. Figure 2B shows cumulative histograms of the sensor noise at 1 Hz over four 10-hour periods

spread over a total of 110 hours for sensors deployed on a dry desert surface as in Figure 2A. The median sensor noise voltage is $70 \text{ nV}/\sqrt{\text{Hz}}$, and no individual noise voltage exceeds $250 \text{ nV}/\sqrt{\text{Hz}}$.

Figure 2. A) eQube electric potential sensor with standard deployment. B) Standard deviation (V/mA) as a function of data averaging time for six sensors at the end of one deployment. C) Standard deviation at the beginning of the next deployment.

A particular benefit of capacitive sensing is that because a very high input impedance amplifier is required, a capacitive measurement is essentially independent of the resistance of the earth where it is located. Laboratory data show that the signal recorded by the sensors in Figure 2A is accurate to 0.015% across the frequency range 0.01 Hz to 10 Hz for earth resistance varying from 1Ω to $10^6 \Omega$. A further key metric is measurement stability. Figures 2B and 2C show the standard deviation of the spectral peak of a 0.5 Hz square wave measured 1.2 km and 1.6 km from a cased well source connected as in Figure 1A. The sensors for the data plotted in yellow and orange are 40 m apart, while the other four eQube pairs are 20 m apart. The horizontal axis is the number of 16-second spectra that are averaged. The vertical axis is V/mA . The data reach a value of approximately $10^{-11} \text{ V}/\text{mA}$ after 128 averages (= 34 minutes of data). For a 10 A transmitter this corresponds to a minimum resolvable field of $10^{-10} \text{ V}/\text{m}$. This performance is approximately equal to a seabed deployed E-field sensor.

Conclusions

Combining the resolution in Figure 2C with the surface field profile in Figure 1B, the new instrumentation is able to resolve 0.01% changes in the surface field at approximately 3 km radial distance from the well. Forward models show that the enhanced current flow at depth provided by the casing results in measurable signal changes for targets such as CO_2 plumes, steamfloods, water, bypassed oil and potentially even hydrofractures at depths traditionally considered outside the capability of EM.

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