EXPLORATION USE OF HIGH RESOLUTION MAGNETOTELLURICS

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ABSTRACT

High Resolution Magnetotellurics is a passive electromagnetic (EM) system for the exploration for oil and gas in the earth’s subsurface. The research on and use of Controlled Source ElectroMagnetic (CSEM) sounding for offshore hydrocarbons by the major oil companies during the last several years has brought increased oil industry acceptance of the use of electromagnetic technology in the exploration for oil and gas. Passive ElectroMagnetic (EM) sounding, notably Magnetotellurics (MT), uses the natural electromagnetic waves produced by the interaction of earth’s magnetic field with the solar wind. This signal source carries all frequencies. With Controlled Source ElectroMagnetic sounding, the surveyor must generate the source electromagnetic wave that is induced into the earth, and select which subsurface returning frequencies to analyze.

Passive magnetotellurics (MT) must capture and analyze the proper frequencies from the naturally occurring electromagnetic waves returning to the surface from the subsurface of the earth. With Digital Magnetotelluric Technologies’ proprietary Z-SCAN, the raw Magnetotellurics EM signal is demodulated to an audio format for analysis. With a trained operator, using both analog and digital computers, the audio signal can be interpreted (Z-SCAN) to give formation depth (+- 25 feet) (7.5 m) and thickness (> 3 feet) (1 m). Approximately 2,800 feet (850 m) of vertical log can be analyzed per day. Signal strength and character can give a subjective estimate of porosity while phase changes can help identify fluid characteristics. The recorded passive electromagnetic data can also be analyzed entirely by the computer with our proprietary DIGILOG system. The DIGILOG process (which is still under development) can analyze from 1,300 feet (400 m) to 16,000 feet (5,000 m) in a single pass with a depth
accuracy of +- 250 feet (80 m) and will normally flag hydrocarbon zones thicker than 15 feet (5 m). This can usually be completed in one day.

The Z-SCAN and DIGILOG systems in various forms have been in operation since 1994. The results can be divided into two interpretation categories: negative calls and positive calls. The negative calls are over 99% correct. Over 250 positive recommendations have been drilled to date and the success rate is approaching 50%. As with any remote sensing system, including CSEM and High Resolution Magnetotellurics, false positives do occur. We endeavor to reduce the number of false positive recommendations by using area specific calibration to known wells and the integration of available geological, geophysical, and geochemical constraints.

Introduction

Since the early 1990’s, research and the use of Controlled Source ElectroMagnetic (CSEM) exploration for deep water oil and gas has added significant credibility to the use of electromagnetics in exploration (Smit and Wood, 2006). Controlled Source ElectroMagnetics involves inducing an electromagnetic signal into the subsurface and recording the returning signal.

In the Exxon Mobil news release *ears to the ground*, Exxon Mobil’s chief research geoscientist, Dr. Len Srnka asks: “How can you “hear” oil and gas hidden miles beneath the ocean floor?” and states: “the R3M technology we developed allows us to listen to the Earth’s response to electromagnetic fields” (Srnka, 2008). Dr. Mark Rosenquist, senior staff geophysicist, Shell E&P research says of CSEM: “If you have high saturation hydrocarbons it gives a really strong response, and with low saturations you get nothing back. ….it’s almost like an on/off switch” (Durham, 2006). These observations are also applicable to DMT’s high resolution magnetotelluric system.
Further, new industry research uses a combination of Controlled Source ElectroMagnetic Surveys and Magnetotelluric Surveys to provide different insights into the subsurface (Brady, et al., 2009). This is an attempt to reduce false positives generated by CSEM (Brady, et al., 2009, p. 19). In other words, there are responses in the subsurface that appear to be hydrocarbons that are not hydrocarbons.

This new CSEM research has renewed interest in passive EM exploration techniques which use natural electromagnetic energy as the signal source. Of principle interest are telluric and magnetotelluric passive source EM systems. Telluric current methods and results were discussed in papers from 1948 through 1963 (Boissonnas and Leonardon, 1948; Mainguy and Grepin, 1953; Vozoff and Burke, 1964). Additional insight into the use of a different telluric instrument (electrotelluric) and method is discussed by Elam (1986). A more detailed discussion of this telluric method of investigating the earth’s subsurface is given in the passive geophysical prospecting patent by Kober and Procter-Gregg (1987) and then followed by an article discussing theory in more detail by Elam (1990). LeSchack, Wyman and Jackson (2004) discuss the integration of two types of passive telluric systems into an exploration program and the positive results.

In 1953, the advantages gained by looking at both the electric field component and the magnetic field component of the natural occurring EM waves were introduced in the form of the magnetotelluric method (Cagniard, 1953). The High Resolution Magnetotellurics systems we call Z-SCAN and DIGILOG, and Cagniard’s classical Magnetotellurics system are both passive source EM systems. These utilize natural electromagnetic energy generated in part from the complex interaction between the
The natural electromagnetic field contains large quantities of energy over a wide spectrum of frequencies. Kauffman and Keller (1981) state:

“The strengths of such electromagnetic fields are many orders of magnitude greater than the strengths of fields that can be generated with man-made sources on the surface of the earth”.

The quality of the input electromagnetic field used for surveying that originates in the ionosphere can be monitored from the NOAA Geostationary Operational Environmental Satellites (GOES) data displayed at www.sec.noaa.gov/today.html, with the variability of the E and H fields evidenced by Electron Flux (electric field) and GOES Hp (Magnetic field) curves. Another plotted curve, Kp index (www.user.gwdg.de/~rhennin/kp.html) is graphed. A Kp index of 3 or less indicates ideal conditions, while a Kp index of 4 has borderline stability and a Kp index greater than 4 indicates too high a signal activity level for stable Z-SCAN and DIGILOG signal use. Figure 1 displays stable signal conditions on August 28 and 29, 2009 and becoming unstable in the later hours of August 30 (Kp = 6). Kp index actual and predicted data, updated every fifteen minutes, is also available at http://www.swpc.noaa.gov/rpc/costello/index.html.

The large amplitude, essentially “white”, electromagnetic signal enters the earth perpendicular to the air-ground interface and propagates to depth (Brady, et al., 2009, p. 6). The returning signal, re-emanated at changes in electrical impedance boundaries, can
be recorded digitally on magnetic tape or other digitally recordable media (Brady, et al., 2009, p. 6). The data can then be analyzed digitally (DIGILOG) with very little human intervention or by a combination of a digital computer and analog electronic circuits interfaced with a highly trained operator to interpret results in the audio domain (Z-SCAN).

Z-SCAN utilizes electronic circuits for the demodulation of the recorded EM signal to an audio format for interpreting amplitude information for apparent resistivity (Z, impedance) and phase variability for rock fluid identification. A trained operator evaluates and interprets the audio signal characteristics used to generate the apparent resistivity changes and rock fluid data. These results are presented in an electric-log type format which can be readily correlated with down-hole electric logs. The analysis is focused on client-specified depths and normally has a depth accuracy of +/- 25 feet (7.5 m) or better. Hydrocarbon zones 3 feet (1 m) or thicker can be resolved to depths of 7500 feet (2300 m). Thickness resolution diminishes to 7-10 feet (3 m) at depths to 20,000 feet (6100 m). Fluid responses are classified into oil-like, gas-like or water-like or combinations thereof.

For DIGILOG, recorded time data are processed by means of a proprietary 1-D inversion algorithm using the principals outlined by Whittall and Oldenburg (1981). Fourier transforms give the amplitude and phase data available for input into the algorithm to yield the derived electric (green), magnetic (black), and apparent resistivity (red) curves, as shown on the figures. Also produced are electric and magnetic curves for the incremental phase distortion (hydrocarbon activity level) needed for rock fluid analysis. The DIGILOG algorithm combines multiple recorded time segment solutions to
generate a continuous final E-Log-type display from 1,300 feet (400 m) to 16,000 feet (5000 m). Depth accuracy is +/- 250 feet (80 m). By using porosity and activity level thresholds determined from calibration to a known well, potential hydrocarbon zones thicker than approximately 15 feet (5 m) are flagged by the process.

In most areas, a nearby well electric log normally gives a reasonable empirical local calibration for fine tuning of the Z-SCAN and DIGILOG depth, apparent resistivity, and reservoir fluid responses. Once these subtle area-dependent changes are noted, they can be applied to improve the results of the exploration data stations. With our higher frequency sampling than would be predicted by classical MT formulae (Cagniard, 1953) and thus denser depth sampling, the most applicable depth range for the Z-SCAN and DIGILOG technologies is from 0 feet (0 m) to 20,000 feet (6100 m).

**Depth and Porosity-Permeability Response**

“The EM waves interact with conductive formations and induce a response wave that propagates back to the surface” (Brady et al., 2009, p. 6). The air-ground interface marks a large impedance mismatch to the electromagnetic waves returning to the surface reflected from electrical interfaces in the subsurface (Brady, et al., 2009, p. 7-8; Torres-Verdin, 1992). This large impedance mismatch generates a series of higher frequency electromagnetic waves carrying information about the reflected or subsurface returning signals. The resultant currents are sometimes called telluric (electric field) and geomagnetic (magnetic field). “On land, the electric field responds significantly to changes in resistivity in subsurface layers, but the magnetic field has much less
variation.” (Brady et al., 2009, p. 9). By recording the total electric field and the total magnetic field, the frequency, amplitude and phase responses of these two fields can be analyzed. The electromagnetic field recorded by the Z-SCAN and DIGILOG antenna system is in the range of 10 to 22,000 Hertz. These are much higher frequencies than predicted by classical Magnetotelluric (MT) formulae (Cagniard, 1953) for normal oil and gas exploration depths.

A good discussion of the basic MT equations is presented by Nabighian (1988), Kauffmann, et al. (1981). The first exponential term of the simplified Maxwell’s equations, generally referred to as the “Skin Depth”, can be solved for depth by substituting the higher frequency information to form a new, non classical, frequency versus depth solution. Changes in the electrical conductivity in the various subsurface rock formations are calculated from the ratio of the electric to magnetic field components for each of the new frequencies (depths). These changes are integrated over a specified depth interval to form a high resolution apparent resistivity log. One example of a low resolution solution using classical MT data is shown in a paper by Orange (1989) where a resistivity type log is generated using the Bostick 1-D inversion transform. The depth scale for this log is from $10^2$ to $10^6$ feet (approximately 10 to 300,000 m) at a very broad subsurface sampling density. The proprietary DIGILOG algorithm utilizes a similar concept with higher frequency input to achieve denser subsurface sampling. Electronic circuits accomplish this denser sampling in the Z-SCAN.

The integrated apparent resistivity curve becomes the basis for interpreting the relative porosity-permeability of the subsurface formations. Low resistivity indicates
probable commercial porosity and permeability in the rock while higher resistivity on either the electric or magnetic field curves indicates poorer porosity or permeability. Gas zones tend to indicate overall higher resistivity even in a good porous-permeable zone. This is a result of less available salt water within the gas reservoir as discussed in the Fluid Content section below.

**Fluid Content**

Analysis for fluid content is accomplished by comparing the phase shift and phase distortions of the electric field and the magnetic fields at each tuned frequency, i.e. depth. The passive natural EM source signal is relatively steady during the 20 minute recording time of each data station. This is envisioned as a quasi-steady state input signal. Analysis of the time-variant phase distortion, at a depth-specific frequency is the basis for the Z-SCAN interpretation of the reservoir fluid content. The DIGILOG algorithm utilizes a vertical stack of the 1-D inversion results of several segments of the recorded field data. This analytical process preserves the sum of the depth-specific, time-variant phase distortions.

CSEM utilizes a variable frequency source and uses offset gather data processing for the inversion modeling (Brady, et al., 2009, p. 11-12). This data acquisition and processing sequence may “stack out” the depth-specific, time-variant signals that carry reservoir fluid content information.
Oil reservoirs are usually water wet. This means the meniscus connate fluid is water, commonly salt water. Therefore, the oil is electrically resistive and the connate water is electrically conductive. Since the electric field component of the electromagnetic wave will seek the path of least resistance, it will follow the lower-resistivity connate water, bypassing the higher-resistivity rock matrix and any resistive contaminate. These paths, however, are tortuous when a highly resistive contaminate such as hydrocarbon is inserted. Therefore, there will be a travel time differential between alternate paths, thus a phase distortion. An oil reservoir is not the only phenomena that can cause this distortion. Any highly resistive contaminant to a salt water saturated reservoir will appear as a phase anomaly. A shaly sand can cause a phase distortion that can sometimes be mistaken for an oil zone. Highly organic shales such as the Woodford Shale in Oklahoma, or Bakken Shale in the Rockies, give a phase anomaly that is very similar to an oil signal. Careful analysis of the prospect geometry and gathering enough data points to add additional petroleum engineering data such as a gas cap or a depth consistent hydrocarbon/water contact will reduce the overall prospect risk.

In solid rock there is normally no phase shift, thus no, or a very low strength fluid signal. Since in an oil reservoir there are multiple interconnected low-resistive connate water paths, the phase shift can be highly variable and dynamic. This response is usually crisp and can be recognized by the analog-digital system (Z-SCAN) and/or the pure digital system (DIGILOG).
Gas

Gas reservoirs are usually oil wet. Much of the normal connate water has evaporated over geologic time, leaving an oil film. So, the pore fluid (gas) is resistive, the meniscus fluid (oil film) is resistive, and the matrix (sand or limestone) is normally resistive. There also may be micro-thin clay lining of the pore space that may contain bound water which is conductive. The alternate conductive paths in this case are less variable than in an oil reservoir. This significantly changes the relative phase velocities for the electromagnetic wave propagation and gives a phase character with less intense distortion and amplitude throughout the reservoir; yielding another unique phase-shift signature.

Water

Water in the reservoir pore space provides high conductivity with only the matrix being resistive. Since the water in the pore space is interconnected in a permeable reservoir, the high-resistive rock matrix is bypassed by the electromagnetic waves and the phase differentials are very small. Thus the phase shift or distortion for water alone is almost nonexistent when compared to oil or gas. The relatively smooth phase signal for water is also distinctive.

Equipment

One of the distinct advantages of the High Resolution Magnetotelluic field recording system is its small surface footprint. All the equipment is easily carried in a small suitcase-sized case. The field system is comprised of an antenna box containing
antenna arrays and dual channel amplifiers, an external power supply for the antenna system and a digital recording device. The antenna enclosure houses six orthogonal antenna elements, three electric and three magnetic. Due to our higher operating frequencies, these antennas are constructed with small wound coils for the magnetic elements and capacitive plates for the electric elements. Also, unlike classical MT, the recording periods to gain information at all needed frequencies are shortened from several hours to 20 minutes per station. Since the recording time is so short, there is no need to have data from a magnetic base station to remove the earth’s diurnal magnetic field changes from the recorded magnetic field component of our instrumentation. Processing of the recorded signal is normally accomplished back at the home base, but processing can be accomplished at field accommodations if it is necessary to meet deadlines.

**Results and Examples:**

The Z-SCAN and DIGILOG systems in various forms have been in operation for clients since 1994. As a result of evaluating hundreds of prospects and leads for clients, our records indicate through 2008, over 250 wells have been recommended by us and drilled on positive indications from the technology, with a success rate approaching 50%. Nearly as important, our success in predicting the absence of hydrocarbons is over 99%.

Even though many clients are guarded with our results, a few recent examples of pre-drill Z-SCAN logs versus post drill successful Electric Log results are shown in Figures 2, 3 and 4. In each case, the green curve under Z-Signature Response column is the processed electric-field relative resistivity curve, the black curve is the processed
magnetic-field relative resistivity curve and the red curve is the combination of the curves or the Apparent Relative Resistivity curve. The resistivity scale goes from VL (very low) to H for high. The best porosity and permeability is suggested by a close grouping of the 3 curves with maximum displacement to the left (lowest relative resistivity). The fluid signature column has the result of the phase distortion analysis for oil, gas and water using the summed results of the phase modulation indicators. The solid shading represents the strongest result, while the dashed shading indicates a weak result. The modulation column exhibits two sets of numbers ranging from 1 to 3 to indicate the character of the phase-signature fluid identification. These are analyzed separately for the electric and magnetic components of the EM signal for a given constant frequency (depth) over time. From left to right, the first three numbers that pertain to the electric field evaluation are, (1) modulation intensity, varying from 1 for high to 3 for low; (2) the distribution of the distortion in the phase pattern varies from 1 for low to 3 for high; and (3) the variability of the wave pattern is from 1 for highly chaotic to 3 for orderly. The second three numbers repeat the analysis for the magnetic field. Interestingly, our best gas response is a combination of strong gas signature coupled with a weak or strong oil signature. We have had successful results with only strong gas indicated, especially in the Black Warrior Basin, but much of the time a gas only response suggests a tighter, lower porosity or lower permeability reservoir. Strong oil response and a strong water response are indicative of porous permeable reservoirs with the respective fluid result.

For an example of the DIGILOG compared to an electric log in a productive zone, see Figure 5. Figure 6 compares Z-SCAN and DIGILOG results to an electric log in a gas pay zone.
A Few Notes on Using the Technology

The electromagnetic wave propagates in the subsurface normal incident to the bedding planes, so “migration” is necessary in steeper dips. A simple program is available for predicting the true subsurface image point. Also, the antenna setup does not record a point source under the antenna but instead looks at a cone of an ever expanding-with-depth area under and around the antenna. Formulae exist for calculating the diameter of the imaged area. This becomes important in mapping voids in our application to solution mining cavern storage and in the mapping of subsurface channels. The integrated area imaged by the antenna preferentially responds to fluid attributes over non-fluid attributes. Thus we see a brine-filled cavern void as extending further than it actually does as well as seeing channels wider than they actually are. This exaggerated area can be mathematically corrected to true size.

Conditions which preclude the utilization of the technology are high levels of solar activity, Kp higher than 4, and high levels of moisture in the atmosphere or in the ground at the air-ground interface. No useable signal is present during moisture-laden cloud cover, rain or when the surface soil is damper than “moist”.

Conclusion

The High Resolution Magnetotelluric technology, though not perfect in subsurface predictions (as with all remote sensing tools), is an excellent addition to the exploration tool chest. It easily blends with standard electric log data as well as 2-D and
3-D seismic. The cost of a reasonably dense Z-SCAN survey is approximately 25% of the cost of a 3-D seismic survey. Since both Z-SCAN and DIGILOG have a narrow depth focus in the subsurface, they can evaluate specific reservoirs which potentially contain hydrocarbon and verify the depth they occur. This verification attribute also allows the technology to be an excellent follow-up and confirmation tool for surface based direct hydrocarbon indicators such as iodine concentration, radiometric ratios, geomicrobial, micromagnetics, as well as soil hydrocarbon sampling, to name a few. Further, the ability to determine potential hydrocarbon presence, thickness and areal extent using the DIGILOG and Z-SCAN systems can give the explorationist a valuable economic measure of reservoir potential early in the prospect confirmation and assembly process.
References


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These charts are internet published by NOAA/SWPC, Boulder, Colorado and give a visual reference for the signal quality of the data recorded by the Z-SCAN instruments.

Figure 1
Comparison of the pre-drill Z_SCAN Log with the post-drill electric log shows a good correlation with zone thickness and reservoir fluid content.

Figure 2
Comparison of the pre-drill Z-Scan log with the post-drill electric log shows a strong correlation with a distinctive gas zone.

Figure 3
Comparison of the pre-drill Z-SCAN log with the post-drill electric log shows good correlation with the thin-bedded gas pay zones.
DIGILOG Example with E-Log Comparison

DIGILOG, Morrow Calibration, Cheyenne Co., Colorado

Figure 5
DIGILOG Example with E-LOG and Z-SCAN comparison

This display allows a comparison of the DIGILOG response and Z-SCAN response to the gas pay zone.

Figure 6