Improved Exploration, Appraisal and Production Monitoring with Multi-Transient EM Solutions

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Summary

Successful as seismic is, it cannot always directly characterize the thickness, lateral extent and storage capacity of the reservoir, and direct hydrocarbon detection is only possible provided the porosity is sufficiently high and the reservoir is charged with gas or light oil. Multi-Transient EM (MTEM), on the other hand, delineates high resistivity layers in the subsurface, provides a quantitative estimate of the transverse resistance (resistivity x thickness), indicates lateral terminations very accurately, and provides the depth to the anomaly quite accurately also. This makes MTEM a valuable tool in conjunction with seismic data and sometimes as a stand-alone solution.

Eight situations are presented where MTEM can provide a solution:

1. Field delineation when seismic fails to map the reservoir properly: The reservoir may lack acoustic impedance contrast to the surrounding rocks, or imaging may be very poor.
2. De-risking low saturation gas: Seismic has similar responses to low saturation gas and highly saturated gas reservoirs. EM, on the other hand, is only sensitive to intermediate and high gas saturations.
3. Imaging through gas clouds: Gas clouds typically have a low gas saturation that scatters the seismic energy, but the effect of low saturation gas on resistivity is very small.
4. CO_2 sequestration: Seismic can only monitor the gas injection provided the porosity is sufficiently high, and provided the reservoir does not have a residual gas charge to begin with. EM can image irrespective of porosity, and it is only sensitive to intermediate and high gas saturations.
5. Fluid evaluation in carbonates. Most of the variation in seismic response originates in porosity variation, whereas the fluid effect is a secondary effect. By combining seismic with EM, the productive parts of the reservoir can be characterized by a combination of low acoustic impedance and high resistivity.
6. Imaging of fault shadows and thrust belts. EM is not refracted and scattered the way seismic waves are allowing resistivity imaging of areas that exhibit shadow areas in seismic imaging.
7. Time-lapse in oil and gas reservoirs. Half of all the producing reservoirs in the world are not amenable to seismic time-lapse due to porosity being too low, fluids too heavy, or imaging

issues. EM time-lapse works with all porosities and non-conductive fluids and is typically unaffected by the imaging problems that can plague seismic.

8. Characterization of heavy oil deposits and SAGD monitoring. Seismic can not detect heavy oil directly, and as a monitoring tool it will see evolved gas and/or live steam. EM is sensitive to temperature, water saturation (S_w) and salinity. Neither method detects changes in oil saturation directly.

Seismic data can in most cases support MTEM data by providing the structural and stratigraphic framework of the subsurface in 3-D. This makes it easier to resolve the issue whether the anomalously high resistivities are due to hydrocarbon charge or resistive lithologies such as coals, dense carbonates, evaporates and igneous intrusions.

Introduction

Hydrocarbons are found in porous rocks typically of sedimentary origin. The presence of oil or gas in the pore spaces, in addition to residual water, changes the elastic properties and increases the resistivity of the reservoir rock. In seismic we can observe a lowering of the bulk modulus and density of the rock when light hydrocarbons are introduced, which in turn leads to a lowering of the P-wave velocity, density (except for heavy oil), acoustic impedance and Poisson's ratio. The magnitudes of these changes depend primarily on the porosity of the rock and the bulk moduli of the fluids in the pore spaces. In addition, draw down of reservoir pressure increases vertical stress that will in turn increase the bulk modulus and add to the time-lapse signal. The limits of detectability are determined by the resolution and S/N of the seismic signal, as well as the level of geological noise.

The resistivity for a given clay-free reservoir (invariant porosity, salinity, temperature and rock matrix) is only a function of S_w and saturation exponent (n) (e.g., Archie, 1942). The type of non-conductive fluid, i.e., oil, gas, CO_2 etcetera is irrelevant in terms of the bulk rock resistivity. To illustrate the effect of varying saturation, the resistivity index is defined as the resistivity of the hydrocarbon charged reservoir divided by the resistivity of the brine charged reservoir expressed as S_w^{-n}, where the saturation exponent is typically close to 2.0. This means that it takes approximately 30 % hydrocarbon-charge to double the resistivity of the rock. At 50 % hydrocarbon-charge, the resistivity has increased a factor four, and at 90 % charge, the resistivity has increased by a factor hundred.

Kaufman and Keller (1983) concluded that resistive layers can best be resolved by measuring the electric field from a galvanic source. The MTEM method is based on a galvanic source, but what is new and unique about it is that both the received voltage and the transmitted current are measured simultaneously, and the impulse response of the subsurface is recovered from these two measurements by deconvolution. Recovering the impulse responses simultaneously for an array of 30 - 40 receiver locations allows the data to be processed in a manner similar to seismic processing, and we use seismic data processing software for data handling, processing and display.

The MTEM Method

The MTEM method is described by Wright et al. (2001, 2002 & 2005). Field equipment and data processing has been developed for land, transition zone and marine data acquisition. Here we will focus on land data as an example. The source dipole and the receiver dipoles are lined up with the source off end, and the receiver arrays in a straight line in front, rear, or as split spread with the source dipole in the center. A transient current is injected into the ground between the two source electrodes, either as a step function, or preferably as a pseudo-random binary sequence (PRBS), and recorded at the receivers as a voltage. The source current is recorded as the closed circuit signal through transmitter, cables, source electrodes and subsurface. Any inductive and/or capacitive effects will modify the “pilot signal”, but the recorded current is the true signal, and this is what is used in the deterministic deconvolution.

Each source – receiver offset results in an impulse response. Inversion is then performed by forward modeling the impulse responses for each CMP of 1-D layered resistivity models and iterating to minimize the difference between model and the field data. The model is updated following each iteration until sufficient agreement has been achieved.

Optimum depth sensitivity is a function of source – receiver offset, and by inverting multiple offsets for each common mid-point (CMP), a resistivity depth profile is generated at each CMP. The final product is then a sequence of 1-D inverted resistivity depth profiles posted side by side in color contoured 2-D displays.

In the marine environment, the acquisition resembles ocean bottom seismic with a cable based receiver array. By staying connected to the receiver array during land and marine acquisition, the recorded signal can be monitored real time as well as the S/N buildup at target depth resulting in optimum efficiency in the field.

Examples of MTEM Solutions

The examples mentioned here by no means constitute a complete list of possible MTEM solutions, but rather some of the most obvious ones.

Field delineation: Seismic may not be able to image the reservoir due to a lack of impedance contrast to the surrounding rocks or due to poor imaging conditions. EM can then outline the lateral limits of the hydrocarbon-charged reservoir and by means of the magnitude of the anomalies show the hydrocarbon pore volume distribution. Stacked thin-bedded reservoirs that cannot be resolved by seismic will render an averaged response on EM, once again estimating the spatial distribution of hydrocarbon pore volume in the entire stack of reservoirs.

De-risking low saturation gas: In reservoirs where the porosity is sufficiently high, seismic can often detect gas directly. However, seismic has a similar expression for uneconomic, low saturation gas as it has for a highly gas charged reservoir. EM requires intermediate to high gas saturations before the resistivity becomes high enough to be detected as an anomaly. Low gas saturation is not detected at all.

Imaging through gas clouds: Gas clouds are formed when the seal over a gas or gas/oil reservoir is leaking, allowing gas to migrate up through the overburden towards the surface. The gas concentration is typically quite low but at the same time variable within the saturation range that affects seismic velocity most dramatically. The result is a dispersed velocity field that is difficult to focus into coherent images. In addition, the absorption of seismic energy is very high in rocks with mixed fluids and actually highest at low gas saturations further preventing successful imaging below the gas cloud.

CO_2 sequestration: This is another area where seismic has already been tested as a monitoring technology, and it works very well provided the reservoir porosity is sufficiently high and there are no imaging issues. EM on the other hand can work with all porosities. Spatial resolution is not as good as for seismic data and low gas saturations are not seen at all, but EM can quantitatively estimate intermediate to high CO_2 saturations much better than what is possible with seismic data.

Fluid evaluation in carbonates: The main source of acoustic impedance contrast in carbonate reservoirs is typically porosity variation, and fluid type has at best a very small secondary effect. This leads to drilling targets of maximum porosity rather than the highest hydrocarbon saturation. By combining seismic with MTEM, the hydrocarbon pore volume distribution in the reservoir can be identified as having a high resistivity in combination with low acoustic impedance.

Imaging of fault shadows and thrust belts: Seismic illumination may be impeded by sharp velocity contrasts along dipping non-parallel interfaces. EM resistivity imaging remains unaffected by these conditions.

Time-lapse in oil and gas reservoirs: This has already become a very important part of the seismic business. However, only approximately half of the reservoirs around the world have rock and fluid properties that are amenable to seismic monitoring. EM has no restrictions regarding porosity or hydrocarbon fluid properties, and a large part of the remaining half of all the reservoirs in the world should be well suited to MTEM time-lapse.

There is also a dramatic difference in the magnitude of the time-lapse signal between seismic and EM. The largest time-lapse difference in seismic is probably in the order of 20 % of the acoustic impedance, whereas in EM, it can span three orders of magnitude. Further, the seismic time-lapse response is quite linear as a function of S_w increase, possibly with a slight increase in gradient towards the end of the life span. EM, on the other hand, displays the most dramatic resistivity change at the early stages in the history of production allowing by-passed volumes to be identified at an early stage making it possible to optimize the infrastructure for the life of the field.

Characterization of heavy oil deposits and SAGD monitoring: Seismic can not directly detect heavy oil in place, and in terms of monitoring it will image the gas in the pore space consisting of evolved hydrocarbon gas and/or live steam. Once again the hydrocarbon type and elastic properties are immaterial to EM, so it is well suited to characterize the STOOIP (Stock Tank Original Oil in Place). The resistivity changes during the SAGD process are governed primarily by temperature, Sw and salinity. Hence, feasibility studies should be done with a reservoir simulator that tracks temperature and salinity as well as the saturations for water, oil, gas and live steam. The resistivity can then be calculated for all the grid cells at different time steps, and suitable time-intervals can be scheduled for MTEM monitoring surveys.

Conclusions

MTEM is not a replacement for seismic but rather a complement, and often the two technologies should be evaluated together for the most accurate solution. Seismic is evaluating the spatial variation in elastic parameters, primarily the bulk and shear moduli and density, whereas EM is exclusively sensitive to resistivity. There are many situations where seismic fails to image the hydrocarbon-charged reservoir due to lack of contrast in elastic parameters, or sub-optimal imaging conditions. Mapping subsurface resistivity with MTEM is often the appropriate solution in those situations.

Half of all the producing fields in the world are not amenable to seismic time-lapse monitoring, but many of them would be very well suited to EM time-lapse monitoring.

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References

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Archie, G. E., 1942, The electrical resistivity log as an aid in determining some reservoir characteristics: Journal of Petroleum Technology, 5, 1 – 8.

Kaufman A. A., and G. V. Keller, 1983, Frequency and transient soundings: Elsevier Science Publ. Co., Inc.

Wright, D. A., A. Ziolkowski, and B. A. Hobbs, 2001, Hydrocarbon detection with a multichannel transient electromagnetic survey: 71st Annual International Meeting, SEG, Expanded Abstracts, 1435-1438.

Wright, D. A., A. Ziolkowski, and B. A. Hobbs, 2002, Hydrocarbon detection and monitoring with a multichannel transient electromagnetic (MTEM) survey: The Leading Edge, 21, 852 – 864.

Wright, D. A., A. Ziolkowski, and B. A. Hobbs, 2005, Detection of subsurface resistivity contrasts with application to location of fluids: U. S. Patent 6914433.