Integrated Electromagnetics for Unconventionals & Reservoir Monitoring

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Summary

One of the key objectives of applying geophysics to unconventional resource problems is the mapping of reservoir fluids in fractures and in the reservoir. While seismic is ideal to map boundaries, fluids are best detected with electromagnetics.

Electromagnetics (EM) has been applied to hydrocarbon and geothermal exploration since the mid 1960's. With time, only magnetotellurics (MT) emerged as viable exploration tool. CSEM has only been successful in the marine environment. The real reason of CSEM not becoming a mainstream geophysical tool lies on the technical side: anisotropy, old hardware and technology, noise sensitivity, low spatial resolution, and foremost-unknown information focus. With the solid success of the marine industry, the emerging use of borehole anisotropy logs, the support from the value chain is sufficient to address the remaining issues.

Anisotropy is also a pivotal technical parameter in the unconventional scenario. We developed over the past decade an array electromagnetic system that acquires all types of electromagnetics data, while allowing dense spatial sampling at lower cost. After developing borehole and land combined seismic and EM systems, we recently completed the marine nodal receiver. The system architecture is broadband similar to seismic nodes. The system can be used as conventional EM systems and also as large channels count acquisition system with full integration of borehole, land and marine.

The system is applied for exploration and production as well as reservoir monitoring for hydrocarbon and geothermal resources. Its use is illustrated by emerging case histories.

This paper is a continuation of Strack and Aziz (2013) on applying electromagnetics to shale reservoir applications and includes further 3D results leading to potentially disruptive methodology. In addition, new hardware components allow the integration of land and marine, surface and borehole.

The honored guest of this symposium, L. Thomsen, was a co-contributor in formulating the ideas in a forum on anisotropy (Strack et al. 2001a and 2001b). Subsequently, together with L. Thomsen we integrated these ideas into a novel marine methods leading to two patents (Strack et al., 2006 and 2008). This technology was then taking to land hardware design, borehole and back to marine. Thomsen continues this work leading to more recent publications (Thomsen, 2014, Neese and Thomsen, 2014).

Introduction

During the past 20 years, for hydrocarbon and geothermal application, controlled source electromagnetics (CSEM) is only used in rare instances. Recently, with the success of marine EM (Eidesmo et al., 2002; Constable, 2010), it is being looked at again and major potential applications that include high value targets are emerging. These are shale/unconventionals application and reservoir monitoring where the EM response could even yield more value than seismic. At the same time technology has progressed such that we can measure more channels at lower cost and interpret today in 3D. The product spectrum has only increased slightly because applications are missing.

To realize the full integration value of EM, we need to look at more efficient acquisition and more integrated acquisition. For this we have developed a series of seismic integrated acquisition systems (borehole, land and marine), which bring down cost per channel thus allowing more channels and more integration. We are hoping that new lower cost; acquisition technology combined with new methodologies will add more effective value integration in 3 dimensions.

In realistic reservoirs (not just in unconventional) one of the technical key issues is anisotropy. Shale formation has an inherent strong electrical anisotropy and the reservoir is relatively thin. As the hydrocarbons in shale gas or shale oil reservoirs are mostly resistive, they give an anomalous EM response. The DHI effect gave rise to the entire marine EM industry and is known as Direct Hydrocarbon Indicator (DHI) or in geophysical terms the 'thin resistive layer effect' (Passalacqua, 1983; Eadie, 1980). Using modern logging tools that measure electrical anisotropy, surface tensor EM measurements can be calibrated and then become more meaningful and tie better to seismic images. In the absence of anisotropy logs, the anisotropy can be estimated using well-known equivalence principle first suggested by Keller and Frischknecht (1967).

For reservoir monitoring, time-lapse measurements as well as proper linkage to the borehole through integrating surface-to-borehole measurements is essential. Combining borehole and surface EM measurements gives calibration points in addition to more sensitivity to fluid variations in the pore space. At the same time linking the EM information to 3D surface and borehole seismic data permits extrapolation away from the well bore. It is essential to carry out feasibility for monitoring applications because the reservoir variations will automatically make this a three-dimensional problem. This is illustrated with examples from hydrocarbon and geothermal reservoirs where even noise measurements were collected to illustrate the feasibility. The additional opportunity lies in coupling EM with seismic to get fluid movements and seal integrity.

On the hardware side the limitations are in cost and lack of interaction between transmitters and receivers, which only allow single transmitter and unfocused receivers to be used. If we add today's accurate timing and sequencing to modern hardware we can use better arrays that allow volume focusing. Coupling this with atomic clocks we can have accurate time on land, marine up to deep water and in the borehole. Our implementation includes high power land sources and receivers (CSEM system), surface-to-borehole arrays and a single well system that can look tens or even 100 m around the wellbore and ahead of the drill bit.

While modern hardware, 3D modeling and calibration can address the key challenges of land CSEM; there are still numerous remaining issues. In order to reach sufficient depth, one needs to deploy a high power transmitter, which brings operations HSE issues. In addition, grounded dipole transmitter is always sensitive to static shift caused by near electrode inhomogeneities. These need to be evaluated at every transmitter location. These issues can all be addressed by careful operation while the volume focusing issue (Where does the information come from in the subsurface?) is difficult to address.

One way to address this is the Focused Source EM methodology described by Davydycheva and Rykhlinski (2009, 2011). This methodology borrows principles used in focused logging where you combine the response of multiple transmitters to measure in the center of the array a differential response that now comes from directly below the receiver that significantly increases the spatial resolution of this method. The FSEM measurement setup allows cancellation of many unwanted effects and obtaining smooth responses along the measurement profile even in the presence of various shallow heterogeneities, which may strongly affect traditional CSEM measurement data. Unwanted effects of inhomogeneities situated laterally with respect to the receiver are cancelled, independently of their proximity to transmitters. First successful field test with this technique has been carried out on land, and further enhancement of the spatial resolution was reached through integration and joint interpretation with seismic. Marine tests are following.

Given this, the technology effort is manageable for high value problems such as reservoir monitoring or shale applications.

We believe that we now are at the time where hardware, methodology, interpretation tools and integration progressed sufficiently to rethink the use of controlled source EM on land.

Technology improvements:

Technology usually consists of hardware, data processing and interpretation software. Key in modern system design is to bring the 3D results directly into the instrument design. This lead to an array concept where you provide unlimited channel count similar to wireless seismic nodes. One of the key requirements is to force learning from seismic (Strack and Vozoff, 1995):

- System must be capable to acquire seismic data simultaneously
- System must be able to work as independent node for all EM methods (and other geophysical methods)
- Broad band: DC to 50 kHz

Figure 1 shows some examples of such an array system. The land version is already being used in 14 different countries with case histories coming slowly online. It has 24/32-bit capability and fulfills all the requirements requested above.
The marine system is in prototype test phase and is based on a well-established marine seismic with the same sensors and acquisition CPU as in the land system. The borehole system contains mostly sensor interface and is adapted to existing systems using one of the seismic channels so that no hardware and software modifications are required. This allows the system to be fielded with the same environmental specifications as the seismic system.

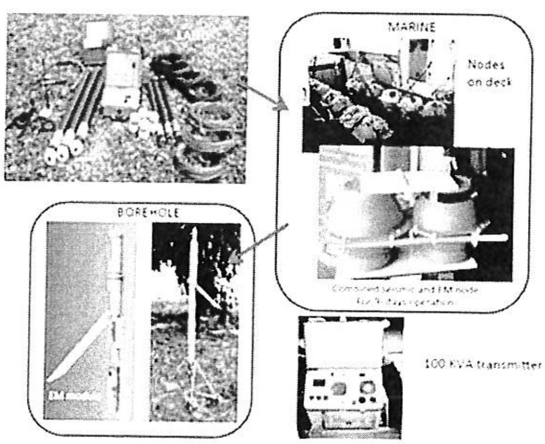

Figure 1. Examples of new array hardware for land, marine and borehole acquisition. For CSEM a 100 KVA transmitter shown on the right is used

- Low power consumption: land < 5 W; marine – 60 -90 days with extended battery pack
- 24 or 32 bit dynamic range as needed
- Unlimited channel capability
- Each node must be expandable to unlimited channels (land & borehole)
- Transition from analog to digital acquisition architecture
- Reduced cost per channel

Methodologies

Given that hardware has improved, given that MT is the workhorse of the geothermal industry with some applications to hydrocarbons then why have we not seen an uptake in CSEM (Nekut and Spies, 1989; Sheard et al, 2006; Strack, 2014). The reason is two fold: One, new interpretation tools and measurements such as 3D modeling/inversion and anisotropic models have not been fully implemented in an industrial environment. Two, the information content between transmitter and receiver is smeared and it is not clear where the response information comes from. Even EM integrated methods such as TFEM (He et al., 2006; He et al., 2010) do not overcome this issue. Recently, Davydycheva and Rykhlinski (2011) proposed a new method similar to the borehole laterolog called Focused-Source EM (FSEM). It allows the differential measurement from multiple transmitters and measuring differential data. The first tests with the technique in Russia were very successful.

Figure 2 shows the land layouts for 2-dimensional and 3-dimensional acquisition. Similar layout can be constructed for the marine systems (still under development)

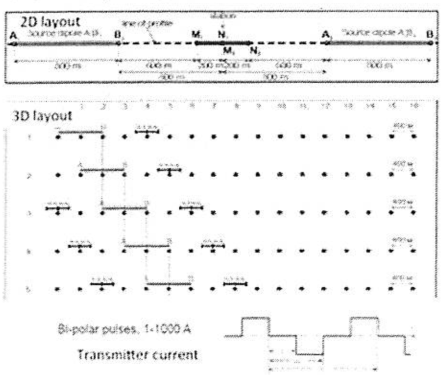

Figure 2: Focused EM layout for 2-D and 3D land acquisitions. The source wave form is shown at the bottom. Examples transmitter and receivers are show in Figure 1.

Figure 3 shows the comparison between an FSEM layout and a conventional TEM layout. Clearly the FSEM enhances the reservoir anomaly as shown in the model below the response curve (inline electric field).

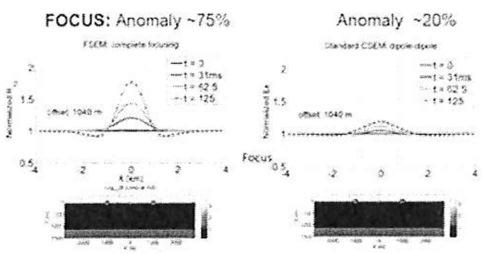

Figure 4 a snap shot of an animated simulation of surface-to-borehole-EM for reservoir monitoring.

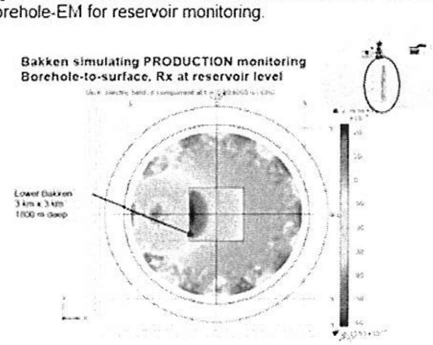

Figure 4: Simulation snapshot of electric field values measured downhole in a shale reservoir. The blue and the red colors are high and low current densities.

Applications:

We consider a synthetic example of a hydrocarbon-bearing reservoir. It clearly shows that the methods can significantly enhance the anomaly. We, in fact, experience this for every reservoir for feasibility and real data.

Another example is to apply new acquisition technology to shale reservoirs, called FSEM. FSEM will give the response at the surface that is directly below the receiver. Often the reservoirs are at significant depth like the Bakken oil plays in North Dakota and minimizing the foot print at depth (focal point) is important to maintain reasonable target parameter accuracy. Here, consider an anisotropic model and surface-to-borehole arrays. We modeled this using 3D finite element modeling and simulated an injection current from the surface (100 A). An example of the snap shot is shown for a shallower reservoir in Figure 4. The ends of the color scale point to high or low electric field (polarity dependent), which are well above the measurable range.

The applications in this would be depletion monitoring of the reservoir and combined fracture mapping of seismic and electromagnetics.

Conclusions

For unconventional resources, electromagnetics will require CSEM on land (and later offshore). The technology has made significant progress and full field array systems are now available. Its use is presently being piloted and will hopefully show that we can today effectively define anisotropic targets.

We are hoping that new acquisition methodologies such as FSEM or integration with microseismic or other seismic methods will clearly improve this. Initial real feasibilities and test data underscore this suggestion.

Reservoir monitoring and shale application are taking land CSEM to high value applications and thus we can expect a significant increase of activities in this area.

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