Tu A4 17

CSEM Revisited - Shales and Reservoir Monitoring

S. Davydycheva (KMS Technologies), I. Geldmacher (KMS Technologies), T. Hanstein (KMS Technologies), K. Strack* (KMS Technologies)

Summary

We study application of controlled-surface EM in shale/unconventional reservoirs and show feasibility of surface-to-surface and borehole-to-surface EM for enhanced oil recovery and reservoir depletion monitoring.

Introduction

During the past 20 years, controlled source electromagnetics (CSEM) has increasingly been used for hydrocarbon or geothermal application. After the success in marine EM (Constable, 2010), the scope of applications for CSEM has been revisited (Tietze et al., 2014, 2015; Strack, 2014). High value targets such as applications in unconventional (shale) basins or in reservoir monitoring have been looked at, since the EM response could yield considerably more value than traditional seismic interpretation alone. At the same time, technology has progressed such that it is now routine to record virtually an unlimited number of channels at lower cost (than in the past) and interpret data in 3D. We also can focus the CSEM information content below the receivers using either vertical electric field measurements or Focused Source EM (Davydycheva and Rykhlinski, 2011).

Typical reservoirs are often characterized by electrical anisotropy; posing a technical hurdle for most standard interpretations. Especially the above mentioned shale formations exhibit an inherently strong anisotropy, and the reservoir layers are sub-resolution thin requiring upscaling. Today's logging tools allow to directly measure electrical anisotropy downhole and, together with surface tensor EM measurements, can be used to calibrate measurements to support a better correlation with seismic images. In the absence of modern anisotropy logs, the anisotropy can be estimated using well-known equivalence principle (Keller and Frischknecht, 1967).

Reservoir monitoring essentially poses a time-lapse exercise, where measurements that link downhole borehole, surface-to-borehole, and surface-to-surface measurements are advantageous; enabling critical calibration and increasing sensitivity to fluid variations in the reservoir. Such a wealth of EM information, tied to 3D surface and borehole seismic data also permits to extrapolate fluid movements and seal integrity away from a given well bore. Because of this complexity, it is necessary to carry out 1D and 3D feasibility studies to fully understand the overall reservoir effects.

Recent advancements in operational hardware are beyond the scope of this paper, but it is understood that operation can be carried out safely and economically on land, from within boreholes and in marine environments including deep water (2-3 km).

One of the key remaining challenges is for the EM response to reach sufficient depth. This could be achieved by higher power transmitters, inherently leading to HSE concerns. In addition, grounded dipoles are highly sensitive to static shifts caused by near electrode inhomogeneities, which are tedious to evaluate at each field location. While these (and other) issues might be addressed by careful field performance, the issue of which subsurface area/volume is associated with the signal response remains.

Methodology

As noted above, technical reasons for CSEM not having become a geophysical tool "of choice" are: electrical anisotropy, low spatial resolution, insufficient technology, noise sensitivity, and –foremost – the unknown response focus, i.e., where does the information come from in the subsurface? In the wake of recent successes of the marine EM industry, the emerging use of borehole anisotropy logs and other advancements, today's CSEM technology can address these issues, as we show below.

Widely accepted passive EM methods, like magnetotellurics (MT) do not respond well to thin resistors such as predominantly found in shale reservoirs. This is due to the fact that natural MT sources, as well as CSEM circuits that utilize an ungrounded current loop (magnetic dipole), both excite only horizontal currents which are not much influenced by thin horizontal resistors and by anisotropy. A CSEM application using a grounded electric dipole excitation is much better suited, since the grounded transmitter excites both horizontal and vertical currents in the formation, making the method sensitive to the resistivity anisotropy. Here we distinguish frequency-domain CSEM, which is more promising in marine scenarios and time-domain CSEM for onshore/land applications, since it is advantageous to record once the transmitter is silent, i.e., after airwave has passed (Kumar and Hoversten, 2012).

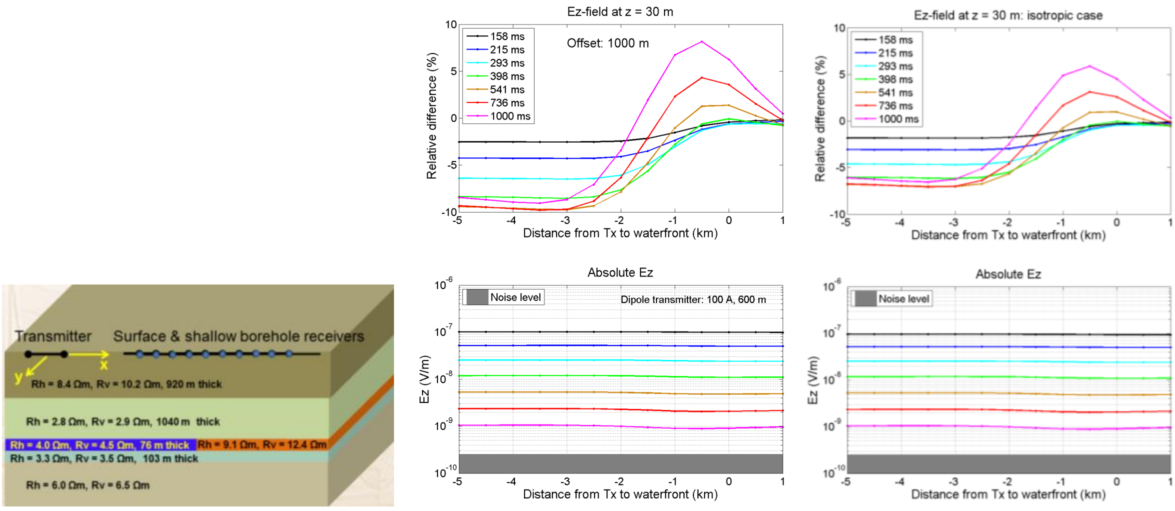
In enhanced oil recovery (EOR), one usually increases the mobility of hydrocarbons through ion mobility. This causes the ions to flow more easily along with the oil, measurable by a reduction in electrical resistivity. Furthermore, electrical property changes appear in the reservoir resulting in contrasts at the flow boundaries. Thus, EM methods provide unique opportunities to track fluid movements and becomes important tool in reservoir monitoring and management (Tietze et al. 2015).

To date, EM applications for reservoir monitoring are in an early stage of development. Several attempts have been reported: The surface-to-borehole technology was developed by Kriegshäuser and Tripp (1997); Tseng et al. (1998); Strack (2004). Wilt et al. (2008) suggest a cross-well and surface-to-borehole geometry for a reservoir monitoring EM system, characterized by a low-frequency axial magnetic dipole transmitter in one well and set of magnetic receivers in an adjacent well. Presently, only limited monitoring applications have been reported.

Example: Surface-to-Surface Application

This presents a feasibility study of surface-to-surface measurements performed for reservoir monitoring. Those EM components which exhibit the strongest anomalies, determined by modeling, were combined with on-site noise measurements to establish technical and commercial viability.

The most promising results were obtained using shallow borehole receivers, since they are most sensitive to vertical currents significantly affected by a resistive oil reservoir or typically more conductive "flooded" rocks. Shallow vertical wells can easily be prepared. The source is established with a grounded dipole transmitter. A simplified 2D model with a reservoir situated at a depth of 2 km is depicted in Figure 1-a. The anisotropic resistivity model was derived from a resistivity log. As the waterfront (blue) moves, the receiver array on the surface records the respective response. For simplicity of this analysis, the *x*-directed dipole transmitter and in-line receivers are co-aligned with the waterfront propagation direction.



(a) (b) (c)

Figure 1*: 2D model of a flooded reservoir and synthetic response of Ez component to the waterfront.*

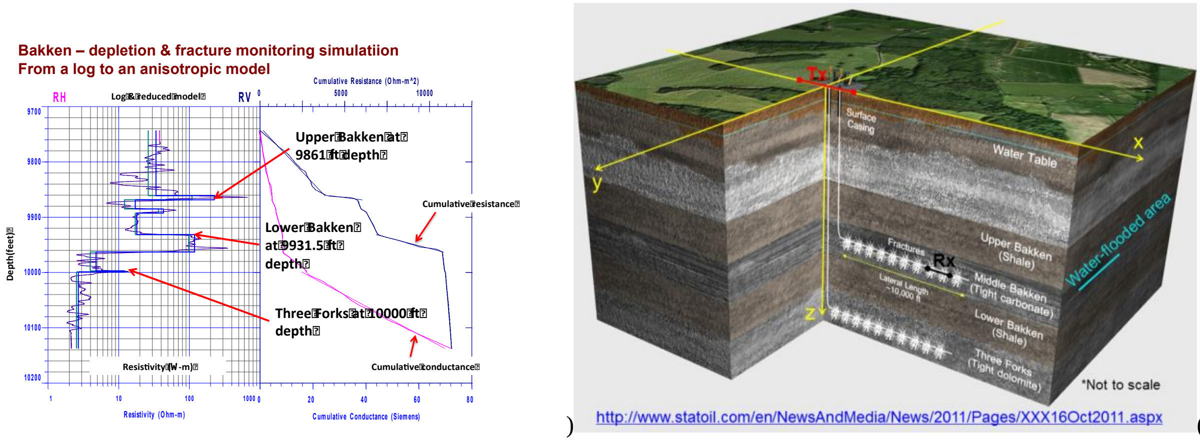
A grounded horizontal electric dipole transmitter response in time-domain was simulated for offsets from 1 to 8 km. In-line receivers were chosen, as they give the strongest response to the resistive reservoir (Strack et al., 1988). To estimate the sensitivity to the reservoir resistivity the response of all three components of the magnetic and the electric field, including the vertical component Ez (available through measurements in the shallow vertical boreholes) were calculated at several times after the transmitter current turn-off. The modeling was performed using 3D finite-difference method by Davydycheva and Druskin (1999) which allows for arbitrary resistivity anisotropy.

The vertical component, Ez, at a depth of z = 30 m is shown in Figure 1-b & c with & without taking the anisotropy into account. It can readily be observed that Ez demonstrates sufficient sensitivity to the reservoir properties. Even the minor anisotropy is essential for the interpretation, and failure to take it into account can lead to wrong estimate of the distance to the water front. Time-domain measurements do not require long offsets which would typically be needed for frequency-domain methods. Ez sensitivity reveals itself at late times after turn-off, where deeper lying strata respond.

Example: Surface-to-Borehole Application

Because unconventional (shale) basins, due to their geological genesis, are characterized by a naturally high electrical anisotropy, they offer a unique potential for CSEM applications to monitor the reservoir status. The example selected here is located in the Bakken formation in North Dakota, North America. Figure 2 illustrates the reservoir/field layout. The reservoir exhibits an average porosity of 7% (courtesy of Microseismic Inc.). In order to realistically model the Bakken reservoir, a resistivity model is derived from the logs as shown in Figure 2-a (Strack and Aziz, 2012).

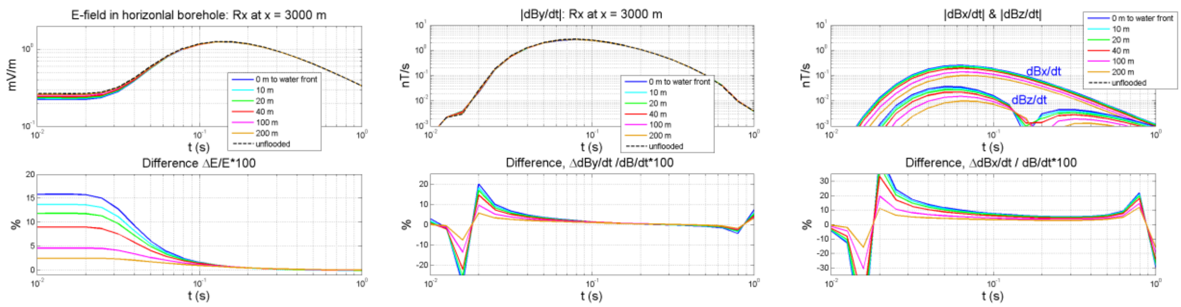
While more recent logging applications allow for direct input of horizontal and vertical resistivity, respectively, most conventional logs are standard induction logs sensitive to the horizontal resistivity and not sensitive to the anisotropy. Since both, horizontal and vertical resistivities, are features of the same lithology, the vertical resistivity can be derived by analyzing the log in terms of total conductance and total transverse resistance (Strack, 1992). The resulting values are “end members” of an ensemble of possible electrical properties and thus all possible models. The figure shows the induction log on the left and the total cumulative conductance/transverse resistance on the right. Derivations from the slopes of these curves result in an anisotropic log model plotted here together with the log on the left. The layer boundaries and resistivities are also shown.



(b)

Figure 2: Bakken field: the reservoir model with resistivities derived from the log (a) with a surface-to-borehole EM system integrated as sketch (b).

Since this reservoir is relatively deep, the surface-to-surface reservoir monitoring application may present difficulties. Indeed, our feasibility study shows only a moderate response of all surface receivers to the reservoir water flooding, not exceeding 1-2% for all field components. Such an environment suggests the use of surface-to-borehole measurements.



(a) (b) (c)

***Figure 3:** Response of borehole electrical (a) and magnetic (b, c) receivers situated in a horizontal well inside the lower Bakken reservoir to a water front. Distance to the water front varies from 200 m to 0. Grounded x-oriented electric dipole, 500 m long, is situated in the origin; its current is 150 A.*

Figure 3 shows 3D modeling results demonstrating good sensitivity of time-domain measurements to a water front moving from negative *y*-direction, from a parallel injector well situated inside the reservoir at the same depth as the producer well, in Lower Bakken (see Figure 2). The injector well is not shown since it is situated behind the (*x*,*z*) plane; the flooded area cross-section is shown in light-blue. The borehole receivers are situated at x = 3000 m inside the lower Bakken reservoir in (*x*,*z*) plane. The water front was modeled as a rectangular block of vertical extend of 31 m, the horizontal extend of 4000 m in *x* and 400 m in *y*. The resistivity of the flooded area (8.16 Ωm) was derived using Archie's law taking into account the reservoir porosity. The background 1D (horizontally-layered) anisotropic resistivity model was derived from a vertical log as shown in Figure 2-a. Since the background model is symmetric w.r.t. (*x*,*z*) plane, B*y* is the only non-zero component of the magnetic field in the borehole receivers inside the unflooded reservoir; it is why B*x* and B*z* "unflooded" are equal to zero and not shown. As the waterfront approaches the producer well, a non-zero B*x* and B*z* emerge, which can be analyzed to determine the distance to the water front.

The signal level is in the range of *mV/m* for the electrical receivers and *nT* for the magnetic receivers which is well above the noise level of the measurement system. The effect of steel casing was also studied; it is not significant, as long as the grounded transmitter is not connected to the casing.

Conclusions

We demonstrated feasibility of surface-to-surface and borehole-to-surface EM for EOR and reservoir depletion monitoring. Multi-channel measurement system including high-power transmitter and three-component electric and magnetic receivers is available and ready for application. In addition, we have run field tests to verify the prediction on real reservoir and to demonstrate the information content focusing below the receiver.

Acknowledgements

We thank Xiayu Xu, Maxim Smirnov and Oleg Bondarenko for valuable help.

References

Constable, S. 2010. Ten years of marine CSEM for hydrocarbon exploration. Geophysics 75 (5), A67-A81.
Davydycheva, S. and Druskin, V. 1999. Staggered grid for Maxwell's equations in arbitrary 3-D inhomogeneous anisotropic media, in: Oristaglio, M., and Spies, B., Eds. Three-dimensional electromagnetics: Soc. Expl. Geophys. 119-137.
Davydycheva, S., and Rykhlinski, N.I.. 2011, Focused-source electromagnetic survey versus standard CSEM: 3D modeling in complex geometrie. Geophysics 76, no.1, F27-F41.
Keller, G.V., and Frischknecht, F.C. 1967. Electrical methods in geophysical prospecting, Pergamon Press.
Kriegshäuser, B., and Tripp, A. 1997. Probing strata of anisotropic complex conductivity using surface to borehole methods. Society of Exploration Geophysicists, Expanded abstracts 2, 1953-1956.
Kumar, D., and Hovesten, G.M. 2012. Geophysical model response in shale gas. Geohorizons 17, 32-37.
Strack, K.M., LeBrocq, K., Moss, D.C., Petry, H., Vozoff, K., and Wolfgram, P. A. 1988. Resolving resistive layers with LOTEM in hydrocarbon exploration: case histories. Paper 4-23, 50th Annual Meeting, European Association for Exploration Geophysicists, The Hague, abstract vol. 158.
Strack, K. M. 1992. Exploration with deep transient electromagnetics. Elsevier, 373 pp (reprinted 1999).
Strack, K. M. 2004. Combine surface and borehole integrated electromagnetic apparatus to determine reservoir fluid properties. U. S. Patent 6,739,165.
Strack, K. M. 2014. Future directions of Electromagnetic Methods for Hydrocarbon Applications. Surveys in Geophysics 35, 157-177.
Strack, K. M. and Aziz, A. A. 2012. Full field array electromagnetic: A tool kit for 3D application to unconventional resources. Geophysical Society of Houston and SEG Spring Symposium, Houston.
Tietze, K., Grayver, A., Streich, R., and Ritter, O. 2014. Recent Developments for Land-based Controlled source EM Surveying, 16 June 2014. DOI: 10.3997/2214-4609.20140561.
Tietze, K., Ritter, O., and Veeken, P., 2015. Controlled source electromagnetic monitoring of reservoir oil Saturation using a novel borehole-to-surface configuration. Geophysical Prospecting 63(6).
Tseng, H.-W., Becker, A., Wilt, M.J. and Deszcz-Pan, M. 1998. A borehole-to-surface electromagnetic survey. Geophysics 63. 1565-1572.
Wilt, M., Donadille, J.M., AlRuwaili, S., Ma, S.M., Marsala, A. 2008. Crosswell electromagnetic tomography in Saudi Arabia – from field surveys to resistivity mapping. 70th EAGE Conference and Exhibition, Rome, Italy.