6th International Symposium on Three-Dimensional Electromagnetics
Berkeley, California, USA, March 28-30, 2017

3D EM modeling for reservoir monitoring applications

Sofia Davydycheva[1] , Ingo Geldmacher[1], Tilman Hanstein[1], and Kurt Strack[1]
[1]KMS Technologies, http://www.kmstechnologies.com/

SUMMARY

Feasibility study of surface-to-surface measurements is performed for reservoir monitoring applications. The strongest response is observed above the edges of the flooded/fracking area. Those EM components which exhibit the strongest anomalies, determined by modeling, are combined with on-site noise measurements to establish technical and commercial viability.

Keywords: hydro-fracking, CSEM, time domain, finite-difference modeling.

INTRODUCTION

After the success in marine EM (Johansen et al., 2005; Constable; 2010), the scope of applications for CSEM has been revisited for onshore/land applications (Tietze et al., 2014, 2015; Strack, 2014). High value targets such as applications in unconventional (shale) basins or reservoir steam/water flood 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.

CSEM applications using a grounded electric dipole in time-domain are promising 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). While using time-domain measurements, the CSEM information content (where does the information come from in the subsurface?) can be focused below the receivers using either vertical electric field measurements or Focused Source EM (Davydycheva and Rykhlinski, 2011).

In **e**nhanced **o**il **r**ecovery, 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.

Reservoir monitoring essentially poses a time-lapse exercise, where measurements that link downhole and surface-to-surface data enable 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.

To date, EM applications for reservoir monitoring are in an early stage of development. Presently, only limited monitoring applications have been reported One of the key remaining challenges is for the EM response to reach sufficient depth. This could be achieved by higher power transmitters.

Tietze et al. (2014, 2015) apply a grounded transmitter connected to a steel casing for reservoir monitoring application.

Palish et al. (2017) apply surface EM measurements to visualize fracking process to a 8000 ft deep reservoir. To enhance the EM response they utilize ceramic proppant with electrically conductive coating, whose conductivity is 500-2000 S/m. They report on a successful field test in Texas.

METHODOLOGY

A 3D modelling based feasibility study of surface-to-surface measurements is performed for reservoir monitoring applications. For simplicity of this analysis, the *x*-directed dipole transmitter is co-aligned with the waterfront propagation direction. Three-component electrical and magnetic receivers are situated on the Earth surface and in shallow vertical boreholes to allow vertical electric field measurements.

Those EM components which exhibit the strongest anomalies, determined by modelling, are combined with on-site noise measurements to establish technical and commercial viability.

WATER FLOOD MONITORING

A simplified 2D anisotropic model with a reservoir situated at a depth of 2 km is depicted in Figure 1. The model was derived from a vertical resistivity log. While more recent resistivity logging applications allow for direct input of horizontal and vertical resistivity, most conventional logs are standard induction logs sensitive to the horizontal resistivity and not sensitive to the anisotropy. Still, the anisotropy can be estimated using well-known equivalence principle (Keller and Frischknecht, 1967; Strack, 1992).

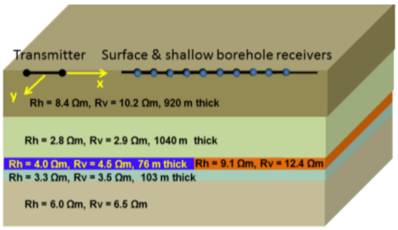

Figure 1. 2D model of a flooded reservoir.

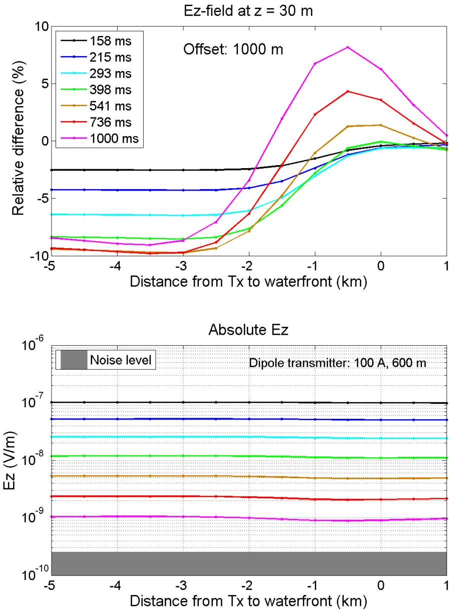

Figure 2. Response of Ez component to the waterfront.

A grounded horizontal electric dipole transmitter response in time-domain was simulated. As the waterfront (blue) moves, the receiver array on the surface records the respective response. 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, for offsets from 1 to 5 km. 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 observation wells can easily be prepared.

The vertical component Ez is shown in Figure 2. It can readily be observed that Ez demonstrates sufficient sensitivity to the reservoir properties. Note that 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.

The modeling was performed using 3D finite-difference method by Davydycheva and Druskin (1999) which allows for arbitrary resistivity anisotropy.

HYDRO-FRACKING MONITORING

Because unconventional (shale) basins 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 3 illustrates the reservoir properties 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 3 (Strack and Aziz, 2013). 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. The layer boundaries and resistivities are also shown.

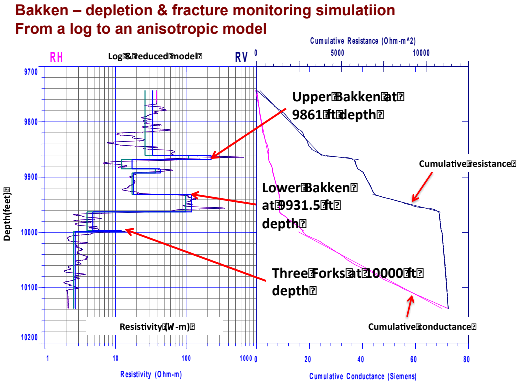

Figure 3: Bakken field: the reservoir model with anisotropic resistivities derived from the log (log: courtesy of Microseismic Inc.)

Figure 4 shows surface-to-surface hydro-fracking monitoring setup scheme over the Bakken field. Detection of proppant injected in horizontal wells in unconventional reservoirs is very challenging task since such reservoirs are typically deep, and the conventional sand-based proppant does not have high enough contrast in the resistivity with respect to the reservoir oil-saturated rocks. Below we consider specially developed detectable proppant of 1000 S/m containing conductive-coated ceramic particles (Palish et al. 2017).

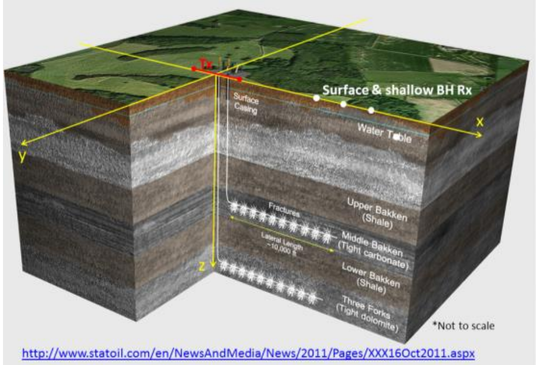

Figure 4: Bakken field reservoir model with a surface-to-surface EM system integrated as sketch.

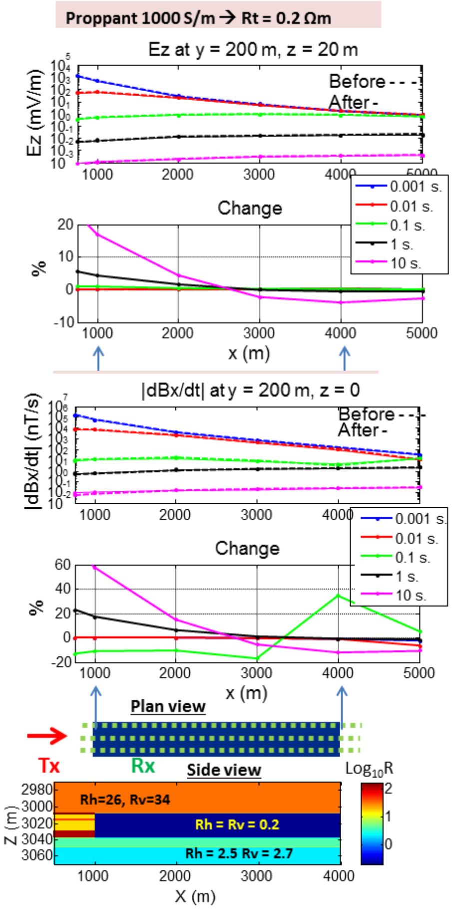

Figure 5: Modeling results for Ez (top) and dB*x*/dt (middle); bottom: the anisotropic reservoir model and the fracture area (dark blue).

We consider a grounded 500 m long dipole transmitter, situated in the origin as depicted. It excites the formation with the current of 150 A. Three-component electrical and magnetic receivers are situated on the surface and in shallow boreholes above the rectangular model of the fracking area (from 1000 to 4000 m in *x*, from -200 to 200 m in *y* and from 3008 to 3039 m in *z*). Taking into account 7% porosity, we estimated the new (isotropic) resistivity of the fracture area, if fully saturated with the proppant, using Archie's law: it is equal to 0.2 Ωm. The anisotropic fracture area is subject of future study.

Figure 5 illustrates the modelling results for the two most sensitive EM components. Transient responses at 0.1 s. and at later times show good sensitivities to the edges of the fracking area. Figure 6 shows the same EM components as functions of time after turn-off in several distances from the transmitter. Again, the maximal deviation of the measurement are observed at 1 and 4 km, right above the fracture area edges.

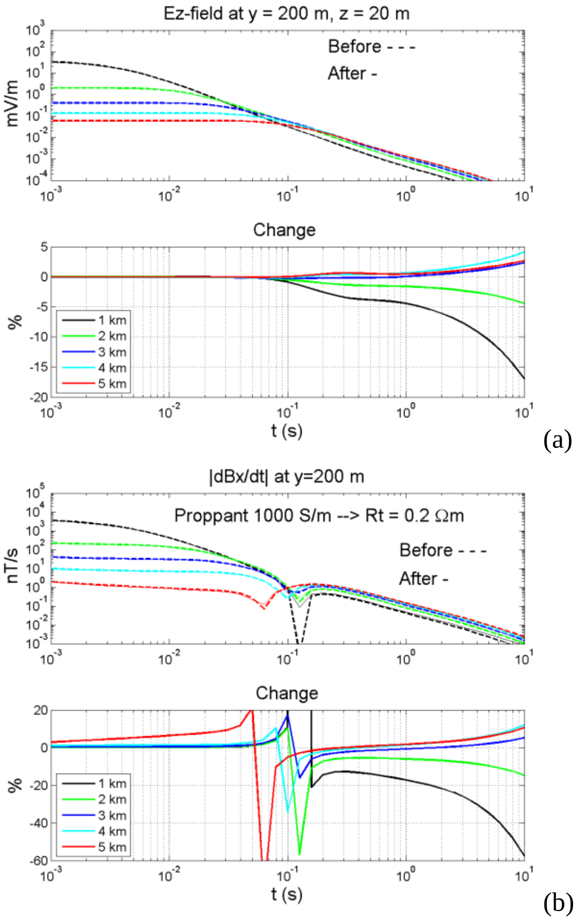

Figure 6: Modeling results for Ez (a) and dB*x*/dt (b) above the fracture area as a function of time after Tx switch-off show good sensitivity to the fracture area above its egdes at 1 and 4 km.

Figure 7 illustrates the case of less conductive (fully saturated salty water and sand based) proppant. This may be much more challenging case; however, a 5-% change in the measured responses is still observed. The signal level is in the range of *mV/m* for the electrical receivers and *nT* for the magnetic receivers which is above the instrumental and environmental noise.

The effect of steel casing was studied as well; it is not significant, as long as the grounded transmitter is not connected to the casing and its electrodes are placed at a distance exceeding 50-100 m from the cased well

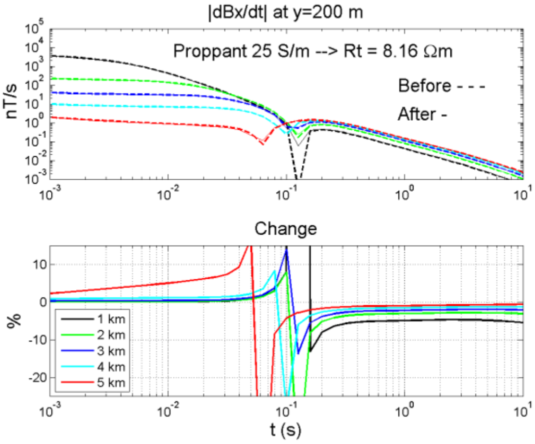

Figure 7: Less conductive proppant: dB*x*/dt above the fracking area as a function of time after Tx switch-off.

CONCLUSION

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

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 feasibility of surface-to-surface EM for reservoir depletion monitoring and for fracture detection was shown. 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.

ACKNOWLEDGMENTS

We appreciate valuable help by Xiayu Xu, Maxim Smirnov and Oleg Bondarenko.

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*: SEG, 119-137.

Davydycheva, S., and Rykhlinski, N.I., 2011, Focused-source electromagnetic survey versus standard CSEM: 3D modeling in complex geometries, *Geophysics* **76**(1), F27-F41.

Johansen, S.E., Amundsen, H.E.F., Røsten, T., Ellingsrud, S., Eidesmo, T., and Bhuyian, A.H., 2005, Subsurface hydrocarbons detected by electromagnetic sounding: *First Break*, **23** (March), 31-36.

Keller, G.V., and Frischknecht, F.C., 1967, Electrical methods in geophysical prospecting, *Pergamon Press.*

Kumar, D., and Hovesten, G.M., 2012, Geophysical model response in shale gas. *Geohorizons* **17**, 32-37.

Palish, T., Al-Tailji, W., Bartel, L., Cannan, C.,Zhang, J., 2017, Far-field proppant detection using electromagnetic methods – latest field results, SPE, *Hydraulic Fracturing Technology Conf.*, *Paper 184880-MS*.

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, EAGE, The Hague*.

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 A.A. Aziz, 2013, Advances in electromagnetics for reservoir monitoring, *Geohorizons (Special shale issue)*, 32-44.

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)