KMS Technologies

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Understanding and overcoming risks of CSEM for reservoir monitoring

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Summary

A new technology for reservoir monitoring includes full field controlled-source electromagnetics (CSEM) and microseismics. To mitigate the risk, we have developed full technology cycle: from patents, hardware, acquisition methodology, to data processing and interpreting in 3D. The system can acquire surface-to-surface and surface-to-borehole measurements. EM data are used to track fluids, due to their high sensitivity to the fluid resistivity while seismic data relate primarily to the reservoir boundaries. Having seismic and EM sensors in the same recording unit allows the addressing of the multi-physics character of the problem early on in the workflow. The system enables acquiring large number of EM data channels at low cost similar to what is done with seismic data.

Typical risks are lack of EM image focus, formation resistivity anisotropy and unaccounted effects of steel casing(s). To mitigate these risks, we apply careful 3D modeling feasibility studies and acquire dense EM field data. In addition, we apply a novel method to focus the EM image information directly below the receiver. Operational risks include low signal-to-noise (SNR) ratio, issues related to the transmitter stability, to the stability of the groundings, and data processing inefficiency. Understanding and mitigation of these risks is key to successful reservoir monitoring job.

Introduction

In enhanced oil recovery (EOR), electrical property changes appear in the reservoir resulting in contrasts at the flow boundaries. The larger the contrast, the larger is the electromagnetic response. Thus, EM methods provide unique opportunities to track fluid movements and flow boundaries. They are important parameters in reservoir management, especially for high value targets such as unconventional (shale) reservoirs or steam/water/CO_2 flood EOR. Thus, the EM data and interpretation could yield considerably more value than traditional seismic interpretation alone. At the same time, technology has progressed such that it is now routine recording virtually an unlimited number of channels at lower cost (than in the past) and interpreting data in 3D.

Surface-to-surface CSEM applications using a grounded electric dipole in time-domain (Strack, 1992; 2014) are more promising for land applications than frequency domain CSEM (Johansen et al., 2005; Constable, 2010), since it is advantageous to record once the transmitter is off, after the airwave has passed (Kumar & Hoversten, 2012).

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 3D modeling feasibility to fully understand the reservoir effects.

To date, EM applications for reservoir monitoring are in an early stage of development. Presently, only limited monitoring applications have been reported (Hoversten et al. 2015, Tietze et al. 2014; 2015; Thiel, 2016).

As novel contribution we derived a methodology and additional measurements where the information content can be focused below the receivers using either Focused Source EM (FSEM) (Davydycheva & Rykhlinski, 2009; 2011) or vertical electric field measurements.

Method: microseismic-EM acquisition system

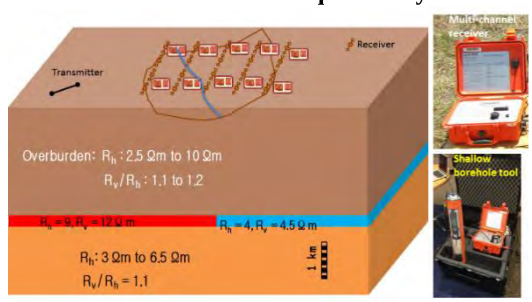

Figure 1: Flooded reservoir model and monitoring setup.

We developed a commercial land microseismic-EM system for reservoir monitoring (Figure 1). The system includes high-power transmitter and multi-component microseismic-EM receivers with practically unlimited number of channels. Since microseismic measurements are already standard tool, we refer to the available literature (Maxwell, 2014) and further consider on EM. Three-component EM sensors are situated on the Earth surface and in shallow vertical boreholes to enable vertical electric field measurement. For this we use a commercial shallow borehole tool (SBHT): shallow observation wells of the depth of 20-40 m can easily be prepared. Deep borehole full field sensors are optional.

Every reservoir monitoring case is carefully studied for feasibility: 3D modeling-based study is performed to determine those of six EM components (3 electric + 3 magnetic ones) which exhibit the strongest anomalies. Mandatory on-site noise measurement is performed to establish technical and commercial viability. The field setup is configured based on the 3D feasibility study, and time lapse data are acquired, processed, calibrated using available well logs and linked to microseismic data.

Figure 2 shows vertical cross-section of a heavy oil reservoir (Passalaqua et al. 2016). Its approximate 3D model (left-center) is used for 3D modeling feasibility study. The blue parallelepiped represents the steam/water flood area of 500x500x140 m. A 400-m long transmitter situated at the origin excites the formation with rectangular impulses, and multicomponent EM receivers above the flood area are shown as triangles.

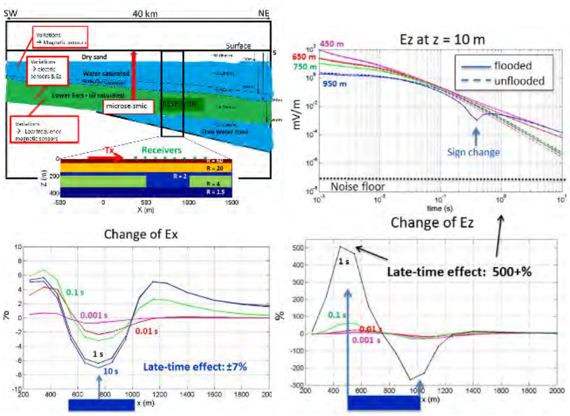

Figure 2: Heavy oil reservoir: steam-injection model (left top), Ex (left-bottom) and Ez (right) responses to the flooded area.

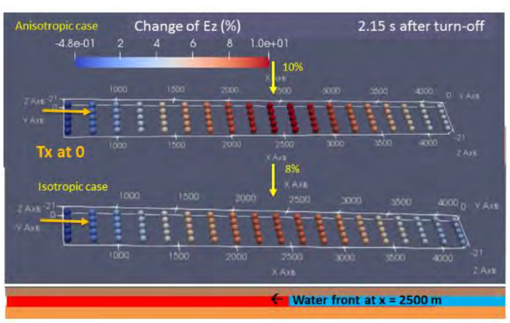

Figure 3: Time lapse Ez change above the waterfront at 2.15 s. after turn-off: anisotropic (top), & isotropic case when Rh = Rv (bottom).

The responses of the vertical electric field before and after the flood are shown in Figure 2 as a function of time after the transmitter turn-off (top-right) and relative responses are shown as a function of the distance to the transmitter (bottom: measurements compared to a fully oil saturated state). They were simulated using a 3D finite-difference (FD) method by Davydycheva & Druskin (1999). Late-time responses are significantly affected, especially above the flood area edges at 500 and 1000 m. Thus, the flooded area contour may be determined with great accuracy through the measurement of Ez component using SBHT in vertical boreholes above the reservoir. Since the reservoir is relatively shallow, the effect is strong enough at relatively early times below 1 s. Ez is the most sensitive to vertical currents significantly affected by resistive/conductive oil/water saturated (unflooded/flooded) rocks. Effect of traditional inline dipole-dipole measurement Ex is in the range of several per cent. It is smaller, since Ex is sensitive to horizontal currents, much less affected by relatively thin resistor (reservoir).

Risk: lack of image focus

In the case of deeper reservoirs, the feasibility often reveals the reservoir response at much later times after turn-off, when signal is close to the noise floor. A simplified 2D anisotropic model as depicted in Figure 1 with the reservoir (red) at the depth of 2 km was derived from a vertical resistivity log. As the waterfront (blue) moves, the receiver array on the surface records the multi-component EM response. In Figure 3, the *x*-directed dipole transmitter is co-aligned with the waterfront propagation direction, for simplicity of the analysis. To estimate the sensitivity to the reservoir resistivity the response of all three components of the magnetic and the electric field, including Ez component, were simulated at several times after turn-off, while the responses were well above the noise floor.

Synthetic time lapse response of the vertical component Ez is shown in Figure 3. It demonstrates sufficient sensitivity to the reservoir properties, while the standard inline component Ex gives only 1.5% anomaly (not shown). The signal level was well above the noise floor measured on the site.

Measurement of the vertical electric field requires drilling shallow vertical wells to place the receivers. If those are unavailable, an alternative FSEM measurement by Davydycheva & Rykhlinski (2011) can help. It utilizes circular electric dipole cancelling ingoing and outgoing horizontal currents and making data sensitive to a narrow column of rocks under the receiver, thus focusing the sensitivity vertically downward, as shown in Figure 4 (left-top), without the need to drill vertical wells.

Figure 4 also illustrates a derivation of 3D model (bottom) for the feasibility study of a complex reservoir in Papua New Guinea. The reservoir is in Jurassic sandstones with overburden of 1000-1500 m of carbonates and 800-1500 m of shales (Hill et al. 2010). The resistivities were taken from magnetotelluric data by Hoversten (1996). We included in the model shallow structures whose effect happens to be very strong: they change the standard CSEM inline dipole-dipole response beyond recognition, as shown in Figure 5.

FSEM method (Figure 6) gives stronger reservoir response and allows partial removal of unwanted shallow effects through the subtraction of measurements acquired at different times after turn-off (Davydycheva & Ryhklinski, 2011).

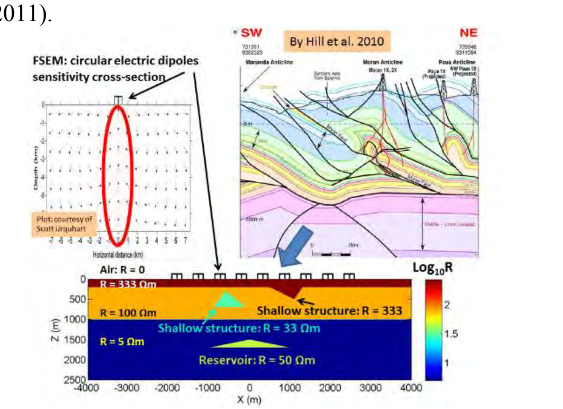

Figure 4: Papua New Guinea feasibility: model setup & derivation.

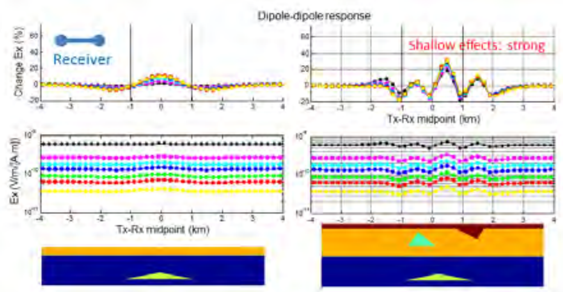

Figure 5: Papua New Guinea case: standard CSEM in the absence (left) and presence (right) of shallow structures. Tx-Rx offset: 1 km.

To go deeper: surface-to-borehole measurements

If the reservoir depth is greater than 3 km, surface monitoring methods may be insufficient due to the lack of sensitivity. Then we utilize surface-to-borehole measurements. Figure 7 shows 3D cross-section of Bakken field reservoir. The formation is excited by a 1-km long grounded dipole transmitter (red). Borehole receivers are situated in a deep horizontal well. Flooded/depleted/hyrdo-fracking target area is shown in light-blue. Figure 8 shows 3D modeling results and demonstrate good sensitivity of time-domain measurements to a water front moving from negative *y*-direction, from a parallel injector well situated inside the reservoir (not shown since it is situated behind the (*x*,*z*) plane) at the same depth as the producer. The deep 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* (bottom-left). The background 1D (horizontally-layered) anisotropic resistivity model was derived from a vertical log, while the resistivity of the flooded area (8.16 Ωm) was derived using Archie's law taking into account the reservoir porosity (Strack and Aziz, 2013). 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.

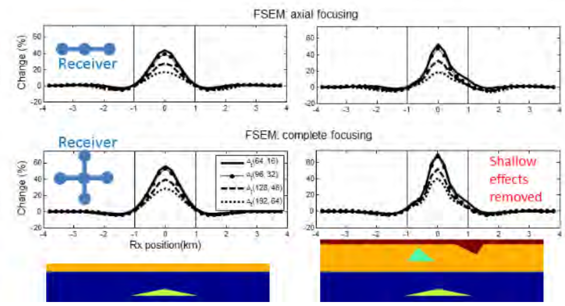

Figure 6: Papua New Guinea case: FSEM feasibility. Offset: 1 km.

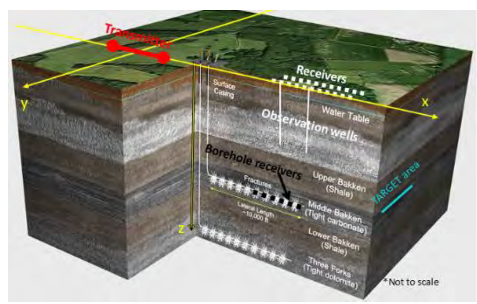

Figure 7: Bakken field 3D cross-section (courtesy of Miscoseismic Inc.) and monitoring setup.

Unaccounted resistivity anisotropy

The resistivity anisotropy is one of the key technical issues for realistic reservoirs. It is determined by the difference in electric rock properties across and along the layering. A moderate anisotropy is always present in shales, sands, carbonates and other sedimentary rocks due to layering during geologic deposition. In addition to this, in shale-sand laminations the horizontal resistivity Rh is typically low, being dominated by the conductive shale layers, whereas the vertical resistivity Rv may be high, dominated by the oil-saturated sands. Thus, their ratio Rv/Rh can sometimes reach ten or even more (see, for example, Barber et al. 2004). The electrical anisotropy significantly affects the CSEM measurements, affected by both vertical and horizontal current flow, so taking it into account is critical. Figure 3 demonstrates a noticeable difference in Ez response in the presence (top) and absence of the anisotropy (bottom), even though the anisotropy ratio Rv/Rh does not exceed 1.2 in this case. Tilted anisotropy can give even more profound effect: anticlines and synclines can fully distort the reservoir anomaly (Davydycheva & Frenkel, 2013). The anisotropy must be estimated from resistivity logs and included to background model for feasibility and final interpretation. In the absence of modern anisotropy logs, the anisotropy can be estimated from conventional resistivity logs using well-known equivalence principle (Keller & Frischknecht, 1967).

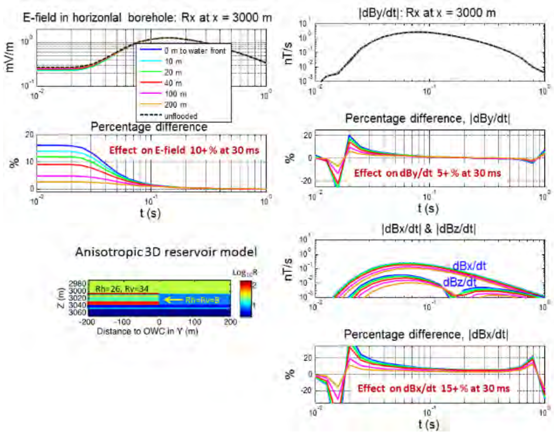

Figure 8: Borehole-to-surface: effect of approaching oil-water contact (OWC) to EM measurements on Bakken field.

Effects of steel casing

Typical reservoir is intersected by multiple cased wells distorting the EM field excited by the grounded transmitter. We found that effect of steel casing on the surface EM field it is not significant, while the transmitter and receivers are not connected to it and their groundings are placed at 200+m from the cased wells (see Figure 9). The electric field inside the vertical cased well is affected up to the depth of ~1 km but can be accounted for. FD modelling (symbols) shows good agreement with independent 3D finite element (FE) modelling (Bachinger et al. 2006) (lines). The magnetic field is practically unaffected. We checked the whole spectrum of our interest from 0.1 to 30 Hz.

Other operational risks and data processing features

The operational risks include (1) possible instability of the transmitter (rectangular) waveform: overshoots are typical; (2) instability of the grounding resistances of the transmitter and receivers; (3) operational/cultural/geological EM noise. To improve SNR, we apply robust proprietary signal processing software. Figure 10 shows an example of processing data acquired using circular electric dipoles on Hockley field test site in Houston suburb in Texas. After filtering, stacking and smoothing the data, we get clean signals in all channels up to several seconds after turn-off, despite very strong cultural EM noise. The data interpretation is a subject for a separate paper.

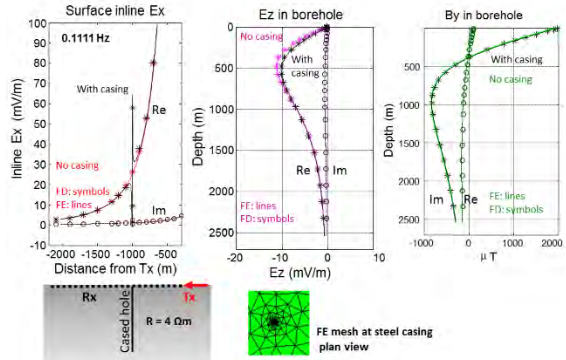

Figure 9: effect of steel casing on the EM field. Left: surface-to-surface; right: surface-to-borehole response; frequency: 1/9 Hz.

Conclusions

A multi-channel full field EM-microseismic measurement system has been developed for surface-to-surface and surface-to-borehole applications. Those EM components which exhibit the strongest anomalies, determined by 3D modeling, are combined with on-site noise measurements to establish technical and commercial viability. The system includes high-power transmitter and multi-channel receivers. Promising results are obtained using shallow borehole tool, sensitive to vertical currents affected by thin horizontal resistors - typical reservoirs. In addition, novel focused measurements on the Earth surface allow focusing the EM imaging information directly below the receiver. The new robust data processing software efficiently de-noise the data. The system stability methodologies were confirmed by actual field measurements.

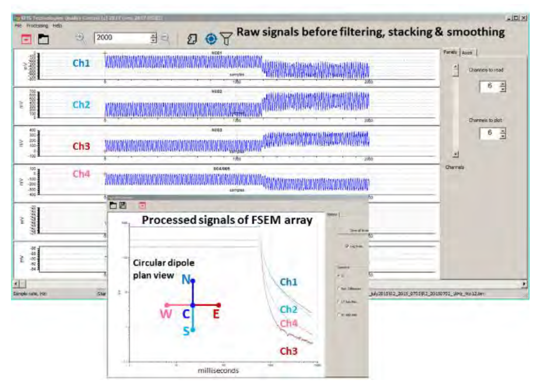

Figure 10: circular electric dipole, four-channel data processing: before (top) and after filtering, stacking and smoothing (bottom).

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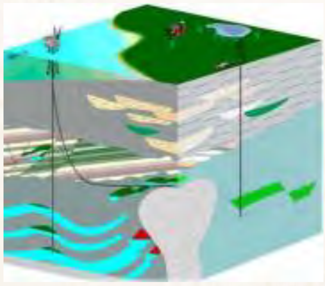

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