Th G107 10

Electromagnetic Monitoring of the Propagation of an Injected Polymer for Enhanced Oil Recovery in Northern Germany

K. Tietze* (GFZ German Research Centre for Geosciences) & O. Ritter (GFZ German Research Centre for Geosciences)

SUMMARY

In an Enhanced Oil Recovery (EOR) pilot project Wintershall Holding GmbH, Kassel, is testing their newly developed biopolymer Schizophyllan in one of their oil fields. Mixture with the highly saline formation water results in a polymer solution with much lower electrical resistivity than the displaced oil within the reservoir. To advance and optimize EOR techniques it is essential to know the spatial propagation and distribution of the injected fluids in the subsurface. At GFZ Potsdam, we investigate the applicability of the CSEM method to monitor the distribution of the polymers solution. Based on a 26-site MT survey across the oil-field and calibration with resistivity well-logs, we constructed a 3D resistivity model of the reservoir region for 3D CSEM forward simulations; main focus of the study was to test the sensitivity of various source-receiver configurations. 3D modelling results suggest that CSEM is sensitive to resistivity changes at reservoir depths, but the effect is difficult to resolve with surface measurements only. Resolution potential increases significantly, however, if sensors/transmitters can be placed in observation wells closer to the reservoir. In particular, observation of vertical electric fields in shallow boreholes and/or use of novel source configurations consisting of vertical and horizontal dipoles appear promising.

Introduction

Enhanced Oil Recovery (EOR) is a technique for increasing the amount of crude oil that can be extracted from an oil field. Following natural oil production and water injection (primary and secondary oil recovery), tertiary techniques like injection of CO2, surfactants, polymer, or a combination is used to enhance recovery of oil.

In an EOR pilot project Wintershall Holding GmbH, Kassel, is testing their newly developed biopolymer Schizophyllan in one of their onshore oil fields in Lower Saxony, Germany. Mixture with the high saline formation water results in a polymer solution with much lower electrical resistivity than the oil within the reservoir. To advance and optimize EOR techniques it is essential to know the areal propagation and distribution of the injected fluids in the subsurface.

At GFZ Potsdam, we investigate the applicability of the controlled-source electromagnetic (CSEM) method to monitor the distribution of the polymer solution and the change in oil saturation in the reservoir. We present results of 3D CSEM simulations and first field data using novel source configurations.

CSEM simulations

In 2012 we carried out a magnetotelluric (MT) survey comprising 26 sites across the oil-field to obtain a model of the regional scale electrical resistivity structure. 17 of these sites were located on a 10 km long profile line approximately perpendicular to the regional geologic strike and centred at the polymer injection well. In addition, 9 sites were deployed along strike of the oil field; the oil-bearing formation is located at approximately 1200 m depth with a thickness of 10 to 20 m. At each site, we deployed two pairs of electrodes in N-S and E-W direction and three induction coil magnetometers in N-S, E-W, and vertical direction. Despite of high noise levels in the area, good quality MT transfer functions were obtained for periods between 0.001 and 1000 s using robust single site and remote reference processing routines (Ritter et al. 1998, Weckmann et al. 2005) and applying filtering techniques to the original times series in order to eliminate periodic cultural noise.

Based on the MT 2D inversion results along the 10 km profile and calibration with resistivity well-logs, we constructed a 1D background resistivity model of the reservoir region for 3D CSEM forward simulation of different scenarios (Fig. 1). We simulated CSEM fields both for a 1D and a 3D reservoir structure located at 1200 m depth. Reservoir resistivities were set to 16 Ωm and 0.6 Ωm for oil-saturated and brine-flushed states, respectively.

Main focus of the study was to test the sensitivity of various source-receiver configurations. For all subsequent CSEM forward modelling we used the code of Streich (2009) and Streich and Becken (2011). As we are interested in the sensitivity towards changes of the electrical resistivity within the reservoir, the results are considered in terms of relative EM field distribution changes before and after injection.

In our first approach, we simulated CSEM results for horizontal grounded dipole sources of 1 km length (source current 1 A/m) located 0.1 m below the surface; receivers are located at 0.05 m depth. For a 1D reservoir (infinite layer), a change of the resistivity from 16 to 0.6 Ωm would be detectable with surface measurements (relative amplitude changes > 10 %) in a wide area. Simulations showed that the best configuration for CSEM field measurements is expected for inline source-receiver distances of 2 to 7 km and a frequency range of 5 to 0.1 Hz. For a 3D reservoir structure (1 x 1 x 0.015 km^3), however, amplitude differences within a survey area of 5 x 5 km^2 around the reservoir and various source-reservoir distances of 0.5 to 5 km range below 2 % and cannot be resolved with confidence with CSEM measurements at surface.

But the 3D modelling results suggested that if sensors (or transmitters) can be placed in observation wells it is possible to measure and monitor changes of the reservoir's resistivity structure. Based on these initial results, we conducted further CSEM forward modelling of the 3D reservoir structure to investigate the potential of borehole-to-surface and borehole-to-borehole configurations. We tested three CSEM configurations (Fig. 2): (i) a vertical dipole, (ii) an L-shaped vertical dipole with horizontal surface extension, and (iii) an L-shaped vertical dipole with horizontal surface extension, but now using the steel casing of the borehole.

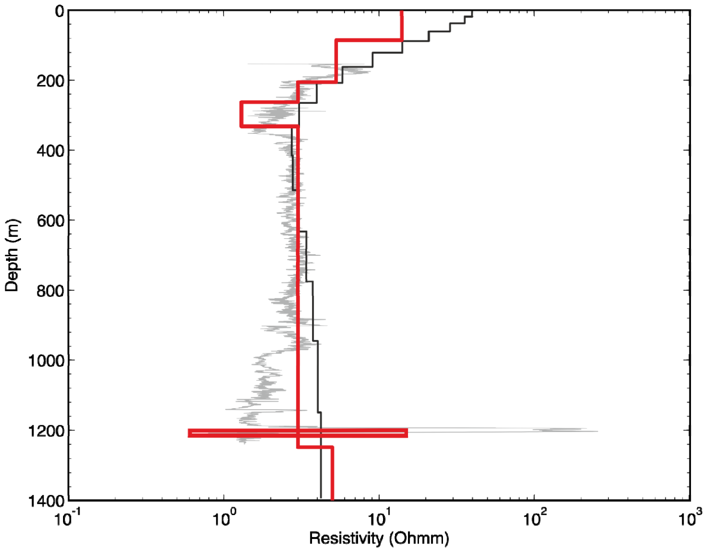

Figure 1 *1D background model (red) for CSEM simulations based on central part of the 2D MT inversion model (black) and resistivity log (grey); reservoir (thickness 15 m) in 1D and 3D simulations is located at 1200 m depth. 2D inversion results of the MT data agree well with the well-log data of a nearby borehole.*

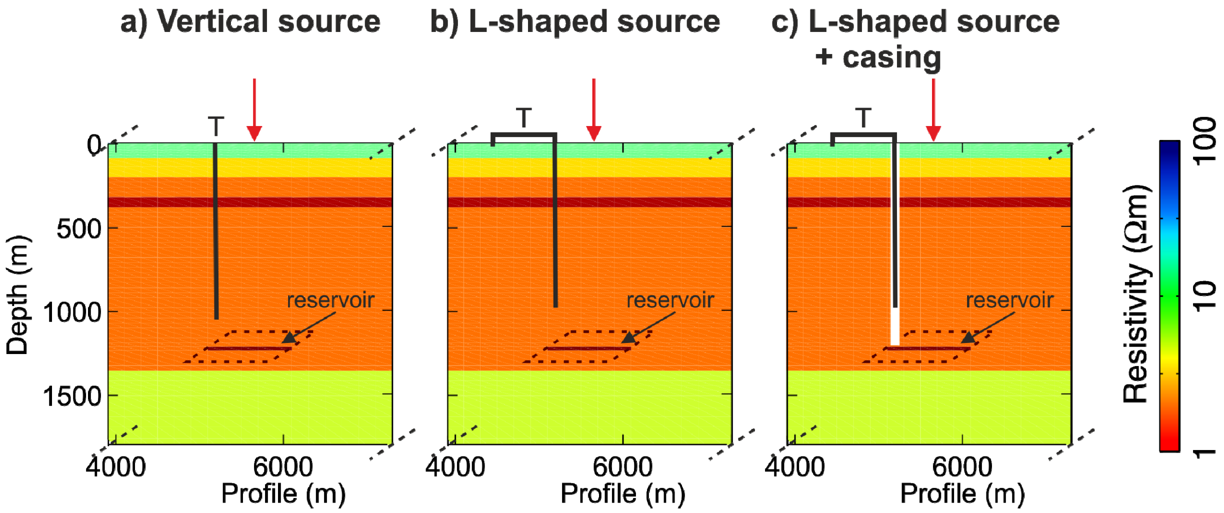

Figure 2 *New transmitter (T) configurations used for CSEM modelling; current strength 1 A/m. (a) Vertical dipole located at 5100 m profile position, i.e. 400 m offset from the injection site. Dipole length 1000 m. (b) L-shaped source, consisting of the vertical dipole described in (a) but with a 500 m long horizontal extension at surface. Current injection is at both ends of the "L", i.e. at depth at a single (isolated) electrode. (c) Same source configuration as in (b) but now including a steel casing. The borehole casing was simulated as a 40 m x 40 m wide and 1200 m deep-reaching column (white zone in (c)), where electrical conductivity is vertical-transverse anisotropic: horizontal resistivities are the same as for the isotropic 1D layered half-space; vertical conductivity was set to 100 S/m simulating the electrically conductive steel casing. Configuration simulates current injection through a single electrode at 4600m profile distance plus the steel casing.*

(i) Vertical dipole source: For this setup, the effect of reservoir changes is small and probably below the resolution threshold under real field conditions both at surface and also at depth. The 3D CSEM simulations of the reservoir suggest that it is unlikely that resistivity changes can be resolved with confidence at surface. For all EM components, field amplitudes decay rapidly when moving away from the source and amplitude changes remain small (< 5 %).

(ii) L-shaped horizontal-vertical source: One end of the dipole is located at 1000 m depth within a borehole close to the edge of the reservoir (see Fig. 2b). The other end point is located at surface, 500 m away from the borehole along the profile. Such a source configuration excites both horizontal and vertical field components. If a horizontal component (in x-direction) is added to the vertical source, changes in the reservoir resistivity structure can be measured and monitored at surface and at depth.

At surface, two electric (Fig. 3a) and the vertical magnetic field components (Ex, Ez, Hz) are above the 10% threshold for frequencies < 5 Hz and source-receiver distances of 1 to 4 km; in particular Ez is suggested to be sensitive over wide areas. If sensors are deployed closer to the reservoir, i.e. in observation wells, measureable effects are even larger (> 20%).

(iii) L-shaped horizontal-vertical source with steel casing: We simulated the influence of a borehole with steel casing using a substitute structure in the subsurface resistivity model. We defined a 40 m wide and 1200 m deep-reaching zone around the source where the resistivities are anisotropic (Fig. 2c). In horizontal direction, the resistivity is that of the layered half-space; in vertical direction we assigned a low electrical resistivity of 0.01 Ωm simulating the influence of the electrically conductive borehole casing. This modifications of the resistivity structure results in current concentration in the subsurface which enhances the field amplitudes and the relative changes, both at depth and at surface.

At surface, two electric and the vertical magnetic field components (Ex, Ez, Hz) are above the 10% threshold for frequencies < 5 Hz and source-receiver distances of 1 to 4 km. Both field amplitudes and amplitude changes are higher than for the same configuration without casing (Fig. 3b). For all field combinations a measurable effect is obtained if sensors can be installed at depth, closer to the reservoir. Technically this source configuration could be realized by using the casing of an abandoned (oil-)well as vertical part of the source.

Conclusions

3D CSEM modelling results suggest that CSEM is sensitive to resistivity changes at reservoir depths, but the effect is difficult to resolve with surface measurements only. Resolution potential at surface increases significantly, however, if sensors or transmitters can be placed in observation wells closer to the reservoir. In particular, observation of vertical electric field component Ez in shallow boreholes and/or use of novel source configurations consisting of vertical and horizontal dipoles appear promising.

Acknowledgements

This project is funded by Wintershall Holding GmbH, Kassel (Germany). The authors would like to thank all participants of the field campaigns for their help. Anna Platz is acknowledged for substantial contribution to MT data processing.

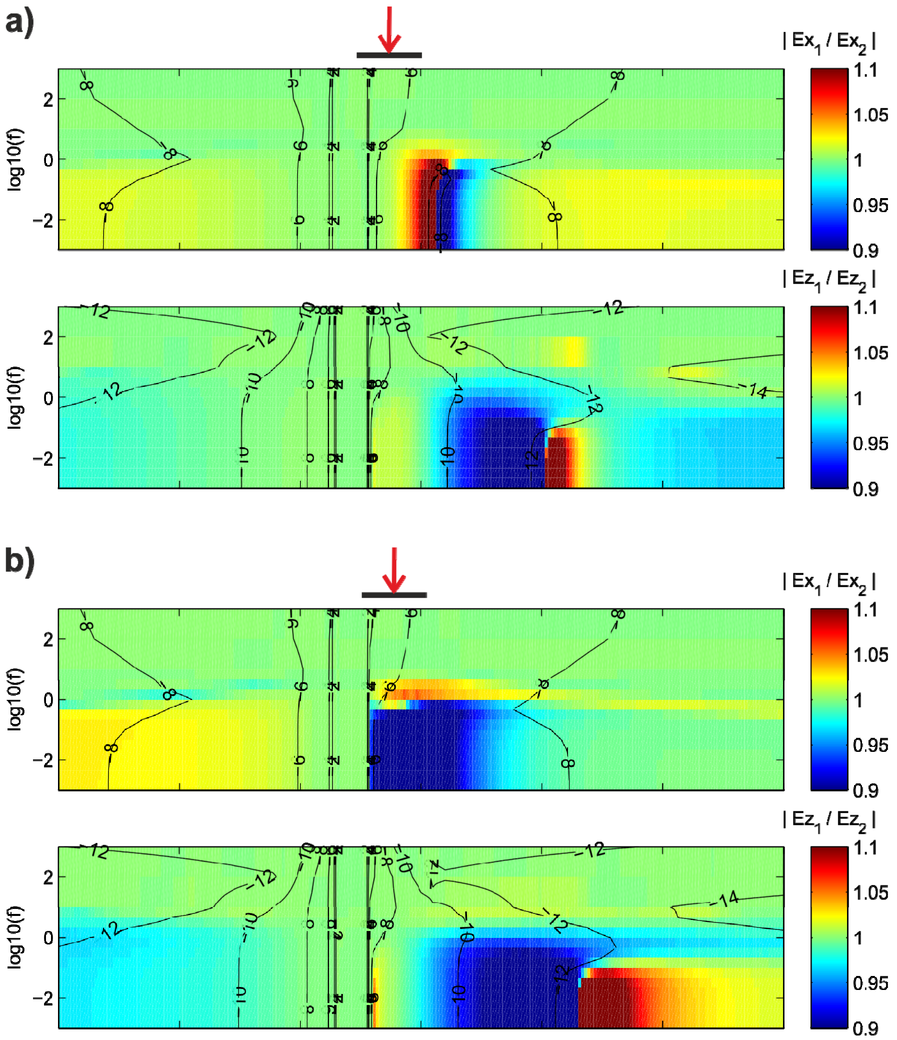

Figure 3 CSEM field responses at surface for the 3D model simulating the L-shaped source and various receiver-source instances and transmitter frequencies. Colours indicate reservoir resistivity of 0.6 Ωm (flushed) relative to field components for the initial state with reservoir resistivity of 16 Ωm (oil-saturated). Isolines show field amplitudes ([log10(V/m)]). Location of polymer injection site is marked by a red arrow; black horizontal line above the top panel indicates along-profile extent of reservoir. Results are displayed for (a) the original model (cf. Fig. 2b) and (b) simulated steel-casing (cf. Fig. 2c).

References

Ritter, O., Junge, A. and Dawes, G. [1998] New equipment and processing for magnetotelluric remote reference observations. *Geophys. J. Int.*, **132**, 535-548.

Streich, R. [2009] 3D finite-difference frequency-domain modeling of controlled-source electromagnetic data: Direct solution and optimization for high accuracy. *Geophysics*, **74**(5), F95-F105.

Streich, R. and Becken, M. [2011] Electromagnetic fields generated by finite-length wire sources: comparison with point dipole solutions. *Geophysical Prospecting*, **59**, 361-374.

Weckmann, U., Magunia, A. and Ritter, O. [2005] Effective noise separation for magnetotelluric single site data processing using a frequency domain selection scheme. *Geophys. J. Int.*, **161**(3), 635-652.