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Onshore 3D CSEM Inversion in Practice

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SUMMARY

Between 2014 and 2016 we recorded land CSEM data across an oil-field in Northern Germany. For current injection, horizontal electric tri-poles were deployed at surface and also a horizontal-vertical source using the steel-casing of a 1.3 km deep abandoned oil-well. Receivers included 5-component (MT) sites, electric-fields-only stations and vertical electric field dipoles in a borehole. 3D inversion of these data is challenging in practice for a number of reasons. Steel casings, which are abundant in oil-fields, are very difficult to model directly with FD or even FE approaches because of the computational overheads. We therefore extended an integral equation method to describe the influence of inductively and galvanically coupled steel-casings by equivalent source currents which effectively generate a secondary primary field. This new approach also considers electromagnetic interaction between multiple wells. The approach is limited though to idealized, perfectly vertical boreholes in a homogeneous half-space. Attenuation of currents along the steel casing depends on background resistivity structure and frequency content of the signals. When used as active sources, which are described as series of point-dipoles in the model domain, care must be taken that the virtual boreholes do not violate the primary/secondary field assumptions as this can lead to severe numerical instabilities or erroneous results. Controlling regularization becomes crucial when inverting onshore field data, which typically contain only a few sources and receivers. We found that smoothness constrained regularization tends to cause oscillating spurious resistivity structures which are easily misinterpreted.

Keywords: Onshore CSEM, 3D inversion, steel casings

INTRODUCTION

The Bockstedt oil field is located in NW Germany towards the northern edge of the Lower Saxony Basin, about 40 km south of the city of Bremen. Today, the basin extends for 300 km by 65 km in the east-west direction and is the most important oil province in Germany. The onshore oil field was discovered in 1954 and has been on stream ever since; until today, more than 80 wells have been drilled.

The Bockstedt CSEM study was initiated by Wintershall and GFZ to enable reservoir saturation monitoring in a time-lapse mode.

Fig. 1 shows the locations of 4 CSEM transmitters and 26 receiver sites across the Bockstedt oil field, which is roughly outlined by the positions of existing boreholes. The area covered is approximately 6 km x 6 km.

Normally, source currents are injected into the subsurface simultaneously via three grounded electrodes (steel rods) but we also connected the transmitter to the steel casing of a 1.3 km-deep suspended oil well. The CSEM signals are generated at a voltage of 560 V and a maximum current strength of 40 A with base frequencies between 1/64 Hz and 16 Hz.

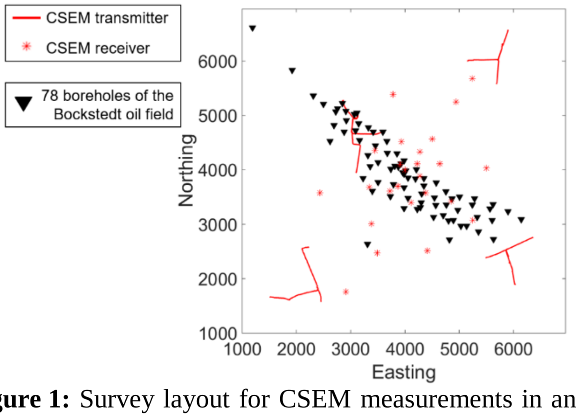

Figure 1: Survey layout for CSEM measurements in an oilfield in Northern Germany: red lines show positions of 4 three-phase current transmitters; red asterisks mark receiver positions; black triangles indicate locations of boreholes.

At the receiver locations, time series of electric and magnetic fields were recorded using the S.P.A.M. Mk. IV data loggers of the Geophysical Instrument Pool Potsdam.

INFLUENCE OF STEEL CASINGS

Boreholes with steel casings typically exist in large numbers in producing oil fields and distort electromagnetic fields in the subsurface. Their geometries are complex as they are very thin but vertically extended and the conductivity contrast of steel to natural materials is in the range of 6 orders of magnitude. To include steel-casings into our FD CSEM modelling and inversion code (Streich, 2009; Streich and Becken, 2011; Grayver et al., 2013), we expanded an algorithm of Tang et al. (2015) and developed a method to describe them as series of substitute dipole sources, which effectively interact with the primary field. The new approach cannot only handle a single well, but an arbitrary number, and their interaction with each other.

We illustrate the influence of metal casings on the distribution of the EM fields with 3D forward modelling. The effect depends on the distance between casing and transmitter, but also on the orientation of the transmitter to the borehole. We found that steel casings distort electromagnetic fields for transmitters at distances of up to 2 km. But steel casings can also be exploited to increase sensitivity at depth.

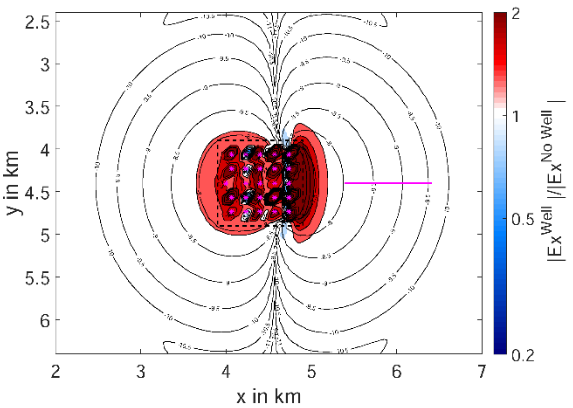

Figure 2: Relative change of the electric field in x-direction at 1300 m depth, caused by 25 boreholes with steel casings. The location of the boreholes is marked by purple asterisks and the purple line marks the position of the transmitter at surface. Colors show the ratio of the electric field with and without the steel casings. Black lines show absolute values of the electric field produced by the boreholes on a log-scale. Computations are for a frequency of 0.1 Hz.

Fig. 2 shows that amplitudes of the electric fields are significantly increased at reservoir level (1300 m depth) by the steel casings, near the center of the reservoir by 100%. The effect is stronger towards the right edge of the reservoir because the strongest currents are found on boreholes closest to the transmitter. Effectively, sensitivity in the model domain is increased towards greater depth but reduced at surface. But sensitivities change not only in vertical direction, but also laterally.

Care must be taken, however, when modelling a steel casing used as active source. Tietze et al. (2015) described a 1300 m long source by 130 equivalent point-dipoles with spacing of 10 m in vertical direction. 129 of the 130 point-dipoles were located within the 1D background structure, above or below a small-scale reservoir structure with a thickness of 15 m. Placing a single one of the point-dipoles within a 3D conductivity anomaly, however, contradicts the secondary field approach of our 3D FD code and can cause severe numerical errors in calculations of electric and magnetic fields over the entire modelling domain. The effect depends strongly on the location of a point dipole within a modelling cell in combination with the staggering scheme used for the forward calculation (see e.g., Streich 2009). Using a staggering scheme with electric fields defined as face normals in the center of the faces and placing the vertical point dipoles towards the horizontal cell centers turned out to be one of the worst possible combinations.

REGULARIZATION

In 3D inversion of onshore CSEM data the number of knowns (observed data) is far lower than the number of unknowns (model parameters, i.e. resistivity values of the model cells). Therefore, a model regularization (model smoothing) has to be applied. In the 3D inversion code used here, model discretization and model smoothing are interrelated in a nonlinear way (Grayver, 2013).

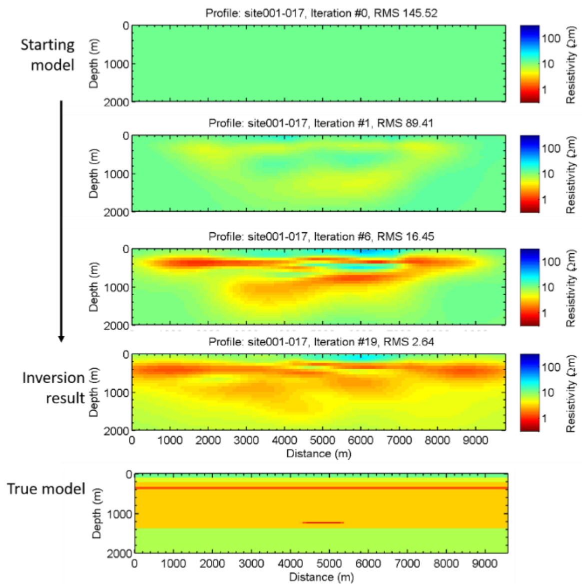

Figure 3: 3D CSEM inversion of synthetic data using field geometry for receivers and transmitters as shown in Fig. 1. From top to bottom: starting model, inversion results after 1, 6, and 19 iterations, true model.

Smoothness constrained inversion minimizes the square of the second derivative of the model (resistivity) structure and is prone to oscillations and artificial layering. The effect is illustrated in Fig. 3. Starting from a homogeneous half-space, the inversion immediately (after the first iteration) introduces artificial layering. The "final" model is still strongly influenced by the smoothing. Measured horizontal electric fields at surface generated by horizontal electric dipoles are most sensitive to horizontally aligned currents in the subsurface. Relying only on this type of source-receiver geometry is likely to amplify the effect of artificial layering. Including additional data, such as horizontal magnetic fields or the vertical electric field can help reduce smoothing artefacts. Construction of a realistic starting model also helps suppressing artificial layering already at the beginning of the inversion process. Resistivity logs, if available, are very helpful in this respect.

A careful choice of regularization parameters is crucial and should be continuously evaluated, e.g. by accompanying inversions of synthetic data. This is particularly important for time-lapse inversion schemes. If smoothing artefacts dominate the starting models for time-lapse inversion, they are likely amplified in subsequent time steps and easily misinterpreted as anomalies.

CONCLUSIONS

CSEM surveys have been acquired across the Bockstedt oil field in NW Germany. The metal casing of an abandoned production well was used successfully for source current injection. We developed a method to include the effect of nearby steel casings into our 3D FD inversion scheme. They are described as series of substitute dipole sources, which effectively interact with the primary field. Smoothness constrained 3D CSEM inversion is prone to oscillations and artificial layering. Better constraints and additional data sets are needed to guide the algorithm.

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