SAN098-1633C
SAND-98-1633C
CONF-980913--

3D EM imaging from a single borehole; a numerical feasibility study

David L. Alumbaugh*, Sandia National Laboratories, Albuquerque, NM, and Michael J. Wilt, ElectroMagnetic Instruments, Inc., Richmond, CA.

Summary

A preliminary study has been conducted to analyze the feasibility of three dimensional (3D) electromagnetic (EM) imaging from a single borehole. The logging tool consists of a vertical magnetic dipole source and multiple 3 component magnetic field receivers offset at different distances from the source. Synthetic data calculated with a 3D finite difference code demonstrate that the phase of the horizontal magnetic fields provides the critical information on the three dimensionality of the medium. A 3D inversion algorithm is then employed to demonstrate the plausibility of 3D inversion using 3 component magnetic field data. Finally, problems associated with introducing biased noise into the horizontal components of the field through misalignment of the logging tool is discussed.

Introduction

Often the drilling of an oil well is followed by a logging process to characterize the region immediately surrounding the well bore. The electromagnetic (EM) induction tool, which provides the formation resistivity, is among the most frequently run logs. Commercial EM induction logging tools use a vertical magnetic dipole (VMD) source and measure the vertical field at offsets of 2m or less. This allows for one dimensional, and sometimes two dimensional, interpretation of the formation adjacent to the wellbore. However, in regions of complex geology it is desirable to have sensitivity to off-axis structures such as fractures or formation heterogeneities. For such an application it is necessary to use both horizontal and vertical magnetic field sensors and to employ multiple source-receiver offsets. At present there are no commercial tools offering this configuration, and only one prototype tool has been described (Sato et al., 1993).

In this paper we demonstrate how three dimensional (3D) information can be ascertained by measuring the horizontal as well as the vertical components of the field generated by a VMD source, and the degree of resolution that is available from these types of measurements.

The source-receiver configuration is shown in Figure 1a. Rather than a standard logging tool where both the VMD source and receivers are all located on a single sonde, we envision a tool consisting of a transmitter 'pod' containing at least one receiver in addition to the VMD source, and several other receiver pods located at various separations away from the source. The different pods are connected together by standard logging cable, and the receivers all measure the three components of the magnetic field. Finally

the source is assumed to transmit multiple frequencies. The frequency that each receiver measures is dependent on source-receiver separation such that over the entire length of the tool the 'induction number' defined as $I = \sigma \omega \mu L^2$, is constant. Here σ is the average electrical conductivity of the medium, ω is the angular frequency, μ is the magnetic permeability (assumed to be that of free space) and L is the distance between the source and receiver. Keeping I constant ensures that the ratio of the scattered fields to the primary free space field is constant. This is important for two reasons; 1) larger separations and lower frequencies allow for increased sensitivity to regions farther away from the borehole than higher frequency-close separation measurements, and 2) the constant scattered field to primary field ratio theoretically provides for a constant signal to noise ratio for the different receivers.

Figure 1 - The proposed extended-offset logging configuration. (a) Best case scenario where the well is straight. (b) The case where the well is deviated at an angle ϕ and offset d between the source and receiver.

Preliminary forward modeling study

To demonstrate why 3D imaging from a single borehole is possible we will analyze the response from a three dimensional body located offaxis from the borehole (Figure 2). The finite difference forward modeling scheme presented in Alumbaugh et al. (1996) has been employed to calculate the response for both the model shown as well as a second model in which the 3D body is flipped across the X and Y axes such that it lies in the negative X-Y half. A vertical VMD source is operating at 10 KHz and 100 KHz. At 10

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

**Portions of this document may be illegible
electronic image products. Images are
produced from the best available original
document.**

KHz a source-receiver offset of 16m is employed, while at 100 KHz a separation of 6m is used. Because the whole space conductivity is 0.1S/m, these separations correspond to background induction numbers of 2.7 and 2.1, respectively.

In Figure 3 we plot the magnetic field amplitude and phase for both frequencies and models. Notice that the vertical field amplitudes and phases (Figure 3a) are identical for the two models. However, although the horizontal field amplitudes in Figure 3b are identical for the two models, the phases differ by 180 degrees. This horizontal field phase information is the critical component needed to reconstruct the 3D nature of the medium. Also note that maximum horizontal field amplitude is approximately 7% of the vertical. Thus these components are well within the 0.1% to 1% primary field noise level that we expect to be able to measure in the field.

Figure 2 - 3D model used in the forward modeling and inversion studies. The left hand figure is vertical cross section through the model at $Y=0m$, and the right hand figure a horizontal depth slice at $Z=0m$. Blue represents a conductivity of 0.1S/m, and red represents a conductivity of 0.33S/m. The well bore extends vertically at $X=Y=0m$ and is shown in white.

Initial inversion study

To test the feasibility of generating a 3D image from a single borehole, we have again employed the model shown in Figure 2. Synthetic data were calculated at seven frequencies spaced logarithmically from 2.1KHz to 210KHz, and source-receiver separations were chosen such that at each frequency an induction number (I) of 3.6 was approximately maintained. We have found empirically that with the noise levels and frequencies that we are employing here that this induction number seems to produce good results. The 21 measurement positions that were employed for each of the frequencies combined with the 3 components of the magnetic field calculated at each position yields a total of 441 data points. The sources and receivers ranged from -75m to 75m depth at 2.1KHz, and -27.5 to 27.5m depth at 210KHz. A spatial sampling interval of 5m was employed at all frequencies except at 210KHz where a sampling interval of 3.5m was used. Random noise with a standard deviation equal to that of 0.5% of the whole space vertical magnetic field magnitude were added to each datum, and the scheme developed by Newman and Alumbaugh (1997) was used to invert the data.

The image that results from inverting these synthetic data with a starting model consisting of a 0.1S/m whole space is shown in Figure 4. Notice that the general position of the 3D inhomogeneity is located very well, but the resulting image is smoothed and the conductivity of the anomalous body is not accurately recovered. This is in part due to the ill posed nature of the problem and in part due to the regularization process that is used to stabilize the inversion (Newman and Alumbaugh, 1997). We expect that the resolution of these images may improve as we learn more about the appropriate controls on the inversion parameters, and the inversion scheme is optimized for this particular problem.

Figure 3- Results calculated for models shown in Figure 2. Model 1 refers to results calculated with 3D body in the positive XY quadrant as shown, and Model 2 for the body flipped symmetrically such that it lies in the negative XY quadrant. a) Vertical magnetic fields. b) Horizontal (X) magnetic fields.

Although these results are very promising, the model employed is fairly simplistic. Usually the geometry of an oil reservoir is much more complex. To determine the ability of the inversion scheme to produce interpretable images in a more realistic scenario, the model shown in Figure 5 has been employed. The 3D target is embedded in a layered background medium. Again an induction number of approximately 3.6 was employed with seven frequencies spaced logarithmically from 1KHz to 100KHz. The spatial sampling interval was 5m in all cases and sources ranged

from -75m to 75m depth. A total of 200 unique source-frequency combinations were employed and thus 600 data points were used to produce the image. 1% Gaussian noise was added to each datum.

Figure 4 - Inversion of synthetic results for the model shown in Figure 2. The conductivity ranges logarithmically from 0.1S/m (blue) to 0.33S/m (red). The well bore extends vertically at $X=Y=0$ m and is shown in white.

The results for this numerical experiment are shown in Figure 6 where the starting model is that of the layered background. One would think with this starting model we should recover the geometry fairly well. However, notice that although we have imaged the 3D target within the region of interest, the layered model has been distorted. In addition, a conductive anomaly appears offaxis in the conductive layer below the target zone. These problems can be explained by two phenomena; 1) the forward model used to generate the synthetic data employed a finer grid than that used in the inversion therefore introducing numerical errors into the inversion, and 2) the regularization is applied such that the whole model, not just the model update, is smoothly varying from one point to the next. Thus in those regions away from the borehole where there is limited sensitivity of the measurement tool to the conductivity structure, the resulting image is dominated by the smoothing process. Thus the layered background model is so severely smoothed that the image is degraded.

Even with the associated problems, the scheme did recover a 3D target within the zone of interest, and thus we have recovered the primary information we hoped to obtain. On a side note, since the layered background structure produces no horizontal fields, the image also yields valuable information about the sensitivity of the vertical component of the fields to layers extending away from the borehole. It is quite surprising how depth-limited this sensitivity really is.

The effects of tool rotation and offset on the horizontal fields

For inversion purposes, we often assume that the data contain random Gaussian noise. However with the tool configuration shown in Figure 1, there is the danger of corrupting the data with biased noise. This bias comes

from deviations in the well and thus mispositioning of the different receiver pods with respect to each other. This mispositioning allows the measured horizontal fields to become contaminated with 1) a component of the vertical field that is introduced by the receiver and transmitter not being parallel, and 2) the horizontal fields that are present off axis due to incorrect positioning (Figure 1b).

Figure 5 - 3D model used in the second inversion study. The left hand figure is vertical cross section through the model at $Y=0$ m and the right hand figure a horizontal depth slice at $Z=0$ m. The conductivities vary logarithmically from blue to red with blue representing 0.05S/m, and red 0.33S/m. The well bore extends vertically at $X=Y=0$ m and is shown in white.

Figure 6 - Inversion of synthetic results that were calculated from the model shown in Figure 5. The conductivity ranges logarithmically from 0.05S/m (blue) to 0.33S/m (red). The well bore extends vertically at $X=Y=0$ m and is shown in white.

To illustrate the effects of deviated wells on the measurements, and why these deviations need to be determined prior to data processing, we have calculated the effects of different amounts of wellbore rotation and offset on the response of a fracture model. Each curve in Figure 7 assume a constant horizontal offset (d) and angle of rotation (ϕ) between the source and receiver for all positions up and down the well. Although every measurement point along the wellbore being subject to the same offset and rotation is unrealistic, it demonstrates how this biased noise can contaminate the data.

In Figure 7a the vertical magnetic fields show little error being introduced due to the rotation and offset. However the horizontal fields shown in Figure 7b are very susceptible to the this biased error., especially the amplitude. Notice that for the 0.4m-8 degree case, the bias is almost as large as the anomaly. Thus much care will need to be taken when making these measurements and processing the data to make sure that the respective orientations of the transmitter and receivers are known.

Discussion and Conclusions

In this paper we have demonstrated the plausibility of generating a 3D image of the region surrounding a borehole. If a VMD source is employed, the phase of the horizontal components contain the necessary information to reconstruct 3D geology. To this point only simplistic models have been investigated. We will be using these numerical tools to examine the use extended offset logging in other geological scenarios including horizontal wells, and to help in instrument design. As part of this latter study, lower frequency measurements will be examined to investigate the possibility of 3D logging through casing as discussed in Wilt and Alumbaugh (1998).

Both the forward and inverse modeling was completed using a massively parallel computer available at Sandia National Laboratories. The forward models took approximately 2 hours for a mesh consisting of 222 000 cells to finish all calculations using 216 Pentium-Pro processors. The inverse problems took approximately 1.5 to 4 hours to complete 3 to 5 iterations using 512 processors for a 100 000 cell mesh. Thus at present powerful computers will be needed to process this type of data.

Acknowledgments

This work was performed at Sandia National Laboratories with funding provided by ElectroMagnetic Instruments, Inc. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

References

- Alumbaugh, D.L., Newman, G.A., Prevost, L., and Shadid, J.N., 1996, Three-dimensional wide band electromagnetic modeling on massively parallel computers: *Radio Science*, **31**, 1-23.
- Newman, G.A., and Alumbaugh, D.L., 1997, Three-dimensional massively parallel inversion - I. Theory; *Geophys. J. Int.*, **128**, 345-354.
- Sato, T., Osato, K., Takasugi, S., and Uchida, T., 1996, Development of the Multi-Frequency Array Induction Logging (MAIL) Tool; *Geothermal Resources Council Transactions*, **20**, 637-642.

Wilt, M.J., and Alumbaugh, D.L., 1998, Electromagnetic methods for development and production; state of the art: *The Leading Edge*, In Press.

Figure 7- Results calculated for a fracture model assuming different horizontal offsets in the x direction between the source and receiver (d in Figure 1b), and different angles of rotation (ϕ in Figure 1b). (a) Vertical magnetic fields. (b) Horizontal (X) magnetic fields.