Deep, Accurate Structural Interpretations through Time Domain EM Techniques

L.J. Davis and R.W. Groom, Petros Eikon Inc.

Summary

Inversion techniques are frequently used by geophysicists when interpreting airborne and ground time-domain electromagnetic data. Here, we examined critical factors for obtaining satisfactory inversion results in deep sedimentary environments. In particular, it was found that a precise knowledge of system parameters is essential, and that seemingly small errors in these parameters may cause misleading inversion results. However, with accurate information of the system parameters exceptionally accurate structural interpretations can be made. We also demonstrate the ability of wide-offset ground TEM to resolve deep structure.

Introduction

Time-domain electromagnetics (TEM) is a popular geophysical method, used in mineral exploration, groundwater, and increasingly in oil and gas exploration. With an airborne system, a large region can be surveyed quickly and with accurate reliable inversion techniques, useful geological interpretations over large regions can be developed. Ground TEM surveys can take more time to collect but we show that extremely deep and accurate structural results can be obtained through correct practices.

Ideally the inversion results should correlate with known geology, though of course there are limitations on its ability to resolve 3D structure due to the nature of the stacked one-dimensional techniques. However, sometimes inversions may yield unsatisfactory results even with a reasonable starting model. For this study we performed inversion analyses on TEM data in an area in which there was prior information on the geology. We wished to examine issues that may lead to poor inversion results, and in particular to examine the importance of accurate system settings, which were found to be critical in the modeling study by (Davis and Groom, 2009). Ground inversion results in the same area are shown for comparison correlated to known geology and drilling results.

Method

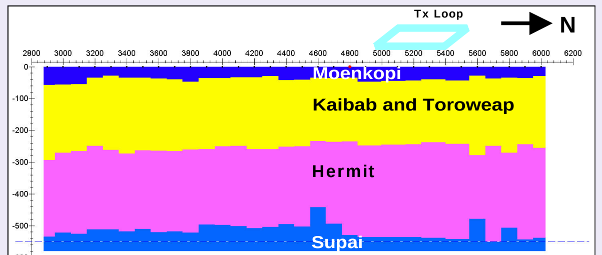
For the inversions of the airborne and ground TEM data, EMIGMA v8.1 (PetRos EiKon, 2010) was used (Groom and Jia, 2005; Jia et al, 2009). The response in the time domain is considered to be a convolution of the current impulse response with the current waveform and the system response (both of the transmitter and receiver). The inversion can handle several different types of current waveforms and other parameters that may vary substantially between different TEM systems and surveys. The accuracy of the system parameters for a given survey is not always considered carefully by the geophysicist. In EMIGMA, we were able to invert the data through a variety of settings, including different system parameters, to study the effect of their accuracy on the results. We use waveform files to check various system parameters as needed.

Location

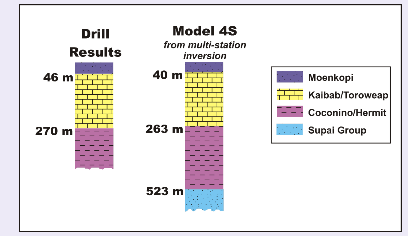
As an example, we consider TEM data collected north of the Grand Canyon in Arizona. The geology is a thick, flat-lying sequence of sedimentary rocks. There is limited lateral variation in subsurface structure. Drill results are available for several drill holes in the area. Several airborne surveys were performed at this site in addition to a wide-offset ground TEM survey with a PROTEM system.

High Resolution, Wide-Offset, ground TEM

For the PROTEM survey, a 400 x 400 m loop was used. Data was collected on two lines, extending 2 km south of the loop.

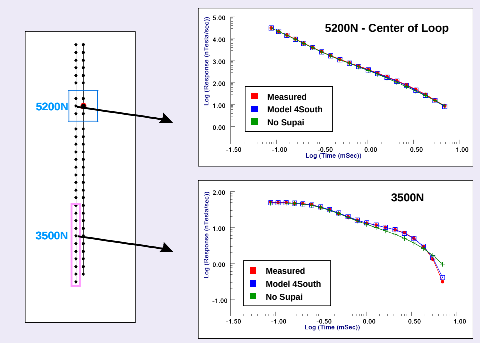


Stacked 1D constrained inversion for ground PROTEM data on Line 650.



Comparison of the results for a representative drill hole south of the calibration survey, and the model from a multi-station 1D inversion on the eleven southmost stations on Line 650 of the PROTEM survey. The model from the multi-station inversion fits reasonably well across the ground survey. The depths of the upper formations according to the inversion are in excellent agreement with the drill results. Although the drill results did not extend to the Supai Group, we were able to resolve this formation using the PROTEM data. The resistivity of the top layer (Moenkopi) is in agreement with nearby VLF-R and Max-Min data.

Survey design: the collection of wide-offset data was essential for resolving the deep structure. If the bottom layer in the model (Supai Group) is removed from the model, then it has a significant effect on the decay at wide offsets, but not on the in-loop or short-offset response.

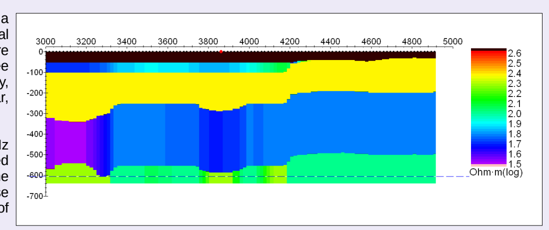


Airborne TEM - MEGATEM

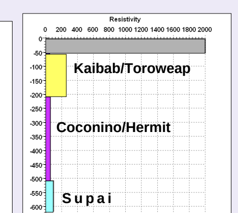
Several airborne datasets were collected at the site, including MEGATEM data. MEGATEM is a fixed-wing system flown by Fugro Airborne. The base frequency was 30 Hz, and while all three components were collected, we focused on Hz as it had the cleanest data. The data contains 20 off-time channels. Although 5 on-time and 15 off-time channels are standard for Fugro data, the increased off-time channels improved resolution and were important for understanding the data. The MEGATEM system used a half-sine current waveform. The waveform file provided by Fugro contains high altitude data (essentially freespace response), and this was used to determine the pulse width.

The 4-layer 1D model from the ground TEM was used as a starting model for inversion of the MEGATEM, with an additional shallow layer. The resistivity and thickness of each layer were constrained. The result does not fit the response at the first three channels. Furthermore, it is inconsistent with known geology, despite the use of a reasonable starting model. In particular, there is an unexpected resistor at the surface.

In the first inversion, an upper bandwidth frequency of 15 kHz was utilized, but through modeling of the data, it was determined that the upper bandwidth was actually lower. Analyses of the waveform file, including modeling of the freespace response and spectral analysis, supported this, and an upper bandwidth of 4 kHz was subsequently used.



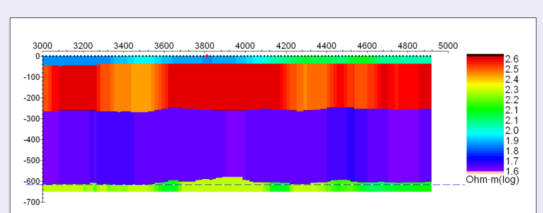
Inversion Results with Incorrect System Representation



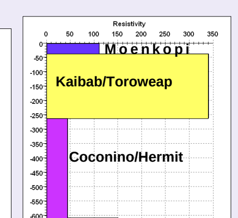
Model at 4200

A second inversion was performed with the correct bandwidth as mentioned above, and this yielded significantly improved results. The inversion was both consistent with geology and fit the early-time data well.

These results show the importance of using the correct system bandwidth when inverting airborne data. If the correct settings were used, then we were able to obtain good results through the inversion. However, the airborne data does not have the sensitivity to the deep geology of the wide-offset ground TEM survey. Although the Supai Group is present in the inversion result above, the airborne data has limited sensitivity to its exact resistivity and depth, and cannot be used to precisely determine its depth.



Inversion Results with Correct System Representation



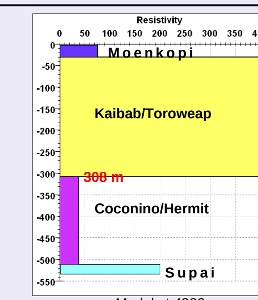
Model at 4200

Airborne TEM - VTEM

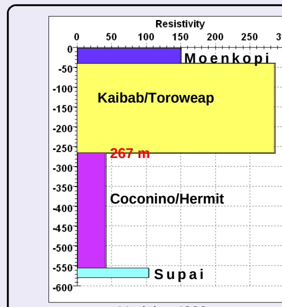
Inversion Results with Incorrect System Representation

VTEM data was collected over the same area as the MEGATEM. VTEM is a helicopter system with an in-loop receiver. The base frequency was 30 Hz and there were 28 off-time channels. The specifications for the VTEM current waveform was determined from a study of the provided waveform files. The pulse width is 4.46 ms and the 1.54 ms turn-off is approximately 77% of a quarter-sine.

In the initial inversion of the VTEM data, all but the first two channels were inverted. These channels are earlier than the nominal VTEM time channels and appear inconsistent with the other data. The same starting model and constraints were used as for the final MEGATEM inversion. The results are not in agreement with the ground data and drilling information: the top layer (Moenkopi) is too conductive and the second layer (limestones) are too thick at about 300 m vs. 265 m.



Model at 4200



Model at 4200

Inversion Results with Correct System Representation

Through comparison of the VTEM data with the ground model, simulated using the VTEM configuration, it was found that the ground model had a smaller response than the VTEM data at early times and a larger response than the VTEM data at mid-late times. As we are confident in the ground model, due to its consistency with geologic information at this site and other geophysical data, it was concluded that there was an issue with the VTEM data. Shifting the time channels 0.03 ms earlier and multiplying the data by 1.15 resolved this discrepancy (Davis and Groom, 2009).

After applying these changes, another inversion was performed on the VTEM data with the same starting model and constraints. Excellent results were obtained in the second inversion.

Critical issues for Airborne Inversion

1. Precise knowledge of several system parameters is required for accurate inversion of the data:

- *-Pulse width*
- *-Time gate positions*
- *-Impulse response of the coils*
- *-System geometry*
- *-Dipole moment*
- *-Waveform shape*

2. A calibration site at which ground EM data is also available serves to identify any problems in the airborne data and to check the system parameters listed above. For the VTEM data, we were able to adjust the amplitude and positions of time channels so that the data were consistent with the other systems. Following these adjustments, we were able to obtain excellent inversion results.

Conclusions

It was found that one significant factor affecting the quality of inversion results is accurate knowledge of system parameters. These are critical for obtaining meaningful inversions results for airborne TEM. Key system parameters include pulse width, waveform type, precise time channel locations, and impulse response of the receiver coils. These must be accurately represented in the inversion algorithm. Careful analysis of the waveform files provided by the survey company can be helpful in determining the correct settings. We have shown that seemingly minor differences in system parameters can have a significant effect on the results. However, if these parameters are precisely known, then we can develop an accurate structural model of the earth. We also demonstrated the usefulness of having a calibration site at which ground EM is also collected for the purpose of identifying any problems with the airborne data.

It was also shown that wide-offset ground TEM is effective for determining structure at depth and this technique is recommended for deep exploration in sedimentary environments.

References

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Acknowledgments

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