Site characterization and reservoir monitoring using time-lapse SQUID-TEM survey

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Summary

This paper presents a new geophysical method of reservoir characterization and monitoring using the measurements of the controlled source time domain electromagnetic data by highly-sensitive SQUID (Superconducting Quantum Interference Device) magnetic sensors (SQUID-TEM).

We have conducted a feasibility study of the SQUID-TEM survey for reservoir monitoring during CO2 sequestration in the Middle East test site. The SQUID-TEM measurements have been made before and after seawater/CO2 fluid injection into the subsurface reservoir. The goal was to produce 3D resistivity models around the injection borehole before and after the seawater/CO2 fluid injection and determine the injected fluid's location after the injection.

The results of the inversion of the post-injection survey data clearly showed the location of the conductive zone associated with the injected seawater/CO2 in the reservoir.

Introduction

The monitoring survey consisted of an electric bipole transmitter and multiple SQUID magnetic field receivers located around the injection borehole. There were 61 SQUID observation points in the baseline survey (before injection), and 69 SQUID observation points in the survey after the injection. The advantage of the SQUID receivers over the conventional induction coils is that SQUID measures all three components of the transient magnetic field, **B**(t), generated by the transmitter, while the induction coils measure the time derivatives d **B**(t)/dt. It is well known that the time derivatives of the magnetic field decay much faster with time than the field itself, thus limiting the depth of the survey's investigation.

We have also developed the 3D inversion method and software for transforming the SQUID-TEM data into the 3D subsurface resistivity model. Our method is based on the contraction integral equation (CIE) forward modeling and re-weighted regularized conjugate gradient (RRCG) inversion algorithm (Zhdanov, 2015). This method and software (EMVision®) were used to recover the three-dimensional distribution of the resistivity of the subsurface in the area of interest.

Method of 3D SQUID-TEM data inversion

An appropriate inverse modeling method is required to recover subsurface resistivity distribution from the measured surface transient magnetic fields recorded by the SQUID sensors. The 3D numerical modeling for this project was based on the contraction formulation of the integral equations (CIE) method (Hursán and Zhdanov, 2002; Zhdanov 2009, 2018).

The CIE method is performed in the frequency domain. The corresponding frequency-domain EM fields are then transformed to the time domain to model the field survey system. The frequency-to-time domain transform is based on a cosine transformation of the imaginary part of the frequency spectrum to a step response. The step response is then convolved with the time derivative of a half-waveform (positive on time followed by the off time).

The inversion was carried out using re-weighted regularization method (Zhdanov, 2015). In our implementation, all weighting functions were selected based on their integrated sensitivities. As a result, they provide equal sensitivity of the observed data to cells located at different depths and at different horizontal positions. Thus, our weighting functions automatically introduce appropriate corrections for the vertical and horizontal distribution of the resistivity. Upon completion, the quality of the inversion is appraised by the data misfit and visual inspection of the model.

Case study of reservoir monitoring

The pilot SQUID-TEM surveys for reservoir characterization and monitoring were conducted at the test site in the Middle East. The SQUID-TEM survey layout is shown in the map below (Figure 1).

The SQUID-TEM data were acquired pre- and post-injection with the sensor spacing of 50 m in the vicinity of the injection well and 100 m in the surrounding area, respectively. There is a power line lying on the west side survey area (black line in Figure 1), which generates non-negligible artificial noise with 50Hz clearly recognized on the acquired raw signal. The effect from the powerline was removed during the processing of the data.

We have applied the 3D inversion methodology outlined above to the pre-injection (baseline) and post-injection survey data.

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A time range between 0.0001 s and 0.01 s was selected for inversion based on the modeling studies. The data within this time range were most sensitive to the subsurface resistivity model and contained little noise.

The inversion grid dimensions and optimal parameters of the inversion were selected based on the interpretation of observed data and the anticipated depth of the seawater/CO2 fluid injection, as well as a proprietary optimization workflow such as detailed sensitivity analysis.

The dimensions of the inversion domain were 2,000 m by 2,400 m by 1,600 m in X (Easting), Y (Northing), and Z (Elevation) directions, respectively. This domain extended at 1,000 m on each side of the injection well in the X direction, at 1,200 m in the Y direction, and from 0 to approximately 1.6 km depth from the surface in the vertical direction. The inversion grids were identical for the pre- and post-injection data inversions. We have also used the upper and lower resistivity boundaries for the allowed resistivity variations of 10,000 and 0.1 Ohm-m, respectively.

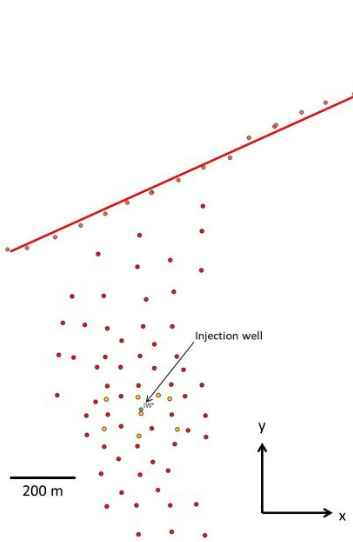

Figure 1. Map of the SQUID-TEM survey layout. The red line indicates the electric bipole transmitter position.

The inversions converged to a global RMS misfit of about 2.0, a statistically reasonable value indicating a relatively low misfit level between the observed and predicted data.

Figure 2 presents the distribution of the local RMS misfit for different stations for post-injection inversion. The RMS misfit is close to 1, nearly everywhere except next to the source. This can be explained by a strong source effect in this area.

The baseline field data inversion revealed resistive formation at depths below 300 m, with the more conductive region in the near-surface (Figure 3). We should note that in Figure 3, the intersection of two vertical sections corresponds to the position of the borehole.

The inversion of the post-injection monitoring data shows a newly formed conductive zone at about 700 m below MSL and centered slightly northeast of the borehole (Figure 4), indicating the location of the injected seawater/CO2 fluid.

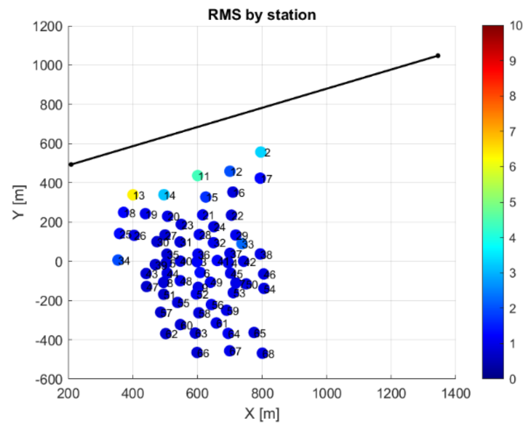

Figure 2. Station-by-station distribution of the local RMS misfit.

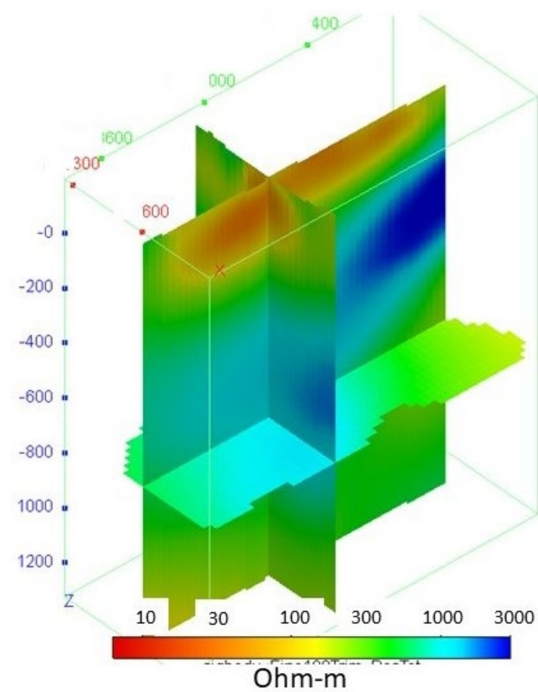

Figure 3. 3D view of the inverse resistivity model produced by the inversion of the baseline SQUID-TEM survey data

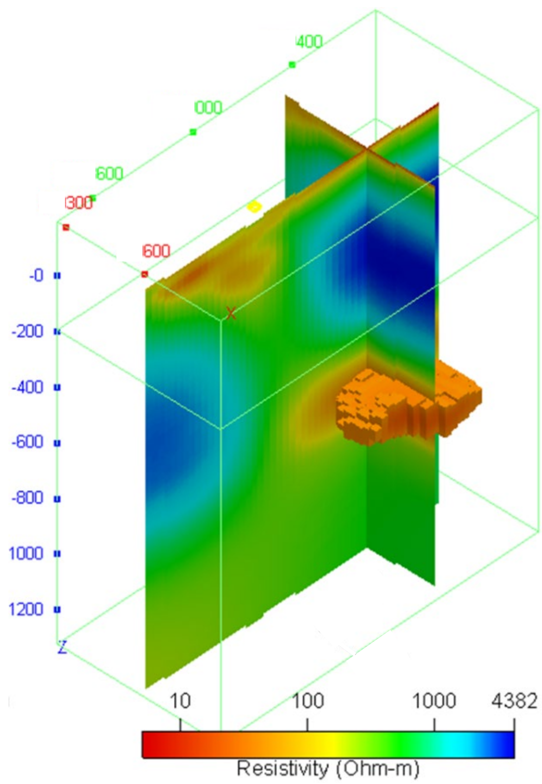

Figure 4: 3D view of the inverse resistivity model produced by the inversion of the SQUID-TEM survey data after injection. Cell less than 50 Ohm-m are shown in the target area.

We have also plotted the vertical cross-section of the conductivity difference between the baseline and post-injection monitoring inversion results (Figure 5). We plot the conductivities in this figure because the differences in the observed data are directly proportional to the conductivity variations. Note that we use the linear scale for conductivity in this image to show both positive and negative changes in conductivity after the injection. This figure clearly shows the position of the injection zone in the formation near the borehole.

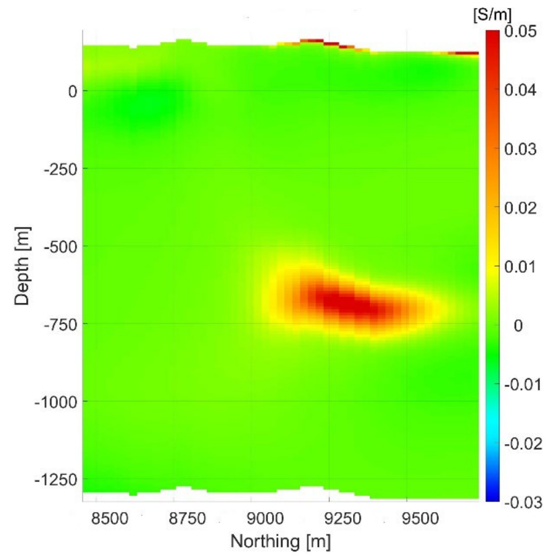

Figure 5: Vertical cross-section of the conductivity difference between baseline and post-injection monitoring inversion results.

Conclusions

The SQUID-TEM survey was deployed at the test site in the Middle East for site characterization and monitoring of seawater/CO2 fluid injection into the reservoir. The measurements were conducted before and after injection to determine the ability of the SQUID-TEM survey to monitor the fluid flow in the reservoir.

The inversion of the post-injection survey data clearly identified the new conductive zone centered about 700 m deep and offset slightly to the northeast of the borehole. This zone is interpreted to be the location of the injected CO2 and seawater mixture.

This result demonstrates that the SQUID-TEM method represents a powerful technique for monitoring the injection of conductive fluids at depths of nearly 1 km.

Acknowledgments

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