Using Electromagnetic Methods to Image SAGD Steam Chambers

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Steam Assisted Gravity Drainage (SAGD) is an enhanced oil recovery method, used to produce bitumen from oil sands. Two horizontal wells are drilled at the bottom of the bitumen reservoir (Butler, 1994). Steam is injected into the top well and a steam chamber grows upwards and outwards. The steam heats the oil which drains downwards and is captured by the lower horizontal well. The success of this technique is dependent upon having the steam propagate throughout the bitumen layer. Unfortunately, mudstone laminations in the reservoir conspire so that the steam does not always propagate as desired and it is therefore important to image steam chambers so their location and growth can be monitored.

The injection of steam into a bitumen layer will significantly affect the electrical conductivity (Mansure et al., 1993). Electromagnetic surveys thus have great potential to image steam chambers but the methodologies have not been adequately tested. Tøndel et al. (2013) show application of electrical resistivity tomography (ERT) for SAGD in a pilot study program and other applications in fluid-monitoring are discussed in the literature (e.g. Ramirez et al. (1993) and Oldenborger et al. (2007)). Currently, the usual implementation of electrical surveying is to acquire ERT data in vertical wells and then invert the data, often by assuming the earth's geometry is 2D. The combination of less-than-optimal survey design and potential restriction to 2D inversion yields lower quality images that may be contaminated by artifacts. Results can be improved by inverting the ERT data in 3D and further improved by modifying the survey to work with multiple-frequency electromagnetic methods.

There is a rich variety of possible electromagnetic surveys that can be carried out. Sources can be grounded or inductive. Grounded sources can be confined to a well or extend between two wells. Inductive sources can be in a well or exist as a large loop on the surface. Possible measurements can be voltages, as in the usual ERT surveys, and/or 3 components of the magnetic field. Data can be acquired in the frequency domain where data are amplitudes and phases of an EM field. Each frequency samples the earth differently and hence joint inversion of many frequencies can provide higher resolution than working with DC data alone as done in ERT. The experiment can also be carried out in the time domain so that full waveform EM data are recorded and subsequently inverted. There is a plethora of possible combinations and a major aspect of the current research focuses on developing a practical yet effective methodology to design electromagnetic surveys for steam chamber monitoring and to assess the increased resolution that might be possible by carrying out full 3D inversions of the EM data.

To illustrate the benefits, we show results from a synthetic example that emulates the Athabasca oil sands environment. The bitumen layer lies beneath a thin, electrically conductive cap rock and

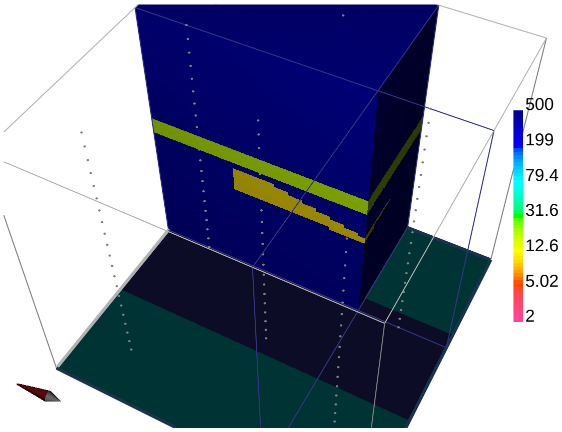

Figure 1: A sliced view of the synthetic resistivity model. The pyramid-shaped steam chamber lies below a conductive cap rock. The steam chamber and cap rock are surrounded by a uniform background. Note that the cap rock and the steam chamber are not in contact. Colourbar is in Ωm. The gray dots show the receiver locations in the six vertical wells.

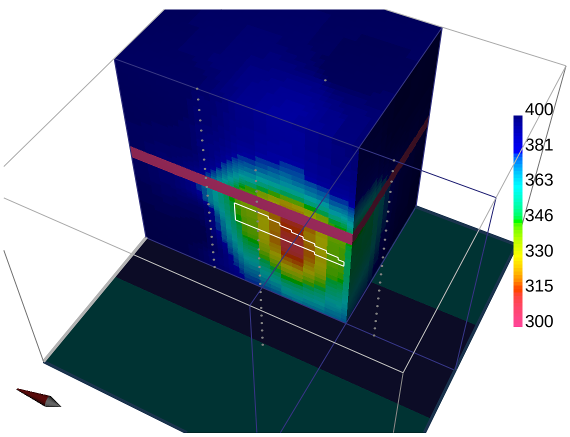

Figure 2: Recovered resistivity model from the 3D inversion of 2D ERT data, collected in four vertical wells (gray dots). A smooth, spherical anomaly lies in the location of the true anomaly but lacks the spatial resolution to define the true shape. Combined with the overestimated resistivity value, this model is inadequate. The color scale has been altered compared to Figures 1 and 3 so that the shape of the recovered anomaly can be seen. Colourbar is in Ωm. The true anomaly is outlined in white.

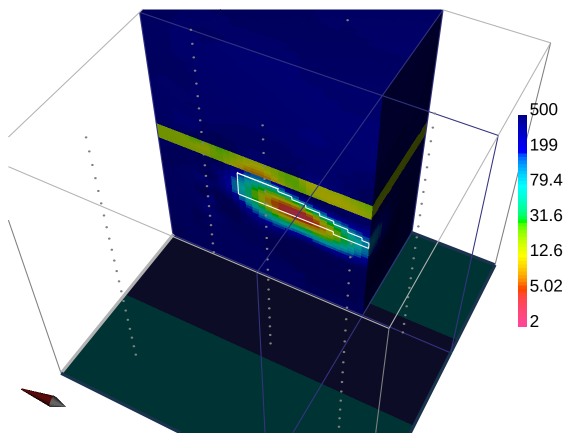

Figure 3: Electromagnetic data, measured at receivers in 6 vertical wells (gray dots), is inverted to recover a resistivity model. The steam anomaly is recovered in the correct location. The pyramid-shape of the true anomaly is nicely recovered and the resistivity approaches the true value. The recovered anomaly is clearly distinguished from the cap rock. The recovered model shows that the survey design, the data, and the inversion process are capable of recovering the steam chamber in the presence of a conductive cap rock. Colourbar is in Ωm. The true anomaly is outlined in white.

hosts the conductive steam chamber (Figure 1). The incorporation of the cap rock in the problem is important because it can greatly distort signals from an ERT experiment. The low resistivity steam chamber has a pyramidal shape that is designed to reflect a scenario where the steam has expanded asymmetrically. Ideally, we want to recover the shape of this chamber as well as its resistivity. Using 4 vertical wells surrounding the chamber, our ERT survey was comprised of 98 grounded source transmitters and 40 voltage measurements per transmitter, divided into two 2D surveys. For this geometry, none of the 2D inversions produced satisfactory results. A somewhat better result is obtained by carrying out a 3D inversion of the DC resistivity data (Figure 2). However, resolution is still not adequate and the magnitude of the resistivity is not well recovered. We alter the survey to employ 24 transmitters distributed in 6 vertical wells and measuring the vertical electric and 3-component magnetic fields from 124 receiver locations at seven discrete frequencies ranging from 1 Hz to 10 kHz. Inversion of the electromagnetic data produced a superior image (Figure 3) than the 2D or 3D DC resistivity inversions.

Our work demonstrates the potential of enhanced electromagnetic methods for imaging subsurface steam chambers. Continuing research aims to further investigate electromagnetic techniques in order to understand how they can be utilized to monitor SAGD chambers over time.

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