Electromagnetic Imaging of CO_2 Sequestration at an Enhanced Oil Recovery Site

Barry Kirkendall (Kirkendall1@llnl.gov ; 925-423-1513)
Jeff Roberts (Roberts17@llnl.gov ; 925-422-7108)
Lawrence Livermore National Laboratory
7000 East Avenue
Livermore, CA 94550

1.1 Introduction

Lawrence Livermore National Laboratory (LLNL) is currently involved in a long term study using time-lapse multiple frequency electromagnetic (EM) characterization at a waterflood enhanced oil recovery (EOR) site in California operated by Chevron Heavy Oil Division in Lost Hills, California (Figure 1). The petroleum industry's interest and the successful imaging results from this project suggest that this technique be extended to monitor CO_2 sequestration at an EOR site also operated by Chevron. The impetus for this study is to develop the ability to image subsurface injected CO_2 during EOR processes while simultaneously discriminating between pre-existing petroleum and water deposits. The goals of this study are to combine laboratory and field methods to image a pilot CO_2 sequestration EOR site using the cross-borehole EM technique, improve the inversion process in CO_2 studies by coupling results with petrophysical laboratory measurements, and focus on new gas interpretation techniques. In this study we primarily focus on how joint field and laboratory results can provide information on subsurface CO_2 detection, CO_2 migration tracking, and displacement of petroleum and water over time. This study directly addresses national energy issues in two ways: 1) the development of field and laboratory techniques to improve in-situ analysis of oil and gas enhanced recovery operations and, 2) this research provides a tool for in-situ analysis of CO_2 sequestration, an international technical issue of growing importance.

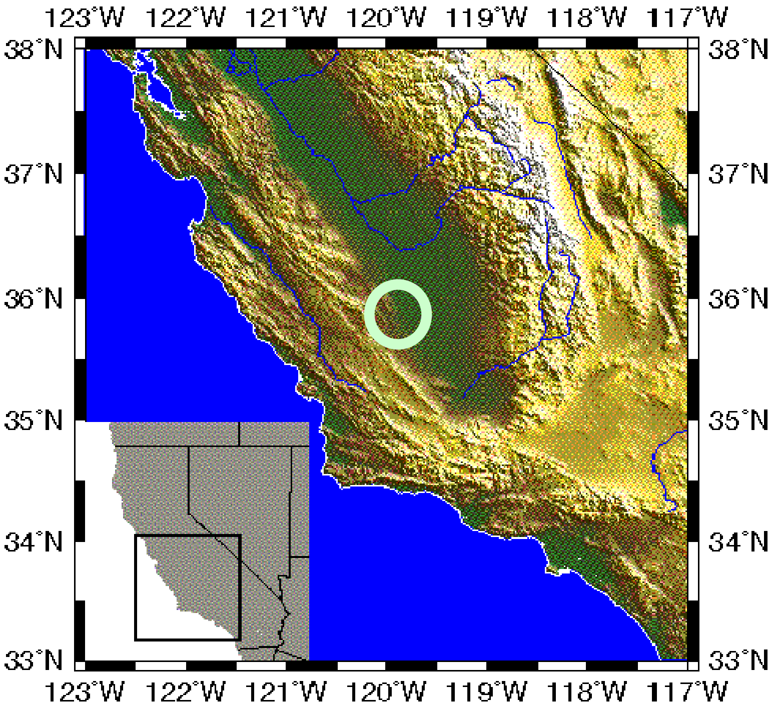

Figure 1. Map showing the location of the Lost Hills Oil Fields in California

1.2 Objective

We are attempting to develop a technique for monitoring in-situ CO_2 sequestration. The initial task is to develop EM methods to image CO_2 sequestration in a petroleum environment. Subsequent tasks include developing permanent sensors to monitor CO_2 sequestrated reservoirs and extending this technique to three-dimensional single-well imaging and cross-well imaging though steel casing.

1.3 Approach

Previously a waterflood site, the proposed CO_2 injection location has typically produced a lower petroleum yield than expected during primary and secondary recovery operations. While CO_2 injection for EOR provides the advantage of higher production yields and viscosity reduction in heavy oil, it has the disadvantage of increased cost; sequestration of industrially produced CO_2 can significantly offset such cost increases. The oil industry is therefore interested in a long-term study into the feasibility of CO_2 injection for the purposes of carbon sequestration and subsurface petroleum mobilization with the eventual possibility of running a gas pipeline to injection boreholes if such processes prove economically viable. Initially, two observation boreholes have been drilled by Chevron USA, core and fluid samples were made available to LLNL, and, because of the highly corrosive CO_2 environment, two of the four pre-existing injection boreholes have also been redrilled and electrically characterized. Chevron began injecting CO_2 into the mature waterflood site in December 2000 and reached full injection pressure in February 2001. This opportunity to image a carbon sequestration EOR site is unique because it provides a highly controlled and characterized subsurface through a pre-injection deployment to acquire a baseline image and unrestricted access to the observation boreholes. A pre-sequestration baseline data was acquired in August, 2000 which will allow time-lapse imaging after the June 2001 deployment.

1.4 Project Description

1.4.1 Laboratory Approach

We propose to measure the electrical properties of samples from the site at conditions of full liquid saturation with oil and as they are invaded with liquid and gaseous CO_2. Measurements will be performed at temperatures and pressures appropriate to field conditions in a specially constructed device specifically aimed at these types of measurements. The system (Figure 2) consists of an externally heated fluid pressure vessel capable of confining pressures up to 10 MPa and temperatures up to 300°C. Pressure is controlled by three different pressure systems—one each for confining pressure and upstream and downstream pore pressure control. Electrical measurements will be performed using two systems, a Hewlett-Packard HP4282 impedance bridge and a Solartron 1260 impedance analyzer. The HP4284 is used to monitor the sample at specific frequencies during periods of heating, pressure changes, and fluid injection. The impedance analyzer is used to make broadband measurements during (10^{-3} to 10^{6} Hz) periods when the sample is at stable experimental conditions. The device and measurement methodology has been tested on oil-filled diatomite samples from the Lost Hills that were injected with brine during EOR (Figure 3). These preliminary measurements showed some unexpected electrical behavior, resistivity increasing during brine injection, that helped interpret the Chevron well-logs and the LLNL crosswell inversions.

The experimental method will be adapted for the CO_2 injection process. A well-characterized water- or oil-saturated sample will be placed in the vessel for electrical measurements at the temperature of the formation (~38-45 C) and a variety of confining and pore pressures. Then, liquid CO_2 will be forced into the sample and the electrical properties monitored as the liquid water is pushed out. This will be easily accomplished at room temperature, as the critical pressure for CO_2 at 31°C is 72.8 atm or ~7.3 MPa (CRC, 1983), well within the operating parameters of the device. Changes in the electrical properties will be noted. Next the pore pressure will be lowered so that the liquid CO_2 flashes to the gas phase. The electrical properties will be again be monitored for a period of time as the sample is held at static conditions to determine if there is a long-term effect. It is important that there is some knowledge of surface conduction mechanisms in the rocks so that any changes in electrical properties because of different surface tensions and wetting behavior can be discerned and understood.

A second type of experiment involves the injection of gaseous CO_2. As above, electrical properties will be monitored as the sample undergoes invasion of CO_2. It may be necessary to pump to relatively high pressures to obtain displacement of water. We will attempt to match reservoir characteristics whenever possible.

Samples undergoing boiling or CO_2 invasion may change geochemically. The nature of the geochemical change will be dependent on a number of factors, including rock chemistry, temperature, pressure, water/rock ratios, and fluid chemistry. These changes can affect measured electrical properties, in particular the surface conductance. Care will be taken to be aware of such changes and their importance to observed geophysical measurements. When necessary, our analyses will include a geochemical component.

1.4.2 Field Approach

Electromagnetic techniques are sensitive to rock pore fluids within the subsurface, which makes them the ideal method for addressing the problems of EOR in a heavy oil environment. In EOR applications, it is also important to discern between injection steam and gases, injection fluids, and formation fluids. The high sensitivity of electromagnetic energy to these physical processes, as well as recent advances in computational ability, inversion code resolution, and field instrumentation, make borehole EM techniques an important tool for such subsurface imaging problems.

During CO_2 sequestration, the high pressure of the injection forces the CO_2 to remain in a liquid state. After delivery to the subsurface formation, however, a volume increase creates a pressure drop which vaporizes the CO_2 to a gaseous state. It is this gaseous state that forces miscibility with the water and oil in the subsurface formation.

In this complex scenario, EM imaging must address the gaseous CO_2, the liquid water leftover from secondary recovery, and the original liquid petroleum in the formation. Based on initial forward model calculations, we expect a large contrast between the formation water and the petroleum / CO_2, but a small contrast between the CO_2 and the petroleum due to the similar inherent electrical conductivities of each component. Resolution of this small contrast will be possible with laboratory results and with improved gas interpretation techniques which will be developed based on higher resolution inversion techniques.

Results of subsurface imaging in the 2-D plane between the boreholes will appear similar to Figure 4, an inverted conductivity image from a tomographic data set with a source frequency of 2.0 kHz. The image in Figure 4 clearly shows the location of the injected electrically conductive water (blue) and the pre-existing resistive petroleum deposits (red). The significance of jointly conducting laboratory and field results can be seen when Figure 4 is interpreted with the petrophysical results of Figure 3. Initially, the lowest injector in Figure 4 does not appear to have infiltrated the formation due to the large resistive body at 1650 ft depth. Figure 3, however, demonstrates that we should expect a sharp rise in resistivity at the onset of waterflooding, which will eventually lower over increased time. Therefore, Figure 4 suggests that injection fluid at 1650 ft depth has only recently penetrated into the formation. We expect this resistive signature to lower over increased time, as shown in laboratory results.

Proposed tomographic data sets will include 2.0 kHz and 4.0 kHz source frequencies and span the entire CO_2 injection interval, approximately 1500 ft – 1800 ft. The proposed observation boreholes are separated by approximately 30 meters, with one of four CO_2 injectors directly between the boreholes. Electrical conductivity snapshot images such as Figure 4 will be acquired every six months for multiple frequencies which will allow the tracking of CO_2, petroleum, and water over increased time.

1.5 Results

In August 2000, LLNL acquired pre-sequestration baseline data which is currently being processed to produce a two-dimensional tomographic image such as seen in Figure 4. In order to do this we first need to correct for well deviation which is significant at this site (Figure 5). In April 2001, LLNL is acquiring a second dataset which can be inverted to an image and compared to the baseline image. We are in the process of building and calibrating our petrophysical laboratory apparatus (Figure 3) to accept the core samples and formation and CO_2 injection fluids. We expect to show preliminary imaging and laboratory results at the May conference.

1.6 Application and Benefits

The real benefit of imaging CO_2 sequestration is determining the location and spatial extent of the injectate in the subsurface. Subsurface fractures and micro-tunneling caused by CO_2 injectate provide alternate subsurface pathways which often produce both legal and environmental problems.

In California, several new power plants which were recently commissioned are sited in the San Joaquin Valley, California which are close to the location of heavy oil production. The CO_2 output of the power factories would be able to be directly and cheaply injected into the subsurface to assist in EOR. This technique could be used to actively image the CO_2 during initial sequestration and then extended, by employing permanent sensors, for longer term reservoir monitoring.

1.7 Future Activities

This study will continue for another 18 months, where LLNL will continue to monitor the CO_2 sequestration and run core sample / CO_2 experiments in the laboratory. We will next focus on inversion optimization techniques in order to help accentuate the small electrical conductivity contrast between sequestrated CO2 and formation fluid (oil sands). Additionally, we will focus on developing field techniques to lower the noise floor in data acquisition.

1.8 Acknowledgements

The authors would like to thank Mike Morea at Chevron for providing access to the wells in addition to tangible well information such as gyroscopic data and induction logs. We would also like to thank Steve Carlson, Pat Lewis, and Duane Smith at Lawrence Livermore National Laboratory for providing field and laboratory support to this point. This work was supported by discretionary funding

1.9 References

Christman, P.G., Gorell, S.B., 1994, *Comparison of Laboratory and Field Observed CO2 Tertiary Injectivity*, Journal of Petroleum Tech., Vol. 226, p. 289.

Green, D.W., Willhite, G.P., 1998, *Enhanced Oil Recovery* - Society of Petroleum Engineers Textbook Vol. 6, Soc. Petroleum Eng., Houston, TX, 545 p.

Kirkendall, B.A., Roberts, J.J., 2000, *Cross-Borehole Electromagnetic Induction at an EOR site: A Joint Field-Laboratory Study*, Submitted to Journal of Geophysical Research, also *Rep.* UCRL-JC-141525, Lawrence Livermore National Laboratory, Livermore, CA.

Kirkendall, B.A., Lewis, J.P., Hunter, S.L., Harben, P.E., 1999, *Progress in Crosswell Induction Imaging for*

EOR: Field System Design and Field Testing, LLNL Internal File Report, UCRL-ID 133468, 17 p.

Shyeh-Yung, J-G.J., 1991, *Mechanisms of Miscible Oil Recovery: Effects of Pressure on Miscible and Near-Miscible Displacements of Oil by Carbon Dioxide*, paper 22651, 1991 SPE annual technical conference and exhibition, Dallas, TX, 6 – 9 October.

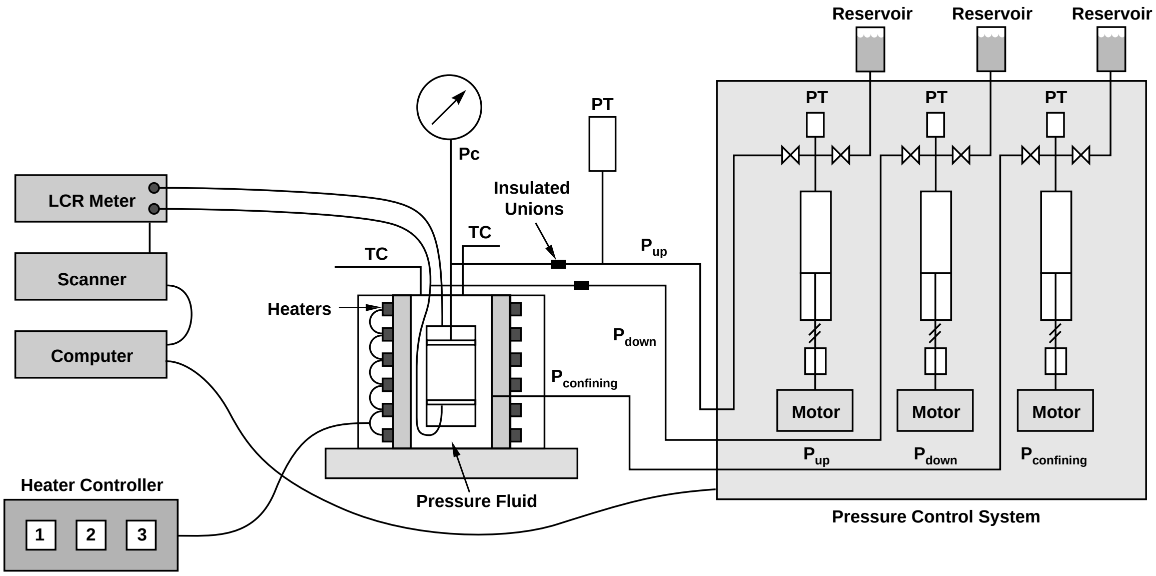

Figure 2. Schematic of the laboratory device to be used to measure electrical properties of rocks at high pressure and temperature. System was designed to enable the investigation of electrical properties of porous media under a variety of conditions. There are three separate pressure control systems, stable temperature control up to 300°C, and computer data acquisition of electrical data and experimental parameters. System can generate pore pressures up to 10 MPa and is easily adaptable for the use of CO_2 as a pore fluid.

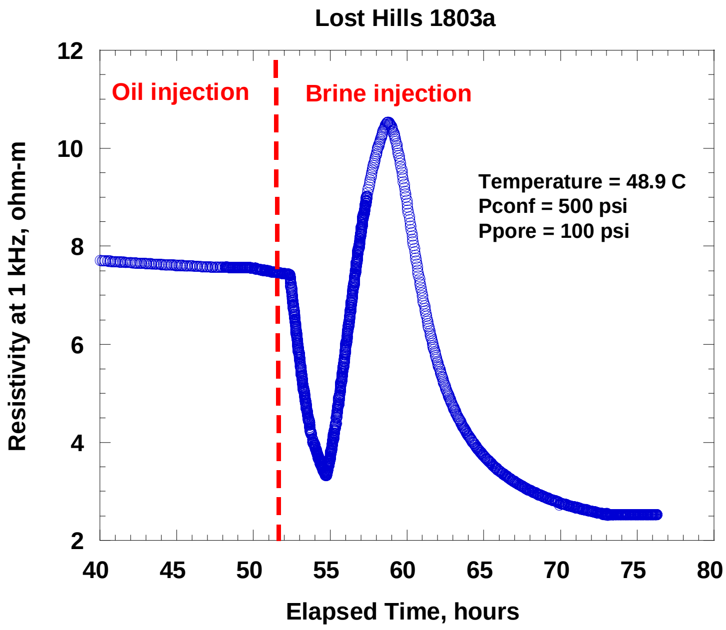

Figure 3 Electrical resistivity of oil-saturated diatomite from Lost Hills, CA during water injection. Resistivity of some sample increases temporarily during the brine injection process. This helps explain the relative lack of low resistivity in parts of the well-logs expected for brine saturated rocks.

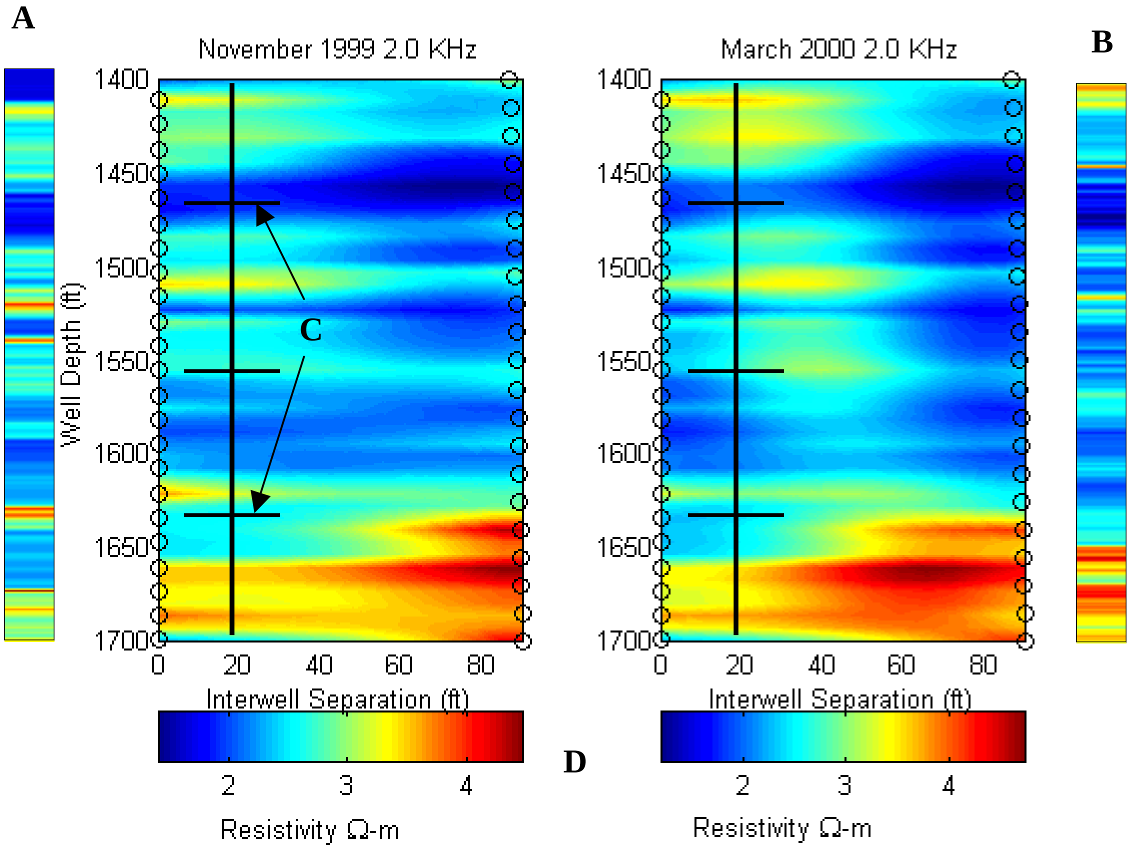

Figure 4 Electrical conductivity time-lapse image of a 2.0 kHz tomography at Chevron Heavy Oil Division, Lost Hills, California. The left image was acquired in November 1999, while the image on the right was acquired in March 2000. The transmit borehole on the right (indicated by circles) corresponds with the long-offset induction log (A), while the receive borehole on the left corresponds with induction log (B). The injection well and perforation regions, C, is off-plane approximately 10 ft. into the paper. The colorbar, D, is in conductivity (Ω/meter). Bluish regions represent the conductive injection fluid, while the reddish regions represent the pre-existing oil. CO_2 would appear as a deeper red since the conductivity is typically less than oil.

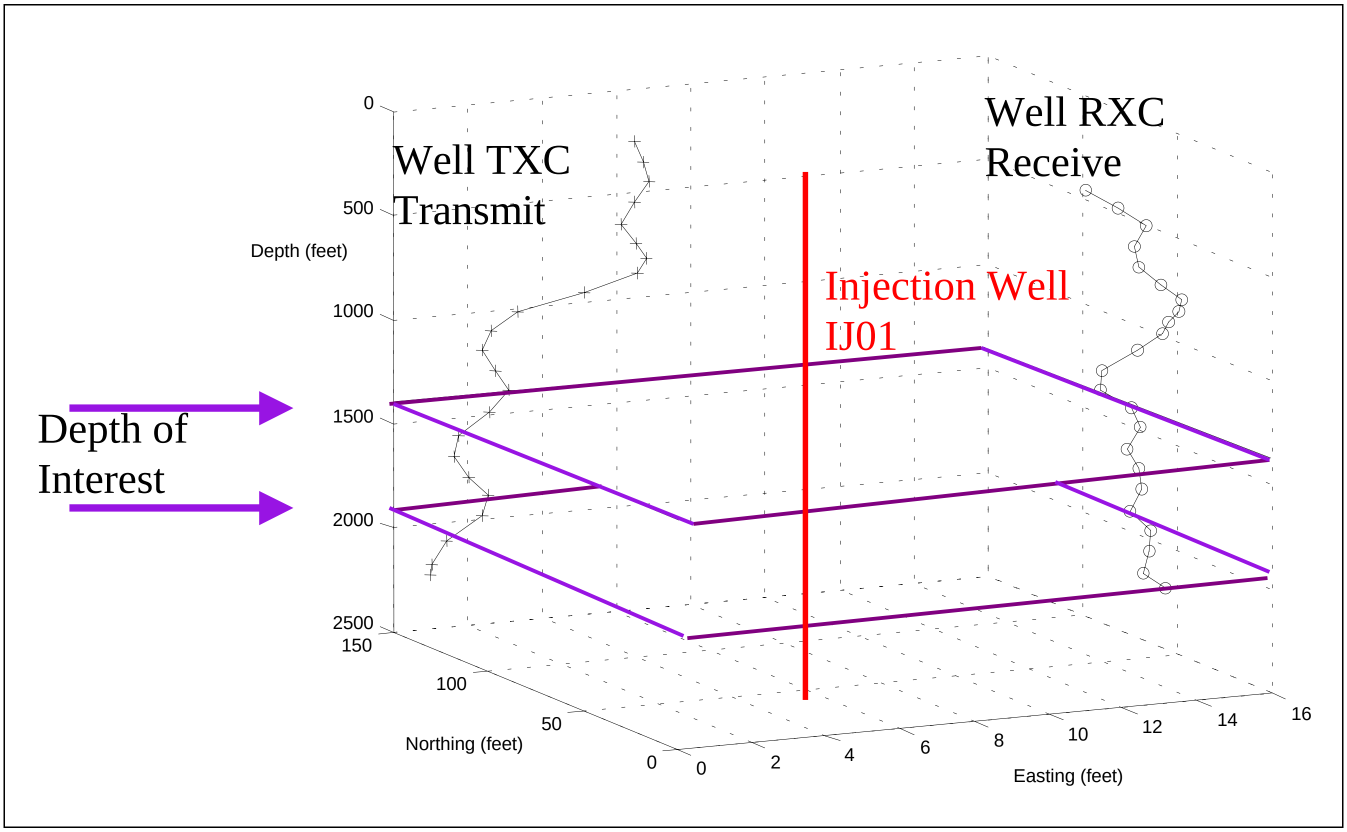

Figure 5 Gyroscopic data of wells TXC and RXC with the relative location of the injector well (IJ01). The inversion algorithm will not converge with such large well deviations. Newman (2000) has incorporated into a finite difference inversion algorithm factors which accept known well deviations and adjust the resulting electromagnetic fields.