A Feasibility Study of Non-Seismic Geophysical Methods for Monitoring Geologic CO_2 Sequestration

Erika Gasperikova and G. Michael Hoversten

Lawrence Berkeley National Laboratory, One Cyclotron Road, MS:90R1116, Berkeley, CA 94720

Introduction

Because of their wide application within the petroleum industry it is natural to consider geophysical techniques for monitoring of CO_2 movement within hydrocarbon reservoirs, whether the CO_2 is introduced for enhanced oil/gas recovery or for geologic sequestration. Among the available approaches to monitoring, seismic methods are by far the most highly developed and applied. Due to cost considerations, less expensive techniques have recently been considered. In this article, the relative merits of gravity and electromagnetic (EM) methods as monitoring tools for geological CO_2 sequestration are examined for two synthetic modeling scenarios. The first scenario represents combined CO_2 enhanced oil recovery (EOR) and sequestration in a producing oil field, the Schrader Bluff field on the north slope of Alaska, USA. The second scenario is a simplified model of a brine formation at a depth of 1,900 m.

The feasibility of each geophysical technique depends on magnitude of the change in the measured geophysical property produced by increasing the concentration of CO_2, and on the inherent resolution of the technique. Furthermore, their applicability also depends on the measurement configuration. EOR/sequestration projects in general, and Schrader Bluff project in particular, are characterized by relatively thin injection intervals with multiple fluid components (oil, hydrocarbon gas, brine, and CO_2). This setting represents the most geophysically difficult end member of a complex and wide spectrum of possible sequestration scenarios.

Gravity methods are a measure of density, electrical methods primarily respond to earth material resistivity, and seismic methods depend on both density and elastic moduli. These physical properties are generally well known for CO_2, typical reservoir fluids, and various combinations of both (NIST, 1992), and therefore it is possible to assess expected changes in geophysical properties. CO_2 is resistive, and thus electrical methods are candidates in brine bearing formations. For most of the depth interval of interest for sequestration, CO_2 is less dense and more compressible than brine or oil; therefore, gravity and seismic methods are reasonable candidate methods for brine or oil bearing formations. At shallow depths and lower pressures, CO_2 has gas-like properties and none of the geophysical methods is a good candidate for monitoring CO_2 within a shallow dry natural gas reservoir. Even in this case, however, since brine formations are commonly found above gas reservoirs, geophysical methods could still be useful for leak detection. Research continues to refine the information available on the influence of varying CO_2 saturations on seismic and electrical properties.

The bulk rock density D_{bulk} of the reservoir is calculated using

$$D_{bulk} = (1 - S_w - S_{CO_2})D_{grain} + S_w D_{brine} + S_{CO_2} D_{CO_2} \qquad (1)$$

where, S_w is the brine saturation, S_{CO2} is the CO_2 saturation, D_{grain} is the grain density, D_{brine} is the brine density and D_{CO2} is the CO_2 density. We neglect the density effect of CO_2 dissolved in the brine. Quartz sand grains (D_{grain} = 2650 kg/m^3) are assumed. The electrical resistivity of reservoir rocks is highly sensitive to changes in water saturation, as can be seen from Archie's Law (Archie, 1942), which has been shown to accurately describe the electrical resistivity of sedimentary rocks as a function of water saturation (S_w), porosity (ϕ), and pore fluid resistivity (ρ_{brine}). All petroleum fluids (oil, condensate, and hydrocarbon gas) as well as CO_2 are electrically resistive; hence Archie's Law is appropriate for any combination of oil, hydrocarbon gas, condensate, or CO_2 (Figure 1). The bulk resistivity is plotted on a log scale to span the large range of resistivity values as a function of the gas saturation (Figure 1). This high sensitivity to water saturation in a reservoir can be exploited by electromagnetic (EM) techniques where the response is a function of the rock bulk electrical resistivity.

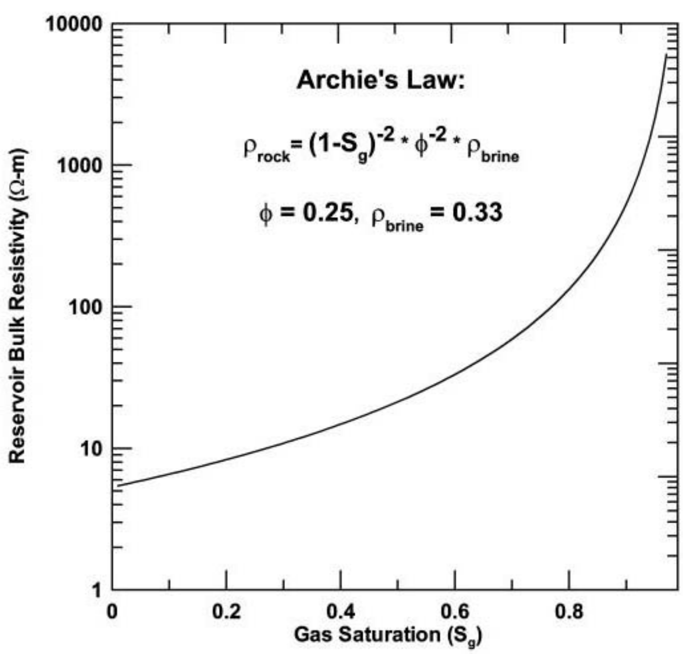

Figure 1. Reservoir bulk resistivity (ρ_{rock}) (in Ωm) as a function of gas saturation (S_g) ($S_g = 1 - S_w$) for a reservoir with brine resistivity equivalent to sea water (ρ_{brine} = 0.33 Ωm) with 25% porosity.

Schrader Bluff Model

The Schrader Bluff reservoir is a sandstone unit with about 30% porosity, between 25 and 30 m thick, at a depth of 1,100–1,400 m. The reservoir unit gently dips to the east, with major faulting running mainly north-south. Faulting includes two faults with offsets in excess of 75 m cut the reservoir, and several smaller subparallel faults. Preliminary evaluations of the Schrader Bluff reservoir show that a CO_2–based EOR could increase oil recovery by up to 50% over water-flooding (Hill et al., 2000). Furthermore, studies concluded that up to 60% of the CO_2 injected as part of the EOR scheme would remain in the reservoir. Time-lapse models of the reservoir were run at initial conditions and 5-year increments out to 2035. A water-after-gas (WAG) injection strategy was considered, which produces complicated spatial variations in both S_{CO2} and S_w within the reservoir over time. Numerical flow simulations of the CO_2 injection process were converted to geophysical models using petrophysical models developed from well log data. These coupled flow simulation – geophysical models allow comparison of the performance of monitoring techniques over time on realistic 3D models by generating simulated responses at different times during the CO_2 injection process. These time-lapse measurements of the reservoir are used to produce time-lapse changes in geophysical properties that can be related to the movement of CO_2 within the injection interval.

Gravity Modeling

In our simulations, the peak-to-peak change in the vertical attraction of gravity (G_z) at the ground surface between 2020 and initial conditions is on the order of 2 μGal, which would be in the noise level of a field survey using current technology (Hare et al., 1999; Brown et al., 2002). The changes in the vertical gradient of gravity (dG_z/dz) between initial conditions and 20 years into the CO_2 injection scheme are approximately 0.01 Eötvös units (EU), also below the noise level of current instruments. Gravity anomalies decay with the inverse square of the distance from their source so high spatial variations in the net density changes within the reservoir are expressed as a subdued response at the surface and only show large-scale changes.

Access to boreholes enables gravity measurements to be made closer to the reservoir, thus reducing the distance to the target compared to observations made on the surface. As expected the calculated magnitude of change in both G_z and dG_z/dz is larger than for surface measurements, although only the change in G_z would be measurable in the boreholes with current commercial technology. It should be noted however, that work on more sensitive borehole G_z and dG_z/dz meters is ongoing and has the potential to significantly lower the sensitivity of such devices in the near future (Thomsen et al., 2003). However, access through only the existing injection wells would substantially reduce the data coverage (Figure 2a). For comparison, Figure 2b shows the net change in CO_2 saturation. G_z map (Figure 2a) was generated using a minimum curvature algorithm for data interpolation; however it is representative of the general features present in all of the other types of interpolation tested. In general, interpretation of the interpolated G_z

changes from the existing 23 boreholes would lead to an over estimate of the CO_2 saturation changes in the reservoir. This problem is particularly evident at the north end of the reservoir where increased CO_2 saturation at two isolated wells produces an interpolated image that would be interpreted as increased CO_2 between the wells where none exists. Borehole measurements need to be used in conjunction with some form of surface measurement to guide the interpolation between wells. Alternatively, pressure testing between wells could provide estimates of spatial variations in permeability that could be used to condition, in a statistical sense, interpolation of the borehole gravity data. Many possibilities exist for combining the borehole data with other information in order to produce more accurate maps of change within the reservoir.

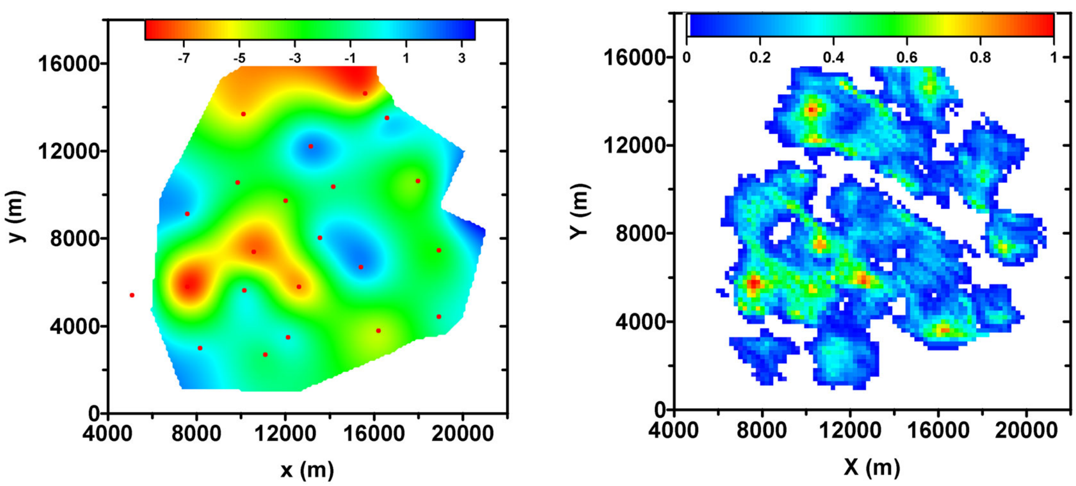

Figure 2. (a) Plan view of the change in G_z (μGal) at a depth of 1,200 m (above the reservoir in this section of the field) between initial conditions and 20 years into CO_2 injection using 23 wells indicated by red dots. (b) Plan view of the net change in S_{CO2} (1 being 100% CO_2, and 0 being 0% CO_2) within the reservoir between initial condition and 20 years into CO_2 injection.

Because density changes within the reservoir are caused by a combination of CO_2, water, and oil saturation changes as the WAG injection proceeds, a one-to-one correlation in space does not exist between the net change in S_{CO2} and the change in G_z. On a large scale, however, a correlation does exist between the change in G_z and the net change in S_{CO2}. For example, the largest changes in S_{CO2} occur in the southwest quadrant of the field, where the largest change in G_z occurs. This scenario, injecting CO_2 into an oil reservoir with multiple fluid components, is the worst case for using gravity to directly map changes in S_{CO2}. In the case of CO_2 injection into a brine formation, there would only be water and CO_2, and the net changes in density within the reservoir would directly correlate with the net changes in $S_{CO2,}$ as would the change in G_z at the surface.

Electromagnetic Modeling

The electrical resistivity of reservoir rocks is highly sensitive to changes in S_w. This high sensitivity to S_w in a reservoir can be exploited by EM techniques, in which the response is a function of the earth's electrical resistivity. One technique uses a grounded electric dipole energized with an alternating current at a given frequency to produce time-varying electric and magnetic fields that can be measured on the earth's surface. In this one configuration the electric dipole consists of two steel electrodes (1 m^2 plates or sections of drill pipe) buried at a shallow depth (1–10 m) separated by 100 m and connected by cable to a low-power generator (a portable 5,000 W generator is sufficient). The measured data consist of the electric field at a given separation from the transmitter, acquired on the surface or within the near surface. This approach combines both relative ease of deployment with high sensitivity to reservoirs of petroleum scale and depth.

The change in the electric field amplitude at a constant source-receiver offset of 2 km for the same interval is overlaid as black contour lines, with peak-to-peak amplitude of 1.2% (Figure 3). There is a direct one-to-one correspondence between the change in S_w and the change in the electric field amplitude. Even though the signal level is low, it can be measured and interpreted given the signal-to-noise ratio of the data. This potentially low-cost monitoring technique is best suited for CO_2–brine systems in which a one-to-one correlation exists between the change in S_w and the change in S_{CO2} (since $S_w + S_{CO2} = 1$). In a petroleum reservoir such as Schrader Bluff, the presence of hydrocarbons eliminates the one-to-one correlation between changes in S_w and changes in S_{CO2}. The correlation between changes in S_{CO2} and changes in the electric field amplitude are not as evident as those between changes in S_w and the electric field data.

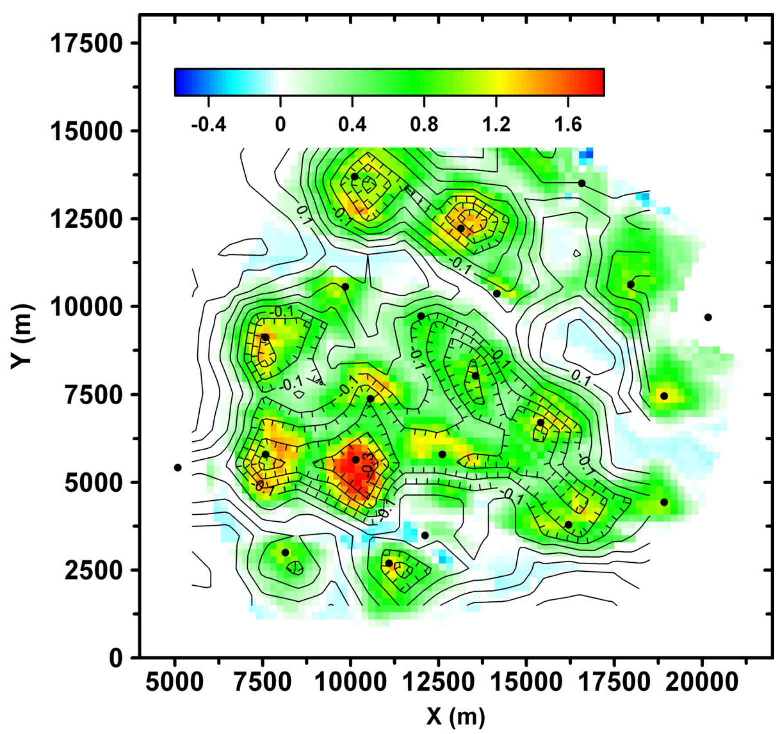

Figure 3. Color contours of the net change in water saturation over the vertical interval of the reservoir between initial conditions and 2020. The change in the amplitude of the

electric field from an electric dipole source at a separation of 2 km is overlaid as black contours. The peak-to-peak change in electric field amplitude is 1.2%. Note the direct correlation between decreases in the electric field amplitude and increases in water saturation (decreased electric resistivity of the reservoir). Black dots show locations of injection wells.

Brine Formation Model

To study the sensitivity of gravity and EM measurements to the presence of CO_2 in a brine formation, we created a model with a 20 m thick target layer at a depth of 1,900 m with porosity of 20% and variable CO_2 and water saturations. The properties (density and bulk modulus) of the CO_2 were calculated assuming hydrostatic pressure at 1,900 m and a temperature of 70°C using the NIST14 code. CO_2 is in a gas phase at these pressure and temperature conditions, and the density estimates at 1,900 m are based on these calculations.

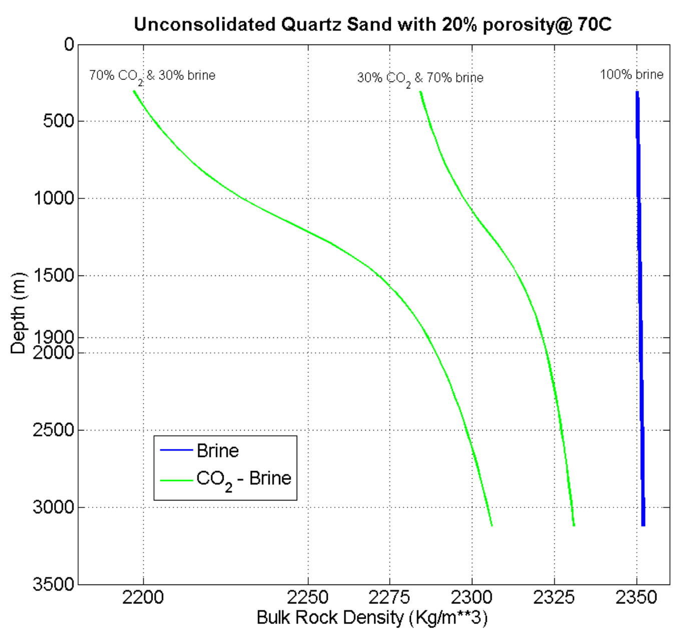

Figure 4. The bulk rock density for quartz sand with 20% porosity at 70°C as a function of depth (assuming hydrostatic pressure) for three different saturations of brine and

CO_2, from left to right, 70% CO_2 – 30% brine, 30% CO_2– 70% brine and 100% brine. Reservoir depth is 1,900 m.

Gravity Modeling

The vertical component of gravity response (G_z) is defined as the difference between the model with and without the quarter space of CO_2 saturated reservoir. When S_{CO2} is changed by 30%, the bulk density of the reservoir changes by 1.3% (Figure 5). The 1.3% bulk density change produces an approximate 20 μGal change in G_z (Figure 6). The 10 μGals contour defines the edge of the structure. This signal can be measured using current technologies. A 5-10 μGal and 3.5 μGal survey accuracy have been reported for gravity surveys at Prudhoe Bay, Alaska. A repeatability of 2.5 μGal and detection threshold of 5 μGal for time-lapse variations was observed in gravity monitor surveys of the Sleipner CO_2 sequestration site in the North Sea. To consider the sensitivity of the vertical component of gravity to lateral changes in the CO_2-brine front, the model (Figure 5) was modified so that the CO_2-brine interface was displaced 1 km to the southeast. This movement of the CO_2-brine produces about a 10 μGal gravity change in G_z (Figure 7).

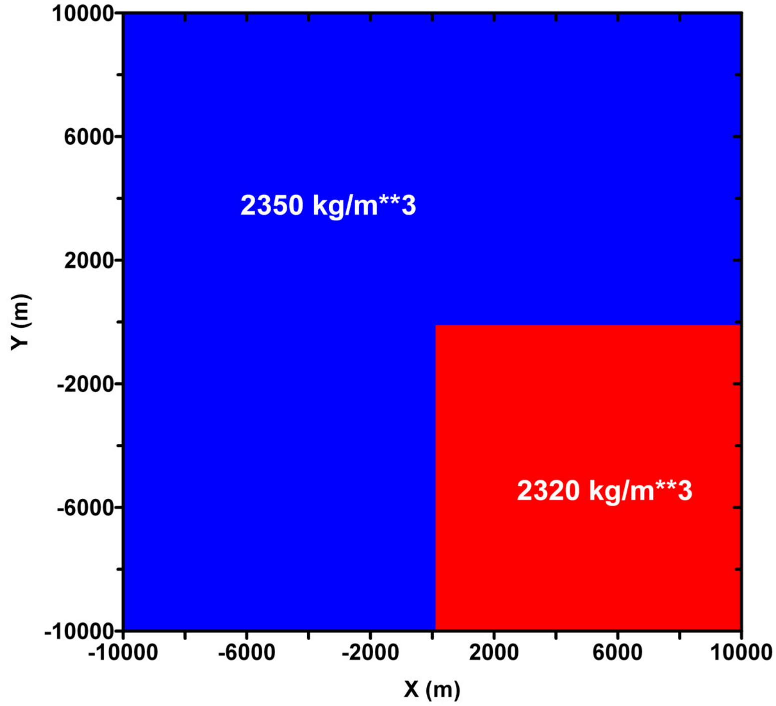

Figure 5. Plan view of a density field (kg/m^3) at the top of the reservoir (depth of 1,900 m) as a function of x and y coordinates for the model with CO_2 and water saturation of 30% and 70%, respectively, at the southeast quadrant, and 100% water saturation everywhere else.

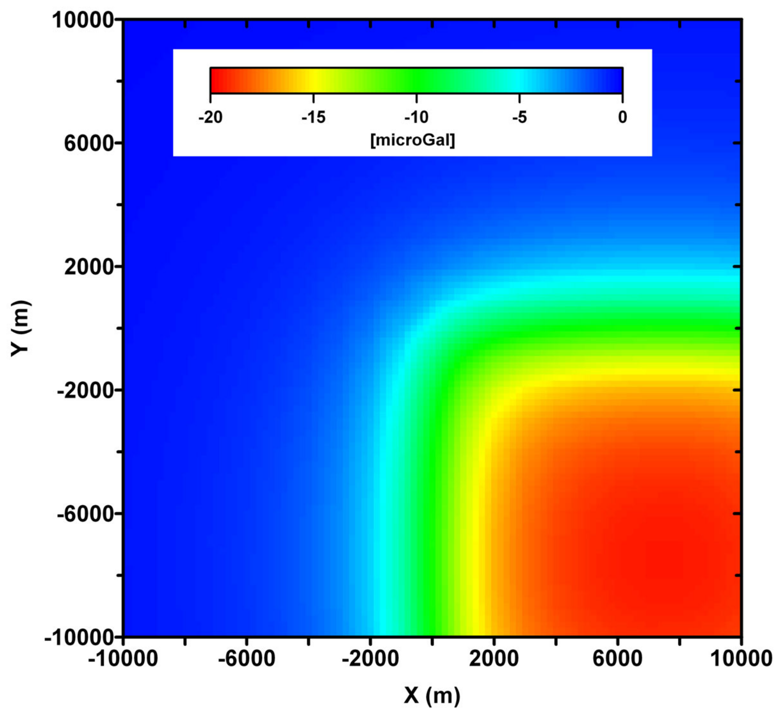

Figure 6. Surface vertical component of gravity (G_z) response of a reservoir with 30% CO_2 and 70% brine saturation at the southeast quadrant and 100% brine saturation everywhere else.

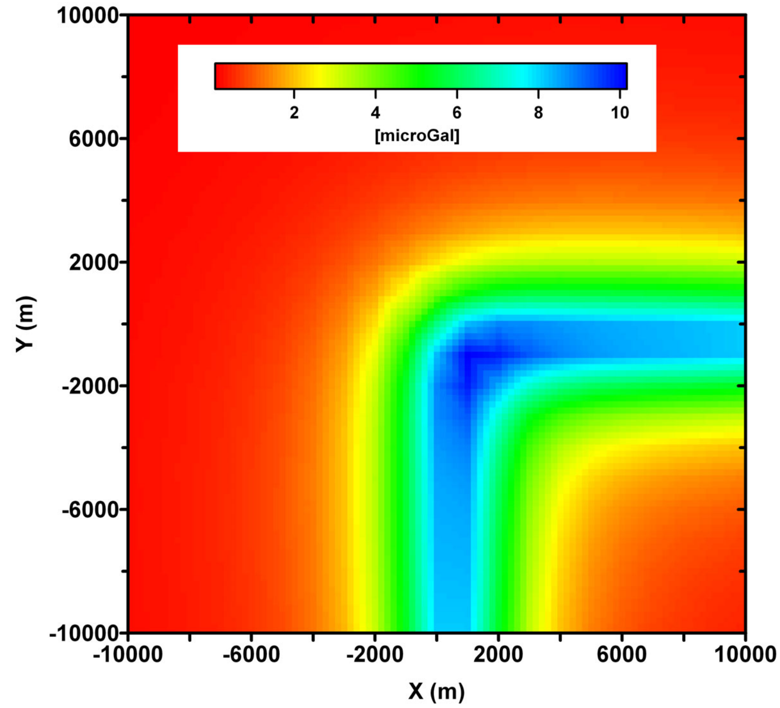

Figure 7. Difference in the vertical component of the gravity (G_z) response produced by moving the CO_2-brine interface by 1 km to the southeast.

A 10% change in CO_2 saturation produces about a 6 μGal response. The maximum response for a model with 90% CO_2 saturation and 10% water saturation is about 55 μGals (Figure 8). On the other end, a model with 10% CO_2 saturation and 90% water saturation gives 8 μGals response, likely on the edge of detectability in the field. For practical considerations, a model with 20% CO_2 and 80% water would be at the lower limit of detection.

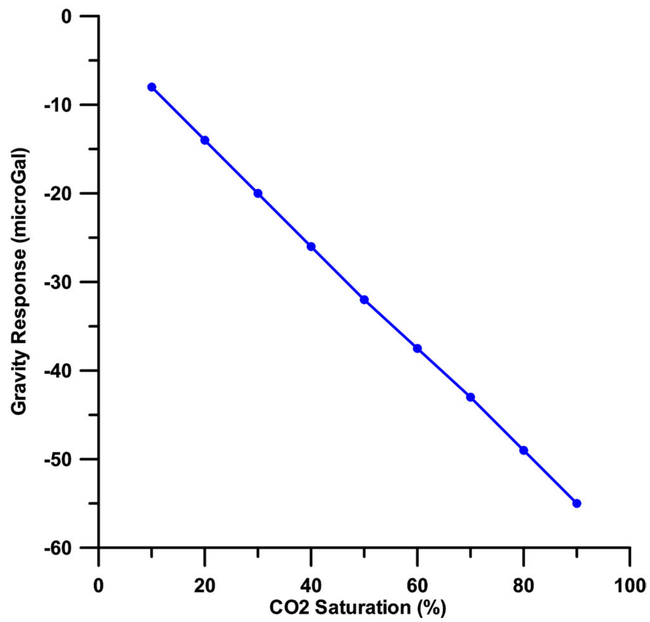

Figure 8. Gravity response (μGal) as a function of CO_2 saturation for the model shown in Figure 5.

Inversion of gravity data is very important, since construction of density contrast models significantly increases the amount of information that can be extracted from the gravity data. However, one substantial difficulty with the inversion of gravity data is its inherent non-uniqueness and lack of inherent depth resolution. This difficulty can be overcome by introduction of *a priori* information. Some authors prescribe the density variations and invert for the geometrical parameters of the model, others assume a constant density contrast and invert for the position of a polyhedral body from isolated anomalies. In another approach, gravity data is inverted directly by minimizing an objective function of the density model that is subject to fitting the observations. This approach also incorporates prior information via a reference model and depth weighting. We adopted an approach described for magnetotelluric data inversion, in which the top and base of the reservoir are known, and we invert for density variation inside the reservoir. The inversion result is a cumulative density change in the reservoir as a function of x and y coordinates (Figure 9). The inversion clearly identifies the anomalous zone, and the density change was recovered within 30% of the true value. This was also found true for the data that contain 2.5 μGal random noise. The level of uncertainty in density estimation would decrease if the reservoir is thicker.

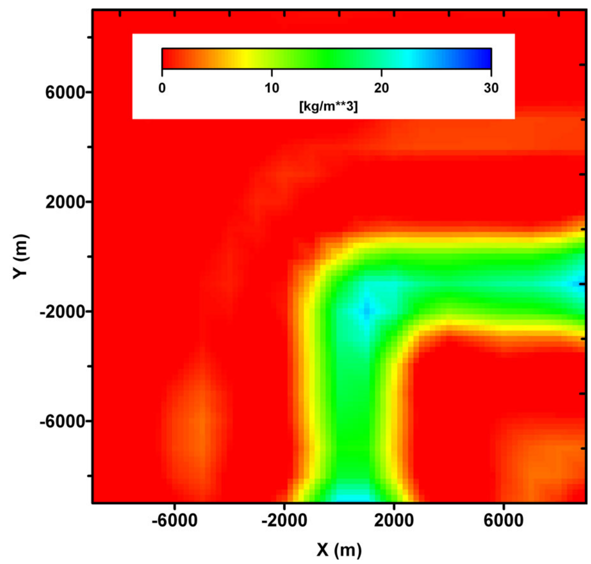

Figure 9. Density change (in kg/m^3) recovered by inversion of the difference in vertical component of the surface gravity response shown in Figure 7 as a function of x and y coordinates.

Electromagnetic Modeling

The same EM system described in the Schrader Bluff study was used here. We calculated the electric field on the surface of the model (Figure 10) using 13 100 m electric dipoles operating at 1 Hz, with measurements of the resulting electric field at a range of separations in-line with the transmitting dipole. For each of the transmitter dipoles, separated by 1,000 m, a response was calculated along the entire profile with receivers separated by 500 m.

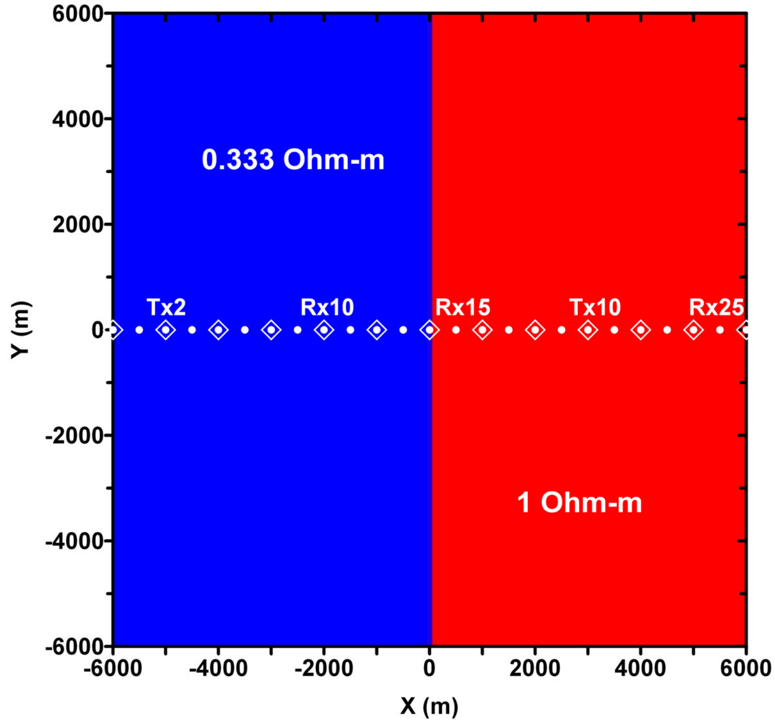

Figure 10. Plan view of resistivity (Ohm-m) at a depth of 1,900 m as a function of x and y coordinates for the model, with CO_2 on the right and brine on the left. Diamonds indicate transmitter locations, while dots indicate receiver locations.

Calculations show that the contact produces an 8% anomaly at an offset of 2 km (Figure 11). Given the signal strength and the expected natural electric field spectrum, we expect to make electric field amplitude measurements on the order of 1%. Thus, the anomalies produced by the CO_2-brine contact should be measurable. If the contact is moved 500 m to the east in the model (Figure 10) and the fields (Figure 11) are differenced we produce percent changes suggesting that a movement of the contact would produce 2% changes in the measured electric fields at offsets of 1 km (Figure 12). Thus the dipole-dipole controlled source EM system should be able to monitor movement of the CO_2-brine contact on the order of 500 m.

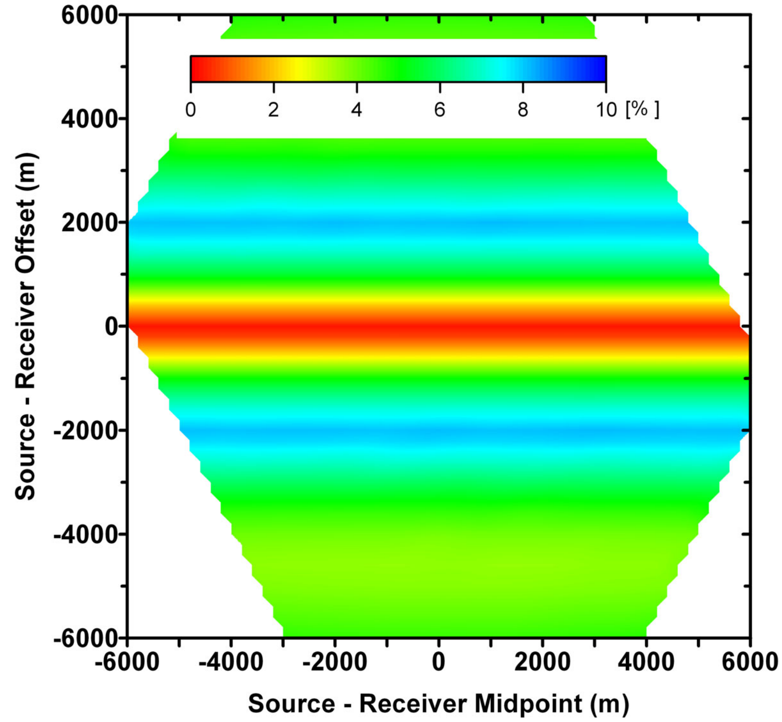

Figure 11. Percent change in the electric field measured in-line with the transmitter dipole as a function of source-receiver offset (Y) and source-receiver midpoint position (X). The change pertains to the model shown in Figure 10.

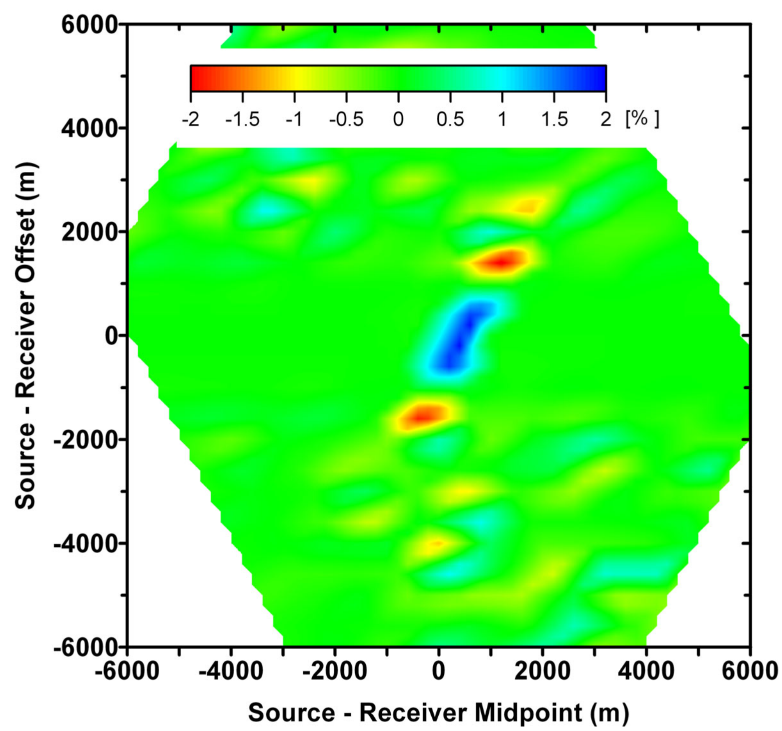

Figure 12. Percent change in the inline electric field amplitudes as the CO_2-brine contact moves 500 m east in the model shown in Figure 10.

Conclusions

Both gravity and EM measurements were modeled for two scenarios, a Schrader Bluff EOR model and a brine formation model. The injection of CO_2 produces a bulk density decrease in the reservoir, that in turn produces a reduction in the gravitational attraction from the reservoir. The spatial pattern of the change in the vertical component of gravity (G_z), as well as the vertical gradient of gravity (dG_z/dz), is directly correlated with the net change in reservoir density.

Schrader Bluff represents the most difficult case of possible sequestration scenarios, because of the relatively thin injection interval and the multiple fluid components resulting from the WAG injection strategy. Changes in the vertical component of gravity on the surface caused by CO_2 injection over a 20-year period were below the level of repeatability for current field surveys. However, measurements made in boreholes just above the reservoir interval are sensitive enough to observe measurable changes in G_z as CO_2 injection proceeds. Such measurements made in numerous wells could map the areas of net density changes caused by injected CO_2 and water within the reservoir.

For the CO_2-brine interface within a 20 m thick reservoir at 1,900 m depth, 30% CO_2 and 70% brine saturation produces a 20 μGal response compared to the model without the CO_2. Changes in the CO_2 saturation of 10% produce changes in the vertical component of gravity of approximately 6 μGal. Based on the published literature, we would expect that repeatability of time-lapse measurements would be on the order of 3 to 4 μGals. This means that a 10% change in CO_2 saturation would be the limit of detectability. We would also expect to be able to see lateral movement of the CO_2-brine front on the order of 500 m from the changes in the vertical component of gravity.

The electrical resistivity of rocks is primarily a function of porosity and water saturation. When the porosity is known, or can reasonably be assumed to have small spatial variation, changes in electrical resistivity are directly related to changes in water saturation. EM techniques can be used to map such spatial variations in electrical resistivity. While the electromagnetic response from an easily deployable field system for the Schrader Bluff model is low, an amplitude change of approximately 8% occurs over the CO_2 –brine contact. The ability to observe this difference would depend on the signal-to-noise ratio of the data. Lateral resolution of contact movement would be expected to be on the order of 500 m, based on 2% change in the electric field amplitudes produced by a 500 m movement of the contact.

The nonseismic techniques presented here show promise as low-cost supplements to seismic monitoring justifying further evaluation and testing under a wider range of conditions. Borehole gravity measurements should be used in conjunction with pressure test data and/or surface seismic data to provide a basis for statistical interpolation of predicted changes in S_{CO2}. 3D seismic acquisition could be limited to a single pre-injection survey in this case. Future plans should incorporate field demonstration of the

EM technique and a study of resolution that can be achieved by inversion of gravity and EM data.

Acknowledgements

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Suggested Reading

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Corresponding author: egasperikova@lbl.gov