WESTCARB Regional Partnership

Controlled-Source Electromagnetic (CSEM) Surveys to Monitor CO_2

John Henry Beyer, J. Torquil Smith, Greg Newman
Geophysics Department

Lawrence Berkeley National Laboratory
Earth Sciences Division
One Cyclotron Road, MS 90-1116
Berkeley, CA 94720

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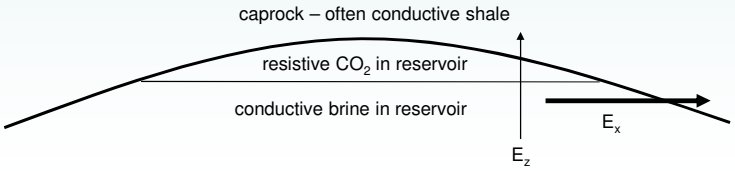
Motivation for Monitoring Commercial-Scale CO_2 Storage with CSEM

- It's generally acknowledged that 3D seismic surveys will need to be performed periodically to monitor commercial-scale CO_2 injections. The surveys are very expensive.
- Electromagnetic (EM) methods may provide a more cost effective monitoring technique that, at a minimum, may reduce the frequency of seismic surveys.
- CSEM may be an effective "early warning" technology for monitoring CO_2 migrating up-dip toward known faults or abandoned wells.
- Recent studies suggest that seismic methods may be ineffective at monitoring patchy saturations of CO_2*

* Padhi, A., S. Mallick, P.K. Mukhopadhyay, H. Behzadi, and V. Alvarado, 2011, Seismic signature of patchy saturation and its implications to time-lapse monitoring of carbon-sequestrated deep saline reservoirs, Soc. of Expl. Geophysicists Annual Meeting, San Antonio, TX, Sep. 21, 2011

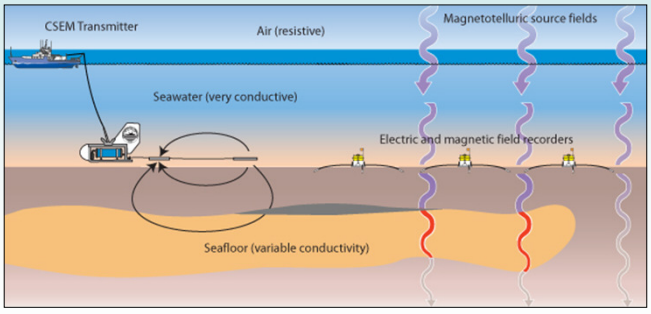
Reservoir Properties Change with CO_2 Injection

- CO_2 concentrations significantly reduce seismic velocity in a reservoir
- The electrical resistivity of supercritical CO_2 is close to that of air – very resistive compared to the conductive brine in a saline reservoir
- Through buoyancy, CO_2 in a reservoir will tend to assume a "pancake" shape (thin and laterally extensive) beneath a caprock or shale layer within a reservoir
- So the EM component most significantly affected by CO_2 in a reservoir is the vertical electric field, the direction of current flow



Marine CSEM

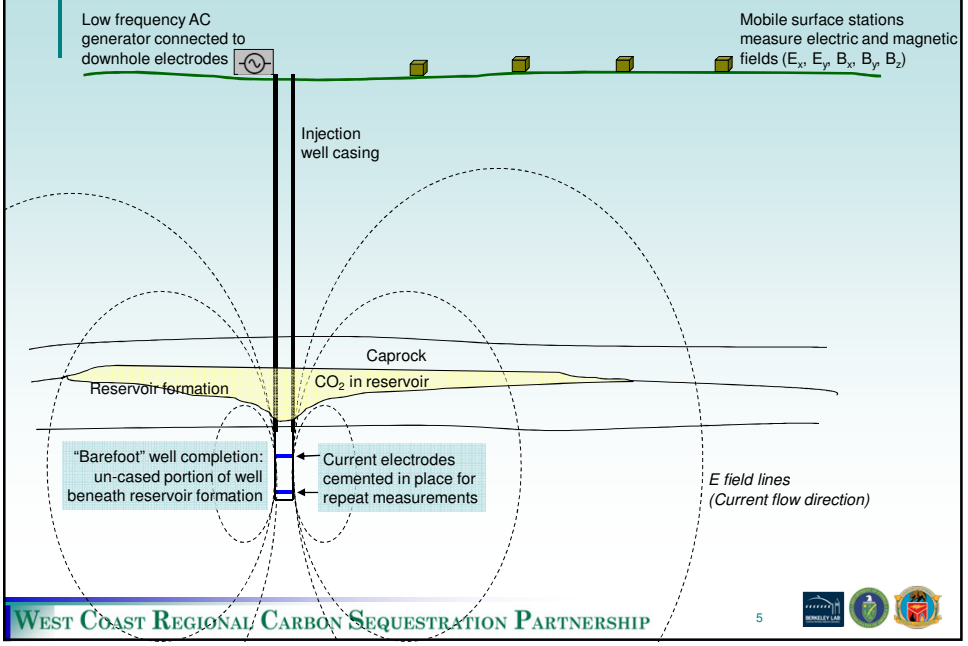
- Model studies demonstrate that marine CSEM surveys can assess oil or gas reservoir depletion as resistive hydrocarbons are produced and conductive brine invades
- Natural EM (magnetotelluric) source fields induce horizontal electric fields and are less effective than a controlled source, which provides a significant vertical E-field component



Marine CSEM survey design: receiver stations on the sea floor, natural (magnetotelluric) fields, and controlled source fields generated by a towed electric dipole array

Source: Scripps Institution of Oceanography, http://marineemlab.ucsd.edu/resources/concepts/CSEM_MT.html

Proposed Land-Based Survey Design



Data Analysis

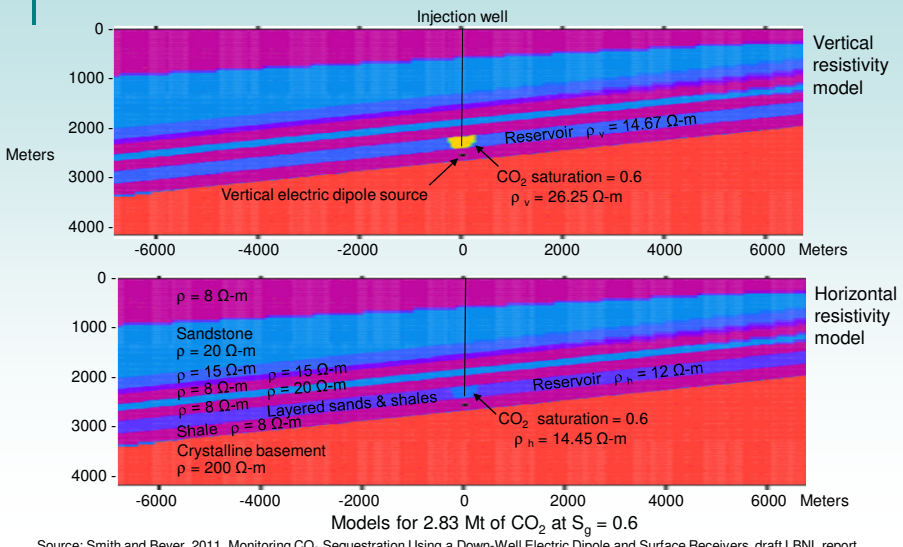
- Use baseline 3D seismic survey to define geologic structure
- Use electric log data from wells to estimate formation resistivities
- Use a 3D EM modeling code - constrained by the electrical resistivity structure above and below the reservoir - to invert for resistivity changes in the reservoir as CO_2 is injected and brine is displaced
- Determine volume of injected CO_2 based on the equation of state at the temperature and pressure of the reservoir
- Use Archie's Law to estimate CO_2-invaded reservoir resistivity based on reservoir porosity, rock resistivity, brine resistivity, and brine saturation
- Conduct baseline and repeat CSEM surveys to detect changes in the distribution and saturation of CO_2 in the reservoir
- *Petrophysical work at LBNL will include measurement of the resistivity of reservoir rocks as CO_2 invades brine-saturated samples at reservoir temperature and pressure*

Evaluation of Sensitivity of CSEM to Monitor CO_2

Modeling performed by Torquil Smith, LBNL Geophysics Department

- Started with geologic model for Kimberlina, where LLNL developed geologic structure from well logs and LBNL conducted dynamic multiphase hydrologic modeling of CO_2 injection
- Used 3DEM code developed by Greg Newman (LBNL Geophysics Department) to calculate EM fields at the Earth's surface for models:
  - Vertical electric dipole source: 2600 m depth, 0.125 Hz, 1 Amp-m
  - CO_2 injected at 2300 m depth: 1.42, 2.83, and 5.66 M tonnes
  - CO_2 saturation (S_g) = 0.3 and 0.6
  - CO_2 volume modeled as a hemisphere
  - For S_g = 0.3, diameters = 544, 712, 966 meters
  - For S_g = 0.6, diameters = 456, 582, 772 meters

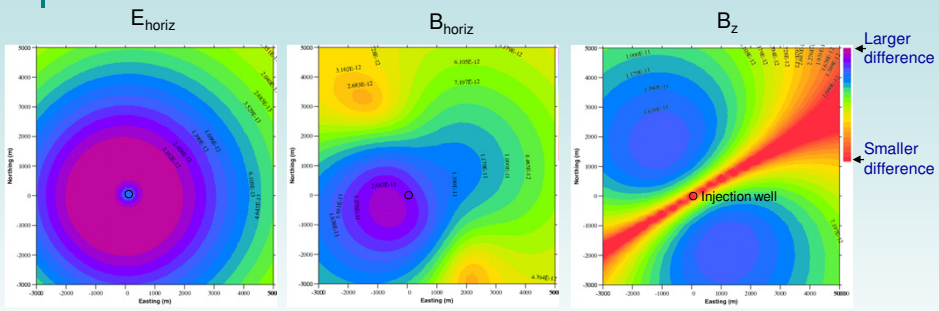
Electrical Resistivity Model with Vertical Electric Dipole Source in Un-cased Part of Injection Well, Beneath Reservoir Formation



Models for 2.83 Mt of CO_2 at S_g = 0.6

Source: Smith and Beyer, 2011, Monitoring CO_2 Sequestration Using a Down-Well Electric Dipole and Surface Receivers, draft LBNL report

Magnitude of difference in EM field components when 1.42 Mt of CO_2 is injected (S_g = 0.3)



Conclusions To-Date

- If the dipole source is scaled for 1500 Amp-m (e.g., 30 Amps, 50 m long), max E-field changes are on the order 20% of the maximum electric fields; max B-field changes are on the order 9% of the maximum magnetic fields
- These anomalies are easily detectable in the presence of instrument and magnetotelluric (natural EM) noise