PROCEEDINGS, CO2SC Symposium 2006
Lawrence Berkeley National Laboratory, Berkeley, California, March 20-22, 2006

SITE CHARACTERIZATION FOR CO_2 GEOLOGIC STORAGE AND VICE VERSA - THE FRIO BRINE PILOT AS A CASE STUDY

Christine Doughty

Earth Sciences Division
Lawrence Berkeley National Laboratory
Berkeley, California, USA 94720
e-mail: cadoughty@lbl.gov

INTRODUCTION

Careful site characterization is critical for successful geologic sequestration of CO_2, especially for sequestration in brine-bearing formations that have not been previously used for other purposes. Traditional site characterization techniques such as geophysical imaging, well logging, core analyses, interference well testing, and tracer testing are all valuable. However, the injection and monitoring of CO_2 itself provides a wealth of additional information. Rather than considering a rigid chronology in which CO_2 sequestration occurs only after site characterization is complete, we recommend that CO_2 injection and monitoring be an integral part of the site-characterization process.

The advantages of this approach are numerous. The obvious benefit of CO_2 injection is to provide information on multi-phase flow properties, which cannot be obtained from traditional site-characterization techniques that examine single-phase conditions. Additionally, the low density and viscosity of CO_2 compared to brine causes the two components to flow through the subsurface differently, potentially revealing distinct features of the geology. Finally, to understand sequestered CO_2 behavior in the subsurface, there is no substitute for studying the movement of CO_2 directly.

Making CO_2 injection part of site characterization has practical benefits as well. The infrastructure for surface handling of CO_2 (compression, heating, local storage) can be developed, the CO_2 injection process can be debugged, and monitoring techniques can be field-tested. Prior to actual sequestration, small amounts of CO_2 may be trucked in. Later, monitoring accompanying the actual sequestration operations may be used to continually refine and improve understanding of CO_2 behavior in the subsurface.

RECOMMENDED SITE CHARACTERIZATON ACTIVITIES

Site characterization must address two issues: the ability to put a large quantity of CO_2 into the subsurface, and the ability to keep it there for a long time. CO_2 injection requires adequate permeability, which can be assessed by well logs, core analyses, and single-well and interference pump tests. CO_2 storage requires adequate connected porosity, which can be assessed by core analyses and tracer tests. Immobilizing CO_2 in the subsurface for long-term geologic sequestration can be accomplished by four primary mechanisms: (1) *Structural trapping*: buoyant free-phase CO_2 is trapped beneath low-permeability layers or faults or in anticline structures. Knowledge of regional geology, geophysical imaging, and well logs provide this information. (2) *Mobility trapping*: multi-phase flow processes immobilize free-phase CO_2. Multi-phase flow behavior of CO_2 and brine provides the best direct information for mobility trapping, but in its absence information from oil/brine systems may be helpful. (3) *Dissolution trapping*: CO_2 dissolves in brine and is no longer buoyant. Brine composition, which may be obtained by collecting undisturbed fluid samples, is needed to quantify CO_2 dissolution. (4) *Mineral trapping*: CO_2 reacts with rock minerals to form carbonate compounds. Mineral compositions and distributions, which may be obtained from core samples, are needed to quantify CO_2/mineral chemical reactions.

Development and application of a numerical model concurrently with site characterization can be used for designing tests, predicting test outcomes to assess the current state of knowledge, and comparing model results to field observations to calibrate unknown parameters and to incorporate new features.

CASE STUDY - THE FRIO BRINE PILOT

At the Frio brine pilot, conducted at the South Liberty field near Houston, Texas, 1600 metric tons of CO_2 were injected over a period of 10 days into a steeply dipping sand layer at a depth of 1500 m. At this depth, free-phase CO_2 is supercritical. The sand layer is on the flank of a salt dome, and laterally compartmentalized by sub-vertical faults. The pilot employed one injection well and one observation well, each perforated over 6 m in the upper portion of the 23-m thick sand. The two wells are separated laterally by about 30 m, with the injection well down-dip of the observation well (Hovorka et al., 2006). Historical oil production at depths around 2400 m provides structural information about the site. Site characterization activities for the Frio brine pilot are summarized in Table 1.

Table 1. Site characterization activities at the Frio brine pilot.

Activity	Monitoring	Information obtained
Review existing data related to historical oil production	3D seismic	Structure of sand and shale layers surrounding salt dome
	Wireline logs in regionally distributed wells	Compartmentalization into fault blocks
Well log analysis	Wireline logs in injection and observation wells	Identify target sand layer and overlying shale caprock
		Extent, continuity, and variability of layers
		Using literature correlations, estimate permeability, porosity, relative permeability parameters
Core analysis from newly drilled injection well	Porosity	Calibrate well-log estimates of porosity
	Permeability	Calibrate well-log estimates of permeability
	Mercury intrusion	Capillary pressure/saturation relationship
Interference well test	Pressure transients	Confirm inter-well connectivity
		Flow properties of lateral boundaries
		Field-scale permeability
		Estimates of pressure increase during CO_2 injection
Aqueous-phase tracer test	Fluorescein break-through curve (BTC)	Single-phase dispersivity
		Porosity-thickness product of sand layer
CO_2 injection	Pressure transients	Two-phase flow properties
	CO_2 arrival at observation well	Average CO_2 saturation between wells
	RST (reservoir simulation tool)	CO_2 saturation profiles at injection and observation wells
	Cross-well seismic	CO_2 distribution between injection and observation wells
	VSP (vertical seismic profile)	CO_2 distribution updip of observation well
Two-phase tracer test (concurrent with CO_2 injection)	Two-phase tracer BTC	Two-phase dispersivity
		Evolution of CO_2 saturation distribution with time

Numerical modeling was used to help determine parameters of the CO_2 injection, and to design the site-characterization well test and tracer test (Doughty, 2005). As field work proceeded, model results were compared to field data, and the model was modified to incorporate new information.

Figure 1 illustrates single-phase site-characterization activities, specifically, an interference well test and a doublet tracer test (Trautz et al., 2005). The well test confirms core-scale permeability measurements on the order of 2 Darcies, and modeling suggests that a small fault within the main fault block should not be considered a closed boundary. The maximum pressure increases seen in the injection and observation wells may be used for equipment design and to ensure regulatory compliance during CO_2 injection. Matching the tracer test with a streamline model produces a small single-phase dispersivity and a large porosity-thickness product, implying that the sand is highly homogeneous and that the effective sand thickness between the injection and observation wells is greater than the 5.5 m inferred from well logs.

Figure 2 shows a time series of RST logs at the injection and observation wells, along with the corresponding model results for CO_2 saturation. The wireline reservoir saturation tool (RST) uses pulsed neutron capture to determine changing brine saturation as brine is displaced by CO_2 (Sakurai et al., 2005). The magnitude of CO_2 saturation provides constraints on two-phase flow properties, whereas the depth at which CO_2 appears provides valuable insights into geology. At the injection well, CO_2 extends below the perforated interval, suggesting that a thin marker bed located just below the perforations does not have nearly as low a permeability as inferred from well logs. In the observation well, CO_2 arrives almost 1 m shallower than predicted by the model, suggesting that a low-permeability layer identified just above the perforations in both wells may not be continuous. These findings are consistent with the large sand-layer thickness inferred from the single-phase tracer test, but only the CO_2 injection provides specific information about how this greater thickness arises.

Figure 3 compares vertical seismic profile (VSP) results for the far-field CO_2 distribution two months after CO_2 injection with model results. The change in amplitude of the seismic response is plotted as a function of offset from the injection well, along three azimuthal angles (Daley et al., 2005). We do not have a quantitative relationship between VSP change in amplitude and CO_2 saturation, so the vertical axes of the plot are adjusted to align these two quantities close to the injection well. Figure 3 shows good agreement between model and VSP in the updip direction (N), but the VSP indicates that the plume has moved farther than the model predicts to the NE and NW. In fact, the plume has moved as far to the NW as it has to the N, suggesting that either our notion of the true dip direction is inaccurate, or that there is significant heterogeneity or anisotropy in the permeability distribution beyond the immediate vicinity of the wells.

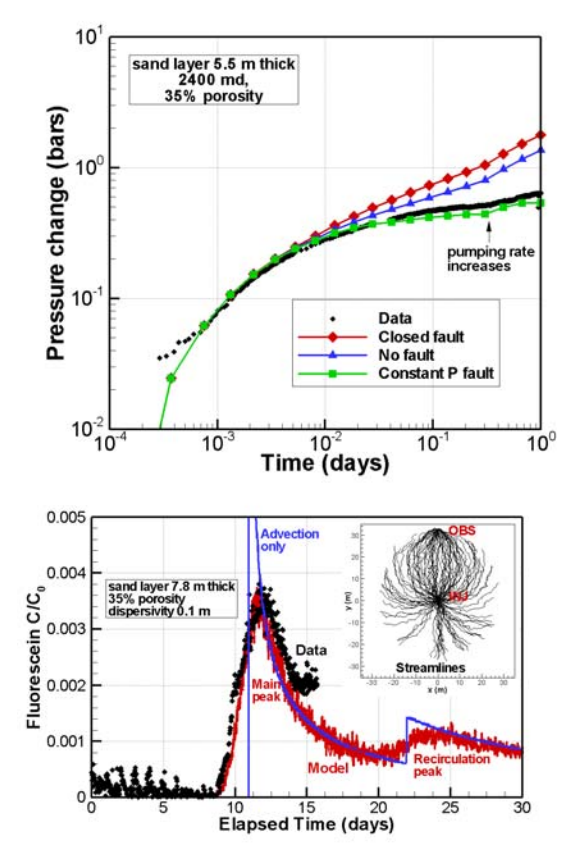

Figure 1. Top frame: Observation-well pressure transient during interference well test and model results considering three different boundary conditions for a small fault near the wells. Bottom frame: Tracer test data and results of a streamline model.

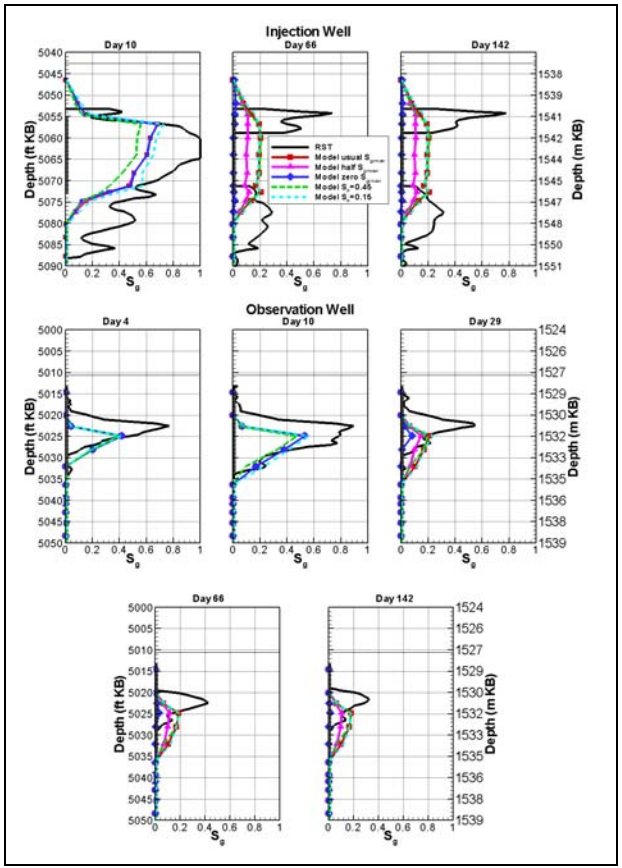

Figure 2. CO_2 saturation profiles inferred from RST logs in the injection well (top row) and in the observation well (bottom two rows). The injection period is days 0-10. Late-time profiles in both wells are less quantitative, due to well workovers conducted following the end of the injection period. Model results considering different two-phase flow parameters are also shown.

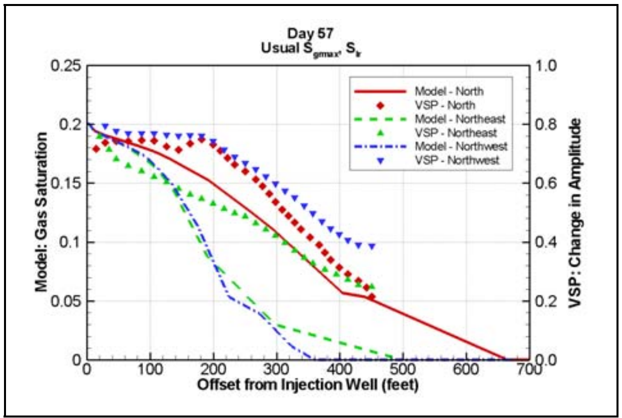

Figure 3. Comparison of VSP and model results for far-field CO_2 distribution.

ACKNOWLEDGMENT

Data provided by and stimulating discussions with members of the Frio brine pilot team are gratefully acknowledged, as is the review of this abstract by Curt Oldenburg. This work was supported by the Assistant Secretary for Fossil Energy, Office of Coal and Power Systems, through the National Energy Technology Laboratory, of the U.S. Department of Energy under Contract No. DE-AC02-05CH1123.

REFERENCES

Daley, T.M., L.R. Myer, E.L. Majer, J.E. Peterson, 2005, Acquisition of time-lapse, 6-component, P- and S-wave, crosswell seismic survey with orbital vibrator and of time-lapse VSP for CO_2 injection monitoring, presented at 75th annual International Meeting of the Society of Exploration Geophysicists, Houston TX, Nov. 2005.

Doughty, C., Flow modeling for CO2 sequestration: The Frio brine pilot, presented at AGU Fall Meeting, San Francisco, CA, December, 2005.

Hovorka, S.D. S.M. Benson, C. Doughty, B.M. Freifeld, S. Sakurai, T.M. Daley, Y.K. Kharaka, M.H. Holtz, R.C. Trautz, H.S. Nance, L.R. Meyer, K.K. Knauss, Measuring permanence of CO_2 storage in saline formations – The Frio experiment, *Environmental Geosciences*, in press, 2006.

Sakurai, S., T.S. Ramakrishnan, A. Boyd, N. Mueller, and S.D. Hovorka, Monitoring saturation changes of CO_2 sequestration: Petrophysical support of the Frio brine pilot experiment, presented at Society of Petrophysicists and Well Log Engineers 46th Annual Logging Symposium, New Orleans, LA, 2005.

Trautz, R.C., B.M. Freifeld, and C. Doughty, Comparison of single and multiphase tracer tests results from the Frio CO_2 pilot study, Dayton Texas, presented at National Environmental Technology Laboratory Fourth Annual Conference on Carbon Capture and Sequestration, Alexandria, VA, May 2-5, 2005.