II.3.3 Geophysical Monitoring of Geologic Sequestration

Investigators
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Background

Subsurface monitoring will be required to provide: (1) early warning of reservoir leaks to address public safety concerns; (2) images of the space-time distribution of injected CO_2 to aid optimization of injection and storage; and (3) input to the safety case analysis expected to be required for a permit and licensing process. Geophysics offers a variety of methods that operate over a wide range of geological environments, reservoir scales, and depths. The challenge is to track the flow of CO_2 while simultaneously monitoring for leaks in a growing subsurface volume. Moreover, a thorough description and predictive simulation of the monitoring capability may be required for the safety case when a site is presented for licensing.

During the initial phase of the study, we developed models that estimate the changes in bulk rock-fluid properties with injected CO_2. We then considered several geophysical monitoring methods, e.g., seismic, electrical, magnetic, electromagnetic, gravity, and surface deformation (Wynn[54]) and performed sensitivity analyses for each. See summary below. The major conclusion of this initial study was that seismic methods provide the most effective and universally applicable technology for subsurface monitoring for the various geologic storage scenarios of coal beds, deep saline aquifers and depleted oil and gas fields. However, seismic imaging, as we know it from the petroleum industry, is too expensive for continuous or repeated long-term monitoring. Our ongoing research is focusing on the development of cost-effective time-lapse seismic imaging techniques that can potentially provide quasi-continuous monitoring and adapt to address safety concerns. We’re following the guiding principle that the monitoring effort must decrease with time, barring a reservoir problem, and eventually cease altogether when safe containment is no longer a concern.

Summary of Subsurface Monitoring Options

This section summarizes the results of our scoping study on the applicability of various geophysical methods for monitoring CO_2 sequestration. The details of this study are given in Wynn[54]. He explored the available options for monitoring formations undergoing CO_2 injection. Rock physics models were used to determine the time-lapse changes in relevant physical properties (acoustic, electrical, etc.) for a variety of rock types at the pore scale. These rock physics models were used in a synthetic formation model to estimate field or measurement scale changes. Results from different settings were compared to suggest optimum monitoring techniques for monitoring geologic sequestration. Also examined were the potential uses of each technique for monitoring CO_2 migration, seal integrity, and mass balance. Seismic, electromagnetic, gravitational, and geodetic methods are the four broad types of subsurface geophysical monitoring examined. Direct sampling methods such as monitoring wells have high spatial resolution but low spatial coverage. Subsurface geophysical imaging techniques generally have high spatial coverage with limited spatial resolution, but have the added benefit of being remote. While a monitoring well would have to penetrate the formation seal to gather meaningful hydrologic data or fluid samples, possibly creating conduits for CO_2 to escape, seismic imaging may be used to image the area of interest without such intrusion.

In seismic monitoring, the changes we may detect are changes in velocity, reflectivity, and possibly attenuation. The bulk of the velocity changes resulting from saturation effects occur with only a small amount of CO_2 in the pore space. For this reason seismic monitoring will be very useful in leak detection and for monitoring CO_2 migration. Seismic monitoring should be able to detect thin layers of CO_2, under favorable circumstances meaning that migration paths should show up in a reflection survey and the presence of CO_2 in overlying zones should be easily detectable. The acoustic velocity of fluids under most reservoir conditions is typically above 1000 m/sec, whereas the velocity of CO_2 is considerably less. Figure 35 shows velocities of CO_2 at different pressures and temperatures. Figures 36 and 37 are examples of wave velocity changes in CO_2 flooded sandstone and CO_2 flooded coal. The velocity change due to CO_2 flooding is significant, which favors the seismic monitoring.

Resistivity surveys are the simplest method of assessing subsurface conductivity. At the large separation distances required for monitoring CO_2 sequestration such techniques will detect only the average changes in the reservoir and may be of too low resolution to be of any use. Another option is crosswell electromagnetic measurements. At the low frequencies necessary to propagate EM waves across field scale distances the resolution is fairly low, and the measurements are strongly affected by the conductivity structure near the source and receiver.

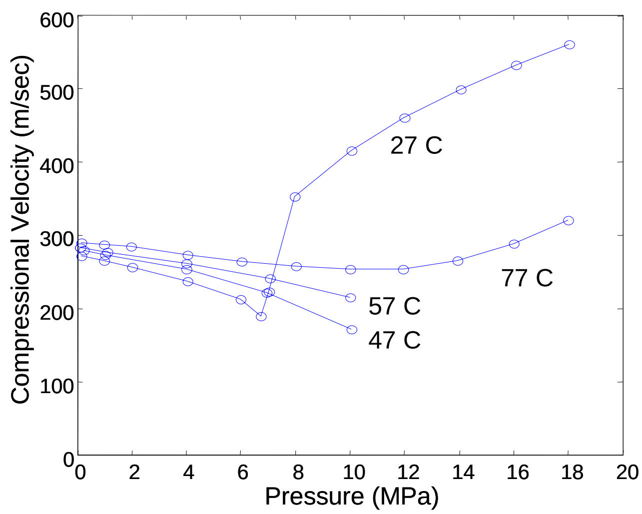

Figure 35: P-wave velocities of CO_2 (Wang and Nur[55]).

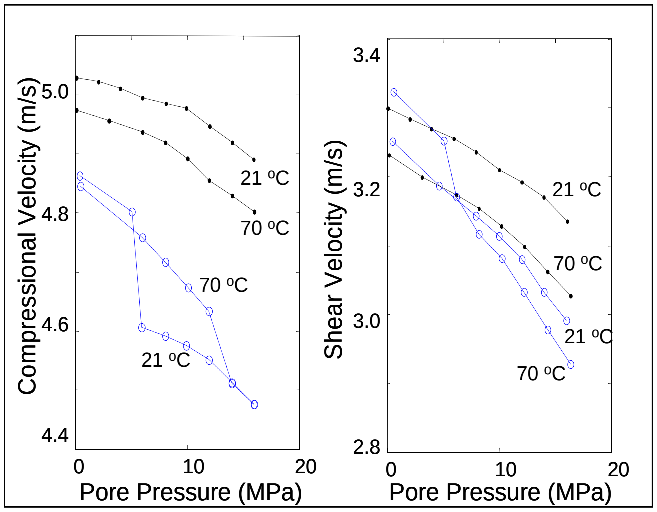

Figure 36: P-wave velocities in hydrocarbon-saturated and CO_2-flooded sandstone. Black lines are isotherms for hydrocarbon-saturated rocks, and blue lines are isotherms for flooded rocks. Confining pressure for the plots is 20 MPa (Wang and Nur[55]).

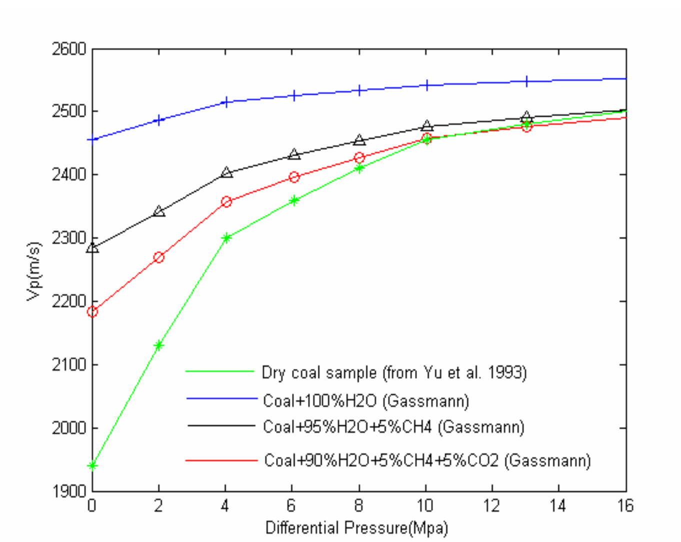

Figure 37: Predicted P-wave velocities in a CO_2-flooded coal from Gassmann's equation (Gassmann[56]) and laboratory data from Yu *et al.*[57].

Gravity monitoring is only suitable for making very low-resolution mass balance measurement, and that too in shallow formations as the signal falls off inversely with distance squared. Geodetic techniques measure displacements or displacement gradients at the earth's surface. Such techniques are commonly used in the study of earthquakes or volcanoes but may also have limited applications in monitoring CO_2 sequestration under certain conditions. In a stable tectonic environment, measured deformation over a sequestration site should only be the result of induced pressure changes at depth due to fluid injection. However, surface geodetic techniques, much like gravity, are very low-resolution techniques.

The results of Wynn's[54] study are summarized in Table IV. Not surprisingly seismic, being a versatile, high-resolution technique has the widest range of uses and is not limited by geologic setting. The SACS project at Sleipner has certainly confirmed the ability of seismic monitoring to track CO_2 in the subsurface.

Table IV: Summary of the usefulness of geophysical techniques by use and setting.

	Seismic	Electromagnetic	Gravity	Deformation
Mass Balance	low res.	low res.	good	good
CO_2 Migration	good	good	low res.	low res.
Leak Detection	good	good	low res.	no
Geologic Setting	any	aquifers	any	oil and gas
Rock Strength	any (soft better)	any	any	soft
Formation Depth	any	any	shallow	shallow

Adaptive Seismic Monitoring: A New Approach to Time-Lapse Subsurface Imaging

Our proposal for subsurface CO_2 monitoring is to trade the conventional approach of high spatial/low temporal resolution for a new approach providing low spatial/high temporal resolution monitoring. The premise upon which this approach is based is that the high-resolution features are predominately static and do not change significantly during the injection cycle of the storage process. We are developing strategies for seismic imaging though the approach is applicable to other imaging methods as well. The conventional seismic approach (Figure 38) that's used for hydrocarbon reservoirs is to produce a temporal sequence of high-resolution images or snapshots m_i, taken years apart as reservoir development progresses. Changes in the reservoir are detected by differencing the snapshots. For many reasons the differences often have much lower resolution than the individual snapshots, e.g., data acquisition is not repeatable and true reservoir changes are often larger scale. Our new approach (also Figure 4) is designed to build upon the high-resolution baseline image (produced as part of the site-selection process) with a sequence of low-resolution difference images Δm_i, each taken perhaps months or even weeks apart. To maximum acquisition repeatability, we propose to instrument the storage field with permanently emplaced seismic sources and detectors. To accelerate data processing and data analysis, the time-lapse data sets are recorded with reduced spatial and temporal sampling and coverage. The smaller data are then processed to explicitly parameterize a time-varying reservoir model (Day-Lewis *et al.*[58]). Changes in fluid saturation (without the high-resolution static background) are directly imaged rather than through difference images. Moreover, we propose new survey geometries, acquisition schemes, and processing methods that are aimed at reducing costs and providing quasi-real-time monitoring capability. We are calling this new approach Adaptive Seismic Monitoring (ASM).

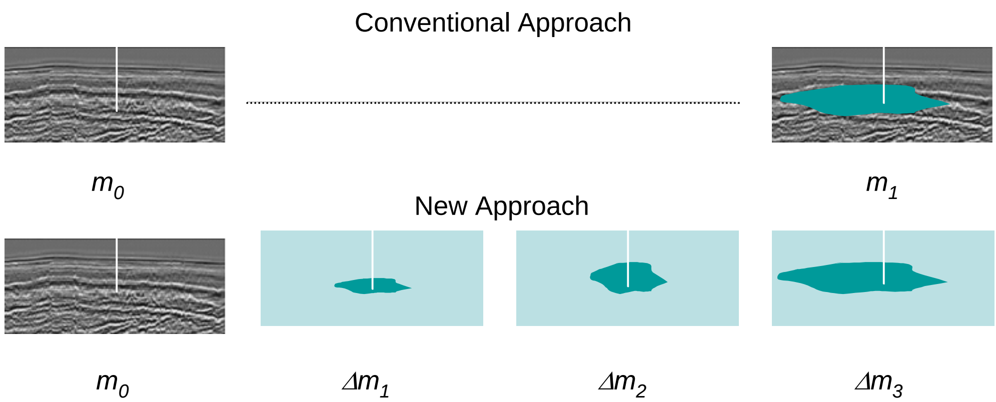

Figure 38: The conventional time-lapse imaging approach is to produce a sequence of snapshots, m_i, each taken perhaps years apart, e.g., m_0 and m_1 in the upper figure. Our new approach (ASM) is to produce a larger sequence of lower resolution difference images, Δm_i, taken perhaps months or even weeks apart. The baseline image m_0 is the same in both cases and comes from the site selection and characterization study.

An example of a new acquisition strategy is the Stanford Cross-Linear array illustrated in Figure 39. Seismic sources and detectors are distributed along three linear arrays, two along the surface and one along the injection borehole. The 3-axis arrays provide reduced 3-D resolution, but at greatly reduced acquisition and processing costs relative to the usual 2-D surface array. Both sources and receivers are permanently embedded to maximize survey repeatability and reduce deployment costs. Additional surface lines may be added or different sections of the Cross may be activated at different times to track the CO_2 front or to target specific reservoir zones or problems areas. Our new approach includes signal coding to permit the use of low-power sources for continuous operation; these attributes in particular enable quasi-real-time monitoring.

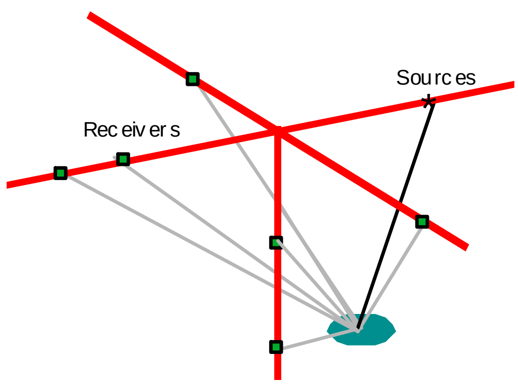

Figure 39: The Stanford Cross-Linear array incorporates 3-axis linear source/detector arrays emplaced along the surface and embedded along the injection borehole. Both in-plan and out-of-plane imaging is possible with this configuration. Sampling and the dimensions of the apertures of the arrays may be adjusted for resolution and subsurface coverage.

Results

A Synthetic Study on Seismic Monitoring

In order to test the many possibilities, we have developed some modeling tools for simulating the imaging of seismic data. So far, we are performing tests in two spatial dimensions. In this section, we present results for simulation study on full aperture imaging. During the next phase of the project, we will move to three spatial dimensions and limited aperture simulations. The synthetic model simulates shallow reservoir sands (e.g., less than 1000m) with a porosity of 35%. Four snapshots of the seismic velocity before and during CO_2 injection are shown in Figure 40. During injection, CO_2 replaces water in the formation resulting in assumed saturation levels of 20% CO_2 and 80% water. The P-wave velocity decreases from the pre-injection value of 2000 m/s to the post-inject value seen in the plumes of 1270 m/s. The changes in velocity are estimated using Gassmann's equation (Gassmann[56]). Spatial dimensions, reservoir geometry, and seismic properties of the model are intended to be similar to those found at Sleipner.

We computed seismic datasets for each of the reservoir images shown in Figure 6. Each dataset was then processed using prestack depth migration (e.g., Bleistein & Gray[59]) as the imaging method. The resulting time-lapse images of seismic reflectivity, shown in Figures 41, clearly show signatures of CO_2 saturation. Indeed the synthetic images show a skeletal resemblance to the time-lapse images from Sleipner, albeit with fewer details. We can see from Figure 41 that the amplitude differences in the time-lapse images indicate the changing contrast in reflectivity associated with changing CO_2 buildup just below impermeable horizontal interfaces. While there are also some imaging artifacts, the effects of the CO_2 are easily distinguished in these full aperture images. One of the imaging artifacts is the downward shift in the apparent depth of reflectors below CO_2 saturated zones. While an artifact of the image generation (wrong velocity), this downward shift may be used in a feature extraction scheme for real-time leak detection.

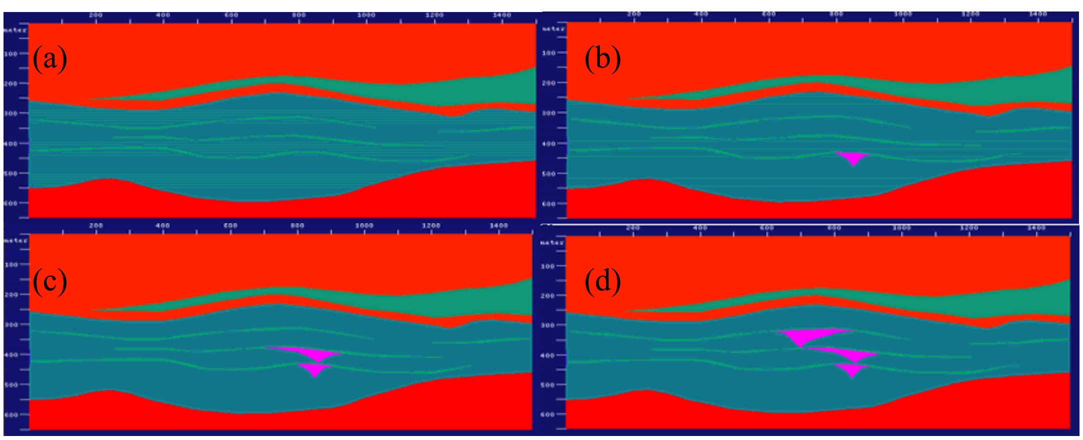

Figure 40: Four snapshots from a synthetic model of a reservoir experiencing CO_2 injection: (a) before injection; (b)-(d) three subsequent snapshots after injection illustrate the evolution of low velocity plumes of CO_2 generated as CO_2 migrates upward through shale breaks and accumulates below low permeability barriers.

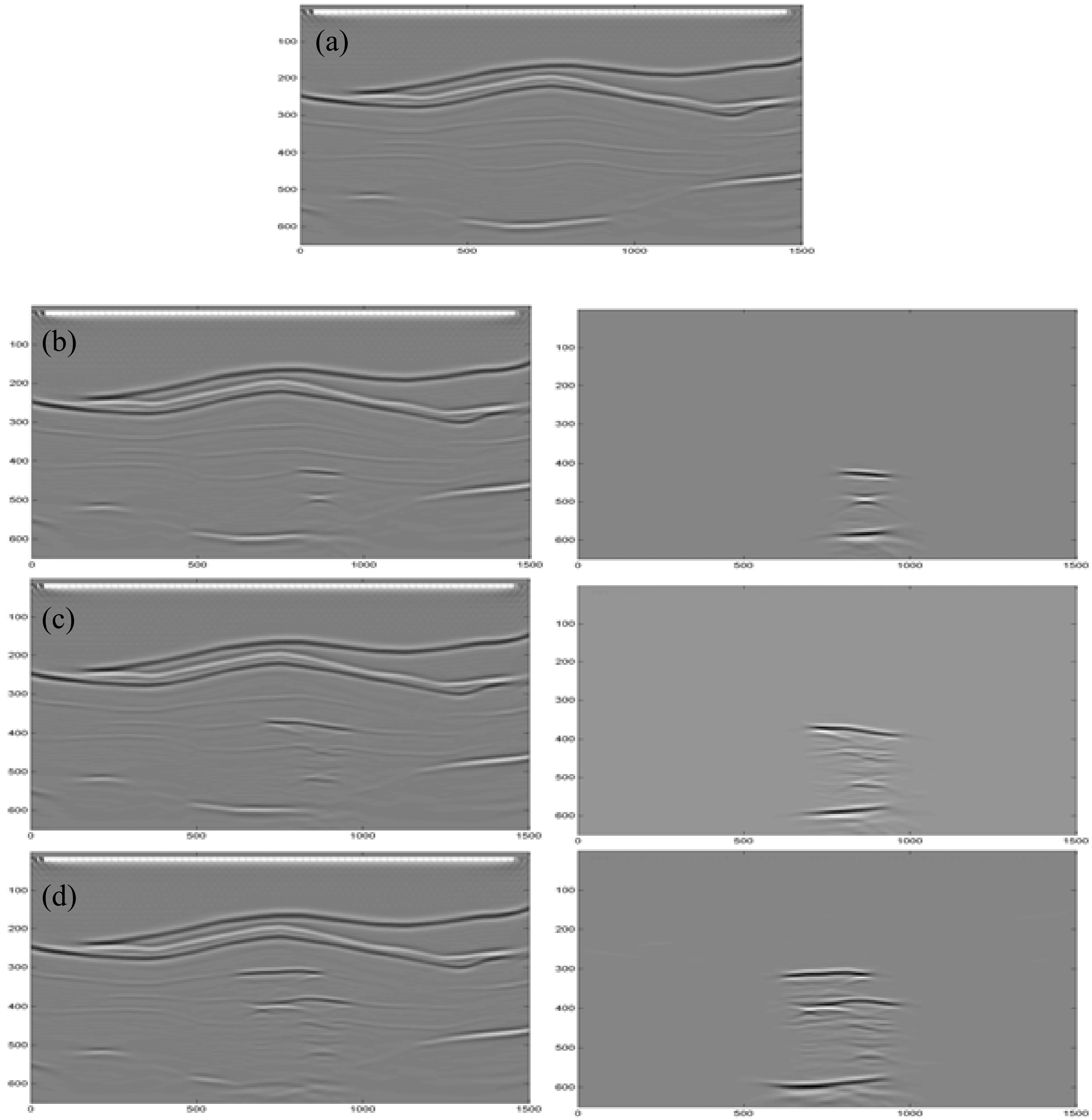

Figure 41: Time-lapse seismic images of the storage reservoir undergoing CO_2 injection. The images were created using prestack depth migration and full aperture datasets. (a) baseline; (b) – (d) time-lapse images (left column) and difference images (right column).

Diffraction Tomography

The simulations described above demonstrate that our modeling tools are fully capable of realistically capturing the effects of CO_2 seen in field data. Nevertheless, these realistic tools are much too complicated and slow to explore the parameter space required to develop Adaptive Seismic Monitoring. In order to study the important issues, we need a rapid way of investigating the effects of sampling, aperture dimensions, and signal frequency and bandwidth on image quality. To that end, we are using diffraction tomography based on the Born approximation as a solution to the Helmholtz equation (Devaney[60], Harris[61], and Wu and Toksoz[62]). While this method is elegant and especially useful for the simulation problem at hand, it has also been used on 2-D and 3-D field datasets (Bleistein and Gray[63], Keho and Beydoun[64], Louie *et al.*[65]). To differentiate the two imaging approaches presented here, diffraction tomography is best described as providing a quantitative velocity inversion based on weak inverse scattering theory while prestack depth migration is a qualitative "transpose" method based on back propagation. Diffraction tomography images the changes in velocity in the volume whereas migration images the changes in reflectivity at interfaces. Both have strengths and weaknesses. We needn't decide which to apply for the real-world monitoring problem at this time. While migration is far more practical for large field datasets, the analytical elegance of diffraction tomography is more useful for addressing the design problems of adaptive monitoring.

We assume that we have a baseline high-resolution seismic dataset prior to the injection of CO_2. The seismic wavefield used to produce the baseline image is denoted $U^o(\boldsymbol{r})$. When CO_2 is injected, the wavefield is perturbed to $U^1(\boldsymbol{r})$. The difference between the two is the scattered field $U^{sc}(\boldsymbol{r})$ that's generated by the injected CO_2. It can be shown that the scattered wavefield is linearly proportional to the Fourier spectrum of the changes in the medium created by the CO_2:

$$U^{sc}(\hat{r},\hat{s}) = U^1 - U^o \approx \frac{U^o k^2}{4\pi r} e^{+ikr} \int_V O(r')e^{-i\boldsymbol{k}_s \cdot \boldsymbol{r}'} d\boldsymbol{r}' = \frac{U^o k^2}{4\pi r} e^{+ikr} \tilde{O}(\boldsymbol{k}_s), \tag{22}$$

where $\tilde{O}(\boldsymbol{k}_s)$ is the Fourier transform of the perturbation in the medium $O(\boldsymbol{r})$ caused by the CO_2. The scattering vector $\boldsymbol{k}_s = (\hat{\boldsymbol{r}} - \hat{\boldsymbol{s}})\,\omega/c$ is used to define the set of angles and frequencies that can be used to sample the Fourier support of the medium with a combination of source and detector locations and signal frequencies. We use the spectral support as a filter to obtain a bandlimited spectrum of the medium. Inverse Fourier transform of the bandlimited spectrum gives a reconstruction of the medium for the considered geometry of sources and detectors and frequency bandwidth. Figure 42 shows the result of applying filters corresponding to surface seismic source-receiver apertures.

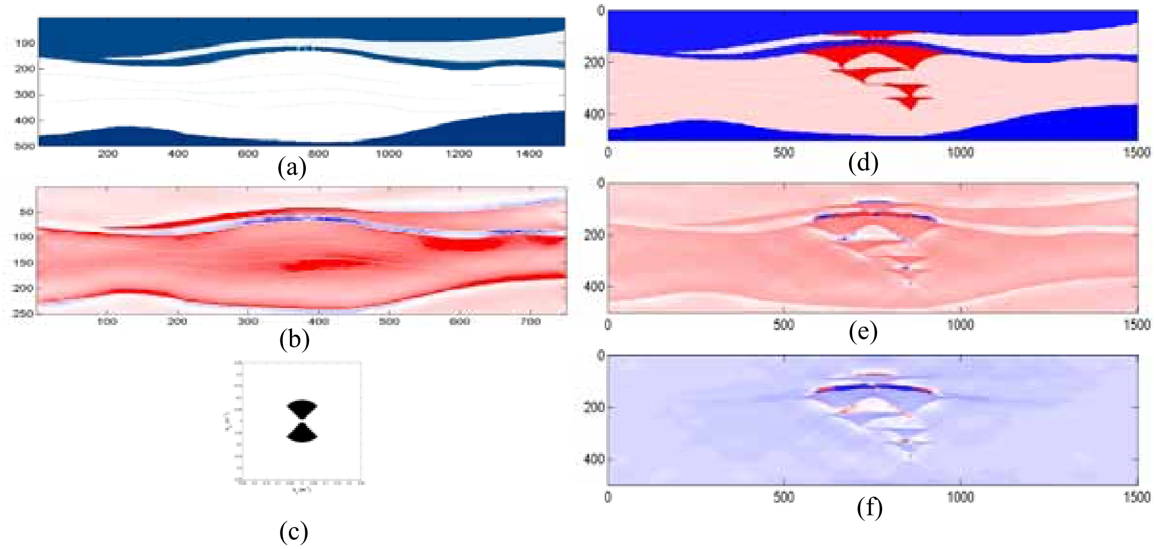

Figure 42: Time-lapse simulation from diffraction tomography: (a) Original earth model; (b) Diffraction tomogram for (a); (c) Spectral filter for a relatively wide surface seismic aperture; (d) Earth model with CO_2; (e) Diffraction tomogram of (d); (f) Difference tomogram. These images illustrate the ability of diffraction tomography to detect volumetric changes unlike migration that detects changes at the interfaces.

Barriers and Issues to large scale monitoring:

After years of injection, significant amounts of undissolved CO_2 could extend several kilometers laterally, potentially finding leakage pathways far away from the injection wellbore. These potential leak paths include abandoned boreholes and geological features such as faults and fractures in the subsurface. Monitoring must cover a significant portion of the reservoir if not the entire storage volume. Nevertheless, monitoring should not continue indefinitely nor should continuous monitoring be required during the entire life of the injection cycle. The questions of how much monitoring, how long and how often have not been answered and are expected to be responsive to regulatory and safety issues. Although monitoring costs may be relatively small in comparison with capture and transportation costs, they are nonetheless real expenses associated with disposal of a waste material. Efforts to improve the technical capability and reduce the direct cost of monitoring should be rewarded with easier public acceptance and truly safer reservoirs. It will be important to include monitoring as an integrated part of the site-specific sequestration project and begin the monitoring process with the baseline characterization study.

The ability to monitor a reservoir should be one of the many criteria considered when selecting a storage site. Also, the capability to predict the behavior or simulate the monitoring process is expected to be an important site-specific licensing issue. We have some concern regarding the conflicting requirements for leak detection and other safety issues (monitoring the entire storage volume) versus monitoring to assess process efficiency, i.e., following the front to track where the CO_2 is going. For this concern alone, the monitoring strategy must be adaptive to meet changing resolution and coverage requirements with time. This is the guiding principle of our adaptive seismic-monitoring approach.

Progress

In the area of assessment of seal integrity, the projects are all beginning to take form. The biggest step we have made this year is developing important collaborations with a number of different companies, laboratories, and individuals. From these, we have gained resources, data and individual expertise and guidance that will aid in the success of our projects. Taken together, our three projects cover all of the possible options for geologic CO_2 sequestration. This will provide a meaningful breadth to our work. Individually, the projects will look deeply into the geomechanical issues unique to each specific setting. We are clearly moving towards a better understanding of how geomechanics influences the seal capacity, integrity and sequestration potential in the three geologic CO_2 storage options. This is a fundamental step in making widespread CO_2 sequestration operations a reality. Only through large-scale implementation will CO_2 sequestration make a significant impact in stabilizing atmospheric CO_2 concentrations.

In the area of flow prediction, we have completed a review of simulation tools available for CO_2 sequestration, and we now have working code available for compositional simulation of sequestration in gas fields, with or without condensate present. We also have a model working for streamline simulation of the injection period of aquifer sequestration with dissolution of CO_2 in the brine and gravity segregation. We are engaged presently in work to understand the interplay of physical mechanisms that act on various time scales for aquifers and coalbeds. Those analyses will guide the selection of simulation methods and tools that will be the toolkit for designers of sequestration projects. In some areas, continued development of the streamline approach will be useful, but for others, other simulation tools will be required. The overall objective is to provide tools for flow prediction that represent accurately the physical mechanism that dominate flow and storage and that are efficient enough that they can be used to design the hundreds of projects at the scale that will be required for widespread application of geologic sequestration.

In the monitoring area, we have completed a scoping study that considered a wide variety on subsurface monitoring methods. From this study, we concluded that seismic is the generic preference for the widest range of storage scenarios, container depths, and geological environments. We next turned our attention to the development of cost-effective seismic-monitoring strategies that could be adapted to changing reservoir conditions. We developed simulation capability involving rock and coal properties with CO_2, seismic modeling, and imaging. Our simulation of a simplified model for Sleipner is remarkably similar to the Sleipner field observations. Moreover, we have developed a simulation tool, in diffraction tomography, for rapidly investigating the tradeoffs among imaging issues such as data-acquisition geometry, sampling, signal frequency and signal bandwidth. This rapid simulation capability has been tested but has not yet been used to design or optimize the Adaptive Seismic Monitoring system. This will come in the next phase of the project. Other activities not described in detail above include specific considerations for monitoring enhanced coal bed methane production (Akintunde, 2004) and the estimation of seismic-attenuation properties for rocks at low seismic frequencies.

Future Plans

In the seal integrity portion of the project in the next months, through the continued collaboration with Dr. Rutqvist, we expect to develop the simulations of CO_2 sequestration for the specific setting like the one we are trying to model in the Powder River Basin. We continue to work on the Ohio River Valley Storage Project, with Amie Lucier working on the project with collaborators at the Schlumberger-Doll Research Laboratory through May. Our geomechanical model and fracture characterization will be complete by mid-summer. Amie Lucier will also work on developing a geomechanical workflow for assessing reservoir suitability using South Eugene Island 330 as a case study during a fall internship at the ExxonMobil Exploration Company.

Work in the area of flow prediction will proceed on several fronts. We will use streamline simulations of aquifer injection to create a suite of initial conditions for a set of high-resolution, high-order finite difference simulations to examine the interplay of heterogeneity, dissolution, gravity segregation of injected CO_2, slow density-driven convection in the brine phase, and diffusion. Those simulations will allow us to judge which simulation tools are appropriate for prediction of what happens in an aquifer after injection has ceased based on the physics of the displacements. We will also continue to develop the physical picture and related simulation tools for coalbeds, and we will continue to investigate experimentally the behavior of multicomponent adsorption of mixed gases in coal.

Future work on monitoring falls into two areas:

(1) Development of specific technology for the assessment and implementation of an adaptive monitoring system. This will include data acquisition, data processing, and analysis and leak-detection procedures. Although we're focusing our attention on seismic, the lessons learned and procedures developed will apply to other methods (deformation, electromagnetic,…) as well. This effort involves considerable numerical simulation studies, using both the realistic migration toolkit as well as the diffraction tomography toolkit. We anticipate testing our strategies for an adaptive seismic-monitoring system on field data. The final piece of the monitoring strategy we plan to pursue is the analysis and interpretation tools for container assessment and leak detection.

(2) Development of a decision procedure and scoring system for assessing the suitability of a site for monitoring. This process of decision analysis will be similar to the reservoir analysis used to estimate the likelihood of success of 4-D seismic projects in the petroleum industry. It will include site-specific information such as reservoir depth, fluid history, pressure history, rock type, overburden rock, seismic data quality, etc. Of course, however, our scoring system will be based of CO_2 storage issues rather than oil and gas recovery issues.

Publications

Papers, reports, and theses

1. Cakici, M.D., Cooptimization of Oil Recovery and Carbon Dioxide Storage, Engineer Thesis, Stanford University, December 2003.
2. Seto, C.J., Compositional Streamline Simulation: An Application to Gas Injection for Enhanced Condensate Recovery in Condensate Reservoirs, MS Report, Stanford University, June 2003.
3. Wynn, D., Survey of Geophysical Monitoring Methods for Monitoring CO_2 Sequestration in Aquifers, M.S. Thesis, Department of Geophysics, Stanford University, 2003.
4. Orr, F.M., Jr., Storage of Carbon Dioxide in Geologic Formations, invited paper for Distinguished Author Series, *J. Petroleum Technology*, in review, April, 2004.

Presentations

1. Orr, F.M., Jr.: "Energy and Global Change: CO_2 Sequestration in the Earth's Crust and Deep Ocean," Petroleum Engineering Department, University of Texas at Austin, March 31, 2003.
2. Orr, F.M., Jr.: "CO_2 Sequestration in the Earth's Crust and Deep Ocean," National Research Council Committee on Alternative Strategies for Future Production and Use of Hydrogen, April 23, 2003.
3. Seto, C.J., Jessen, K., and Orr, F.M., Jr: "Enhanced Condensate Recovery and CO_2 Sequestration," IEA Workshop on Enhanced Oil Recovery, Regina, September 7-10, 2003.
4. Orr, F.M., Jr., Zoback, M.D., and Kovscek, A.R.: "Geologic Sequestration of CO_2: Storage Mechanisms and Potential for Leaks," MIT Carbon Sequestration Forum, Cambridge, November 6, 2003.
5. Orr, F.M., Jr.: "Energy and Global Change: CO_2 Sequestration in the Earth's Crust and Deep Ocean," Chemical Engineering Department, University of Utah, November 18, 2003.
6. Colmenares, L. and Zoback, M. D., CO_2 Sequestration and ECBM in the Powder River Basin: *Eos. Trans. AGU, 84*(46), Fall Meet. Suppl., Abstract GC32A-02, 2003.
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