Highlights of the 2009 SEG Summer Research Workshop on "CO_2 Sequestration Geophysics"

David Lumley (U. W. Australia), Don Sherlock (Chevron), Tom Daley (LBNL), Lianjie Huang (LANL), Don Lawton (U. Calgary), Ron Masters (Shell), Michel Verliac (Schlumberger), Don White (Geol. Survey Canada)

Introduction

The 2009 SEG Summer Research Workshop on "CO_2 Sequestration Geophysics" was held August 23-27, 2009 in Banff, Canada. The event was attended by over 100 scientists from around the world, which proved to be a remarkably successful turnout in the midst of the current global financial crisis and severe corporate travel restrictions. Attendees included SEG President Larry Lines (U. Calgary), and CSEG President John Downton (CGG Veritas), who joined SRW Chairman David Lumley (UWA) in giving the opening welcome remarks at the Sunday Icebreaker. The workshop was organized by an expert technical committee (see side bar) representing a good mix of industry, academic, and government research organizations. The format consisted of four days of technical sessions with over 60 talks and posters, plus an optional pre-workshop field trip to the Columbia Ice Fields to view firsthand the effects of global warming on the Athabasca glacier (Figures 1-2). Group technical discussion was encouraged by requiring each presenter to limit themselves to 15 minutes of presentation followed by a 15 minute open discussion period. Technical contributions focused on the current and future role of geophysics in CO_2 sequestration, highlighting new research and field-test results with regard to site selection and characterization, monitoring and surveillance, using a wide array of geophysical techniques. While there are too many excellent contributions to mention all individually here, in this paper we summarize some of the key workshop highlights in order to propagate new developments to the SEG community at large.

The Big Picture

Roel Snieder (CSM) opened the workshop with a thought-provoking presentation on the societal challenges we are facing to implement carbon capture and storage. By various estimates, we need to sequester about 4 Gton/yr of CO_2 (carbon dioxide) in order to make any significant impact on reducing CO_2 emissions, which is equivalent to 15% of current global CO_2 production. This amount is also equal to the total mass of oil produced worldwide per year! Further, the cost to sequester 4 Gt/yr of CO_2 is estimated to be in excess of $200 Billion USD/yr. Currently, the largest commercial CO_2 storage projects sequester about 1 Mt/yr, and Chevron's Gorgon project in Australia plans to sequester 3-4 Mt/yr, so the number of commercial CO_2 sequestration projects would need to be increased by a factor of 1,000 or more to achieve the 4Gt/yr goal. Hence much remains to be done to implement a full-scale CO_2 storage infrastructure. Snieder further stated that annual CO_2 emissions in the USA could be reduced 40% by energy conservation and efficiency implementations, at a fraction of the cost of CO_2 geo-sequestration. This raises the question of whether we are focused on the best CO_2 mitigation solution, and of how to reduce the cost of CCS (carbon capture and storage)? David Lumley discussed the fact that governments and policy makers around the world are introducing various methods to reduce CO_2 emissions in the form of carbon fines, taxes, or cap and trade systems. For many industrial applications, the CO_2 generated cannot easily be reduced by energy conservation or efficiency measures (for example LNG – liquid natural gas – processing plants). This is causing a scramble within industrialized nations to map out their largest CO_2 point sources and characterize their available basins in terms of suitable sites for CO_2 storage. As an example, Australia has recently become the first nation to lease offshore acreage for the sole purpose of exploring for potential CO_2 storage reservoirs. Larry Myer (LBNL) emphasized that geophysics will play a key role in site selection and characterization of CO_2 storage reservoirs, and also in the monitoring and verification of CO_2 over time as it is injected into deep geologic formations, especially to quantify and reduce the risk of possible CO_2 leakage.

Site selection and characterization

Ron Masters (Shell) and Don Lawton (U. Calgary) kicked off this session with the interesting comment that "upstream is the new downstream", meaning that CO_2 produced by upstream processes is leading us back to the downstream by injection of CO_2 into the subsurface. Most of the formations being considered for CO_2 storage are either depleted hydrocarbon reservoirs or deep saline aquifers, with the latter containing orders of magnitude more space available for CO_2 sequestration. Stefan Bachu (Alberta Research Council) presented a detailed methodology to rank candidate reservoirs for CO_2 storage. Sequestration sites will be selected based upon their storage capacity (structural volume, porosity…), their injectivity (permeability, pressure…), and their sealing capacity (structural and stratigraphic traps, caprock and fault seal, capillary pressure , geochemistry…). Most of these criteria require geophysical methods to estimate the CO_2 storage parameters, thus there may be a surge of new geophysical activity associated with CO_2 site selection and characterization studies. Additionally, regulators are discussing the concept of "region of influence", in the sense that each CO_2 injection project will have an effect over some region of the subsurface, and geophysical techniques will be required to help define and monitor this region to ensure that a CO_2 project does not interfere with other subsurface users (petroleum, minerals, groundwater, natural gas storage, waste disposal…).

Rock and fluid physics

There were several excellent contributions on the rock and fluid physics of CO_2 saturation. Most CO_2 storage reservoirs will be at depths, pressures and temperatures that place the CO_2 in a supercritical fluid state. When pure CO_2 is supercritical, its physical and chemical properties can be highly variable and complex (eg., Figure 3 by Picotti et al., OGS Italy), and the addition of small impurities (like methane) make the CO_2 properties even more complicated. There is broad agreement that more lab studies and research are needed to understand the behavior of CO_2 in rocks at reservoir pressures and temperatures. One of the recurring issues was patchy saturation: the fact that the velocity change in a rock as a function of CO_2 saturation depends strongly on the spatial size of the CO_2 fluid "patches" compared to the wavelength of the geophysical measurement. Chisato Konishi (OYO) presented results from the Nagaoka CO_2 pilot test in Japan, showing clear evidence in repeated time-lapse logs that the velocity-saturation curve was more linear than the classic Gassmann curve, but not as linear as the so-called high-frequency patchy saturation curve (see paper by Lumley in this issue). Bill Harbert (U. Pittsburgh) showed core measurements and SEM (scanning electron microscope) images of lab-saturated cores that exhibited both the effects of patchy saturation and geochemical alteration. It is an open question whether patchy saturation measured in the lab at MHz frequencies, and in log data at 100 kHz, is a significant effect in surface seismic data at 100 Hz. The velocity-saturation relationship is important for designing monitoring experiments, interpreting field data results, and quantifying the amount of CO_2 present in the subsurface from geophysical images and inversions. The geochemical effects of CO_2 were another prominent theme; the fact that CO_2 can react with the rocks over short times scales, for example as CO_2 dissolves into water and forms carbonic acid that can dissolve calcite in the rock matrix or grain contact cement (see for example the paper by Vanorio and Mavko in this issue) .

There is strong evidence from seismic data and geochemical fluid sampling that the reactive nature of CO_2 is significant and has thus far been significantly underestimated. More research is needed to better understand the reactive nature of CO_2 in rocks as a function of mineralogy, pressure, temperature, water chemistry etc., and its responses in geophysical data.

Geophysical modeling

Numerous excellent papers were presented to show the state of the art in geophysical modeling of CO_2 injection. Examples were presented showing computational simulation of complex responses from CO_2 injection models, including simulation of seismic data (Aldridge, Sandia Natl. Lab; Lumley, UWA; Picotti, OGS Italy; et al.), EM and gravity data (Gasperikova, LBNL), flow simulation (Cavanagh, Permedia; Williams, BGS), and coupled flow -geomechanical modeling (Rutqvist, LBNL; Morris, LLNL; et al.). Figure 4 shows an example of poro-elastic FD seismograms differenced after simulated CO_2 injection (Aldridge & Bartel, Sandia Natl. Labs). Common concerns in simulation were related to the fact that we are not yet confident that we have the correct physical relationships in our models to accurately predict the effects of CO_2 in a rock at depth with our geophysical data. There was a healthy discussion about the relative merits and accuracy of CO_2 flow simulations using the conventional Darcy-flow approach (proportional to pressure gradient); reactive transport (including geochemical reactions) and the invasion-percolation method (dominated by capillary pressure). It seemed clear that more research is needed to calibrate our geophysical modeling results, and thereby assist with the goal to obtain more accurate interpretations of CO_2 geophysical images.

Geophysical monitoring

Seismic monitoring is proving to be a key technology for monitoring and verification of CO_2 storage. 4D seismic surveys are being used to monitor the location of CO_2 injection, volumetric extent of CO_2 migration, and detect possible leaks in CO_2 at faults and seals. Borehole seismic techniques, such as VSP (vertical seismic profiling) and passive microseismic, are being used to obtain high-resolution images of CO_2 near the wellbore, and to monitor fracturing and microseismicity ahead of the CO_2 front and along reactivating fault planes. There is a need for seismic acquisition techniques that are environmentally friendly, sparse, low-cost and can be repeated on a frequent basis to monitor CO_2. Fred Herkenhoff (Chevron) presented a paper by Cocker et al. (this issue) showing the extraordinary effort Chevron is undertaking to monitor CO_2 injection at the Gorgon project offshore NW Australia, on Barrow Island which is a Class A nature reserve and contains several species of flora and fauna found only on the island. Tom Daley (LBNL) showed recent results in borehole seismic imaging, including spectacularly clear images of CO_2 at the Frio test site in Texas, where they found the as-yet unexplained result that the 4D P-wave velocity anomaly is significantly stronger than predicted, with little or no accompanying S-wave anomaly in the reservoir (Figure 5). Lianjie Huang (LANL) and Jonathan Ajo-Franklin (LBNL) demonstrated techniques to optimize sparse acquisition designs for both subsurface and borehole seismic geometries to obtain the best images of CO_2 at minimal cost.

David Lumley discussed several practical issues related to using 4D seismic to monitor CO_2 (see this issue), including situations for which further research is needed to extract weak 4D signals in depleted-gas (eg. Otway) or hard-rock (eg. Weyburn) reservoirs, and to correctly image CO_2 layers when strong impedance contrasts caused by CO_2 injection into soft-rock reservoirs creates complex wavefields that lead to imaging artifacts (eg. Sleipner). Roman Pevzner and Milovan Urosevic (Curtin U.) demonstrated that they have obtained an unexpectedly strong 4D anomaly at the Otway Phase1 project in Australia where CO_2 is being injected into a depleted gas reservoir, and are currently working on modeling and interpretation analysis to explain the result. Peter Wills (Shell) presented an interesting concept to use time-lapse seismic refractions to undershoot a CO_2 injection zone, and we look forward to seeing the results of a field test.

There is a significant and growing activity in passive microseismic techniques to monitor CO_2 injection. Various presenters demonstrated that passive seismic arrays can be used to locate microseismic events generated by microfracturing along the CO_2 front, and along fault zones reactivated by CO_2 injection pressure. Jim Rutledge (LANL) showed an excellent example of a CO_2 EOR (enhanced oil recovery) project in which microseismic monitoring appears to both detect the front of the CO_2 plume, and show that a small local earthquake was natural and not induced by the CO_2 injection (Figure 6). Papers by Mike Kendall and James Verdon (U. Bristol) showed respectively that passive arrays deployed in multiple boreholes could be used to determine fault/fracture displacement motion and related stress magnitudes and orientations using earthquake "beach-ball" analysis, and compared the microseismic responses of water injection to CO_2 injection.

Seismic monitoring, whether from the surface or borehole, active or passive source, is giving new insights into the geomechanical effects of CO_2 injection. Compaction, dilation and stress-arching in and around the reservoir due to CO_2 injection can propagate along reactivated faults or up to the surface where it may be measured as ground deformation. Giacomo Falorni (TRE) and representatives from MacDonald Dettwiler (MDA) both showed impressive time-lapse inSAR satellite radar images (very low cost) at the In Salah CO_2 injection project in Algeria, where ground deformation of up to 5mm/yr was mapped to give insights about the relationship between faults and CO_2 in terms of flow permeability (Figure 7). Jonny Rutqvist (LBNL) and Joe Morris (LLNL) showed how they could build geomechanical models coupled to flow simulations, including fault geometries and shear-stress data from borehole breakouts, to match the asymmetric ground deformations observed in the inSAR images. Incorporating geomechanical models and flow simulation with geophysical data is an active area of research.

Erika Gasperikova (LBNL) discussed non-seismic geophysical methods for monitoring CO_2, especially EM and gravity. These techniques can be orders of magnitude less costly than seismic, but at much lower resolution. EM techniques can be extremely sensitive to the presence of CO_2 by orders of magnitude in comparison to seismic, since CO_2 is electrically resistive compared to salty brine water. Similarly, gravity techniques are linearly sensitive to the density contrast of CO_2 (Figure 8). Both EM and gravity techniques can be improved by placing sensors in boreholes to get closer to the reservoir signal, current noise thresholds for gravity have decreased to about 3 microGals. Dana Kiessling (Potsdam) showed that the electrical resistivity borehole and surface arrays at the Ketzin CO_2 project were clearly able to detect small amounts of injected CO_2 (60,000 tonnes at 640m depth) that seismic apparently could not detect. Since seismic cannot easily detect CO_2 saturations below a few percent, nor quantify the difference between medium and high CO_2 saturation levels, there is keen research interest in combining the high-resolution capability of seismic with the CO_2 sensitivity of EM and gravity techniques.

Interpretation and Inversion

Interpretation of CO_2 geophysical images can be complex. There were several presentations with alternative interpretations of the Sleipner 4D seismic data and this generated a lot of discussion. It was clear that after 10+ years we still don't fully understand the rock physics or the nature of the CO_2 distribution within what appears to be the relatively simple Utsira sand reservoir. David Lumley showed with 2D finite-difference full waveform elastic modeling and PSDM (prestack depth migration) that one or two layers of CO_2 generates an image with multiple artifacts that looks remarkably similar to the Sleipner 4D seismic images currently being interpreted as up to 11 layers of CO_2. Gareth Williams (BGS) showed that by using flow modeling, they could not match the rapid advance of CO_2 to the north observed at Sleipner using the so-called "CO_2 chimney" model, and that the velocity decrease in the Utsira reservoir is two times stronger than expected for the amount of CO_2 that has been injected. Bob Benson (CSM) showed several land data examples of CO_2 EOR projects, and that interpretations of both P-wave and S-wave data could be complicated by combined effects of CO_2 saturation and pressure changes, and can vary from reservoir to reservoir. Benson showed a surprising example of CO_2 flowing downward (against buoyancy) below the presumed water contact into a wet zone, which was later drilled and verified in fact to be hydrocarbon bearing. Don White (GSC) presented qualitative 4D seismic images of CO_2 distribution at the Weyburn project (Figure 9), and stated that further research was needed to quantify the images in terms of CO_2 saturation with respect to enhanced imaging, rock physics, pressure effects, and geochemical reactive effects. Jason McCrank (Shell) showed that CO_2 injection in coal is even more complicated than clastic or carbonate reservoirs, and comparatively less is understood about the complex nature of CO_2 in coals as it interacts and reacts with coal fractures and cleats, releasing methane and causing time-varying changes in porosity and permeability. Papers presented by Abe Ramirez (LLNL) and Menno Dillen for C. Ravaut (SINTEF) showed recent developments in inversion. Ramirez demonstrated the use of a Bayesian Monte Carlo Markov Chain stochastic inversion to simultaneously invert joint geophysical data sets and thereby reduce the uncertainty inherent in inverting a single data set. Dillen gave a progress report on 2D full-waveform acoustic inversion of the Sleipner 4D seismic data, and stated that they are encountering challenges inverting the data which underscored earlier observations that the Sleipner images of CO_2 are more complex than perceived.

Risk Assessment

Risk can be defined as the probability of an event occurring, multiplied by the consequence of that event. The top two risks that the public often associates with CO_2 sequestration are: 1) that CO_2 will leak to the surface causing damage or loss of life; and 2) that CO_2 injection will trigger an earthquake large enough to cause damage or loss of life. Clearly geophysics has a key role in assessing the public's most important perceived risks. Jerry Coggins (Shell) presented a methodology to quantify the risks of a CO_2 sequestration project, particularly with respect to containment and leakage, and stressed the need to compare the risk of CO_2 sequestration to the risk of other projects, and the risk of not doing anything. Lumley reported a result from the Hedberg CO_2 conference that society tends to judge an acceptable risk as being about 1 in 10,000, which is approximately the same risk as being involved in a fatal car accident, and that by analog analysis from statistical data from CO_2 EOR and natural gas storage projects, the risk of catastrophic failure or loss of life in a CO_2 sequestration project is much lower than this acceptable risk level. Curt Oldenberg (LBNL) spoke about the concept of leakage and the implications to risk assessment within a workflow they have developed. CO_2 migrating out of the primary reservoir it is injected into should not necessarily be considered as leakage if the CO_2 does not migrate far enough to threaten other resources such as potable water or present a risk to safety. A subsurface volume that is larger than the primary reservoir should be defined as the storage region and only migration of CO_2 outside of this larger region should be termed as leakage.

Conclusions

Geophysical reservoir monitoring and verification for CO_2 sequestration has a number of unique challenges that do not apply to hydrocarbon reservoir surveillance. This is in part due to the particular physical and chemical properties of CO_2 in its supercritical phase, but is also driven by the very different demands and value drivers that apply. The properties of CO_2 vary widely under different pressure and temperature conditions, and the range of different geological environments that are targets for sequestration (saline aquifers, depleted fields, EOR, coal…). In addition, a number of different trapping mechanisms co-exist (mobile, residual, dissolved and mineralized) and the relative amount of CO_2 trapped by each mechanism, and its geochemical reactive nature with the rock, changes over time, making the interpretation of time-lapse geophysical data very complex.

Requirements for CO_2 monitoring are also unique. Safe storage must be demonstrated for the long term (thousands of years) and detecting very small amounts of leakage is vital, as is quantifying the amount of CO_2 present from geophysical data, thus a high level of sensitivity is required. Value drivers are related to satisfying regulators, demonstrating permanent containment so that governments can accept long term liability and accounting for carbon credits. Unlike the case for oil and gas production, there is no direct economic benefit to improving a CO_2 surveillance program. This is motivating a drive towards lower cost complementary alternatives to 4D seismic, such as gravity, EM and satellite radar. These methods can also be employed to sample the temporal gaps between expensive repeated 3D seismic surveys in order to provide more frequent data for early warning of unpredicted CO_2 flow or potential for leakage.

There is also a desire for improved sensitivity and quantitative analysis of geophysical data to meet potential regulatory requirements for carbon accounting, which are still in the early stages of development. This is resulting in a push to integrate multiple geophysical methods that complement seismic, particularly in terms of improving estimates of CO_2 saturation in the ground. Seismic monitoring primarily measures changes in saturated rock compressibility, and therefore cannot easily quantify changes in CO_2 saturation larger than about 30% (adding a little CO_2 makes the rock as compressible as adding a lot of CO_2). However, EM and gravity methods have a more sensitive response to changes in CO_2 saturation. With constraints on the plume location provided by seismic, joint inversion of these complementary geophysical datasets can potentially yield more accurate measures of injected CO_2 volume and mass.

Acknowledgments

Many thanks go to Ms. Amy Watson (SEG) for her immense help in organizing the workshop logistics, and to Schlumberger, IKON, Nexen, PennWest, PGS and PTRC for their generous donations to help sponsor workshop activities. We would like to acknowledge our colleague Partha Routh (ExxonMobil) for his contributions to the workshop and this summary. TD would like to acknowledge partial funding from from the U.S. Department of Energy (DOE) under Contract No. DE-AC02-05CH11231.

Suggestions for Further Reading

1. R. Snieder and T. Young, 2009, *Facing major challenges in carbon capture and sequestration*, GSA Today, in press.
2. Lumley, D., Adams, D., Wright, R., Markus, D., and Cole, S., 2008, *Seismic monitoring of* CO_2 *geo-sequestration: realistic capabilities and limitations*, SEG Expanded Abstracts, **27**, no. 1, 2841-2845.
3. Daley, T., Myer, L., Peterson, J., Majer, E., and Hoversten, M., 2008, *Time-lapse crosswell seismic and VSP monitoring of injected* CO_2 *in a brine aquifer,* Environ. Geol., **54**, 1657-1665.
4. Rutledge, J., Zhou, R., Huang, L. and McPherson, B., 2008, *Microseismic monitoring of* CO_2 *injection in the Aneth oil field, San Juan County, Utah*, Expanded Abstracts, AGU Fall Meeting.
5. Raikes, S., Mathieson, A., Roberts, D., and Ringrose, P., 2008, *Integration of 3D seismic with satellite imagery at In Salah* CO_2 *sequestration project, Algeria*, SEG Expanded Abstracts, no.1, 2856-2858.
6. Gasperikova, E., and Hoversten, M., 2008, *Gravity monitoring of* CO_2 *movement during sequestration: Model Studies*: Geophysics, **73**, WA105-WA112.
7. White, D., 2009, *Monitoring* CO_2 *storage during EOR at the Weyburn-Midale field*, The Leading Edge, **28**, no.7, 838-842.

SIDE BAR: 2009 SEG Summer Research Workshop Organizing Committee:
David Lumley, SRW Chairman (U. Western Australia); Tom Daley (Lawrence Berkeley Natl. Lab); Kevin Dodds (BP); Ola Eiken (StatoilHydro); Lianjie Huang (Los Alamos Natl. Lab); Don Lawton (U. Calgary); Ron Masters (Shell); Tom Ridsdill-Smith (Woodside); Partha Routh (ExxonMobil); Don Sherlock (Chevron); Michel Verliac (Schlumberger); Don White (Geol. Survey Canada);

Figure 1: Our SRW group of risk-tolerant CO_2 geophysicists standing on the ice of Athabasca Glacier, Alberta, Canada. Note Chris Juhlin (Uppsala) trying to hedge his bet on which side of the crevasse is safer (photo courtesy of David Lumley).

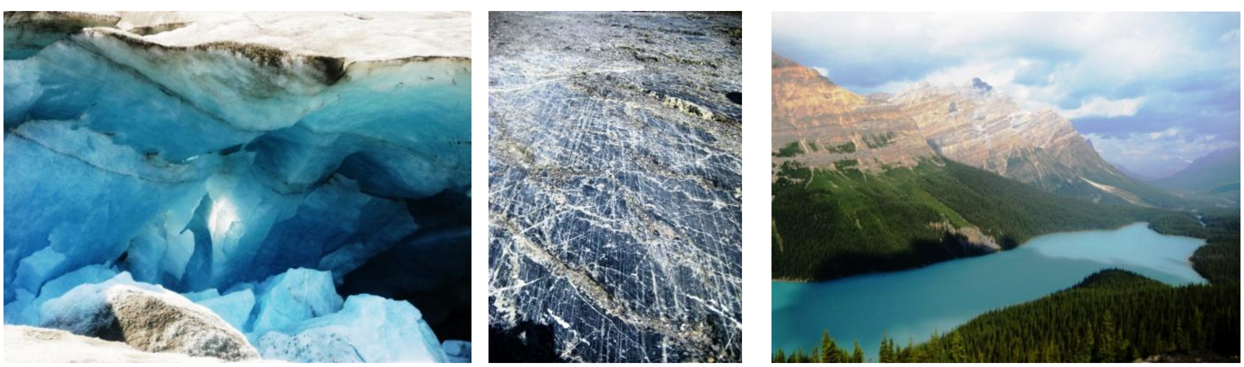


Figure 2: (a) pristine blue glacier ice illuminated by a shaft of sunlight focused through a crevasse; (b) 10,000 year-old glacial striations etched upon basement rock exposed at the receding toe of the glacier; (c) Peyto Lake exhibiting the spectacular turquoise water of the region created by super-fine “rock flour” ground up by glacier movement and suspended in glacier meltwater (photos courtesy of David Lumley).

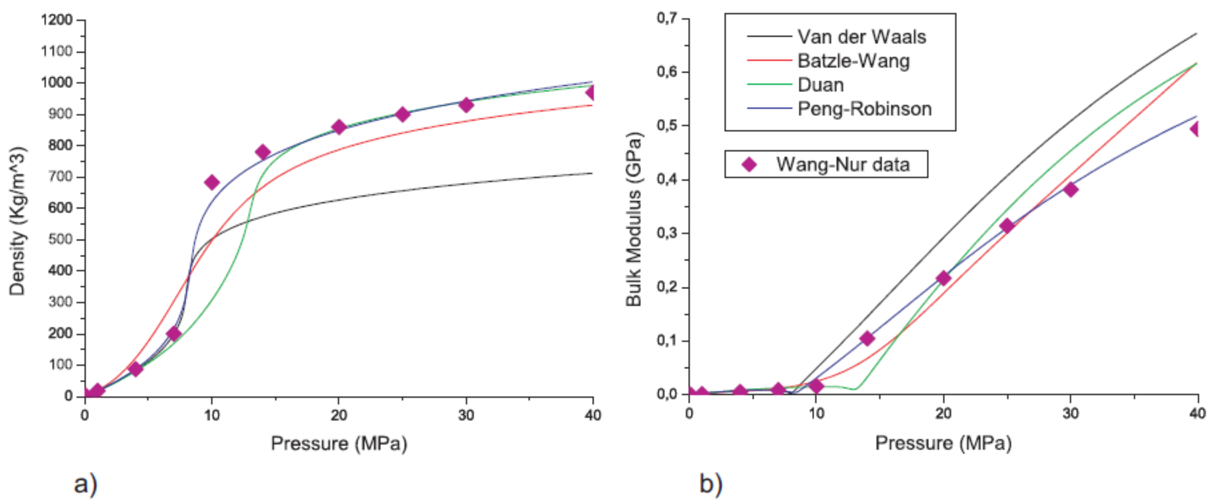


Figure 3: Density (a) and bulk modulus (b) of CO_2 versus pressure for a temperature of 37^{o}C calculated with different Equations of State (EoS). The experimental data of Wang and Nur (1989) shows that the Peng-Robinson EoS provides the most accurate modeling curves (Picotti et al., OGS Trieste, Italy).

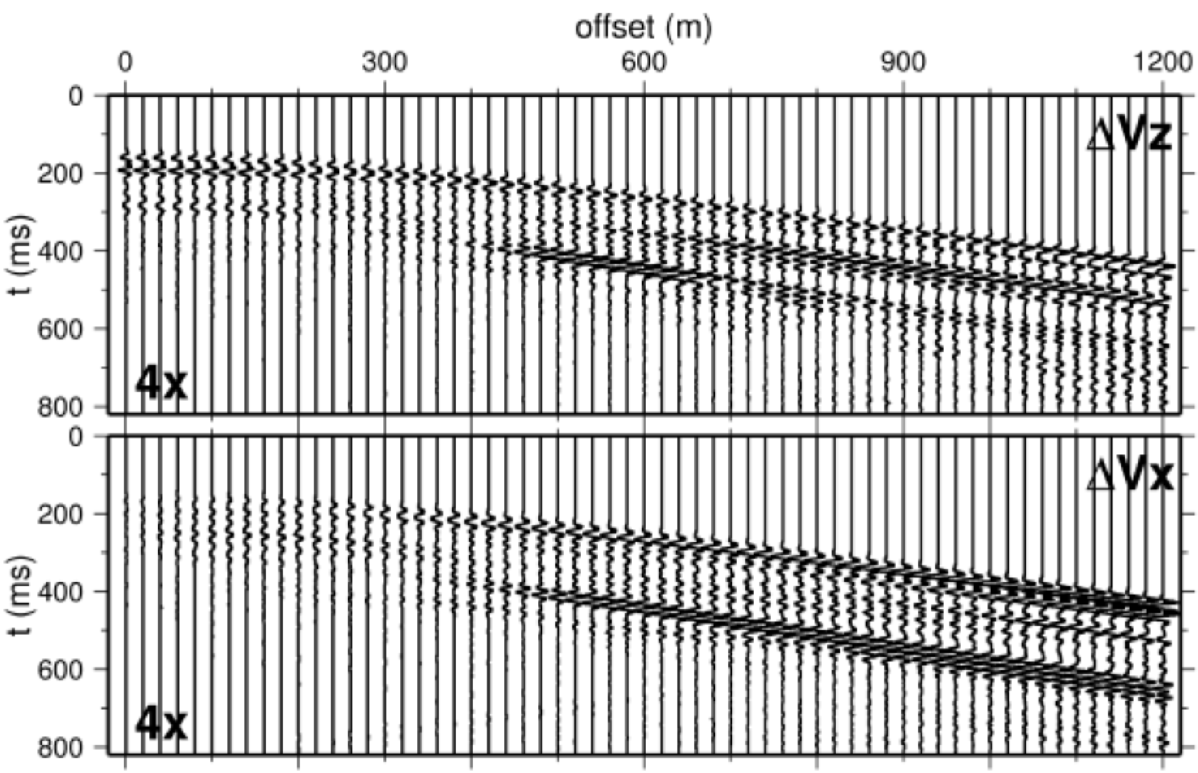


Figure 4: Difference AVO responses, obtained by subtracting traces calculated for 25% CO_2 saturation from those for 100% water saturation in a porous sandstone layer (Aldridge & Bartel, Sandia Natl. Labs).

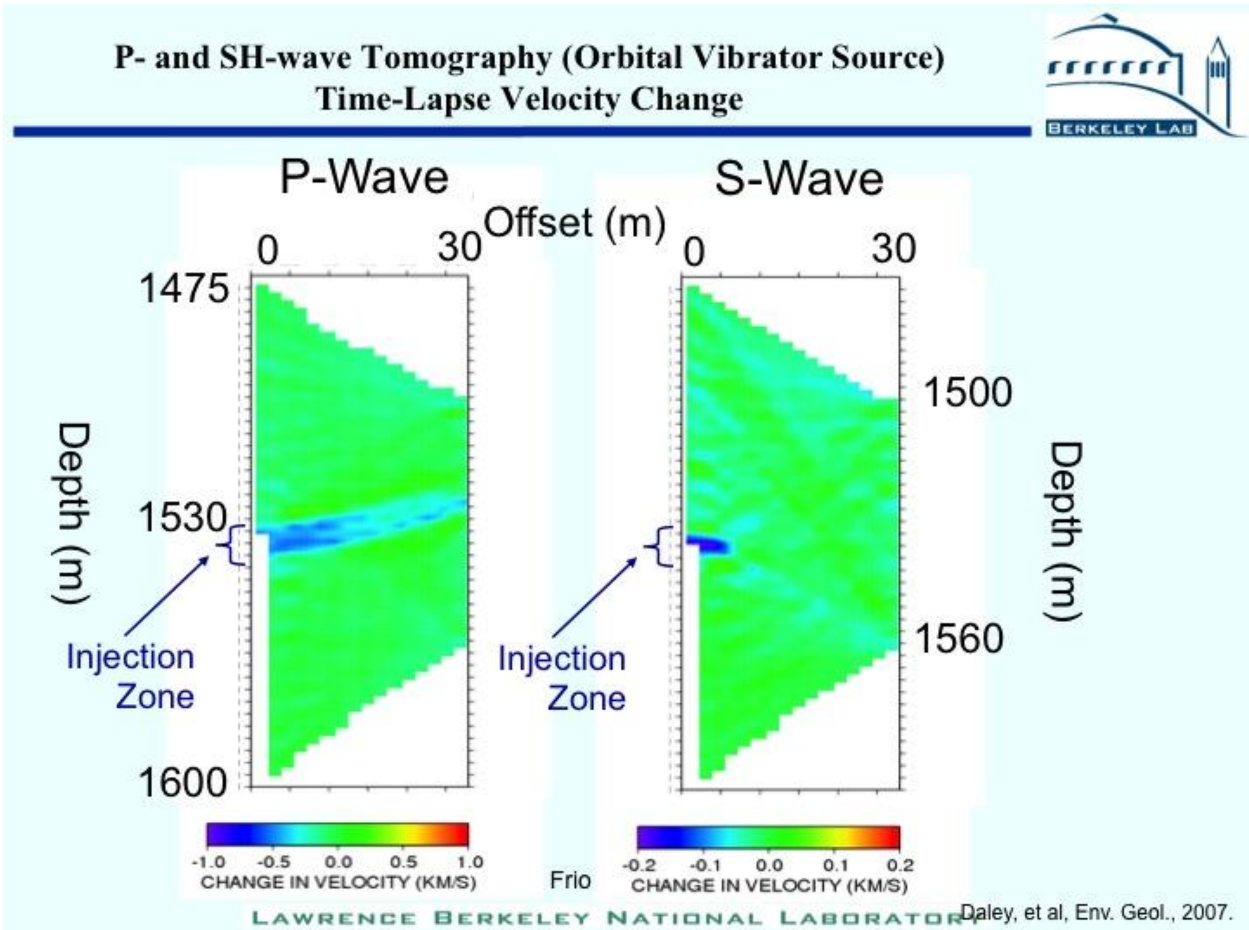
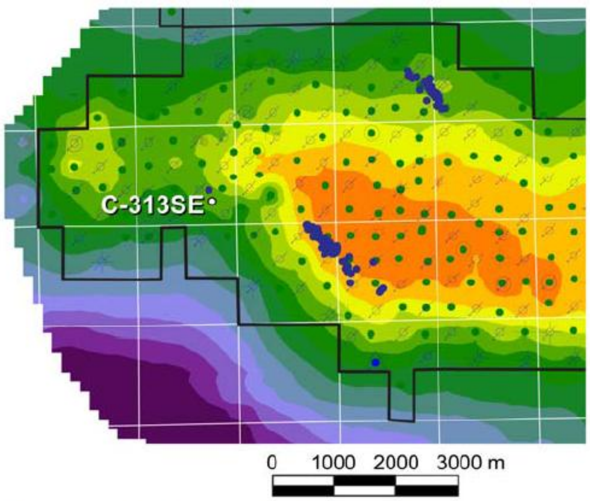
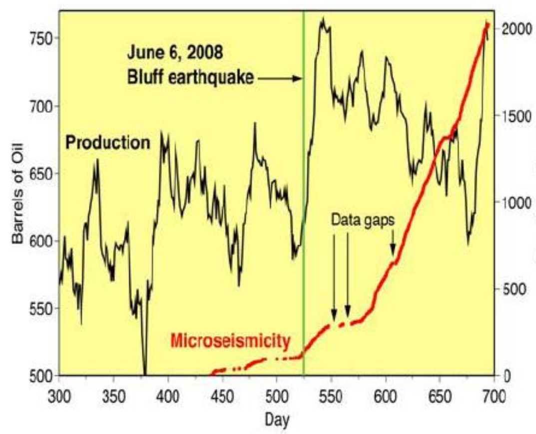


Figure 5: Crosswell seismic tomography results at the Frio CO_2 injection test site showing time-lapse Vp anomaly (left) and Vs anomaly (right). Note that the Vp anomaly shows clear indication of presence of injected CO_2, however the anomaly magnitude is much stronger than the rock physics models predict. In contrast, the Vs anomaly is concentrated locally at the injection point, but shows no change within the reservoir (Daley et al., Env. Geol., 2007).



Microseismic epicenters (blue circles) superposed on structure at top of the reservoir.



Correlation of increased oil production and reservoir seismicity following local earthquake.

Figure 6: (a) structural contour map of the Aneth reservoir (Utah) showing microseismic event locations (blue dots) recorded in a passive seismic array for this CO_2 EOR project. Southern cluster interpreted to be related to stress-induced fracturing ahead of CO_2 front, northern cluster interpreted as stress-induced fault reactivation or stress arching in the overburden. (b) graph of oil production and microseismicity versus time showing both increased substantially following a regional M3.7 earthquake 15km west of the reservoir, suggesting it affected the stress regime in the reservoir. In general, a passive microseismic array may be useful to show that an earthquake is, or is not, related to CO_2 injection and thereby provide an early warning system (and insurance) against possible fault reactivation and fault-seal leakage (courtesy Jim Rutledge et al., Los Alamos Natl. Lab).

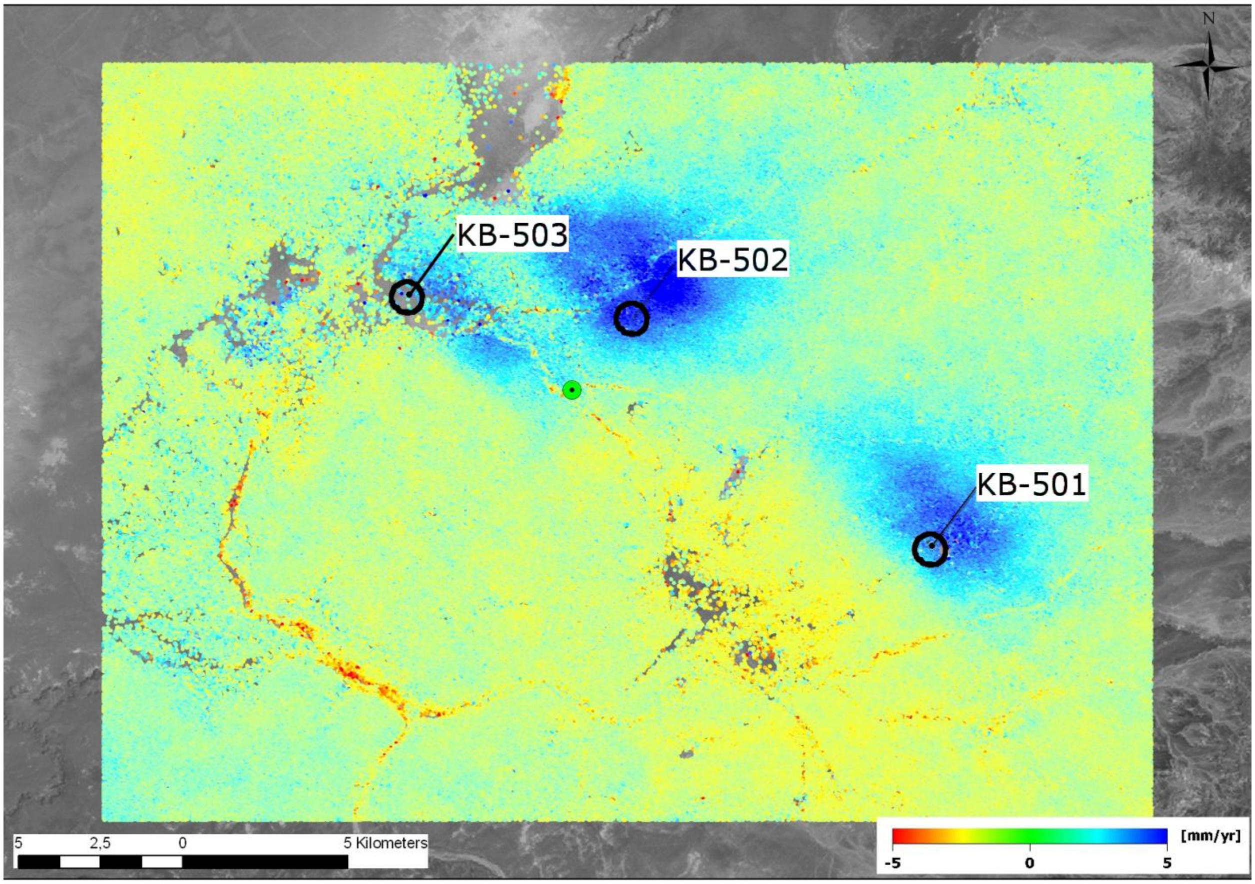


Figure 7: Time-lapse inSAR satellite radar image at the In Salah CO_2 sequestration project, Algeria. The blue anomalies correspond to as much as 5 mm/yr uplift in surface ground deformation caused by CO_2 injection at about 1.9 km depth (courtesy BP, StatoilHydro, Sonatrach and TRE Canada).

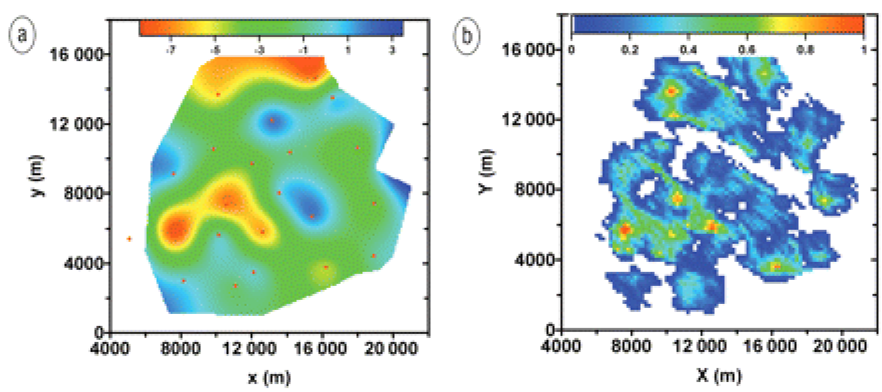


Figure 8: (a) simulated gravity anomaly corresponding to (b) CO_2 saturation flow simulation (Gasperikova and Hoversten, 2008).

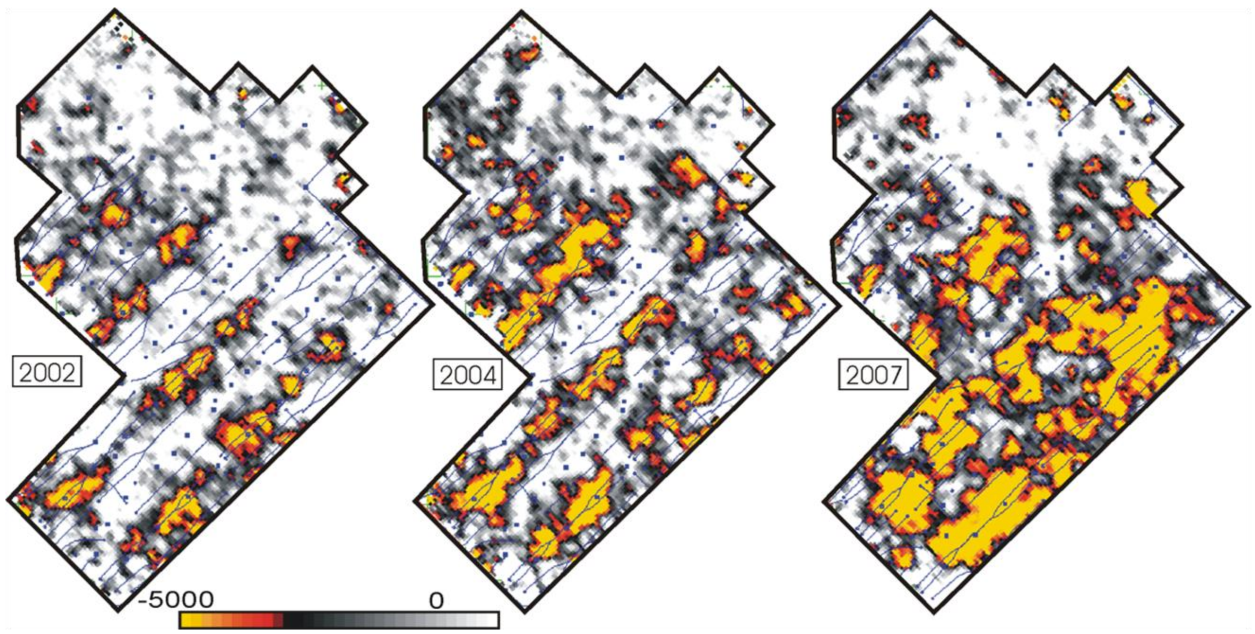


Figure 9: Qualitative 4D seismic map-view images of CO_2 saturation at the Weyburn CO_2 EOR injection project in Canada (White, 2009).