**Monitoring of Hydrocarbon and Carbon-sequestrated Formations**
**Using Time-lapse Seismic and Electromagnetic Data**

**Advisors**
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**Summary:** We propose to carry out a feasibility study to combine seismic and electromagnetic imaging techniques to the time-lapse monitoring of carbon sequestrated formations and hydrocarbon reservoirs. Seismic and electromagnetic data complement each other and together, they could provide a powerful geophysical monitoring tool. This research work is interdisciplinary involving expertise from the departments of Geology and Geophysics and Chemical and Petroleum Engineering. To our knowledge, use of seismic and electromagnetic data for time-lapse monitoring has not yet been attempted. In the future, we could approach the US Department of Energy with the results of this feasibility study with a proposal for combined seismic and electromagnetic processing. This will put the School of Energy Resources in the forefront of carbon sequestration monitoring research.

**Proposed Research:** Use of time lapse seismic data has proven to be an effective tool for the monitoring of existing hydrocarbon reservoirs. Differences in seismic attributes such as reflection amplitudes, extracted P-and S-wave velocities and densities between different seismic surveys at different times of production can be shown to be related to the production history of the reservoir. These temporal variations have been effectively used in constraining the porosity, permeability, and water saturation in reservoir flow simulation models. This permits improved resolution of the reservoir's dynamical flow state that is difficult to achieve using production data alone.

To characterize global warming induced by greenhouse gas increases, there are now substantial research efforts on the injection (sequestration) of carbon dioxide ($CO_2$) into depleted hydrocarbon reservoirs and aquifers. Such carbon sequestration requires constant (c.a., weekly to monthly) temporal monitoring of the sequestrated formations to ensure that the $CO_2$ is in place and does not disturb the integrity of surrounding rock formations. It is believed that the use of time lapse seismic data is potentially one of the most effective tools for monitoring of such carbon sequestrated formations.

Although the use of time-lapse seismic imaging has been effective in a variety of reservoir characterization experiments over the past decade, many issues remain unanswered. Time-lapse seismic analysis consists of acquiring spatially coincident three dimensional (3-D) seismic data volumes at different times. Temporal variations between these individual 3-D seismic gathers can be correlated with fluid movements, temperature and pressure changes or reservoir deformation. It is assumed that nothing but the reservoir properties have changed over time and the differences in different seismic properties extracted from these data sets can be directly related to the fluid movements in the reservoir caused by production and/or injection.

Seismic data acquisition is however not repeatable due to environmental (e.g., water table changes) and source-coupling variations (e.g., different Vibroseis units). Consequently the data acquired over the same area at different times are never the same. To effectively apply time-lapse analysis, it is therefore necessary to apply cross-equalization filters to these data sets so that all temporal seismic response variations are mapped into the volume representing the reservoir. These cross-equalization filters generally vary in time and space and affect the relative amplitudes of the seismic data. To accurately correlate seismic attributes with respect to reservoir production history, there is a growing interest to extract acoustic properties, such as P- and S-wave velocity and density. But, extraction of these properties can be in serious error if the relative amplitude content is not maintained during processing. This problem is even more serious for carbon sequestration experiments where the primary objective is to inject $CO_2$ at different concentrations into subsurface formations and use time-lapse methods to monitor the movement of the injected $CO_2$ in the liquid $CO_2$/water/salt multi-phase system. Such monitoring requires the use of seismic waveform inversion methodologies to extract acoustic properties and calibrate these extracted properties with respect to $CO_2$ concentration and its topological disposition (e.g., super-critical $CO_2$ snap-off).

Figure 1 is a real well-log data with brine saturated sand between 14,000-14,175 feet (black curves). This brine formation is replaced by a mixture of 80% brine-20% $CO_2$ (cyan curves) and 20% brine-80% $CO_2$ (red curves). As expected, the density is extremely sensitive to the $CO_2$ concentration. The P-wave velocity shows a drastic drop as the brine is replaced by 20% $CO_2$ by volume, but the P-wave velocity is relatively insensitive as the $CO_2$ content is increased from 20% to 80%. Noteworthy is that the S-wave velocity is relatively insensitive to changes in $CO_2$ concentration. Given these predicted material property variations, the formation density will dominantly control the temporal seismic variations for carbon sequestrated formations. Constraining temporal density variations will require amplitude-variation-with-offset (AVO) or waveform based inversion methods. These full-inverse methods demand that the relative seismic amplitude variations are preserved via accurate cross-equalization prior to inversion.

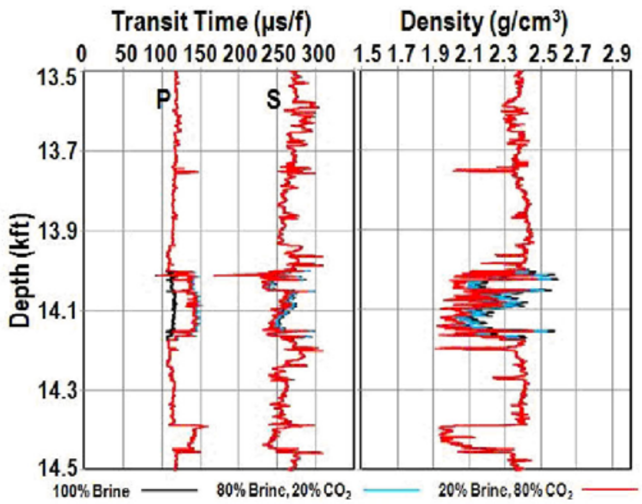


**Figure 1 (to right):** Real well-log data with brine-saturated sand at 14,000-14,175 ft. replaced by 20% and 80% $CO_2$.

While extracting acoustic properties and relating them to the formation fluids is effective at shallow depths, this methodology loses sensitivity at deeper depths due to higher pressures. Consequently, usage of a complementary geophysical method in addition to seismic is useful. Recently, there has been a considerable development in electro-magnetic (EM) methodologies. Surface EM tools penetrating up to a depth of 2500-3000 m at frequencies of 50-60 Hz are now available (e.g., http://www.emtek.as). EM methods provide the measurement of subsurface electrical resistivity. As hydrocarbons are more resistive than brine, a time-lapse EM and seismic imaging/inversion will be valuable to monitoring hydrocarbon reservoirs. In its pure state, super-critical $CO_2$ is more resistive than brine. However, as the $CO_2$ is diffused into the brine solution, Carbonic acid will be formed making the fluid more conductive. EM monitoring of carbon sequestrated formations will therefore exhibit an initial increase in the formation resistivity and then a gradual decrease as $CO_2$ is dissolved into brine. This behavior in formation resistivity will be insensitive to the formation depth and therefore the conjunction of lapse EM and seismic would be a powerful tool for carbon sequestration monitoring.

Our primary goal of this proposal is to validate the feasibility of joint EM and seismic imaging using synthetic data generated from real well-logs. An outline of the proposed research is as follows.

(1) Identify two well-logs: one with known hydrocarbon reservoir sand (Well-1) and the other with known brine sand (Well-2). A full suite of logs, including P- and S-wave sonic, density, neutron porosity, gamma-ray, and resistivity/induction logs is required.
(2) Compute a suite of new logs from Well-1 by replacing the hydrocarbon formation with different concentrations of brine.
(3) Compute a suite of new logs from Well-2 by replacing the brine formation with different concentrations of $CO_2$.

(4) Model fluid substitution to evaluate effects of fluid trapping and multiphase flow hysteresis.
(5) Compute synthetic seismic and EM data with surface source and receivers from all well logs from steps 1-4 above.
(6) Perform full waveform inversion of synthetic seismic data computed in step 5. These waveform inversions will extract acoustic properties from each data set. These extracted acoustic properties are compared with the original models to validate the effectiveness of waveform inversion for reservoir and carbon-sequestration monitoring.
(7) Analyze the EM data from step 5 and verify if it is capable of measuring the changes in the formation fluid properties. Start working on the development of an EM inversion methodology.

Tools for computing synthetic seismic and EM data and inverting seismic data using a full waveform based method are in-hand. Dr. Pradip Mukhopadhayay who has recently joined the department of Geology and Geophysics as post-doctoral associate to work on the UW DOE sequestration project comes from EM background. He has independently developed an EM modeling code that will be the key to our EM modeling and inversion research. The Department of Chemical and Petroleum Engineering will provide expertise in the evolution of the complex multi-phase system (e.g., de-salting, water evaporation, and $CO_2$ 'snap-off') as described in steps 2, 3 and 4. The impact of this proposed research will be broad. A joint application of seismic and EM for time-lapse monitoring has never been attempted. We are in communication with an EM service company to negotiate an EM survey at the carbon sequestration site at Moxa-Arch where time-lapse seismic data will also be available. Subsequently, we can approach the US Department of Energy with the results of this feasibility study with a proposal for joint seismic and EM studies for carbon sequestration. This will certainly put the School of Energy Resources in the forefront of carbon sequestration monitoring research with a unique technology.

**SER GA student description, current funding and professor's advising history**

We request two SER GA assistantships to support two PhD students over the next two years. One graduate student will work on seismic modeling and inversion while the other will work on the EM modeling and inversion. One PhD student will be hired for Fall 2009. The other student is Mr. Hansen who is a third year PhD student of Dr. Dueker. Mr. Hansen has one paper in a major peer-reviewed journal in press and another in preparation and has proven to be a capable student who can program seismic wave propagation algorithms. Currently, Dr. Mallick is using his UW DOE funds to support a new post-doctoral employee Dr. Pradip Mukhopadhyay and has no available funds to support Mr. Hansen. While Dr. Dueker does have NSF funds for the next two years, the burn rate of three PhD is creating balance sheet stress. Hence, we propose that the combination of a SER GA assistantship package and Dr. Dueker's NSF grants be used to support Mr. Hansen on this project over the next two years.

Dr. Dueker currently advises three PhD candidates who are in their 2-3 year of study. These PhD's are supported on two National Science Foundation grants that are large mutli-discipline projects to seismically image sub-surface seismic velocity variations beneath British Columbia and Colorado. Dr. Dueker has graduated two PhD's and three Master's students since his hiring in the fall of 2000.

Dr. Mallick has recently moved to UW from the oil and gas industry and is seeking to hire 1-2 graduate students for Fall 2009. Approval from the SER to support one of these new graduate students to work on the EM modeling and inversion would be greatly appreciated.

Dr. Alvarado currently advises 3 PhD's and 1 Masters at the University of Wyoming, supported by the Enhanced-Oil Recovery (EOR) Institute and startup commitments, working in several aspects of EOR. Dr. Alvarado has graduated two PhD's and two Masters at PUC-Rio, Brazil, and currently co-advises two PhD's. Petrobras and CNPq (the Brazilian National Science Foundation) have awarded financial support since 2004. He has also collaborated with time-lapse seismic feasibility studies.