8th Biennial International Conference
& Exposition on Petroleum Geophysics

"HYDERABAD 2010"

P-387

Geophysical Monitoring Carbon Sequestrated Brine Aquifers - A Feasibility Study

Subhashis Mallick* and Pradip Kumar Mukhopadhyay,
Department of Geology and Geophysics, University of Wyoming, Laramie, WY 82071
***Vladimir Alvarado**, Department of Chemical and Petroleum Engineering,*
University of Wyoming, Laramie, WY 82071

Summary

We perform a synthetic time-lapse case study to investigate the effectiveness of geophysical tools for time-lapse monitoring carbon sequestrated deep saline aquifers, using a real well log from the Moxa-Arch, western Wyoming where a carbon sequestration demonstration project in two aquifers is currently being considered. We compute synthetic seismograms for the original well model and for the model with brine in one of the aquifers being replaced by 50% CO_2*. Inverting the vertical component of the computed responses with a full waveform algorithm, we find that although the Poisson's ratio can be extracted accurately, density could only be extracted with confidence with a good prior knowledge of the background density and the inversions are heavily constrained to these background values. Fluid substitution with different CO2 saturations however, show that the formation Poisson's ratio drops drastically as the brine is replaced with as little as 20%* CO_2 *and stays nearly constant as CO2 saturation is increased further. Density, on the other hand shows a gradual drop with increasing concentration of* CO_2*, indicating that it is density not the Poisson's ratio that will play a major role for an effective monitoring of carbon sequestrated aquifers. Since inverting both vertical and radial components of the computed responses in a multicomponent waveform inversion methodology can accurately extract density, we conclude that converted wave seismic data will be useful for monitoring of carbon sequestrated aquifers. As converted wave data are sensitive to anisotropy, a multicomponent waveform inversion for anisotropic medium will correctly handle anisotropy in real data. Combining flow simulation models with seismic inversion will allow quantifying the effectiveness of inversion in predicting post-injection CO2 bubble movements inside the formation at different time intervals. Finally, with recent advances of electromagnetic (EM) data acquisition, processing, and inversion methodologies, it is important to study if EM could be effectively used in conjunction with seismic for monitoring of carbon sequestrated aquifers.*

Introduction

Considerable research efforts are underway to mitigate greenhouse gas emission by sequestrating (injecting) CO_2 into depleted hydrocarbon reservoirs and deep saline aquifers. Since the available pore volume in aquifers is larger than that in depleted hydrocarbon reservoirs and they are more abundant in nature (Juanes et al, 2006), sequestration into saline aquifers is important for a long term solution to the greenhouse gas emissions. Any sequestration study however requires regular monitoring of the storage formations to ensure that the supercritical fluid is in place and does not disturb the geological integrity of the surrounding rocks.

Using a fluid substitution, waveform modeling, and waveform inversion, we investigate in this paper if seismic or any other geophysical data could be used as an effective tool for time-lapse monitoring carbon sequestrated saline aquifers.

Outline of the methodology and results

For our analysis, we use a real well log data from the Moxa-Arch area, western Wyoming. Feasibility of CO_2 sequestration into two formations, Nugget sandstone and Madison Limestone in this area is currently being investigated. Average depth of the Nugget sandstone is about 13,000 feet (4000 meters) while that for the Madison limestone is approximately 17,000 feet (5200 meters).

We compute full waveform synthetic seismograms for the original well model (unsequestrated model) and for the model in which the brine in the Nugget formation is replaced by 50% CO_2 (sequestrated model). Figure 1 shows both models and computed vertical component synthetic seismic responses in incidence angle and time domain. To compute the angle domain synthetic responses of Figure 1, we first computed the responses in time and offset and then partially stacked the offset domain data over the angle mutes using the procedure outlined in Resnick (1983). Notice that replacing brine with CO_2 produces a small change in P-wave velocity (V_P), practically no change in S wave velocity (V_S) and a large drop in density. The changes in V_P and V_S also result in a considerable change in the Poisson's ratio as shown in Figure 1. These differences in acoustic properties show some subtle changes in the reflection amplitudes in the computed full waveform seismograms inside the red box in Figure 1. The primary challenge for effectiveness of seismic monitoring therefore lies in whether it is possible to reliably extract acoustic properties from these subtle differences in reflection amplitudes.

Figures 2 and 3 are the inversion results of the unsequestrated and sequestrated vertical component seismograms of Figure 1. The inversion methodology used is waveform based that accounted for all wave modes in the algorithm. Notice that the seismic inversion was able to extract the drops in the Poisson's ratio quite accurately. While the drop in the density due to CO_2 sequestration is captured well by the inversion, in general a visual comparison of the inverted and true models in Figures 2 and 3 indicate that the Poisson's ratio is more reliably extracted than the density.

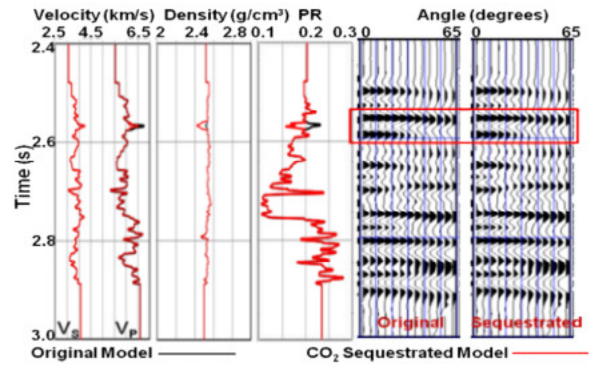

Figure 1: Real well-log data, shown in two-way P-wave time and computed full waveform synthetic seismograms. The original well-log data is in black. A brine saturated sand formation immediately above 2.6s is replaced with 50% brine and 50% $CO_2$and these CO_2-sequestrated welllog curves are in red. Notice that the red and the black curves are identical except at the sand formation where brine is replaced by CO_2.

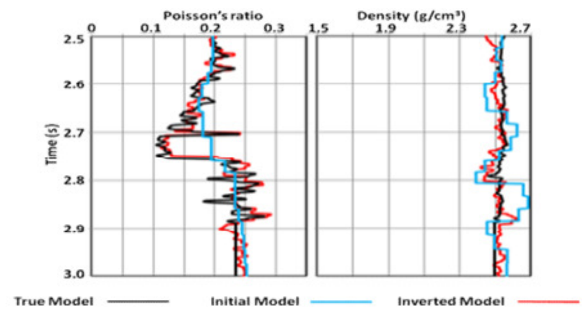

Figure 2: Inversion result of the unsequestrated synthetic seismograms of Figure 1. The inverted Poisson's ratio and density are shown and compared with the true model. The initial model, shown in cyan is obtained from the P-wave stacking velocity and average VP-VS and VP -density relations.

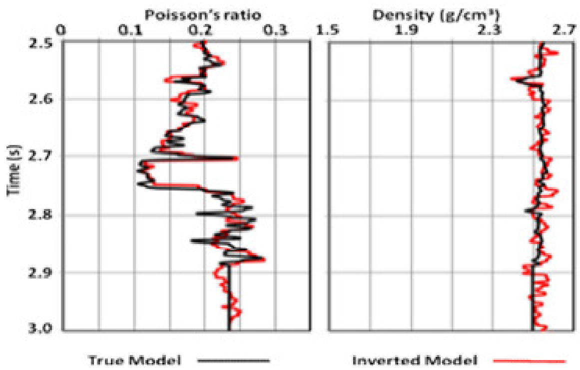

Figure 3: Inversion result of the CO_2-sequestrated synthetic seismogram of Figure 1. The initial model used for this inversion is the final inverted model (red curves) of Figure 2.

Discussion

Inversion of the vertical component of the response, shown in Figures 2 and 3 demonstrate that it is Poisson's ratio not density that is accurately extracted from these inversions. In an ideal carbon sequestration experiment, it is expected that CO_2 at different saturations will be sequestrated into a given formation at different times and the available geophysical method be able to successfully monitor the movement of the injected CO_2 in the formation at different time intervals. Given the fact that the inversion of vertical component seismic data can accurately estimate the change in formation Poisson's ratio than the formation density, is Poisson's ratio the sufficient property for carbon sequestration studies?

Figure 4 is a section of the same well-log data of Figure 1 where the brine-saturated Nugget sandstone is replaced by 20, 50, and 80 percent CO_2. Notice that the Poisson's ratio drops drastically when the brine is replaced by as little as 20% CO_2 and stays nearly constant as the CO_2 concentration is increased further. Formation density on the other hand shows a gradual decrease as the CO_2 concentration is increased from 20-80%. Given these predicted material property variations, the formation density will dominantly control the temporal seismic variations for carbon sequestrated formations. Seismic inversion results shown in Figures 2 and 3 on the other hand demonstrate that it is the Poisson's ratio, not the density that can be accurately extracted from the vertical component seismic data. Reflection amplitudes on vertical component seismic data are dominantly controlled by primary (P-P) reflections. It is well known that the P-P reflections are relatively less sensitive to the variations of density than the mode converted (P-S) reflections and it has been shown in an earlier study (Mallick, 2000) that inverting both vertical and radial components of reflection seismic data in a multicomponent waveform inversion scheme can extract density more reliably than inverting the vertical component data alone. As noted previously, the differences between the vertical component synthetic seismic responses for sequestrated and unsequestrated models in Figure 1 are subtle. Figure 5 is the offset domain radial component of the response for same models. The responses shown in Figure 5 are not corrected for normal moveout, nor are they compensated for the geometrical spreading loss. However, the long offset reflection amplitudes from the sequestrated formation in these two seismograms are noticeably different, and this is the key feature that allows an accurate extraction density when the vertical component of the response is inverted in conjunction with the radial component in a multicomponent inversion scheme. If density is the key player for the monitoring of the carbon sequestrated aquifers, it may therefore be necessary to acquire time-lapse converted wave seismic data and jointly invert both vertical and radial components of the response using a multicomponent waveform inversion.

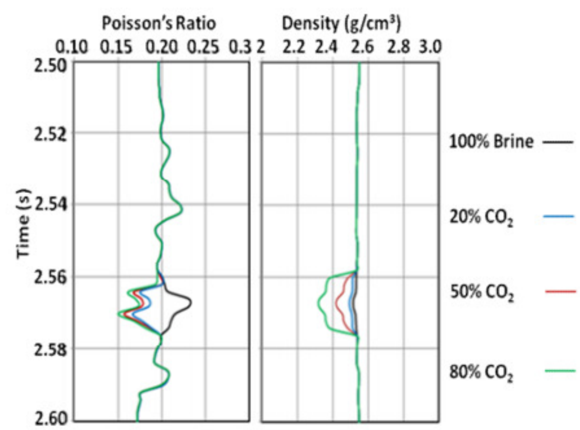

Figure 4: Poisson's ratio and density when the brine saturated sand is replaced by different concentrations of CO2.

Although multicomponent inversion can reliably extract formation density, a lot of issues need to be addressed before such an inversion could be implemented in practice for time-lapse monitoring of carbon sequestrated formations. Converted wave data are sensitive to anisotropy. In general, carbon sequestration is likely to take place in deep saline aquifers that are overlain by thick impermeable shales acting as natural seals for the injected CO_2. Most shales are anisotropic. In Moxa-Arch for example, both Madison limestone and Nugget sandstone are overlain by anisotropic shale layers. In addition, the Madison limestone itself is fractured and is likely to be anisotropic. Therefore, to successfully apply inversion to time-lapse seismic data, it is not only necessary to develop a multicomponent waveform inversion methodology but it is also necessary that such an inversion can handle anisotropy.

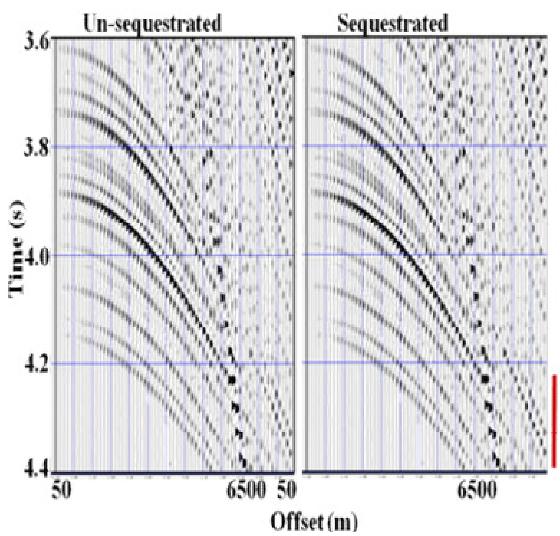

Figure 5: Radial component of the synthetic seismic response of the unsequestrated and sequestrated models of Figure 1. These synthetic responses are in offset domain and without any NMO or geometrical spreading correction. The red line indicates the long-offset reflection from the layer that has been sequestrated with CO_2. Notice that there are visible differences between the long-offset reflection amplitudes in the unsequestrated and sequestrated seismograms.

Inversion for anisotropic medium has been previously addressed by Sen and Mukherjee (2000), Ferguson and Sen (2007), and Bansal and Sen (2007) among others. These methods invert prestack seismic data in intercept-time and ray-parameter (τ-p) domain. Mallick (2000) also demonstrated an application of multicomponent waveform inversion in τ-p domain for isotropic medium. Although τp domain inversion in an anisotropic medium has an advantage because of the fact that in the plane wave domain we do not have to worry about the phase and group velocities and angles, it however has a serious practical disadvantage. To avoid aliasing due to integral transforms and to achieve the desired resolution that is required for carbon sequestration studies, a τ-p inversion demands acquisition of multicomponent seismic data at a very fine spatial sampling. Acquisition of such a finely sampled seismic data on a regular basis at the sequestration sites could be prohibitively expensive. Angle-domain prestack waveform inversion, outlined by Mallick (1999) on the other hand does not demand such a fine spatial sampling and could therefore be a practical alternative to time-lapse monitoring of CO_2 sequestrated aquifers.

For multicomponent seismic waveform inversion, we therefore propose to restrict to angle domain rather than τ-p domain. Following the procedures given by Mallick (1999), we start with NMO-uncorrected prestack vertical and horizontal component seismic data. For every trial model in inversion, we then compute the P-P and P-S group angle gathers from the observed seismic data and match with the corresponding synthetic P-P and P-S group angle gathers and continue this matching until a desired level of convergence is achieved between the synthetic and observed data. Such a multicomponent waveform inversion for transversely isotropic medium with a vertical symmetry axis (VTI medium) is currently under development and testing, and the results from this inversion will be shown during the presentation.

In addition to multicomponent inversion, it is also important to develop a good understanding of postinjection movement of CO_2 plumes inside the aquifer and investigate if seismic or any other geophysical data could be effectively used to monitor such movements. $CO_2$is a greenhouse gas and its leakage out of the sequestrated formation is undesirable for environmental and safety reasons. It is therefore important to gain as much information regarding the state of CO_2 inside the aquifer as possible from the geophysical monitoring tools. There are primarily four trapping mechanisms through which CO_2 is stored in a brine aquifer- (1) hydrodynamic trapping where the buoyant CO_2 remains as mobile fluid within the aquifer but is prevented from flowing back into the surface by an impermeable cap rock (seal), (2) solution trapping, where CO_2 is dissolved into brine as carbonic acid, (3) mineral trapping, where CO_2 geochemically reacts with the rock minerals, and (4) residual trapping where the trailing part of the injected CO_2 plume is disconnected through capillary action and is trapped as an immobile fraction by a process known as CO_2 snap-off. Recent studies by Juanes et al. (2006) show that the residual and hydrodynamic trapping are most important in the time scale of our interest while solution and mineral trapping mechanisms are relatively slow processes. Running simulation models, Juanes et al. (2006) also show that the residual and hydrodynamic trappings are equally important for geological sequestration in brine aquifers. From the existing well and seismic data, we can generate three-dimensional (3-D) aquifer models of reservoir flow (porosity, permeability) and seismic (V_P, V_S, density) properties. We can then sequestrate CO_2 from one well into this 3-D model and run flow simulation to study the evolution of post-injection evolution of CO_2 plumes at different time periods. Using actual core samples, it is also possible to run saturation experiments using the capillary pressure apparatus and a coreflooding system to measure relative permeabilities in drainage and imbibition, derive the relative permeability and capillary pressure hysteresis for the aquifers and include them into the simulation models. This will allow modeling the residual trapping mechanism into the simulations and predict realistic distribution of CO_2 within the aquifer as a function of time. Seismic models from different time intervals from such a simulation can then be obtained and 3-D finite difference synthetic seismograms using such models could be inverted to calibrate the observed seismic response to CO_2 plume evolution.

Even though time-lapse seismic data and seismic inversion are by far the most effective geophysical monitoring tools, it is still worthwhile to investigate the possibility of using a supplementary monitoring method. With recent advances in the acquisition, processing and inversion, EM is rapidly emerging as a valuable tool for hydrocarbon exploration. Conventional dipole source EM however has a relatively low penetration depth. Circular electric dipole source (CED), introduced by Mogilatov (1992) and Mogilatov and Balashov (1996) on the other hand is reported to have a maximum penetration depth of about 2500-3000 meters. EM is therefore still far from being considered as alternative to seismic for carbon sequestrations where to ensure that the sequestrated CO_2 does not contaminate the fresh groundwater that could potentially be used for drinking; the depths of receiving formations are always going to be in excess of 3000 meters. It is however still worthwhile to develop EM modeling algorithms with CED and possibly with other source parameterizations and investigate if EM can achieve a deeper depth of penetration and it could potentially be used as a supplementary tool for future monitoring of carbon sequestrated aquifers.

Conclusions

Multicomponent seismic data is an effective tool for monitoring carbon sequestrated aquifers. To gain enough information on the post-injection movement of the CO_2 plumes inside the aquifer at different time intervals, it is necessary to integrate reservoir simulation models with seismic inversion. Although EM methodologies at present cannot be used for monitoring carbon sequestration monitoring, it is worthwhile to carry out modeling studies to see if EM could be effectively used as a complimentary future monitoring tool.

Acknowledgements

This research is funded by the US Department of Energy Grant DE-NT0004730.

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