A cost-effective monitoring strategy for carbon-sequestrated deep saline aquifers

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Abstract

Substantial research efforts are now underway on injecting (sequestrating) carbon dioxide (CO_2) into deep saline aquifers. These sequestration efforts require remote monitoring using available geophysical tools to ensure that the sequestrated CO_2 is in place and does not disturb the geological integrity of the surrounding rocks. Since seismic method is the only accepted geophysical tool that can potentially image detailed subsurface information, here we develop a monitoring strategy using seismic data alone. Fluid substitution at different concentrations of CO_2 in a brine filled aquifer and comparing its elastic properties with the original indicate that the formation density will play the key role in successful monitoring of carbon-sequestrated aquifers. As multicomponent seismic data are more sensitive to subsurface density variations than vertical (P-wave) component data, we believe that multicomponent seismic data are necessary for obtaining an accurate subsurface pre-sequestration model. As multicomponent data are more expensive than conventional (P-wave) data, acquiring multicomponent data both for baseline and for successive monitoring surveys is not cost-effective. Since above-normal pore pressure due to sequestration is likely to fracture the overlying formations, we investigate if microseismic events generated from these fractures could be utilized for monitoring. Inducing microseismic events with different fault-plane source mechanisms and computing passive seismic responses from them, we find that these computed responses are sensitive to the fracture fault plane geometry, and passive seismic data could be a potential monitoring tool. We conclude that if multicomponent seismic data could be acquired prior to sequestration as a baseline survey and inverted for an accurate pre-sequestration elastic earth model, we can then use passive seismic data for subsequent monitoring. This strategy, in turn, may provide a cost-effective way to monitor carbon sequestrated deep saline aquifers.

Introduction

To mitigate greenhouse gas emissions, significant ongoing research focuses on sequestrating CO_2 into deep saline aquifers and depleted hydrocarbon reservoirs. The available storage volume in aquifers is significantly larger than the combined pore space in oil and gas reservoirs. In addition, subsurface aquifers are geographically more widespread than depleted hydrocarbon reservoirs. Finally, current research indicates that the sequestrated CO_2 into a brine saturated aquifer could provide permanent storage for large volumes of this greenhouse gas underground (Juanes et al, 2006; van der Meer and Wees, 2006). Consequently, sequestration into saline aquifers offers compelling advantages over its alternative in depleted hydrocarbon reservoirs.

Carbon sequestration is however not complete unless the sequestrated formations are remotely monitored to ensure that the injected gas is in place and does not disturb the geological integrity of surrounding formations. Above-normal pore pressure caused by the injected CO_2 may fracture surrounding rocks, which, in turn, could serve as potential conduits for leakage. It is important to detect these rock failure events so that adequate measures can be taken to mitigate such leakage risk conditions.

To avoid migration of the sequestrated CO_2 into fresh groundwater, all future sequestration projects will take place in saline aquifers existing at depths in excess of 12,000 -13,000 feet (3700-4000 meters). CO_2, injected to such depths will be in supercritical phase (Juanes et al, 2006) and monitoring such supercritical carbon-sequestrated aquifers is a challenge. Out of different geophysical tools, seismic is effectively one of the methods applicable to those or even greater depths. It must be noted that the injection of the supercritical phase involves complex drainage and imbibition (or rewetting) cycles leading to significant changes in saturation distributions within the aquifer formations. We argue that to improve the interpretation of seismic monitoring techniques, dynamic, multiphase flow simulations of supercritical CO_2 injection into aquifers must be consistently combined with inversion methods that incorporate the correct representation of the seismic response as a function of the saturation distribution. In turn, the correct input of two-phase flow functions, capillary pressure and relative permeabilities to dynamic simulators requires the evaluation of saturation history on adequate rock analogs in laboratory experiments. The post-injection scenario is represented by imbibition processes impacted by buoyancy-driven flows in addition to capillary-pressure gradient driven water flow (Suekane et al., 2009). These imbibition processes may give rise to a patchy saturation distribution (Shi et al., 2007, Carcione et al., 2006) of the injected fluid, likely controlled by trapping mechanisms such as snap-off. To accurately predict such post-injection patchy saturation from seismic data, it is necessary to combine a state-of-the-art seismic inversion methodology with dynamic multiphase flow simulation models. Here, we concentrate solely on the monitoring strategy using a state-of-the-art waveform inversion of multicomponent seismic data. Combining such inversion with dynamic multiphase flow simulation models is currently under investigation and will be discussed in a subsequent paper.

Changes in elastic properties due to CO_2 sequestration

Figure 1 is a portion of a real well-log data, shown in two-way P-wave travel-time from the Moxa-Arch region of Western Wyoming, USA where real sequestration experiments into some representative aquifer formations are currently under investigation. The Poisson's ratio, computed from the P- and S-wave sonic, and density are shown in Figure 1. One of the representative aquifers, known as the Nugget sandstone occurring between 2.56 and 2.58s in Figure 1, is sequestrated with different concentrations of CO_2 and the fluid substituted properties are shown and compared with the original properties in Figure 1. Notice that the Poisson's ratio drops drastically when as little as 20 percent CO_2 is injected into the formation and stays nearly constant as the saturation is increased further. The formation density on the other hand shows a gradual drop as a function of CO_2 saturation. Our fluid substitution experiments on a variety of aquifers in this region (not shown) indicate that CO_2 sequestration produces a very little change in the P- and S-wave velocities (V_P and V_S). Although these slight changes in V_P and V_S produces a large drop in Poisson's ratio at relatively shallow depths, with increasing depths this drop is also not very large. The density however shows a gradual drop as a function of CO_2 saturation irrespective of the depth.

Given the changes in elastic properties shown in Figure 1 and discussed as above, it appears that it the density not the V_P or V_S (or Poisson's ratio, which in fact is a function of V_P and V_S) that is likely to play the key role for monitoring of carbon-sequestrated aquifers. In our investigations on the applicability of using seismic data for monitoring, we must therefore concentrate on the accuracy estimating density from observed seismic data.

Inversion of synthetic seismic data

Figure 2 is the complete well log in depth, a portion of which in two-way time was shown previously in Figure 1. We replaced an aquifer formation between 5100-5200m with 50% CO_2. The original well data are in black while the fluid substituted data are shown in red. As expected, the fluid substitution resulted in a large drop in density, but a slight change in V_P and V_S. Figures 3 and 4 are the synthetic seismograms computed respectively for the original (un-sequestrated) and sequestrated models of Figure 2. Both vertical and horizontal (radial) components of the computed synthetic seismic responses are shown in these Figures. These synthetic seismograms are full wavefield responses for a horizontally stratified medium computed using a reflectivity modeling algorithm (Kennett, 1983).

To investigate the potential of seismic data in estimating subsurface properties so that they could be used for monitoring carbon sequestrated formations, we first invert the vertical component of the computed responses using a full waveform P-wave inversion methodology (Mallick, 1999). For these inversions, we first velocity analyze the original (un-sequestrated) vertical component synthetic data to obtain

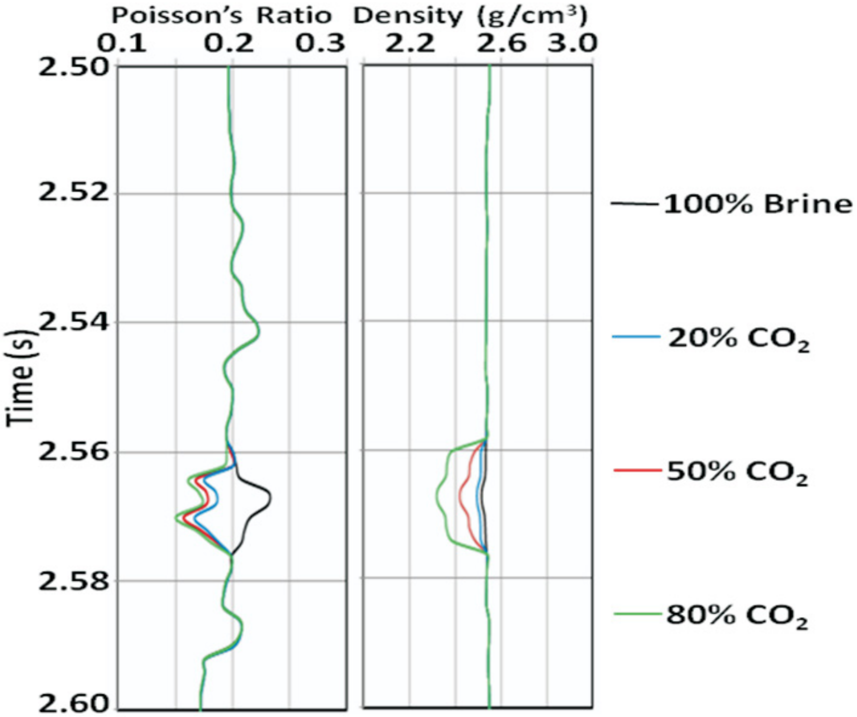

Fig. 1 Poisson's ratio and density when the brine saturated Nugget sandstone formation between 2.56 and 2.58s is replaced with different concentrations of CO_2.

the initial P-wave velocity model. We then extract the overall V_P-V_S and V_P-density relations from the well data and use these relations to estimate initial V_S and density models from the initial V_P model extracted from the velocity analysis. We then use this initial model of V_P, V_S, and density to invert the un-sequestrated vertical component synthetic seismic data. Finally, we use the inverted model from the un-sequestrated synthetic data as the initial model for inverting the sequestrated vertical component synthetics. Figures 5 and 6 are the results from these inversions.

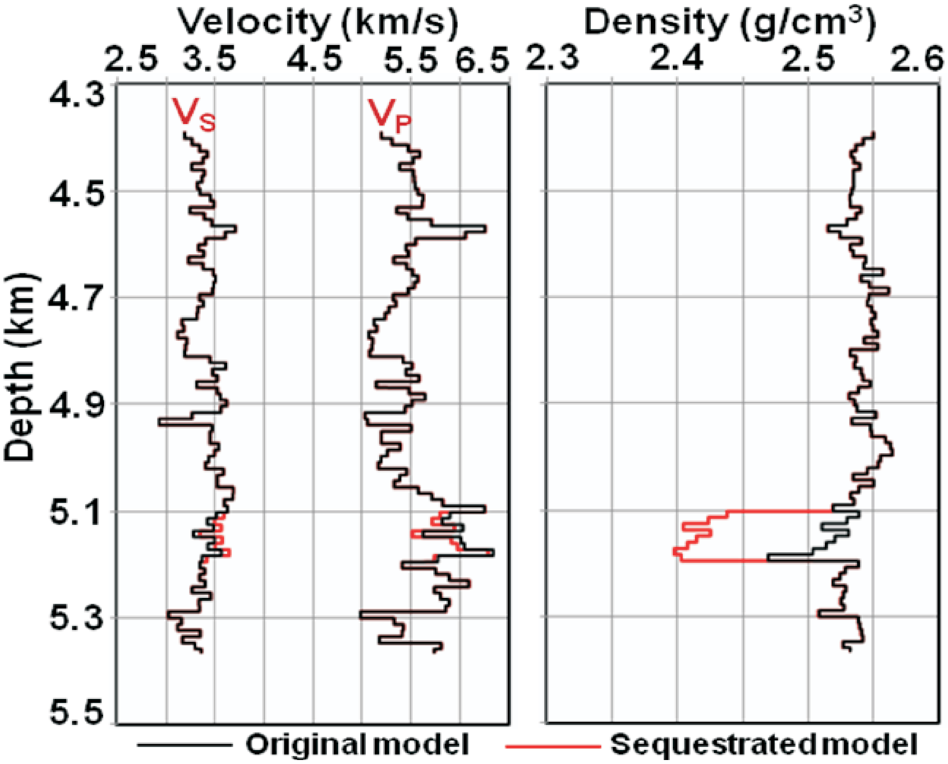

Fig. 2 Well-log data from the Moxa-Arch. A saline aquifer formation between 5100-5200m is sequestrated with 50% CO_2. The original logs are in black while the CO_2 sequestrated logs are in red.

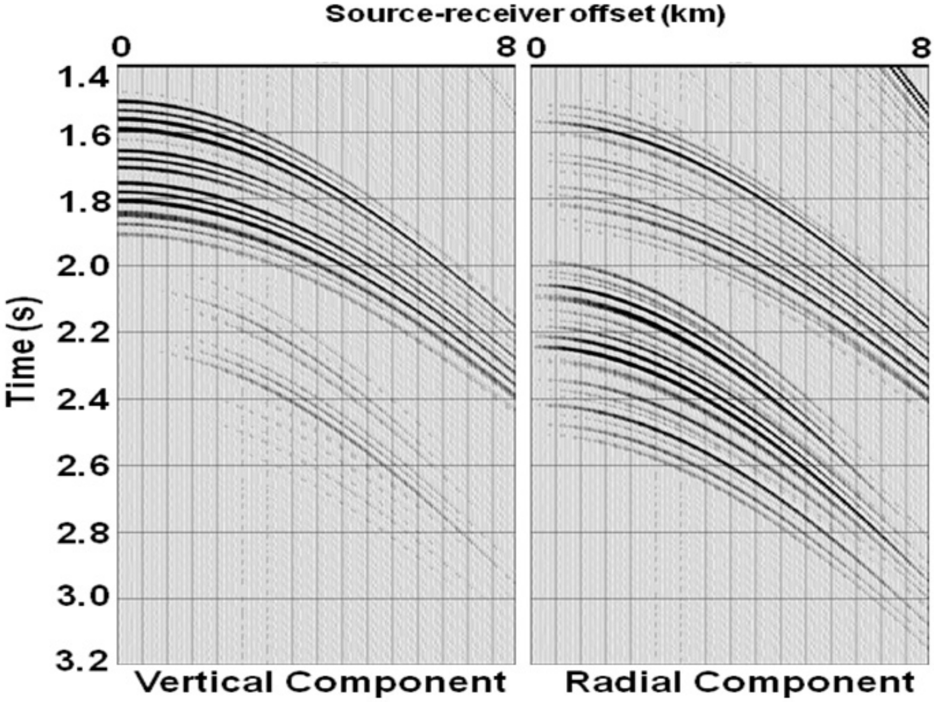

Fig. 3 Vertical and horizontal (radial) components of response for the original (un-sequestrated) model of Figure 2.

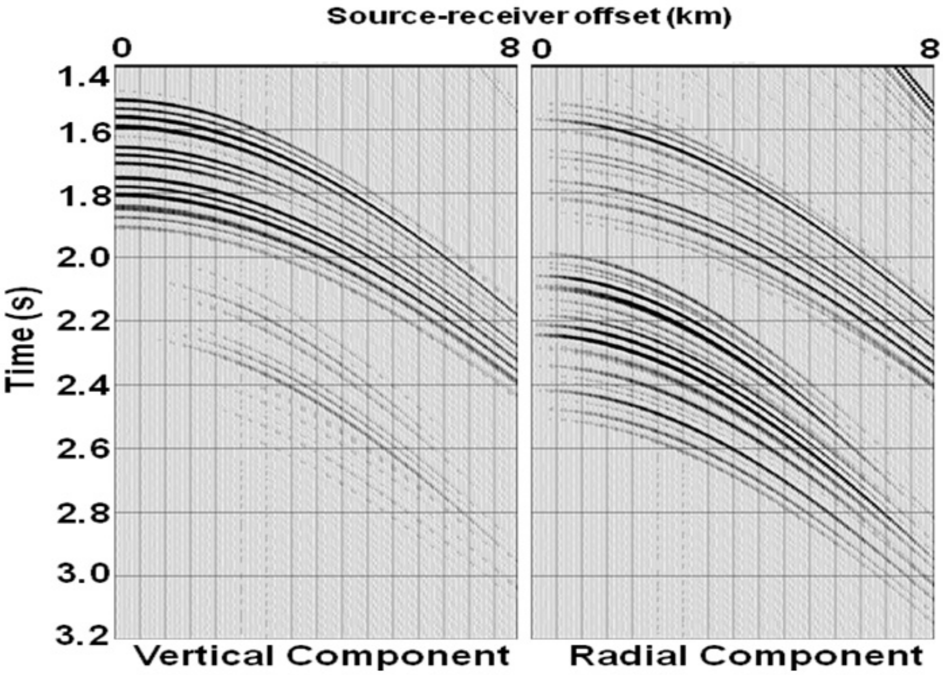

Fig. 4 Vertical and horizontal (radial) components of response for the sequestrated model of Figure 2.

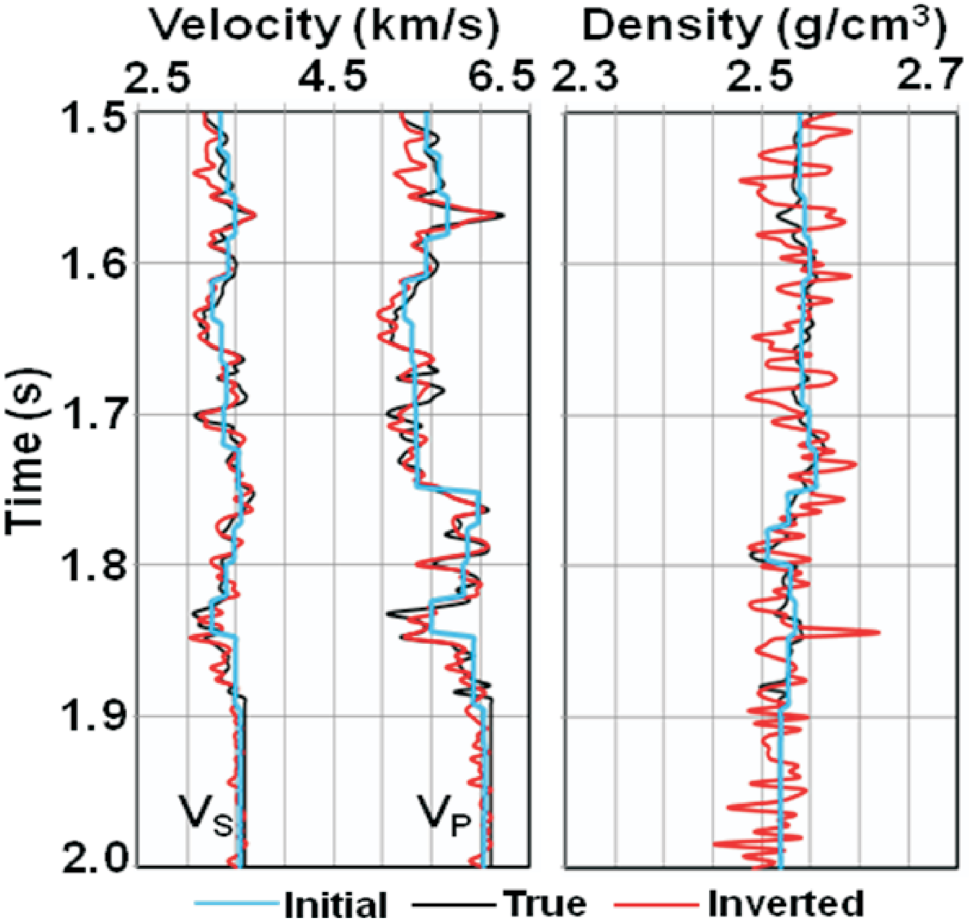

Fig. 5 P-wave (vertical component) waveform inversion result of the un-sequestrated synthetics of Figure 3.

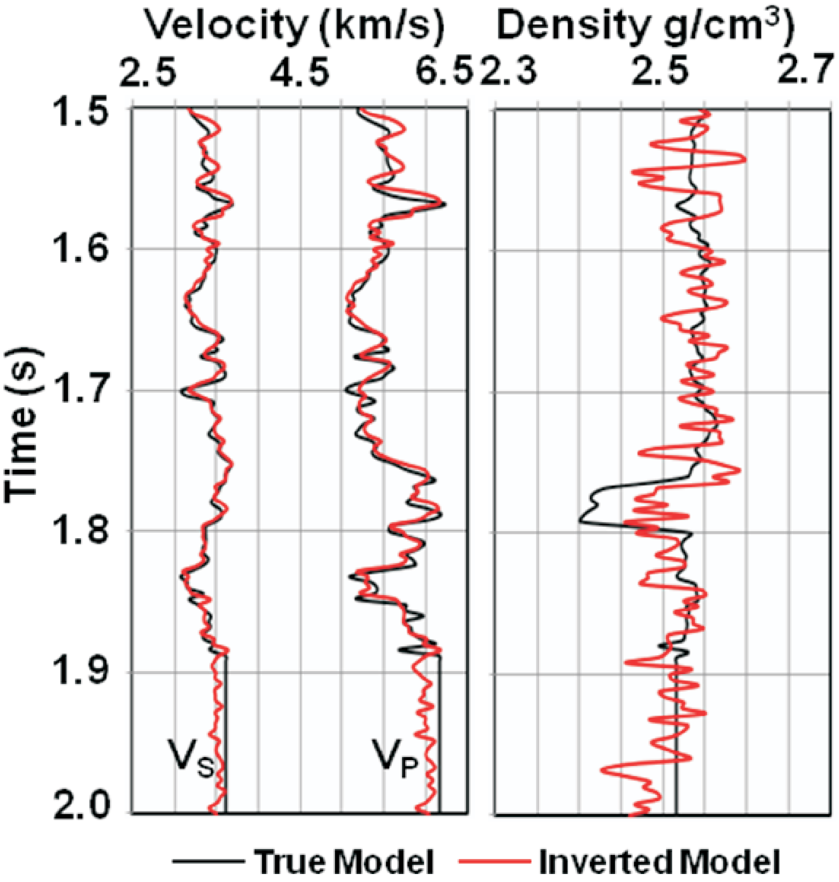

Fig. 6 P-wave (vertical component) waveform inversion result of the sequestrated synthetics of Figure 4. The initial model used for this inversion was the inverted model (red curves) of Figure 5.

Figures 5 and 6 clearly demonstrate that while V_P and V_S estimates from inversion are quite good, the density estimates are rather poor. We could, in fact constrain the density heavily to the initial models and get a good density estimate as it is typically done for a 3-term amplitude-variation-with-offset (AVO) inversions (for details, see Mallick 2007). However, our primary objective here is to look for a robust methodology for estimating density from seismic data so that it could be effectively used in carbon sequestration monitoring. Considering the volume of CO_2 that must be captured and sequestrated to fight global warming, many future sequestration experiments are likely occur is areas where 3-D seismic data will be available, but well control may be sparse. Obtaining a good initial density model and constraining density heavily is not therefore feasible in most of these situations.

Inversion results of Figures 5 and 6 are for the vertical component of seismic response. Vertical component responses are dominated by primary (P-wave) reflections. Notice that in the vertical component responses in Figures 3 and 4 the primary reflections (between 1.5 and 1.9s zero offset time) are strong while the mode-converted reflections (between 2.0 and 2.5s zero offset time) are rather weak. Since P-wave reflections are not very sensitive to density, it is not surprising that these inversions do not give a very reliable density estimate.

Instead of the vertical components, if we draw our attention to the radial components in Figures 3 and 4, notice that they show strong mode-converted reflections. In addition, the P-wave reflections are also strong in the radial components with increasing offsets. Mode-converted reflection coefficients are sensitive to density. This follows directly from the Bortfeld approximations to reflection coefficients (Bortfeld, 1961; Aki and Richards, 1980). Using both vertical and radial components in a multicomponent waveform inversion should therefore give a better estimate of density compared to what could be obtained from vertical component inversion results of Figures 5 and 6.

We developed a multicomponent waveform inversion methodology in which both vertical and radial components of the responses are simultaneously inverted. The exact methodology used for this inversion will be discussed in a separate paper and here we only show the results in connection with the carbon sequestration study. For multicomponent inversion, we used exactly the same initial models that were used for the vertical component inversion. Figure 7 shows the density estimates from both un-sequestrated and sequestrated synthetics from multicomponent inversion. Estimates of V_P and V_S are similar to the ones in Figures 5 and 6 and are therefore not shown.

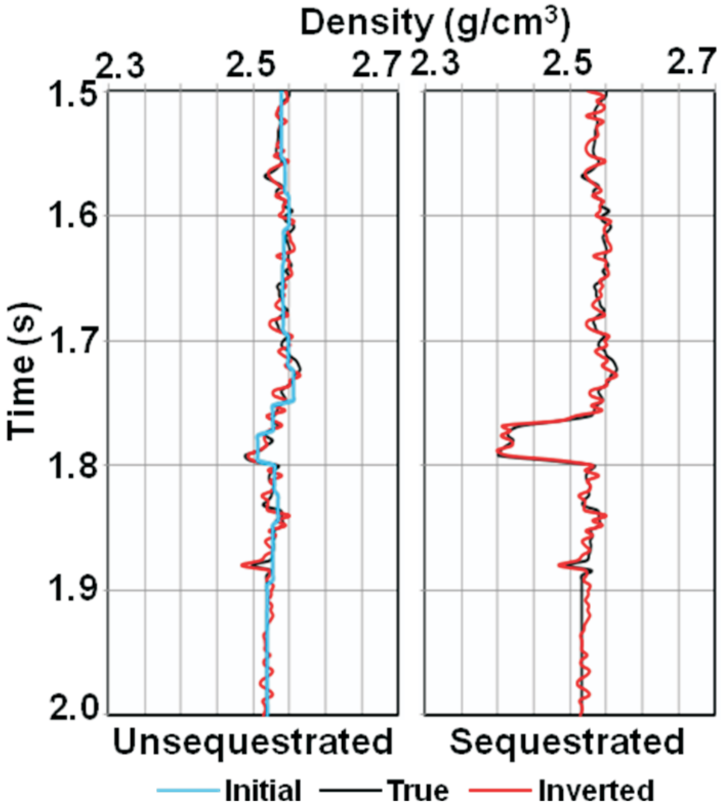

Fig. 7 Density estimates from multicomponent waveform inversion. As for the vertical component inversion, the initial model for sequestrated synthetics is the inverted model from the unsequestrated synthetics.

Notice that the multicomponent inversion could accurately estimate the density.

The monitoring strategy

Considering that the density is likely to be the key player and multicomponent waveform inversion can estimate density much more reliably than the P-wave only inversion, we believe that the multicomponent seismic data are necessary for an effective monitoring of carbon sequestrated saline aquifers. Acquisition and processing of multicomponent seismic data is however much more expensive than conventional P-wave data. Acquiring multicomponent seismic data as pre-sequestration baseline survey and subsequent acquisitions during and after sequestration for monitoring may not therefore be very cost effective, and we must look for some alternative methods. It is likely that the above normal pore pressure due to CO_2 sequestration will fracture the surrounding rock formations. If we deploy passive seismic sensors, microseismic events from these fractures could then be recorded. Assuming that we have a baseline pre-sequestration multicomponent data and obtain a reliably good subsurface model, these microseismic data could then be potentially used for subsequent monitoring. In addition, as these fractures are the potential conduits for CO_2 leakage, detecting and characterizing them will have an added advantage of mitigating such leakage-risk conditions.

To investigate the possibility of using passive seismic data for monitoring, we induce microseismic events with different focal mechanisms slightly above the sequestrated formation at 5100 m in Figure 2. We compute a point double-couple moment tensor solution for a given microseismic event caused by a fracture from the fracture strike, dip, and rake following the procedures given in Aki and Richards (1980). We then incorporate this moment tensor source into the reflectivity algorithm and compute the passive seismic responses at the surface for each microseismic event. Keeping the strike and rake fixed, Figures 8 and 9 show the vertical and radial components of the response from fractures with different dip angles.

Figures 8 and 9 demonstrate that the observed passive seismic responses clearly depend upon the dip of the fracture planes inducing the micro-seismicity. Also notice that the responses from 30° and 150° fracture dips are identical. Similarly the responses from 60° and 120° dips are also identical. These identical responses from different fracture dips belong to the classical problem of fault-plane ambiguity in earthquake focal mechanism solutions (for details, see Aki and Richards, 1980). For carbon sequestrations, we will be mostly interested in the fractures above the sequestrated formation through which CO_2 may leak out. Because these fractures are likely to be caused by the above normal pore pressure in the sequestrated formation underneath, they are

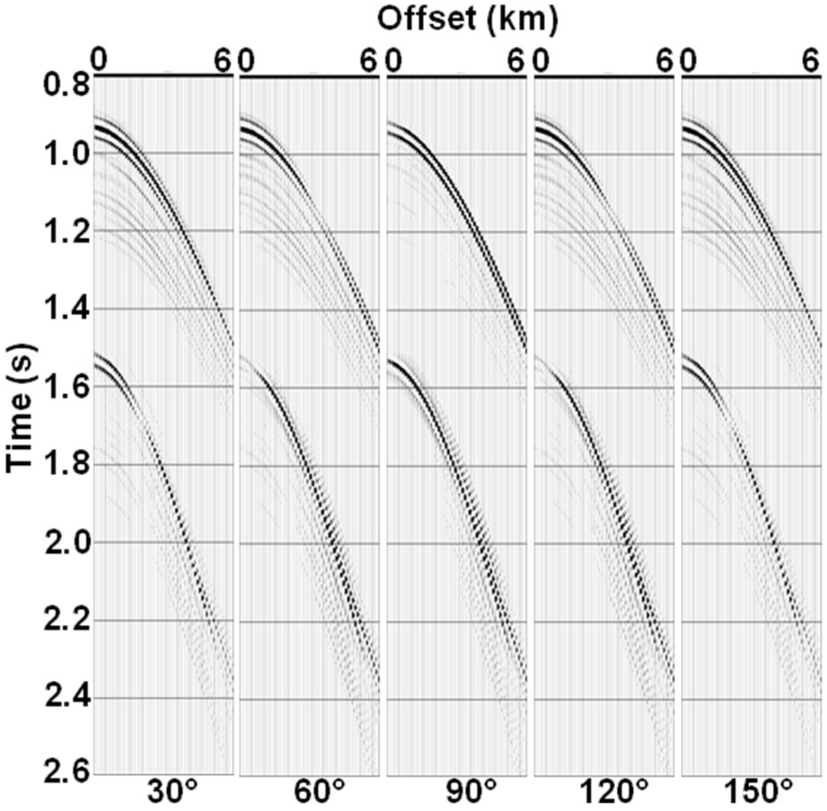

Fig. 8 Vertical component of passive seismic response caused by fractures with different dips induced immediately above the sequestrated formation in Figure 2.

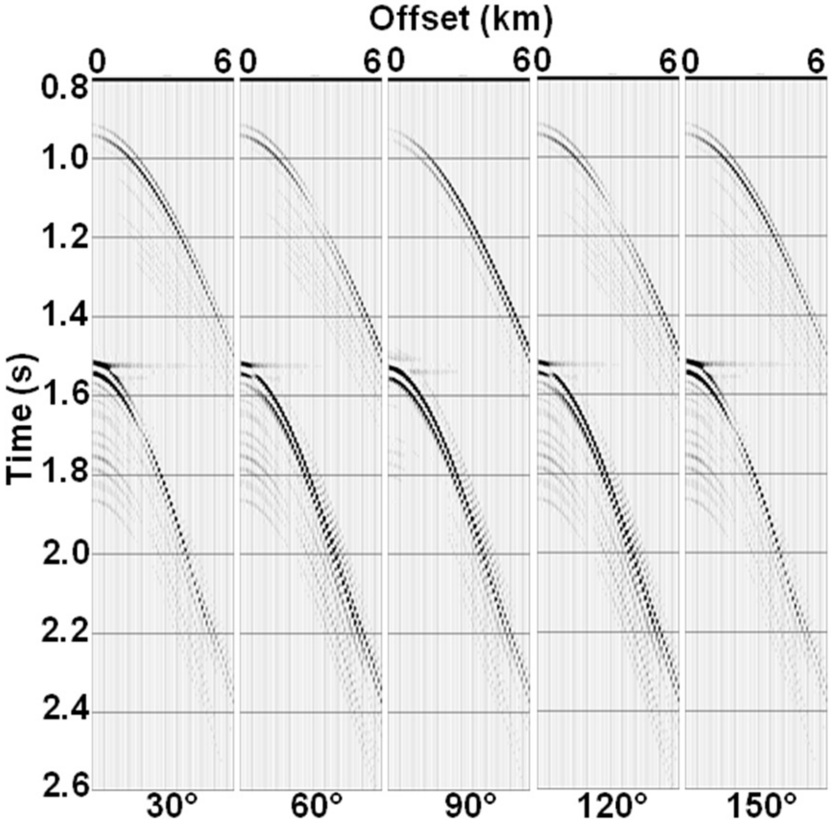

Fig.9 Radial component of passive seismic response caused by fractures with different dips induced immediately above the sequestrated formation in Figure 2.

more likely to be near vertical and reverse-fault solutions than normal fault solutions. Based on this argument, we should then be able to resolve the fault plane ambiguity from recorded passive seismic data. Assuming that the initial subsurface model is known from the baseline multicomponent data, we can therefore invert the passive seismic data for fracture characterization and micro-seismic event location. Once the focal mechanism from each micro-seismic event is obtained, we can then invert the same data for changes in the aquifer properties. This should in turn, provide a cost effective strategy for monitoring the carbon sequestrated deep saline aquifers combining multicomponent active source seismic data as baseline survey and successive passive seismic recordings for monitoring.

Our primary focus in this study was to demonstrate the feasibility of combining multicomponent seismic with passive seismic data for carbon sequestration monitoring. To prove our concepts, we have therefore used horizontally stratified models only. We are in the process of developing a multicomponent waveform inversion methodology for laterally variable medium. Additionally, we are using the available well and seismic data from the Moxa-Arch region to build a 3-dimensional (3D) elastic earth model. We will synthetically sequestrate CO_2 into some representative aquifer formations in this model and run multiphase flow simulations to predict subsurface models at different time intervals after sequestration. Using analog core samples, we will also run saturation experiments and include the results of these experiments into the simulation models so that we obtain a realistic patchy distribution of post-injection CO_2 within each aquifer volume. Computing multicomponent synthetic seismic data for the original (un-sequestrated) and sequestrated models, inverting them for subsurface properties, and calibrating the inverted properties to post-injection CO_2 saturations will then provide an effective monitoring strategy for real sequestration experiments. Demonstrating CO_2 sequestration using this 3D Moxa-Arch model and combining inversion with multiphase flow simulations is currently under investigation and will be discussed in a subsequent paper.

Conclusions

Sequestrating CO_2 in different saturations and computing the equivalent fluid-substituted properties indicate that the density is more sensitive to the change in CO_2 saturation than V_P and V_S. To effectively monitor carbon sequestrated saline aquifers, the available geophysical tools must therefore be able to predict density to a reasonable accuracy. Because multicomponent seismic data can accurately predict density, it is necessary to use multicomponent seismic data for monitoring CO_2 sequestrated aquifers. Since acquisition and processing of multicomponent seismic data is expensive, acquiring such data for pre-sequestration baseline survey and for monitoring surveys during and after sequestration is prohibitively expensive. Above normal pore pressure due to sequestration is likely to cause fractures, and computing micro-seismic events caused by such fractures we find that the passive seismic data could potentially be used to characterize and locate such fractures and monitor the carbon sequestrated formations. We therefore believe that using multicomponent seismic data as a baseline survey prior to sequestration and combining it with passive seismic data for subsequent monitoring during and after sequestration is a cost-effective strategy.

Acknowledgements

This research was funded by the US Department of Energy contract DE-NT0004730.

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