SENSITIVITY AND COST OF MONITORING GEOLOGIC SEQUESTRATION USING GEOPHYSICS

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ABSTRACT

Monitoring of geologic sequestration projects will be needed in order to manage the process of filling the reservoir, verify the amount sequestered in a particular volume, and detect leaks. The sensitivity of geophysical methods depends, first of all, on the contrast in geophysical properties produced by introduction of CO_2. Rock physics models were used to calculate anticipated contrasts in seismic velocity and impedance in brine saturated rock when CO_2 is introduced. The phase behavior of CO_2 has large effects on property contrasts over the depth and temperature range of interest in geologic sequestration projects. Detectability depends critically on the spatial resolution of the method. Numerical simulations were performed to evaluate how small a volume of CO_2 could be detected in the subsurface by seismic methods. Results from a model based on Texas Gulf Coast geology showed that a wedge of CO_2 in a 10 m thick sand could be detected. The size of the Fresnel zone was about 320 m. Costs of performing 3-D land seismic surveys were estimated for a hypothetical project in which the CO_2 produced by a 1000 MW coal fired power plant is sequestered. Results indicate monitoring costs may be only a small percentage of overall geologic sequestration costs.

INTRODUCTION

Monitoring of geologic sequestration projects will be needed in order to manage the process of filling the reservoir, verify the amount of CO_2 sequestered in a particular volume, and detect leaks. It is natural to consider geophysical techniques because of the large body of experience in their application in the petroleum industry. Other techniques, including hydrologic pressure testing, geochemical tracers, and surface deformation also are potentially applicable as part of sequestration monitoring, but will not be discussed in this paper. The scale of sequestration projects will be similar to or greater than that of petroleum reservoirs. With current technology the only practical approach to achieving the required spatial coverage at reservoir scale is the use of surface techniques. High-resolution wellbore and inter-well (crosswell) geophysics will be part of a monitoring program, but these methods are either limited to sampling near the wellbore or currently too expensive to consider for monitoring of the entire reservoir volume.

Surface reflection seismic is the most highly developed surface geophysical technique. It is used more often in the petroleum industry primarily because of its high spatial resolution compared to other surface techniques. For sequestration projects, surface reflection could be used to define the subsurface structure, similarly to how it is used in petroleum exploration. For monitoring of sequestration projects, the most

likely mode of application would be time-lapse, in which the difference between two surveys would be used to evaluate the movement of the CO_2. Though the use of time-lapse is becoming more common, it is a much less mature discipline than exploration seismology. A topic which continues to be an active area of research in petroleum geophysics is the interpretation of time-lapse for fluid properties (and distribution). Interpretation can be difficult because of the co-existence of multiple fluids, i.e., oil, brine and methane, along with changing pressure. Injection of CO_2 increases complexity by adding another fluid phase.

Two separate, though related, issues need to be addressed in evaluating the applicability of surface geophysical techniques. The first is whether CO_2 produces a sufficient contrast in the measured geophysical property to enable detection, and the second is spatial resolution. These will be discussed in this paper in some detail for seismic, since it is the surface technique with highest spatial resolution. Other techniques will be addressed in subsequent papers. Though it has the highest spatial resolution, surface seismic is also the most expensive. This paper also reports some preliminary estimates of the cost of monitoring using geophysical surface methods.

GEOPHYSICAL PROPERTY CONTRASTS

Surface seismic techniques analyze the reflectivity of the subsurface, so a measure of the sensitivity of surface seismic techniques for monitoring can be obtained from an analysis of the changes in reflectivity caused by the presence of CO_2. The reflectivity, R, or magnitude of the reflection for normal incident waves at the interface between two thick layers, 1, and 2, is given by:

$$R = \frac{I_2 - I_1}{I_2 + I_1} = \frac{\rho_2 V_2 - \rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1} \tag{1}$$

where I is the impedance of the layer, V is the velocity and ρ is density. Eqn. 1 shows that an impedance contrast can occur whenever there are changes in density and/or velocity, though sometimes both can change in such a way that effects cancel ($I_2 - I_1 = 0$). Thus, reflections are generated at the boundary between different lithologies, and they can also be generated by fluid contrasts. Injection of CO_2 will potentially alter the reflectivity of pre-existing lithologic boundaries or create new reflections.

The bulk density of a fluid saturated rock is simply given by:

$$\rho = \phi\rho_f + (1 - \phi)\rho_{gr} \tag{2}$$

when ϕ is porosity, ρ_f is density of the fluid and ρ_{gr} is the grain density of the rock. The grain density will change very little with pressure and temperature over the depth range of interest in this study, so density contrasts produced by CO_2 will essentially be due to fluid density effects.

Most conventional surface seismic methods use only compressional waves, the velocity of which is given by:

$$V_p = \sqrt{\frac{K + (4/3)\mu}{\rho}} \tag{3}$$

where K is the bulk modulus and ì is the shear modulus of the rock. To first approximation it can be assumed that the shear modulus is not affected by fluids in the pore space. The bulk modulus is a function of both the bulk moduli of the fluids in the pore space and the rock frame. Velocity changes due to CO_2 injection can therefore be related to changes in fluid density and bulk modulus. Determination of the effective bulk modulus for rock containing fluids of different composition and phase is not straightforward and has been the subject of a large body of research which is still continuing. A good synopsis of a number of approaches is given in Mavko et al, 1998.

This study investigates changes of reflectivity as a function of depth for CO_2 in brine formations. It is assumed that fluid pressures are given by the normal hydrostatic gradient for water. A thermal gradient of 10 C per km depth is assumed. It is also assumed that CO_2 is injected only into the sands which have a porosity of 20%. In Figure 1, reflectivity is calculated as a function of depth for a boundary between shale and sandstone. In Figure 2, the boundary is between sand containing CO_2 and sand containing brine.

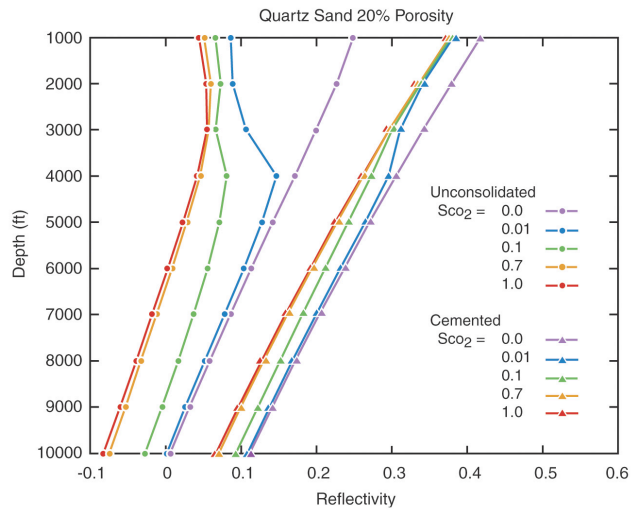

Figure 1: Reflectivity of a shale-sand boundary where sand has 20% porosity and S_{CO2} refers to the CO_2 saturation

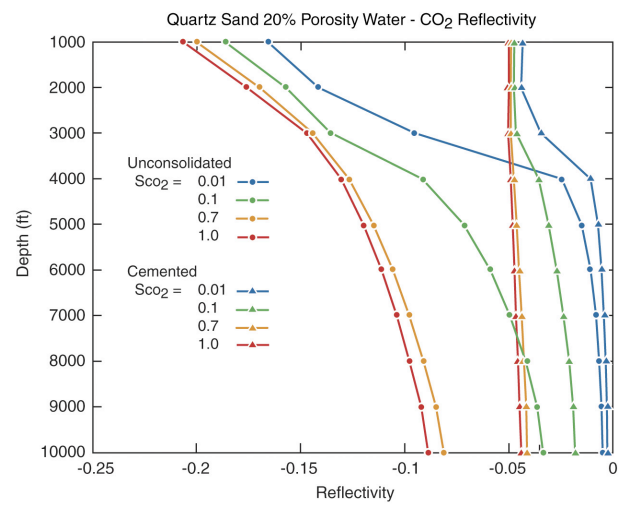

Figure 2: Reflectivity of a boundary between 20% porosity sand containing CO_2 and brine saturated sand, where in the sand.S_{CO2} is the CO_2 saturation

In both cases calculations were carried out for consolidated sandstone with clay cement, and an unconsolidated sand. Bulk densities were calculated using Eqn. 2. The density of brine as a function of pressure and temperature was obtained from work of Batzle and Wang, 1992. The density of brine increases with increasing pressure and decreases with increasing temperature. For in-situ conditions of this study, the thermal density decrease is essentially offset by the pressure density increase. Bulk and shear moduli of the dry sand frame were calculated using the approach of Dvorkin and Nur, 1996. The bulk moduli of CO_2 and brine were derived from results of Magee and Howly, 1994, and Batzle and Wang, 1992, respectively. Wood's equation (Batzle and Wang, 1992) is used for the effective bulk modulus of pore fluid mixtures and Gassmann's equation (Gassmann, 1951) is used for the effective bulk modulus of the sand containing the fluid.

Shale density and shale velocity as a function depth were obtained from well logs considered typical of a Texas Gulf coast geologic setting. The V_p for water-saturated shale varied from 1750 m/sec at 1,000 ft to almost 3,000 m/sec at 10,000 ft. The V_p for water saturated consolidated sand was about 3,800 m/sec at 1,000 ft, increasing by about 1% over the entire depth range. The V_p for water saturated unconsolidated sand increased from about 2,620 m/sec at 1,000 ft to about 3,050 m/sec at 10,000 ft. These velocities are also considered typical of Texas Gulf Coast sediments. Differences between the unconsolidated and

consolidated sand velocities reflect the differences in rock frame rigidity and influence of increasing overburden pressure on this rigidity.

For conditions assumed in the study, Figure 1 shows that the reflection from the shale-sand interface decreases in amplitude with increasing depth before CO_2 injection. As CO_2 is injected, at shallow depth, there is a large decrease in reflectivity. This is primarily due to the reduction in sand velocity, which is approaching that of the shale. Only a small amount of CO_2 (0.01 saturation) is required to cause the velocity reduction, which is consistent with the known effect of "gas-like" fluids. This effect is not observed below 4,000 ft, where the seismic properties of CO_2 are more "liquid-like". For unconsolidated sand, at higher levels of saturation, reflectivity goes to zero and then begins to increase in the negative direction. This means the amplitude of the reflection would go to zero and then start to increase with a change in phase. For consolidated sand, the effect of CO_2 is to reduce reflectivity at all depths. The effects of saturation are less for the consolidated sand because of the rigidity of the rock frame. If the shale velocity were higher than the sand velocity, the effects of saturation shown in Figure 1 would be reversed. That is, at shallow depths, a small amount of CO_2 would increase the amplitude of the reflection from the shale boundary.

In Figure 2 the reflectivity for the brine saturated condition is zero. Introduction of CO_2 results in a reflection, the amplitude of which is close to that generated when CO_2 is injected at a shale boundary. The reflectivity is always negative because the impedance of the sand with CO_2 is always less than that of sand with brine.

SPATIAL RESOLUTION

The size of the region containing CO_2 must be sufficient to generate an interpretable signal at the surface. To begin to put bounds on the minimum size for detectability, seismic simulations were performed using a model in which a wedge of CO_2 is placed in a brine saturated unconsolidated sand layer (Figure 3). The CO_2 saturation in the wedge was assumed to be 50%. The wedge is a rough approximation of the shape of the plume formed by CO_2 injected into (or leaking into) the base of the sand layer. The thickness of the sand was varied from 5 m to 100 m. The width of the wedge was based on the size of the first Fresnel zone: The amplitude of the reflection from an object with a size on the order of our Fresnel zone or smaller will be affected by the size of the object in addition to the impedance contrast. Volumes of CO_2 of this size may be detected but not easily characterized.

Results of calculations for a sand layer at 2,000 m depth are given in Figures 4 and 5. At this depth, the shale has V_p=2,700 m/sec and a density of 2,160 kg/m^3. The sand has V_p=3,050 m/sec and a density of 2,285 m/sec and the CO_2 wedge has V_p=2,530 m/sec and a density of 2,245 kg/m^3. The seismic wave center frequency was 30 Hz, which is consistent with observations of the frequency content of surface seismic in Texas Gulf Coast sediments. For these conditions, the first Fresnel zone diameter is about 320 m. Calculations were therefore carried out for wedge widths of 160 m, 320 m, and 480 m. An acoustic finite difference simulation was carried out using an "exploding reflector" which produces the equivalent of a zero-offset stacked section. A Kirchhoff time migration was run on the results to produce the plots shown in the figures.

The model with a 5 m thick sand layer generated no discernable reflection. This is understandable since the layer thickness was on the order of 5% of the seismic wavelength. Results for the 10 m thick layers are shown in Figure 4. A reflection is generated by the sand layer, but none is observed in the center at the

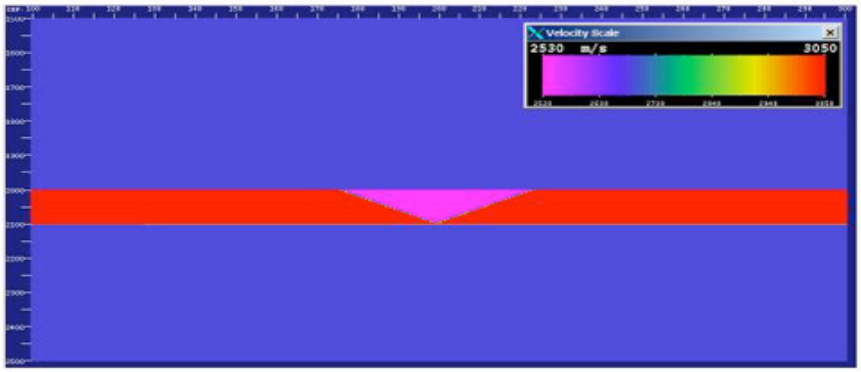

Figure 3: Velocity model for the seismic calculations, showing a wedge containing CO_2 in a sand layer

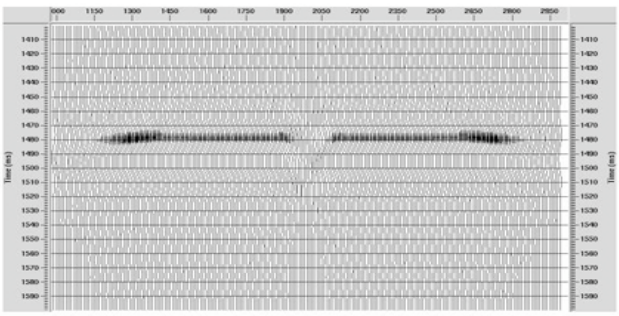

Figure 4: Reflection from a 10 m thick layer containing a wedge of width 160 m

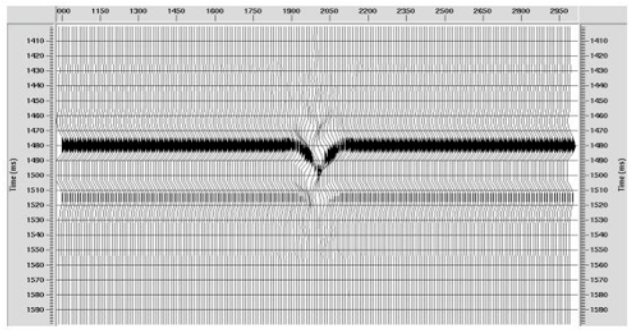

Figure 5: Reflection from a 30 m thick layer containing a wedge of width 160 m

location of the CO_2 wedge. At 2,000 m depth, for the conditions assumed in this model, the impedance difference between the shale and the sand containing CO_2 is almost zero. Figure 5 shows results shows results for the 30 m thick layer. In this case, the CO_2 wedge is imaged, where the reflections are generated at the interface between the brine saturated sand and the sand containing CO_2. There is a sufficient thickness of brine-saturated sand beneath the CO_2 wedge to generate a reflection.

For these models the width of the wedge is less than a Fresnel zone and the layer thickness is on the order or less than the layer tuning thickness. Even though the CO_2 wedge is detected, interpretation of the reflection for fluid properties would be difficult because of geometric effects. A uniform CO_2 saturation and sharp interface between CO_2 and brine are also somewhat unrealistic.

The amount of CO_2 in a cone with a diameter equal to the wedge width was calculated in order to put the size of seismically detectable volumes in context of a sequestration project. For this study, the smallest wedge which could be imaged was 160 m wide. At 2,000 m depth, a cone of this diameter and 30 m high would contain about 20,000 t of CO_2, or somewhat less than the CO_2 production for one day for a 1,000 MW coal fired power plant. A cone large enough to prevent contamination of reflections by geometrical effects would have a diameter of 480 m and thickness of 100 m. This would contain about 17 days of CO_2 production.

COST ESTIMATE

Costs of surface seismic surveys can vary widely depending on surface terrain and the complexity of the survey. Seismic is the most costly of surface geophysical techniques, and, in general, is considered to be an expensive monitoring option. To begin to put seismic costs in perspective to other costs of

sequestration, an estimate was made of the cost of surface seismic monitoring of a hypothetical project for sequestering the CO_2 from a 1,000 MW power plant with a 30-year lifetime. Such a plant, with current technology, would produce about 30,000t CO_2 per day. Storage of this in a 100 m thick layer with porosity of 12% and a capacity factor of 30% (yielding an effective storage volume of 3.6%) would generate a plume of 115 km^2. The cost of a 3-D seismic survey, including interpretation, to image this plume was estimated at $1,500 k. The frequency and length of time over which surveys would need to be conducted is unknown. Assuming six surveys at a five year interval at constant cost would result in a $9 M expenditure for monitoring. Expressed in terms of dollars per ton CO_2 sequestered, this works out to be $0.03/ton. This is a small number compared to other sequestration costs, such as separation. There are large uncertainties in these cost estimates, but it appears that the costs of surface geophysical monitoring would not constitute a large percentage of overall sequestration costs.

SUMMARY AND CONCLUSIONS

Surface reflection seismic is the most highly developed surface geophysical technique and will provide the highest spatial resolution of all techniques. Analysis of the changes in reflectivity due to the presence of CO_2 provides one measure of the sensitivity of seismic for monitoring. Reflectivity was analyzed for cases in which CO_2 was injected into brine saturated, consolidated, and unconsolidated sand. In one case the reflectivity of a boundary between shale and sand was analyzed and in another case the boundary was between sand containing CO_2 and sand saturated with brine. In both cases, the largest changes in reflectivity occurred at shallow depth, when CO_2 properties are “gas-like”. Changes in reflectivity decreased as properties of CO_2 became “liquid-like”. Changes in reflectivity can cause the amplitude of measured reflections to increase, decrease, or possibly disappear depending on the velocity structure before injection. Spatial resolution was evaluated using models in which a wedge represented a plume of CO_2 in a saturated sand layer at 2,000 m depth. For conditions assumed in this study, the minimum sand thickness for imaging a wedge of width 160 m was 10 m. A wedge large enough to prevent contamination of reflections by geometrical effects had a width of about 480 m in a 100 m thick sand. Costs of performing 3-D surface seismic surveys for monitoring the sequestration of CO_2 produced by a 1,000 MW power plant were estimated at $0.03/ton. These results indicate that monitoring using geophysics may represent a small percentage of overall sequestration costs.

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