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4D Seismic Monitoring of CO_2: Practical Considerations

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Summary
4D seismic (time-lapse 3D) can be extremely useful for monitoring of CO_2 injection and storage in subsurface geologic reservoirs. The physical properties of CO_2 with reservoir pressure and temperature, and the properties of the reservoir rocks saturated with CO_2-fluid mixtures after injection, determine the strength of the 4D seismic signal. The quality of the seismic data and images, especially the level of non-repeatable noise and complexity of wavefields, determines whether the CO_2 can be accurately detected and quantified. I discuss several practical considerations that affect our ability to image and quantify CO_2 from seismic data, as related to rock and fluid physics, seismic acquisition and image processing, and seismic inversion.

Properties of pure CO_2

For many storage reservoirs, the pressure and temperature regime will be such that pure CO_2 will exist in the supercritical part of its phase diagram, thus having the physical properties of both a gas and fluid. Figure 1 shows values of the bulk modulus (incompressibility) and density of pure CO_2 at various pressure and temperature conditions, calculated using a combination of the SUPERTRAPP algorithm and the Span-Wagner equation of state method (Lumley et al., 2008). Note that the compressibility and density of pure CO_2 can vary as much as one order of magnitude across the sequestration pressure-temperature range; CO_2 is much more compressible than water, and the density of CO_2 varies from gas-like to fluid-like conditions depending on the exact pressure and temperature. Adding impurities such as methane to pure CO_2 moves the critical point of the CO_2 mixture in the phase diagram, but the overall range of compressibility and density variation is similar.

Properties of CO_2 fluid mixtures

CO_2 is likely to be stored in saline aquifers containing brine (very salty water), or in depleted hydrocarbon (HC) reservoirs containing a mixture of residual oil, water and/or HC gas. In the case of saline aquifers, the injection of CO_2 into brine will make the resulting fluid mixture highly compressible and somewhat less dense, depending on pressure and temperature. Since 4D seismic is sensitive to the fluid compressibility *contrast* of the in situ fluid versus the injectant (Lumley et al., 1997), CO_2 injection in saline aquifers is favorable for seismic monitoring (eg., Sleipner). In depleted HC reservoirs, the situation is more complex since oil has widely variable physical properties, and CO_2 reacts with oil over short timescales to change the physical properties of the residual oil (which is why CO_2 injection is a well-established method for enhanced oil recovery). Since 4D seismic is sensitive to fluid compressibility contrasts, the most favorable conditions for seismic monitoring of CO_2 in depleted HC reservoirs are when the residual oil has a low GOR value (GOR = solution gas-oil-ratio, ie., the amount of dissolved HC gas in the oil), for example at Weyburn. Alternately, conditions which are relatively unfavorable for seismic monitoring of CO_2 exist when the residual oil is high-GOR, or when there is residual HC gas saturation in pore space (for example at Otway).

Properties of rocks saturated with mixtures of CO_2 and in situ fluids/gas

4D seismic is sensitive to the compressibility of the dry rock frame, in addition to pore fluid properties. A good 4D seismic signal requires rocks with high values of porosity and dry-frame compressibility (low bulk modulus). High porosity increases the volume of fluid in the rock to better affect the seismic response, and large dry-frame compressibility allows the seismic to better sense (via fluid compressibility) the type of fluid in pore space. Rocks that are thus favorable for 4D monitoring of CO_2 are unconsolidated sands, turbidites, and heavily fractured material for example. At the Sleipner CO_2 project, the injection of CO_2 into brine-saturated unconsolidated sands creates a huge P-wave velocity (Vp) decrease of up to 60%. Rocks that are relatively unfavorable for 4D monitoring of CO_2 are well-cemented sandstones, tight sands, and stiff carbonates for example. At the Weyburn CO_2 project, the injection of CO_2 into low-GOR residual-oil saturated carbonate rocks creates a small Vp decrease of only a few percent, which is at or near the seismic noise level for detection. At the Otway CO_2 project, the rocks are moderately favorable but the residual HC gas makes it very difficult to detect injected CO_2 with seismic due to the lack of fluid compressibility contrast. It is also worth noting that CO_2 is not an inert fluid. Previous experience monitoring CO_2 injection in enhanced oil recovery projects has shown that CO_2 can react in pore space to alter or dissolve the rock matrix, creating secondary porosity and weakening the cementation or dry frame modulus. These effects can make it difficult to isolate the CO_2 saturation effect alone, which in turn makes it difficult to accurately quantify the amount of CO_2 present using only seismic images. In my opinion many of the 4D seismic anomalies seen at CO_2 sequestration projects today contain reactive CO_2 effects on the rock matrix and may explain why observed 4D CO_2 anomalies are sometimes quite different (eg. larger) than expected or can be simply modeled.

4D seismic imaging of injected CO_2

The ability to image injected CO_2 with 4D seismic depends on the magnitude of the seismic response to CO_2 (i.e. the 4D signal), and the 4D seismic noise level. 4D seismic noise is typically caused by non-repeatability in the acquisition and image-processing of the time-lapse 4D seismic surveys. Seismic acquisition non-repeatability can be caused by unavoidable source-receiver positioning errors between surveys, natural variations in the near-surface soil layer on land (moisture, water table, ground coupling etc.), or water column at sea (tides, wave heights, water temperature, salinity, etc.), and variations in source waveforms, receiver functions and equipment specifications. Seismic image-processing non-repeatability can be caused by unavoidable variations in the image processing flow, the approximate physics of certain imaging operators to account for full wave propagation effects, and the sensitivity of certain nonlinear statistical and data-dependent imaging operators to the presence of 3D noise. As discussed above, the strength of the 4D signal is related to the compressibility of the reservoir rocks, and the compressibility contrast between fluid types. Weak 4D signals arising from CO_2 injection can be caused by hard rocks (eg. Weyburn) and/or low fluid compressibility contrast (eg. Otway), and in these cases extra effort must be spent to optimize repeatability to suppress 4D noise to detect the weak CO_2 signal. In the case of very strong 4D responses to CO_2 (eg. Sleipner), the presence of injected CO_2 is easily detected above the 4D noise level, but the wavefields generated may be complicated by strong internal scattering and wave-mode conversions which are not properly handled by today's image-processing operators, and thus can lead to artifacts in the resulting 4D seismic images. Figure 2 shows an example based on Sleipner reservoir rock and CO_2 properties, in which a 3D earth model was constructed with a single CO_2 layer at the top of the Utsira sand, full visco-elastic seismic wavefield data was generated by finite-difference (FD) modeling, and then image-processed using a state-of-the-art prestack depth imaging processing flow including wavefield separation, multiple suppression, depth migration velocity analysis etc. (Lumley et al., 2008). The 4D seismic difference image in the left panel of Figure 2 shows the single CO_2 layer at the top, contaminated by several imaging artifacts below caused by complex internal scattering and mode conversion not properly handled by the imaging operators. The right panel of Figure 2 shows the actual Sleipner 4D seismic image, which has been interpreted to contain multiple layers of CO_2, but may be contaminated by similar artifacts.

4D seismic inversion to quantify CO_2 saturations

It would be nice to be able to quantify the amount of injected CO_2 present in the reservoir using 4D seismic data. In my opinion this quantification objective faces several big research challenges, including; (a) the injection pressure and saturation changes in the reservoir, including the possible presence of multiple phases of CO_2, are combined in the seismic response and not easy to separate uniquely; (b) pressure-saturation effects may be complicated by CO_2 reactive effects on the rock matrix (eg. cementation) or pore fluids (eg. oil fractionation); (c) basic rock and fluid physics analysis shows that seismic compressibility and velocity are not sensitive to CO_2 saturation levels beyond about 30% S_{CO2} when present as a supercritical "fluid", and beyond about 10% S_{CO2} when present as a supercritical "gas"; (d) the density effect of injected CO_2 is difficult to estimate from seismic data unless there are very large amounts of CO_2 present, and the seismic data is exceptionally clean (low noise) and contains ultra-far offsets and reflection angles; (e) the seismic response to CO_2 can be highly nonlinear and non-unique, thus making it difficult to extract accurate information (such as traveltime, velocity and amplitude) from prestack seismic data or images, as required input for any inversion algorithm.

References

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Lumley, D., Behrens, R., and Wang, Z., 1997, *Assessing the technical risk of a 4D seismic project*: The Leading Edge, **16**, no. 9, 1287-1292.

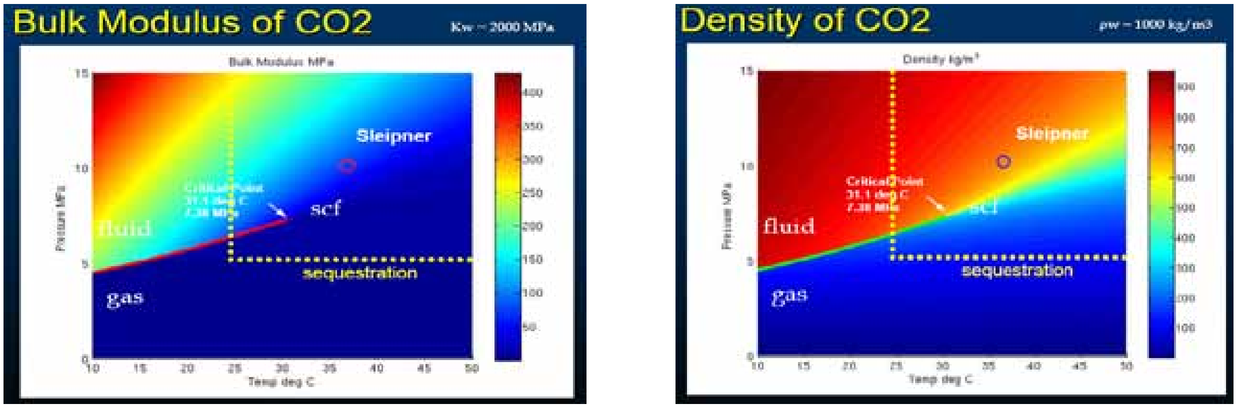

Figure 1: (a) Bulk modulus (left) and (b) density (right) of CO_2 under various pressure and temperature conditions (Lumley et al., 2008).

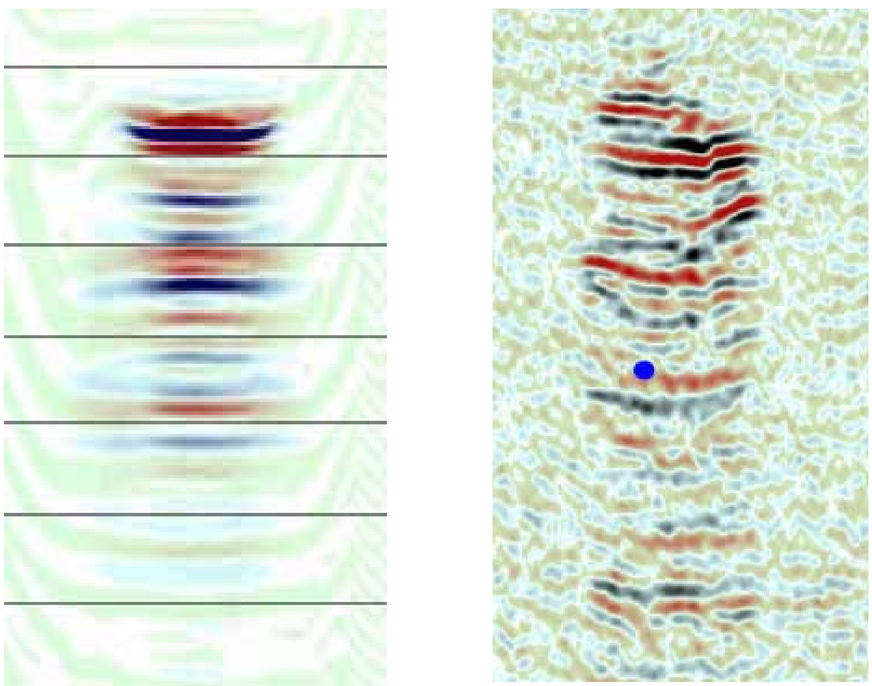

Figure 2: Left panel: time-lapse prestack depth-migrated P-wave *difference* image from synthetic FD data using an earth model with only a single CO_2 layer; Right panel: real time-lapse P-wave difference image at Sleipner interpreted to show several CO_2 layers present. The imaging artifacts in the left panel are caused by strong multiple wave-scattering and mode-conversion effects that are not properly handled by conventional imaging operators, and thus may be misinterpreted as false CO_2 layers, and/or may contaminate the image of the real CO_2 distribution. (Lumley et al., 2008).