Seismic modelling: 4D capabilities for CO₂ injection

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Abstract

The UNIS CO₂ Lab project addresses the problem to turn Svalbard, Norway into a CO₂ neutral community. Eight slim-hole explorations wells were drilled with full coring and electrical logging from the surface to ca. 1000 m depth. A target reservoir for CO₂ storage, at 650-750 m depth, and associated to the Knorringfjellet formation, comprises of mainly shallow marine and paralic sandstones beneath a cap rock of Jurassic shales. Water injection tests, drill core studies, regional seismic, geological studies, and seismic surveys have all been undertaken to assess the physical properties of the reservoir. Here, we study the seismic capability to detect a CO₂ injection. We first assess the impact of porosity and CO₂ concentration on seismic images using an artificial layered reservoir model, defined by 6 homogeneous layers parallel to top reservoir.

The seismic modelling in this study is a 3D prestack-depth convolution developed by NORSAR. This approach accounts for 3D incident-angle-dependent resolution and illumination effects, avoiding the computation and processing of synthetic seismograms. The 3D spatial convolution operator, or Point Spread Function (PSF), is a ray-based estimation of the point-scatterer response of a prestack depth migration (PSDM) at a reference point (e.g., center of the considered target zone). This method allows us to consider an ideal PSF from an analytical PSDM filter, defined by an average velocity at the reference point, a wavelet, a selected incident angle, and a maximum illumination dip.

The described analytical workflow provides the seismic reservoir response to the CO₂ injection. To assess the effect of porosity, we model the seismic response for a fully saturated brine reservoir (model A) and a reservoir with 100% CO₂ concentration (model B). To better observe CO₂ effects on seismic amplitudes, we compute the difference between the two fluid filled reservoirs. Due to a decrease in reflectivity at top reservoir when CO₂ is below (Vₚ decreases), model B has lower reflection amplitudes. As expected, the presence of CO₂ will generate reflectivity on the seismic, at the contact between CO₂ and brine (Fig.1.a). As the CO₂ volume increases with the porosity, the amplitude variations will increase too (Fig.1.a). To assess the effect of CO₂ concentration on the seismic images, we varied the concentration from 0% to
100% within the reservoir (using a constant porosity of 5%). As observed with the porosity study, the CO2 creates a new reflector in the seismic (Fig.1.b). The higher the CO2 concentration is, the higher the seismic amplitude. This is consistent with the amplitude variation observed for the porosity changes. However, when we look at relative differences between consecutive CO2 concentrations, we observe the amplitude of the differences decreases i.e. the bulk modulus is very sensitive to small amounts of CO2, but that sensitivity decreases with increasing CO2. We also study the effect of a gradient CO2 concentration (from 100% to 0%) within the reservoir. In this case, only the base of the CO2 volume seems to appear. This is coherent with the concentration study. We are not able to properly distinguish the concentration change within the CO2 volume.

The final modelling we perform considers more realistic CO2 volumes. We define five different CO2 plume-like extensions, simulating the expansion of a CO2 volume. Here, the PSF will limit the illumination of the flank of the CO2 volume. To properly image the entire plume we need at least a 30°-max dip PSDM filter. In addition to using the analytical PSDM filter, we model the seismic response for 3 marine-type surveys and use a 3D background velocity model that was generated for the entire area surrounding the UNIS CO2 lab (which is not required for the analytical PSDM modelling). Noise was not included in this modelling. Two of these surveys are single lines (at X=0 and Y=0), and the third is a 3D survey with an extension of 4 km in both the X and Y directions. The 3D survey images and correctly places the CO2-brine contact (Fig.2). However, the 2D survey (at X=0) misplaces the contact and the associated amplitude is lower.

The seismic modelling results presented here, use simplistic reservoir models for the UNIS CO2 Lab upper reservoir structure. The first assessment focused on the reservoir response to the CO2 injection for variable reservoir porosities and CO2 concentrations. Even small concentrations of CO2 (5%) are observed on seismic images, but the relative changes in terms of seismic amplitude for higher concentrations are less significant. With real data, it may therefore be difficult to constrain the concentration variation of CO2 over time, but it may be possible to determine the extension of the CO2 volume, depending on sufficient survey illumination. For a second case, we looked at more realistic CO2 volumes, i.e., plume-like geometries, using full 3D modelling. To detect these plumes in their entirety, survey geometries have to be carefully designed to secure the illumination of all flanks. Moreover, a poorly designed survey can misplace the CO2-brine contact.
Figure 1: a) Reflection amplitude (left) and reflectivity (right) variations for 2% (red), 5% (green) and 10% (blue) porosity (the seismic amplitudes are not calibrated and contain a limited-illumination effect); b) Amplitude and reflectivity variation for the CO₂ concentration changes.

Figure 2: comparison of the PSDM images for the 3D and 2D surveys.