We CO2 P03

Monitoring Of CO2 Leakage Using High-Resolution 3D Seismic Data – Examples From Snøhvit, Vestnesa Ridge And The Western Barents Sea

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Summary

Injection of CO2 in subsurface reservoirs may cause overburden deformation and CO2 leakage. The aim of this study is to apply technologies for detection and monitoring of CO2 leakage and deformation above the injection reservoirs. The examples of this study include data from the Vestnesa Ridge natural seep site, the Snøhvit gas field and CO2 storage site region, and the Gemini North gas reservoir. Reprocessing of existing 3D high-resolution seismic data allows resolving features with a vertical and lateral resolution down to c. 1 m and c. 5 m respectively. The current acquisition systems could be modified to image structures down to one meter in both the vertical and horizontal directions. We suggest a monitoring workflow that includes baseline and time-lapse acquisition of high-resolution 3D seismic data, integrated with geochemical, geophysical, and geotechnical seabed core and water-column measurements. The outcome of such a workflow can deliver reliable quantitative property volumes of the subsurface and will be able to image meter-sized anomalies of fluid leakage and deformation in the overburden.

Introduction

The capture of CO_2 in geological formations is potentially the main solution to significantly reduce the amounts of greenhouse gases in the atmosphere (IPCC, 2005). However, deformation in CO_2 sequestration reservoirs related to pressure build-up from CO_2 injection may affect seal integrity and induce CO_2 leakage and migration back to the hydrosphere and atmosphere.

Currently, CO_2 is injected at two carbon capture and storage (CCS) sites on the Norwegian Continental Shelf. The largest site is Sleipner in the North Sea, where 0.9 $MtCO_2$ are annually injected into the 200-250 m-thick sandstone of the Utsira Formation. The second injection site is Snøhvit in the SW Barents Sea, where a volume of 0.7 $MtCO_2$/yr is injected into the lower part of the Stø Formation beneath the gas-bearing formation of the field. Both reservoir formations are supposed to retain CO_2 for at least 1000 years.

The aim of our contribution is to show that any potential leakage and deformation caused by CO_2 injection can be monitored on a meter-scale. The strategy is to acquire time-lapse surveys of high-resolution 3D seismic data of the shallow subsurface as the framework for integrating geochemical, geophysical, and geotechnical data. The examples illustrating the strength of our approach include the Vestnesa Ridge natural seep site, the Snøhvit gas field and CO_2 storage site, and the Gemini North gas reservoir (Fig. 1).

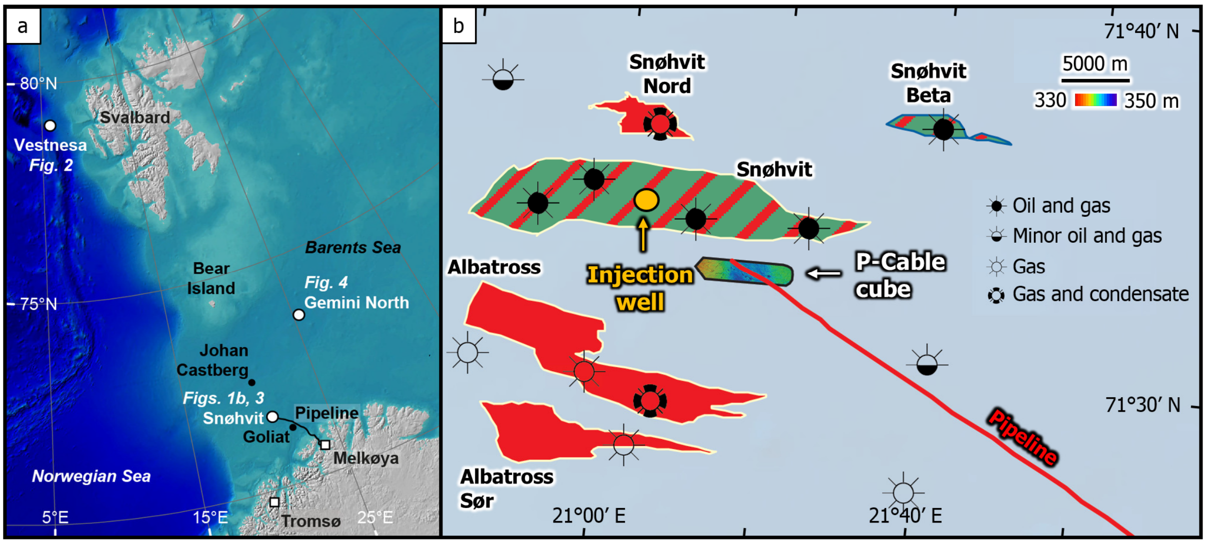

Figure 1 a) *Bathymetric map of the SW Barents Sea with major seabed infrastructure (Goliat, Snøhvit, Snøhvit gas pipeline, and Johan Castberg). White circles show locations of this study.* ***b)*** *Snøhvit gas field, gas injection location (yellow circle), and extent of high-resolution 3D P-Cable seismic volume.*

Methodology and Technology

The P-Cable system (Planke and Berndt, 2003) has short streamers attached to a cross-cable enabling the collection of high-resolution 3D seismic data. The current system is superior for imaging the shallow stratigraphy with a native 6.25x6.25 m or 3.125x3.125 m bin-size and retained frequencies of 200 Hz at depths of 500 m below the seafloor (Lebedeva-Ivanova *et al.*, in press). Theoretical calculations show that the upper 100-200 m of the subsurface can be imaged with a resolution of 1 m in both horizontal and vertical directions (Lebedeva-Ivanova *et al.*, in press).

The three P-Cable data cubes used in this study were acquired with an acquisition line spacing of 50-70 m, an offset range of 105-160 m for all receivers, and air-gun arrays with a total volume of 15 in^3, 30 in^3 and 300 in^3. The seismic cubes have bin sizes of 6.25x6.25 m and 6.25x4.75 m, and a frequency of up to 350 Hz in the uppermost 100 m below the seabed.

The Arctic University of Norway has carried out high-resolution time-lapse surveys using the P-Cable technology over the Vestnesa Ridge, an area with active gas seepage west of Svalbard (Fig. 1a) (Bünz *et al*., 2012; Waage *et al*., in review). Waage *et al*. (in review) have further shown that the repeatability measures for high-resolution P-Cable data strongly depend on the type of sediment. Comparing the spectra of useful signal show frequencies of up to 140 Hz in standard processing (Fig. 2a), and frequencies of up to 500 Hz for high-frequency processing of the high-resolution 3D seismic data of Vestnesa (Fig. 2b). The re-processed data show a sub-meter vertical resolution within the upper 50 m below the seafloor, and a meter-scale resolution between 50 to 150 m below the seafloor (Fig. 2). In addition, re-binning to a bin size of 3.125x6.25 m provides a horizontal resolution of 3 m along in-lines and 6 m along cross-lines. This increase in resolution resulted in more detailed imaging of the sedimentary layering and chimney structures below the pockmarks, and displayed an enhanced fault definition (Fig. 2) when compared to data processed for interpreting deeper levels. The reprocessed data show that the widths of the interpreted chimneys can vary towards the seafloor, and that in some cases seep structures do not reach the seafloor.

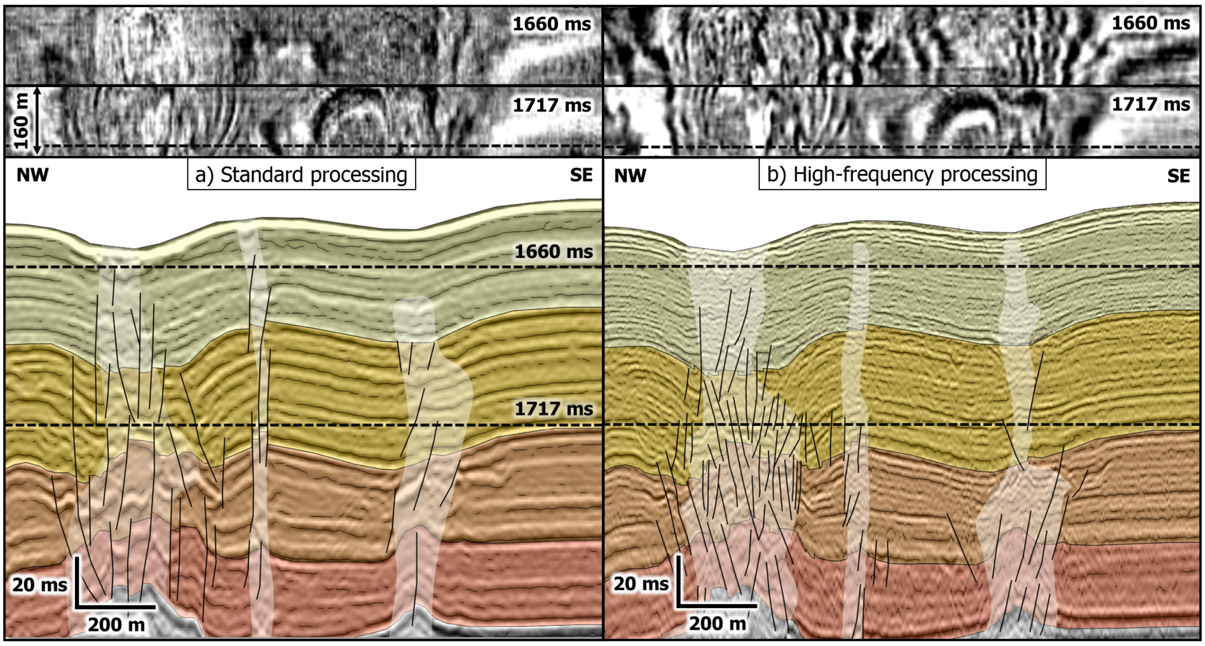

***Figure 2** Comparison between **a)** standard processing (bin size of 6.25x6.25 m) and **b)** high-frequency re-processing (3.125x6.25 m) along the same line within the P-Cable 3D cube acquired on the Vestnesa Ridge. Time slices at depths of 1660 and 1717 ms are given above the seismic sections; dotted lines provide the seismic section location. Seismic data (courtesy of The Arctic University of Norway) image vertical chimney structures below pockmarks associated with acoustic flares in the water column (Bünz et al., 2012).*

Snøhvit Case Study

The Arctic University of Norway collected multibeam echosounder (MBE; Kongsberg EM300, 30 kHz) and high-resolution 3D P-Cable seismic data in the Snøhvit area in 2011 (Figs. 1b, 3). Images generated from this survey include meter-scale glacial and pockmark structures (Fig. 3), and allow correlations of faults with the shallow subsurface (Fig. 3c) (Tasianas *et al*., 2018). MBE and P-Cable data are both imaging the infrastructure on the seabed. Compared to high-resolution bathymetric data, the smaller pockmarks (unit pockmarks) interpreted in P-Cable data are imaged with an increased sharpness (Figs. 3a, 3b). The Snøhvit dataset therefore provides a high-quality baseline survey in an area where CO_2 is currently injected into the subsurface.

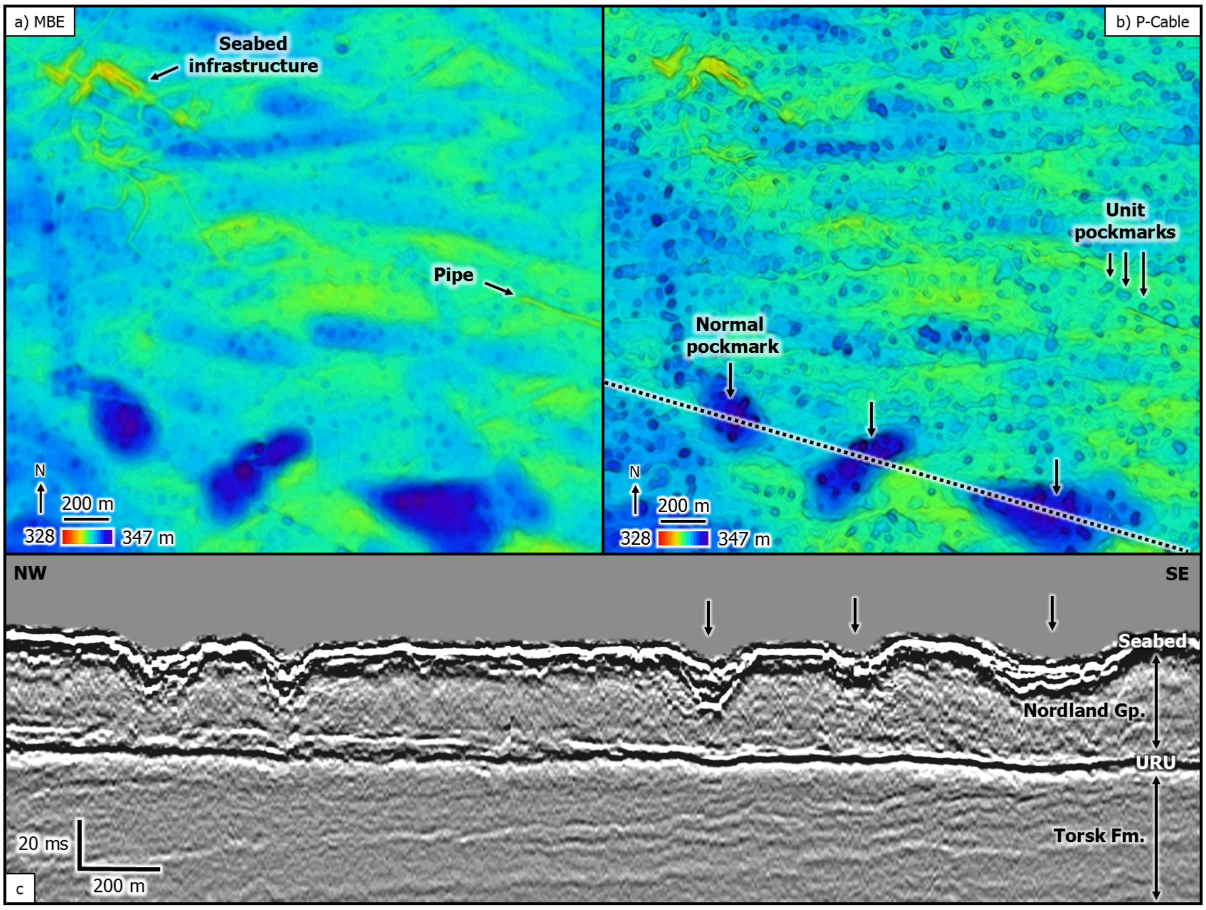

Figure 3 *Pockmarks and seabed infrastructure at Snøhvit.* ***a)*** *Structure map of the seabed using multibeam echosounder (MBE) data.* ***b)*** *Structure map of the seabed using high-resolution 3D P-Cable seismic data. Arrows indicate normal pockmarks shown in the seismic profile in Fig. 3c.* ***c)*** *Seismic profile across normal pockmarks. The glacial unconformity (URU, Upper Regional Unconformity) separates the glacial sediments of the Nordland Group from westwards-dipping sedimentary bedrock of the Torsk Formation. Pockmarks are shown in the structure map in Fig. 3b.*

Gemini North: An Example for the Way Forward

The Gemini North high-resolution 3D P-Cable survey was collected in 2014, three years before the exploration well 7325/4-1 was drilled. As such, the Gemini North is a perfect baseline survey for monitoring changes in the subsurfaces related to offshore activities. Gas-related seismic anomalies, not visible in conventional seismic data, can be imaged at different levels of the shallow stratigraphy, from the reservoir at 500 m below seabed to soft reflections within the glacial package (Fig. 4) (Bellwald and Planke, 2018; Bellwald *et al*., 2018).

Several types of seep anomalies were detected on the seafloor above the main prospect, but the distribution of the geochemical and microbial anomalies do not necessarily overlap. The integration of the seep results with the 3D seismic data suggest that fluids dominantly migrate upwards, but may also migrate laterally by following porous beds and conduits, and that discontinuities in the overburden may filter light from heavy compounds. Therefore, fluid migration pathways in the shallow subsurfaces can be interpreted more confidently by integrating different datasets.

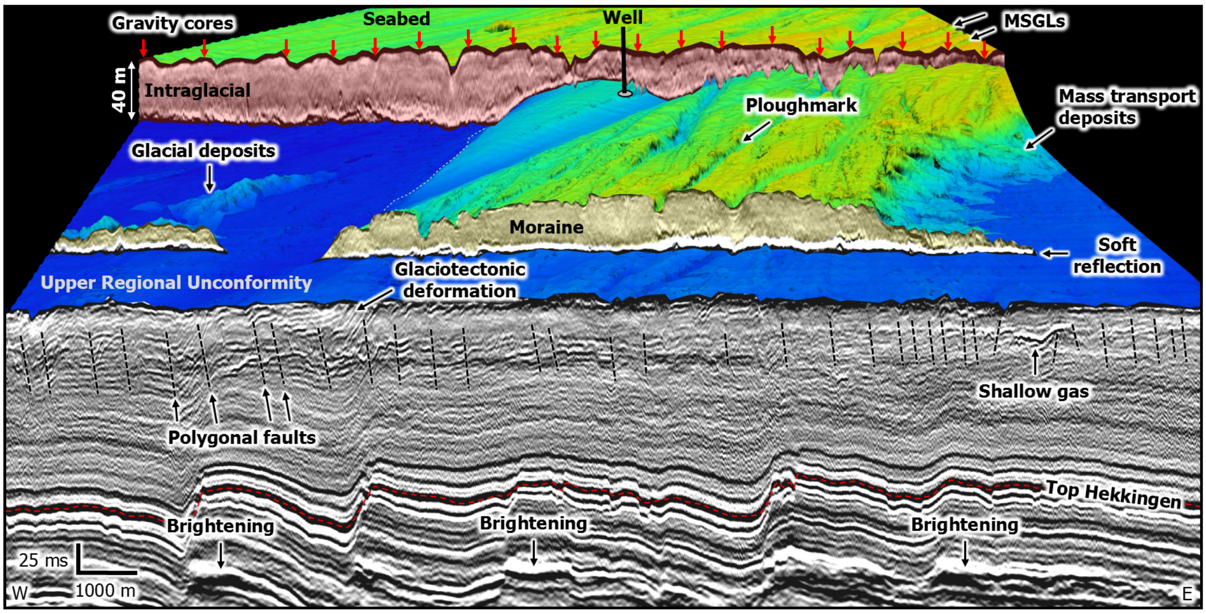

Figure 4 *Integrated approach for the monitoring of CO_2 leakage. The use of high-resolution 3D seismic data allows to image structures and fluid anomalies in the shallow subsurface with a meter-size resolution. The seismic data were collected in 2014, and the exploration well 7325/4-1 was drilled in 2017. MSGL: Mega-scale glacial lineations.*

Conclusions and Outlook

The integration of time-lapse high-resolution 3D seismic data with in-situ measurements of geological properties and seep anomalies is our proposed strategy for monitoring overburden deformation and potential CO_2 leakage above CO_2 storage sites. Our integrated approach allows an effective response for the detection and monitoring of CO_2 leakage. 4D seismic data analysis is a powerful tool to detect changes caused by fluid injection in particular when data are interpreted at detection level rather than resolution level. As fluid injection (or extraction) is capable of deforming the overburden several meters, 4D seismic data have the potential to monitor reservoir pressure variations on much larger scales than borehole measurements.

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