BROADBAND PROCESSING IMPROVES 4D REPEATABILITY AND RESOLUTION AT THE SLEIPNER CO2 STORAGE PROJECT, NORTH SEA

M. Wierzchowska[1], H. Alnes[2], J. Oukili[1], C. Otterbein[1]

[1] PGS; [2] Equinor

Summary

The Sleipner natural gas field situated in the Norwegian sector of the North Sea is the world's longest-running industrial-scale CO2 storage project. The CO2 injection commenced in 1996, inserting almost one million tonnes (1MT) of CO2 per year into the Utsira Fm. By 2020, over 18 MT of CO2 had been securely stored. The acquisition and processing used for Sleipner CO2 seismic monitoring program has evolved over several years in a successful and cost-effective monitoring program. Employing up-to-date processing technologies, including broadband solutions and 3D demultiple, has recently helped to reduce uncertainties in 4D interpretation and increased the resolution needed to reveal new details of the CO2 plume movement. Within the Utsira Fm., it is now possible to track some thin shale layers that can be important for predicting future growth of the CO2 plume. The deeper layers of CO2 are more well-defined. These have been historically difficult to interpret due to poor imaging in the previous 4D datasets.

Broadband processing improves 4D repeatability and resolution at the Sleipner CO2 storage project, North Sea

Introduction

The Sleipner natural gas field situated in the Norwegian sector of the North Sea is the world's longest-running industrial-scale CO2 storage project (Furre et al.,2017). The CO2 injection commenced in 1996, inserting almost one million tonnes (1MT) of CO2 per year into the Utsira Fm., a relatively shallow, up to 250m thick, saline aquifer (Figure 1). By 2020, over 18 MT of CO2 had been securely stored.

The rationale for the CO2 storage operation is the fact that the natural gas produced from the Sleipner Vest field contains about 9% CO2. This contamination must be reduced to less than 2.5 % for the gas to meet saleable specifications. Therefore, the CO2 is being separated from the natural gas and then re-injected into the Utsira Fm. The injection is done via a single deviated well. The injection point is located 1012m below the sea-level, and around 200m below the reservoir top. The overburden of the Utsira reservoir is around 700m thick, and consists of mudstones and clays with no major faulting (Figure 1).

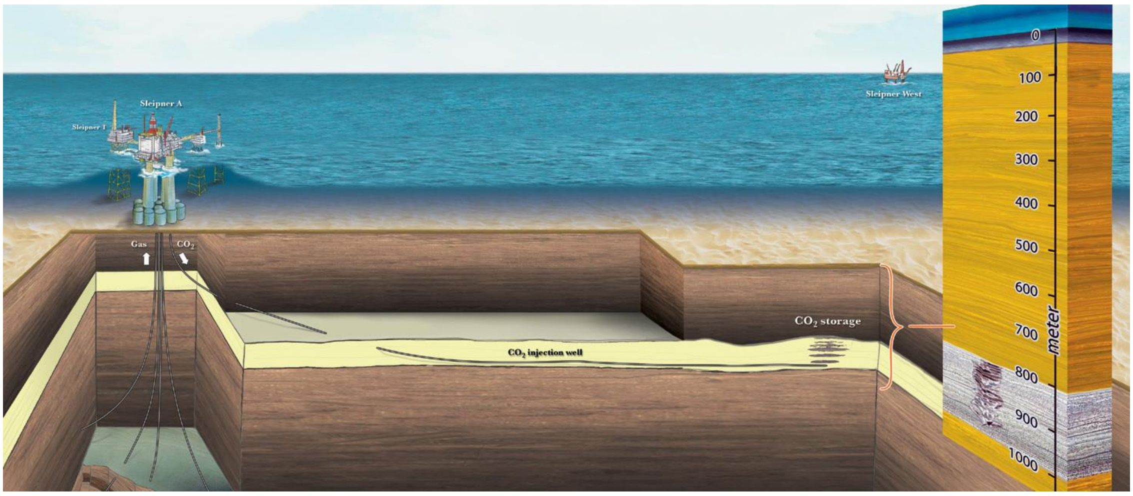

Figure 1 *Geological setting of the Sleipner CO2 storage area*

Cost efficient 3D on 3D seismic monitoring programme

The Sleipner CO2 storage project is regulated by Norwegian law. The monitoring program aims to track the storage performance, understand the CO2 migration and trapping mechanisms in the storage reservoir, and to monitor for any changes in the overburden. Since 1999, a comprehensive seismic monitoring programme has been carried out with ten 3D time-lapse (4D) surveys acquired. The 1994 baseline and the 2004, 2008 and 2020 monitor surveys have been used for the below analysis Table 1). The 2020 monitor survey was acquired with a multicomponent deep-tow streamer system.

Year	1994	2004	2008	2020
Direction	N-S	E-W	N-S	N-S and E-W
Streamer	conventional	conventional	conventional	multisensor
No of streamers	5	10	9	9
Streamer spacing (m)	100	37.5	50	50
Streamer depth (m)	8	8	8	15
Number of sources	2	1	2	2

Table 1 *Acquisition parameters of the 1994, 2004, 2008 and 2020 seismic surveys*

The 2016 analysis (not presented here) indicated migration of CO2 towards the western edge of the survey. Therefore, the 2020 acquisition was extended westwards to cover the nearby structural highs (Figure 2). This added complexity in processing as the platform hole around the Sleipner installations was significant, and had to be partially filled with east-west oriented lines from the 2004 acquisition.

Due to the strong response of the CO2 in Utsira Fm., and the short acquisition (lasting only a few days), all 4D seismic monitor surveys have been acquired with standard 3D specifications to avoid any significant added costs of reconfiguration. Thus, not fully optimized for 4D, these acquisitions came with some repeatability and fold of coverage challenges which had to be solved during the processing.

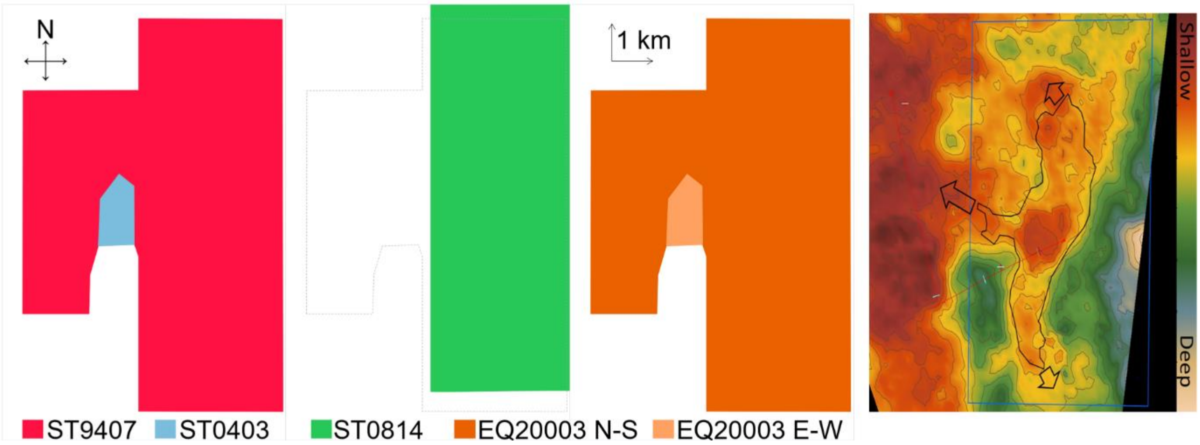

Figure 2 *Fold of coverage evolution in connection to the topography of the Top Utsira Fm. and the possible migration paths analysis. The black polygon is the 2016 CO2 plume extent. The arrows indicate the possible migration paths.*

4D processing to enhance the repeatability and the resolution

The latest 4D processing of the Sleipner CO2 data was carried out in 2020, and the legacy 2008 4D processing sequence was completely revised.

The benefits of the multisensor deep-tow streamer acquisition have been demonstrated for the Sleipner CO2 storage project; with improved broader frequency content compared to acquisition with conventional hydrophone-only cables (Furre et al., 2014). Higher resolution in the interpretation flow improved the ability to resolve small-scale structures in the CO2 layering. Fahimuddin et al. (2016) showed the value of deghosting conventional hydrophone-only data when it can be high-graded against the ghost-free upgoing wavefield data from a multicomponent towed-streamer survey. Therefore, the full broadband processing, performed at 2 ms sample rate, was expected to deliver more accurate amplitude and phase information through reduction of side lobes in the seismic wavelet, and increased resolution which may reveal new details of the movements in the CO2 plume.

Deghosting of the 1994 and 2008 vintages required an improvement in the handling of the low frequencies, especially during the designature processing step when trying to collapse the bubble effects. Any inaccuracies in designature may have minimal effect on 3D images, but manifests itself clearly on 4D differences as low frequency ringing, and later affects other processes such as demultiple (Anderson et al., 2017). The 2020 processing used ghost-free hybrid signatures instead of purely modelled far field signatures. Hybrid signatures combin information from measured near-field hydrophone data to improve the low frequency estimates, with modelled near-field data contributing high frequencies.

The 2020 processing utilized fully 3D demultiple processes as described by Barnes et al. (2015), consisting of seabed convolutional 3D SRME and 3D wavefield extrapolation SRME which were simultaneously subtracted, followed by muted 3D SRME to remove longer period multiples. This uplift in the demutiple sequence significantly improved the interpretability of the CO2 layers.

To compensate for the repeatability challenges coming from the monitor surveys having very different acquisition and coverage configurations, a pairwise 1994 vs. 2008 and 1994 vs. 2020 4D binning approach was chosen to give the optimum repeatability result for this multi vintage 4D project (Brain et al., 2013).

Furthermore, a merge of 1994 data into 2008 data on the western side helped reducing the migration impulse response 4D-noise coming from the lack of migration aperture data at the acquisition edges. The data merge was done carefully ensuring that there was no real 4D change expected between 1994 and 2008 in that western part of the project. A good understanding of the possible CO2 migration paths and the availability of a well-designed baseline survey area allowed the monitor survey to be quite compact.

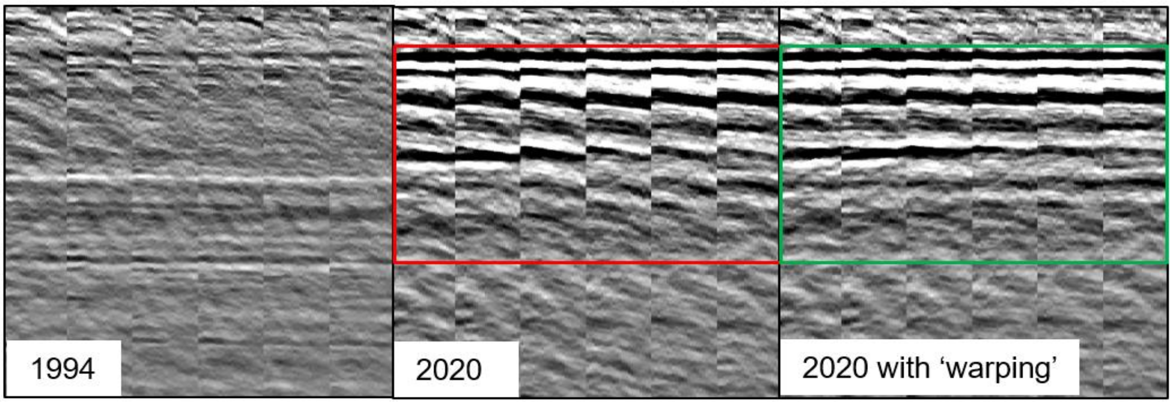

Figure 3 *1994 (left) and 2020 (middle) CMP gathers corrected with the initial stacking velocity field. 2020 (right) CMP gathers with the 'warping' velocity field showing the improvement of the gather flatness, separation, and delineation of the CO2 layers.*

The same velocity field was used to image the baseline and monitor surveys. To correct for the large interval velocity changes after CO2 injection, the picked 1994 residual moveout velocity field was modified to create individual fields for monitor vintages. This was done using a simplified 'warping' technique where time shifts between baseline and monitor surveys were calculated at a distinct reflector below the Utsira Fm. Based on that time shift, a velocity scalar was computed and applied to the CO2 layer. The 'warping' stacking fields improved the gather flatness within the CO2 plume, and resulted in a better stacking response and a better delineation and separation of the CO2 layers as presented in Figure 3.

Interpretation

CO2 at Sleipner accumulates in 9 interpretable layers. The most straightforward way of assessing the migration of the CO2 plume is to use the 4D difference datasets to track the development of the different CO2 layers (Figure 4). Vertical and horizontal resolution is therefore the key when relying on the 4D difference interpretation. In addition, the 4D time shift is an independent measure of CO2 distribution within the Utsira Fm.

In Figure 4, the new and old processing of the 1994 and 2008 datasets are compared. The uplift in the 2020 processing is evident. The base Utsira Fm. reflector and the underlying Skade Fm. is much better imaged (Arrow 1); in particular in the 2008 dataset. This allows for improved 4D time shift estimates. Within the Utsira Fm., it is possible to track some thin shale layers (Arrow 2) that can be important for predicting future growth of the CO2 plume. Finally, on the 4D difference, the deeper layers of CO2 are more well-defined. These have been historically difficult to interpret due to poor imaging in the previous 4D datasets.

Conclusions

The acquisition and processing used for Sleipner CO2 seismic monitoring program has evolved over several years in a successful and cost-effective monitoring program. Employing up-to-date processing technologies, including broadband solutions and 3D demultiple, has recently helped to reduce uncertainties in 4D interpretation and increased the resolution needed to reveal new details of the CO2 plume movement.

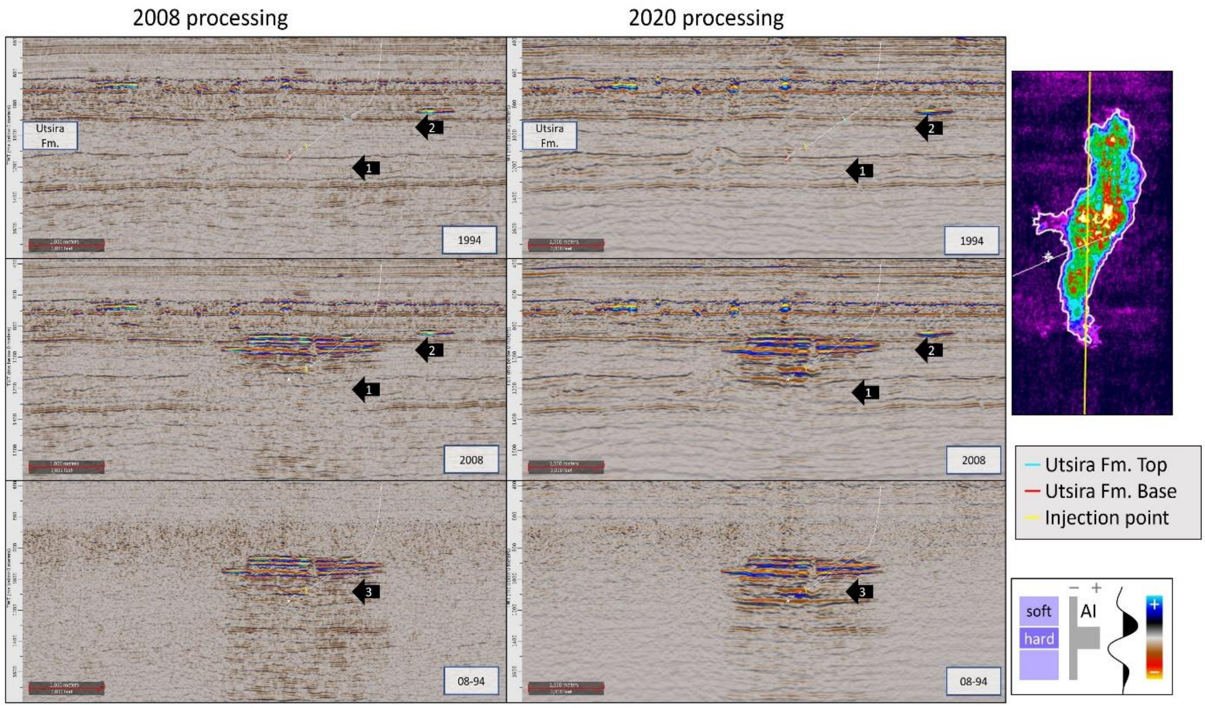

Figure 4 *A comparison of the 2008 (left) and 2020 (right) processing vintages. Baseline (top), monitor (middle) and 4D difference (bottom) from an inline through the injection point. The improved bandwidth of the 2020 processing leads to better imaging of base Utsira Fm. and the underlying Skade Fm. (Arrow 1), improved definition of intra-Utsira Fm. shales (2) and superior imaging of the deeper layers of the CO2 plume (3).*

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