A breakthrough in the imaging of a CO2 plume — using OBN data to the full

Vetle Vinje[1]*, Ricardo Martinez[1] and Phil Ringrose[2] demonstrate how a long-offset, wide-azimuth four-component OBN survey, in combination with Full-Waveform Inversion, can be used to produce detailed 3D images and a geobody of the Sleipner CO2 plume that can be used for quantitative analysis.

Introduction

Sleipnir is the eight-legged mythological horse of the Norse chief god Odin. Sleipnir could outrun any creature even across the sky and the sea. Sleipner is also an oil and gas field development project which includes the world-famous carbon capture and storage site in the North Sea located about 250 km west of Stavanger and the topic of this paper. Sleipner, one of the largest and longest-running carbon storage sites worldwide, has been very valuable as a ‘test lab’ for several monitoring technologies and CO2 flow simulation methods from the initial CO2 injection in 1996 until the present day. Excess CO2 from the Sleipner Vest gas field is constantly scrubbed from the natural gas production using the Amine MEA solvent capture process and injected into the shallow Utsira sandstone aquifer formation through a deviated well from the Sleipner A platform, delivering the CO2 in supercritical phase into the Utsira formation at a depth of around 1000 m. Almost 20 million tonnes have been injected during the last 29 years.

Geology and previous seismic surveys

The Utsira aquifer formation, hereafter termed the *storage unit*, is well suited for carbon storage due to its thick sandstone unit with high porosity (27-40%) and excellent permeability (several Darcy). The storage unit (800-1000m deep) is capped by a 50-100m-thick impermeable mudstone preventing further upward migration of the CO2. There are also several mudstone layers above this level, further adding to the long-term safety of the storage complex. The storage unit itself, although predominantly sandstone, contains several thin mudstone streaks usually less than a metre thick (Furre et al., 2024). This inhomogeneity within the storage formation acts to improve storage effectiveness and is the main reason for the complex flow pattern of the injected CO2 manifested as a total of nine identified layers of CO2 within the storage unit (Eiken et al. 2011, Furre et al., 2024, Martinez et al., 2024).

An extensive series of 4D seismic monitor surveys has been acquired over the Sleipner storage unit. Following the baseline survey prior to injection in 1994, ten monitor surveys (in 1999, 2001, 2002, 2004, 2006, 2008, 2010, 2013, 2016 and 2020) have been acquired by towed streamers with similar survey geometries (Furre, et al. 2024), all, except the 2004 survey, in a north-south direction. In addition, ultra-short streamer data (David et al, 2024a, Dehghan-Niri et al., 2024) and sparse node acquisition (David et al, 2024b) have been successfully tested

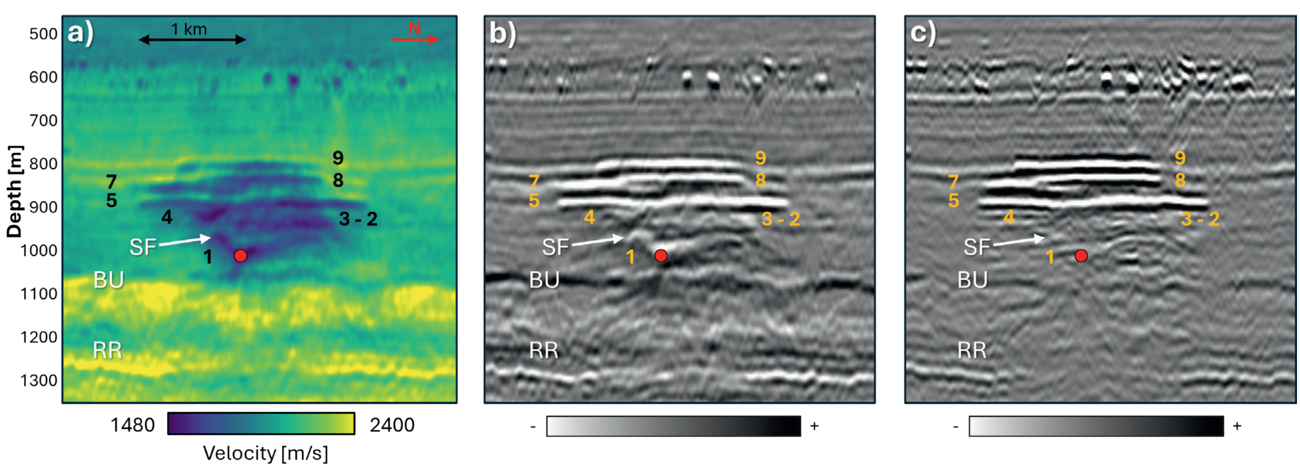

Figure 1 The nine layers of the plume imaged by the 2010 vintage streamer seismic. FWI velocity (a), corresponding FWI image (b) and legacy reflection-based PSTM (c) stretched to depth using the FWI model. The maximum frequency is 42 Hz. Notice the poor imaging of the deepest layers of the plume in the Legacy PSTM image.

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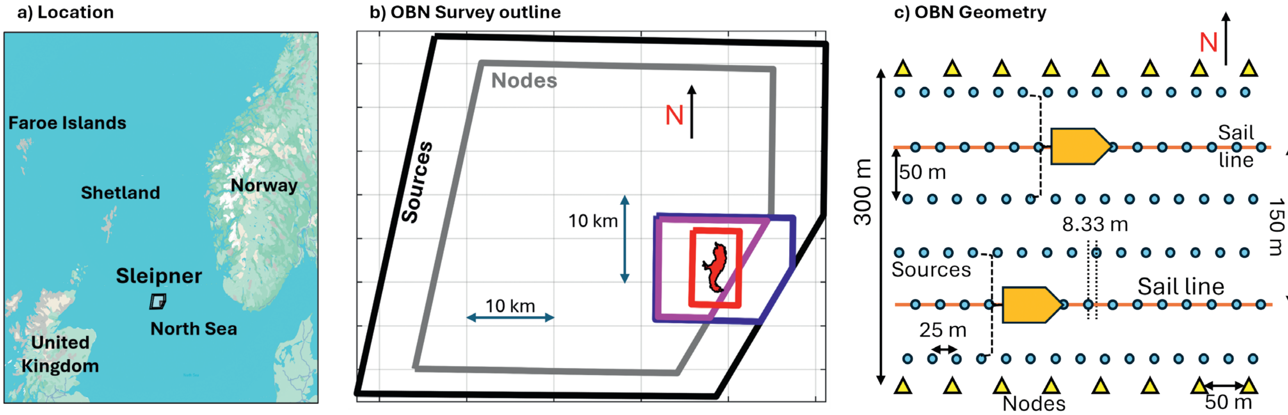

Figure 2 Regional-scale OBN data acquired over the Sleipner field (a); the node and source footprint (b); and the OBN survey geometry with triple-source shooting over the ocean bottom nodes (c). The outline of the CO2 plume is shown in red in (b).

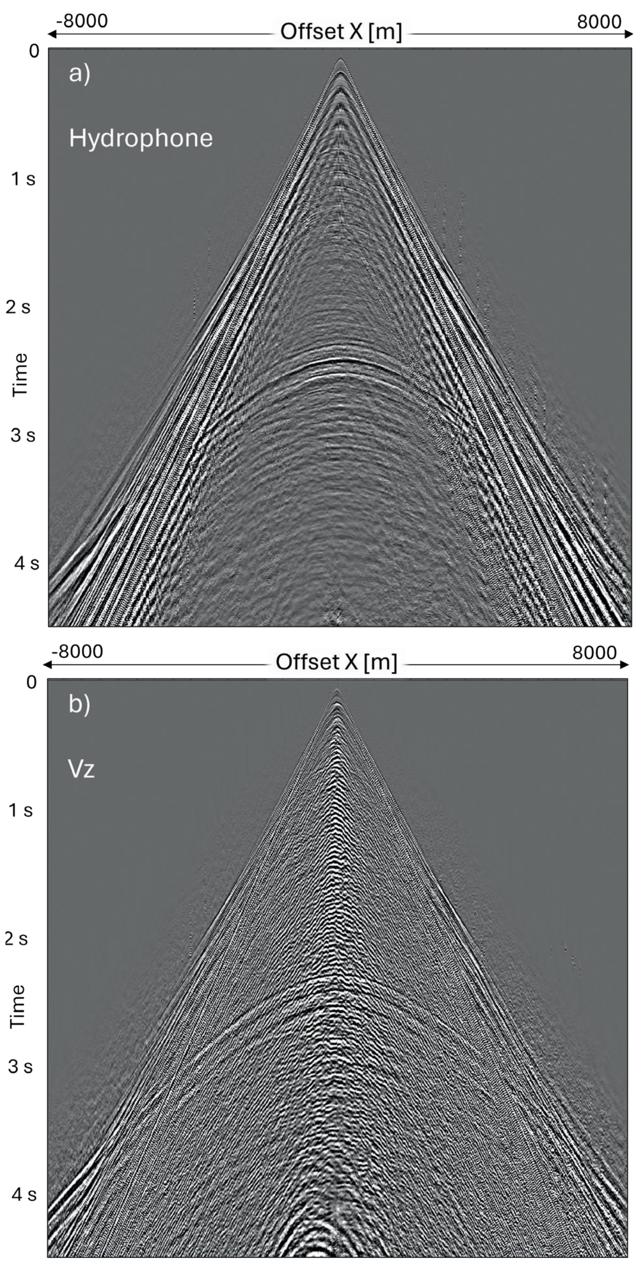

Figure 3 a) hydrophone receiver gather and b) vertical particle velocity (Vz) receiver gather.

as low-cost monitoring tools over Sleipner. As shown in many studies (e.g. Furre et al., 2024 and Martinez et al., 2025a), the injected CO2 is easy to spot on both 3D and 4D seismic images. During the 29 years of injection, the brine in the porous sandstone has been partly displaced by CO2 in a supercritical phase – a fluid with gas-like viscosity and a liquid-like density. It is compressible like a gas but has a density closer to that of water which leads to a significant reduction in seismic P-wave velocity, to even lower values than the velocity of seismic sound in water. The presence of CO2 therefore leads to a significant reduction in acoustic impedance which is why the CO2 is so clearly visible in seismic images.

The low seismic velocity in the CO2 plume is illustrated in Figure 1 a). This is from a Full-Waveform Inversion (FWI) (Martinez et al., 2025a), showing the plume in dark colours with seismic velocities down to 1480 m/s and lower. The FWI is based on the 2010 vintage streamer data with dual-source shooting in flip-flop mode into ten streamers, each 6 km long. In 2010, the total cumulative CO2 injection was 12.1 Mt (Norwegian Offshore Directorate, 2024), which means that the plume was less developed than it is today. Figure 1b shows the FWI image computed as a derivative using the relation of Zhang et al. (2020), which is comparable with Figure 1c showing the legacy Pre-Stack Time Migration (PSTM) image (shown in Furre and Eiken, 2014). Here, the PSTM image was stretched to depth using the FWI velocity and filtered down to the FWI frequencies. The red circle marks the CO2 injection point with the source feeder (SF) serving as the initial upward migration route for the CO2.

The nine layers of the plume, that were already developed and identified in 2010, are numbered from the deepest layer 1 to the uppermost layer 9 trapped against the top seal of the storage unit.

In FWI, the entire wavefield is used, including the multiples and the long-offset data traces. This improves the imaging of the deepest parts of the plume, compared to the legacy PSTM image in Figure 1c. In this image neither the source feeder (SF) nor the deepest layers 1 to 3 are clearly visible. In addition, the ‘shielding effect’ of the high reflectivity of the upper parts of the plume body obscures the imaging of the base of the storage unit (BU) and the deep regional reflector (RR) on the PSTM, while the complete inversion technique in FWI improves the imaging of these deeper units as well.

2023 Ocean Bottom Node survey

These insights convinced us that FWI is the preferred imaging technique for the Sleipner plume. FWI has been demonstrated earlier over Sleipner on streamer data (Mispel et al., 2019, Martinez et al., 2024, Martinez et al., 2025b) and on sparse nodes (David et al., 2024b). However, there is a need for improved data with better azimuth and offset coverage. All the 4D data acquired over Sleipner for the last 30 years has been done using narrow-azimuth towed streamers providing limited offset range and only measuring the acoustic P-waves detected by the streamers in the water.

In 2023, a golden opportunity presented itself to test FWI over the Sleipner carbon storage site using high-quality Ocean Bottom Node (OBN) data. During that summer, Viridien (then CGG) and TGS acquired a full-scale modern OBN survey over the entire Sleipner area, as shown in Figure 2. The grey polygon in Figure 2b shows the 1200 km^2 50 x 300 m four-component node layout area. The black polygon is the 25 x 50 m source carpet shot by a triple-source vessel. Figure 3 shows an example of a node gather from this survey with the hydrophone (a) and vertical particle velocity (b).

A state-of-the-art (acoustic) FWI algorithm (Zhang et al., 2018) was applied to invert for the P-wave velocity using the subset of sources and receivers within the blue and purple polygons in Figure 2 (b). This gives a full-azimuth data set with long offsets of up to 8 km. Horizontal and vertical cross-sections of the P-velocity volume from this FWI is shown in Figure 4. Following the approach described in Martinez et al. (2024), the initial velocity model was a smoothed regional model available in the area. The anisotropic delta and epsilon parameters were estimated from empirical relations using well-logging velocities and gamma-ray logs as shown in Martinez et al. (2024). The inversion honoured a two-layer Q model, with Q = 60000 in the water column, and Q = 180 in the sediments, which agrees with the regional Q model of Carter et al. (2020) for the Norwegian North Sea.

The inversion used the entire wavefield, including primary reflections, ghosts, multiples and transmissions. Moreover, the 4C recordings enabled the use of both the hydrophone (P) and the vertical particle velocity (Vz) data in the inversion. The inversion was run iteratively up to a maximum frequency of 70 Hz. Progressing the inversion beyond this frequency led to minimal improvement in the inversion.

Geobody extraction and volume estimation

The result of the FWI OBN analysis, shown in Figure 4, confirms that we can observe the same nine layers of the plume as in the 2010 vintage streamer seismic (Figure 1). However, since 2010 an additional 7 Mt of CO2 has been injected, bringing the total injected mass from 1996 to 2023 up to 19.1 Mt (Norwegian Offshore Directorate, 2024). Consequently, we observe an increase in the lateral extension of the layers of the plume, especially the upper ones. The maximum frequency of the seismic data in the plume zone (up to 70 Hz in this case) limits the resolution so that the FWI velocities will only show a low-pass version of the true velocity of the CO2 layers. This is illustrated in the synthetic traces in Figure 5 where five low-velocity (1480 m/s) anomalies of decreasing thicknesses are embedded

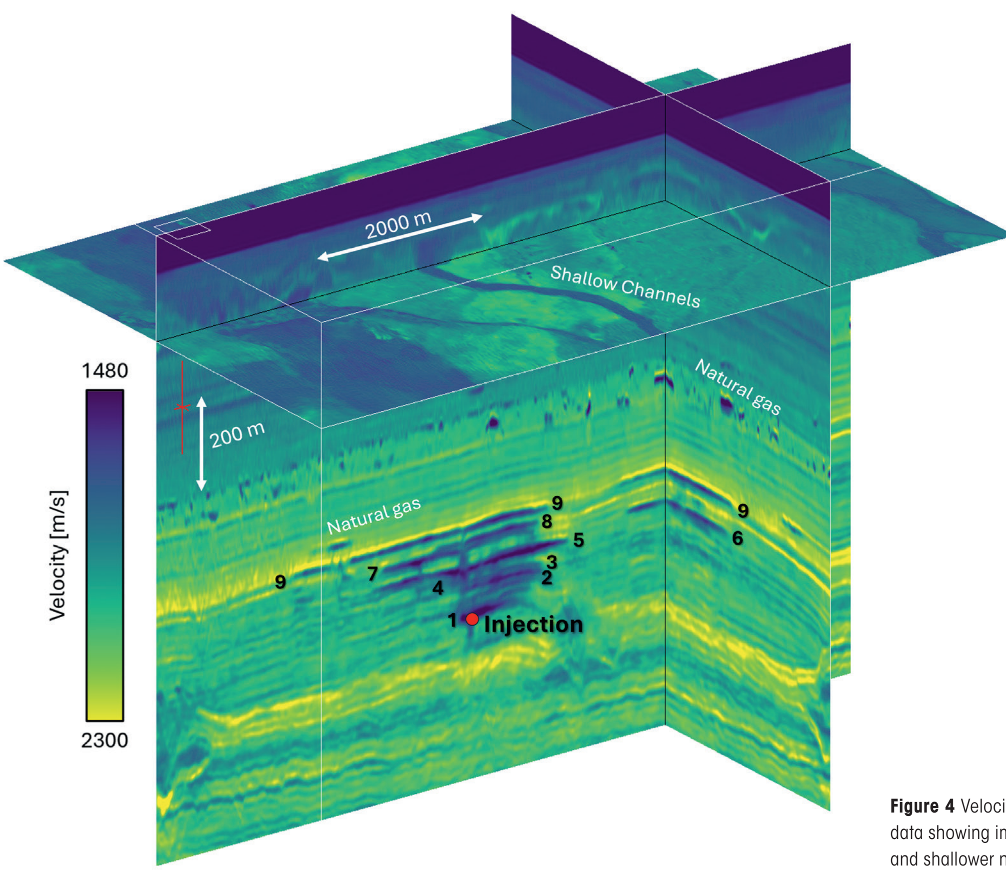

Figure 4 Velocity cube from FWI using the 2023 OBN data showing imaging of the multi-layer CO2 plume, and shallower natural gas pockets and channels.

in a 2045 m/s background. The 1480 m/s velocity represents CO_2-saturated sandstone in the storage unit while the 2045 m/s velocity is an estimate of the surrounding brine-filled sandstone. The true full-band velocity profiles are converted to the two-way traveltime domain where they are lowpass-filtered with a 70 Hz cutoff filter before being converted back to the depth domain. In Figure 5, the black curves represent the velocities in the true blocky layers, while the red curves are proxies for their lowpass-filtered versions, as present in the FWI.

Estimates of the CO_2 layer boundaries and the thicknesses of the layers are found by choosing the mean velocity value between 1480 and 2045 m/s, i.e. 1762.5 m/s. This value is indicated by the yellow circles on the red curves in Figure 5. We observe that for the 20 m and 10 m layers the thickness is correctly estimated. As the true layer thickness decreases towards 5 m we enter the tuning zone. For 5 m the layer thickness is overestimated. When the CO_2 layer gets even thinner, it eventually escapes detection, as for the 2 m layer. The minimum detection limit in this case is 3.5 m. We might hope that the lack of detection of the thin sub-3.5 m layers is compensated by the overestimation of the slightly thicker layers, but it is obvious that the band-limited nature of the seismic data also limits the accuracy in any thickness and volume estimations. Furthermore, the assumption of a constant velocity of 1480 m/s in the plume volume is a gross simplification. The real seismic velocity in the CO_2-saturated aquifer depends on many factors, including the pressure and temperature that varies throughout the plume (Nazarian and Furre, 2022). This illustrates the complexity and potential error bars in volume estimations of CO_2.

To extract a geobody from the complex plume, the 70 Hz FWI velocity in Figure 4 is first upsampled from 3.125 x 3.125 x 2 m to 1.5625 x 1.5625 x 1 m followed by a triangulation of the iso-velocity (V_{iso} = 1762.5 m/s) surface. This geobody is seen towards the north-west in Figure 6 and reveals many details of the CO_2 distribution, both as layers and feeders. The path of the deviated well from Sleipner Vest and the injection point are also displayed. The CO_2 plume is elongated along the north/south with a length of about 5 km, while the width in an east-west direction is around 1 km. There is a distance of about 250 m from the base of the geobody to the uppermost layer 9 which is trapped towards the upper seal at a depth of around 800 m beneath the sea surface. The source feeder at the base of the plume (SF, Martinez et al., 2025b) is massive while the vertical migration routes between the upper layers are more subtle. These vertical pathways are difficult to detect on conventional reflection seismic images, whereas, by using the

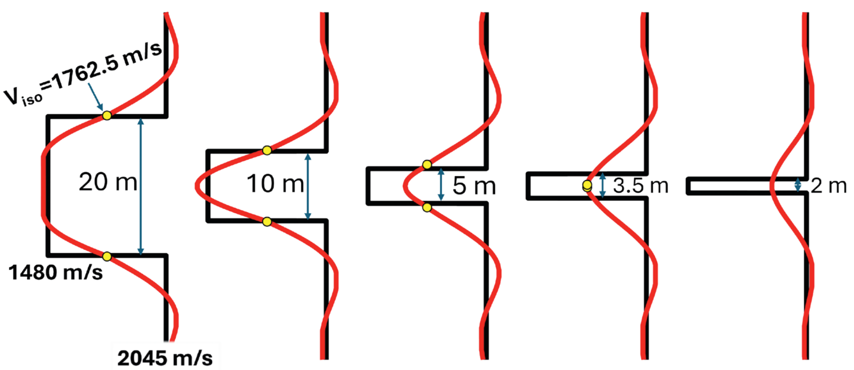

Figure 5 Five vertical profiles of low-velocity (1480 m/s) CO_2 layers with different thickness. The black curve shows the true layer, while the red curve is the low pass-filtered version of the layer using 70 Hz as the absolute cutoff. The velocity value 1762.5 m/s indicated by the yellow circles, is used to estimate the true CO_2 boundary.

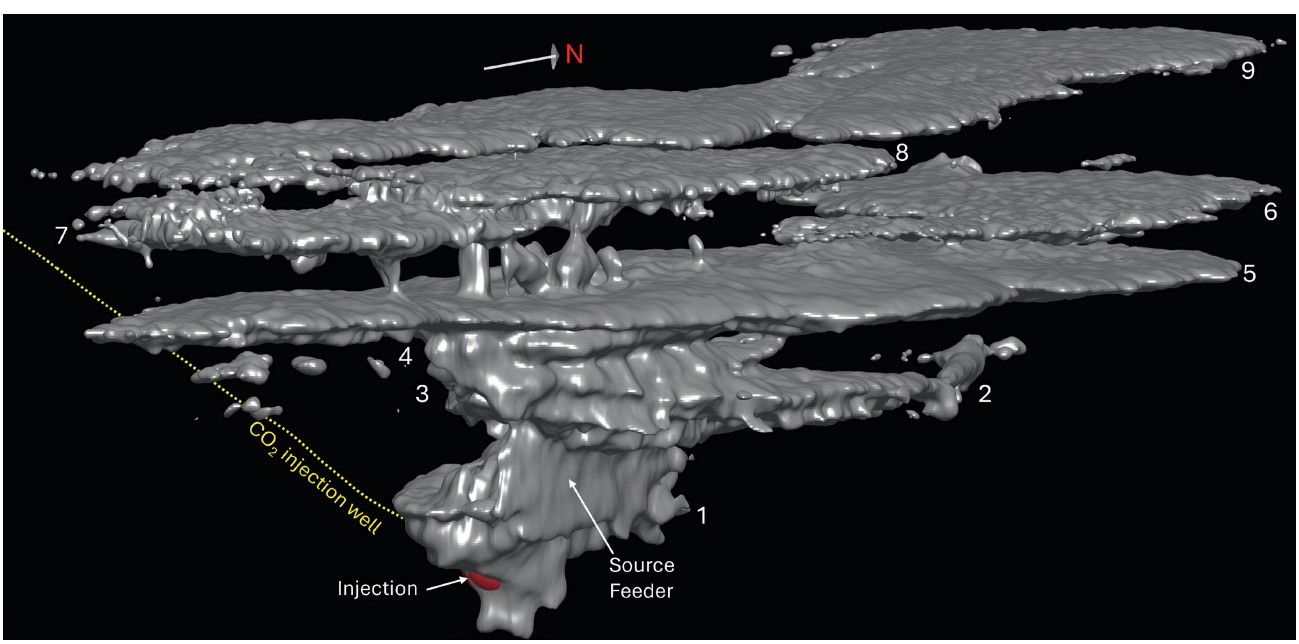

Figure 6 CO_2 plume geobody with the CO_2 injection well and injection point, the source feeder and the nine identified layers. The vertical is scaled up with a factor of five in the plotting.

complete wavefield in the FWI, we can map them much more clearly.

It is also possible to extract the volume of the geobody in Figure 6. We estimated the volume to be 144.8 million m^3 which is 0.1448 cubic km. This would fill a lake of 1000 x 1000 m to a depth of 144.8 m. Or it could fill about 58,000 Olympic swimming pools.

Volumetric measurements like these are valuable for estimations of the mass of CO2 in the Sleipner plume when it is used in combination with estimates of porosity, irreducible brine saturation and the in-situ density of CO2 (a subject of continuing research). They are also valuable for storage assurance, by helping to confirm that the CO2 remains within the storage complex, and for understanding flow mechanisms. These insights have important implications for future storage projects where storage capacities have to be estimated, and pore-space utilisation needs to be optimised.

Conclusions

We have demonstrated that a 2023 long-offset, wide-azimuth four-component OBN survey in combination with the latest version of Full-Waveform Inversion can be used to produce detailed 3D images and a geobody of the Sleipner CO2 plume that can be used for quantitative analysis. We furthermore demonstrate that we can estimate the volume of the CO2 plume quite accurately which gives a good basis for estimation of the mass of CO2 present in the plume (as a mobile dense phase). Mass quantification and phase determination using this geobody is the subject of ongoing research.

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