

Insights from Full Waveform Inversion at Sleipner

Philip Ringrose^a, Ricardo Martinez^{a,b}, and Vetle Vinje^b

^a Centre for Geophysical Forecasting, NTNU, 7491 Trondheim, Norway

^b Viridien, Lilleakerveien 6A, 0216 Oslo, Norway

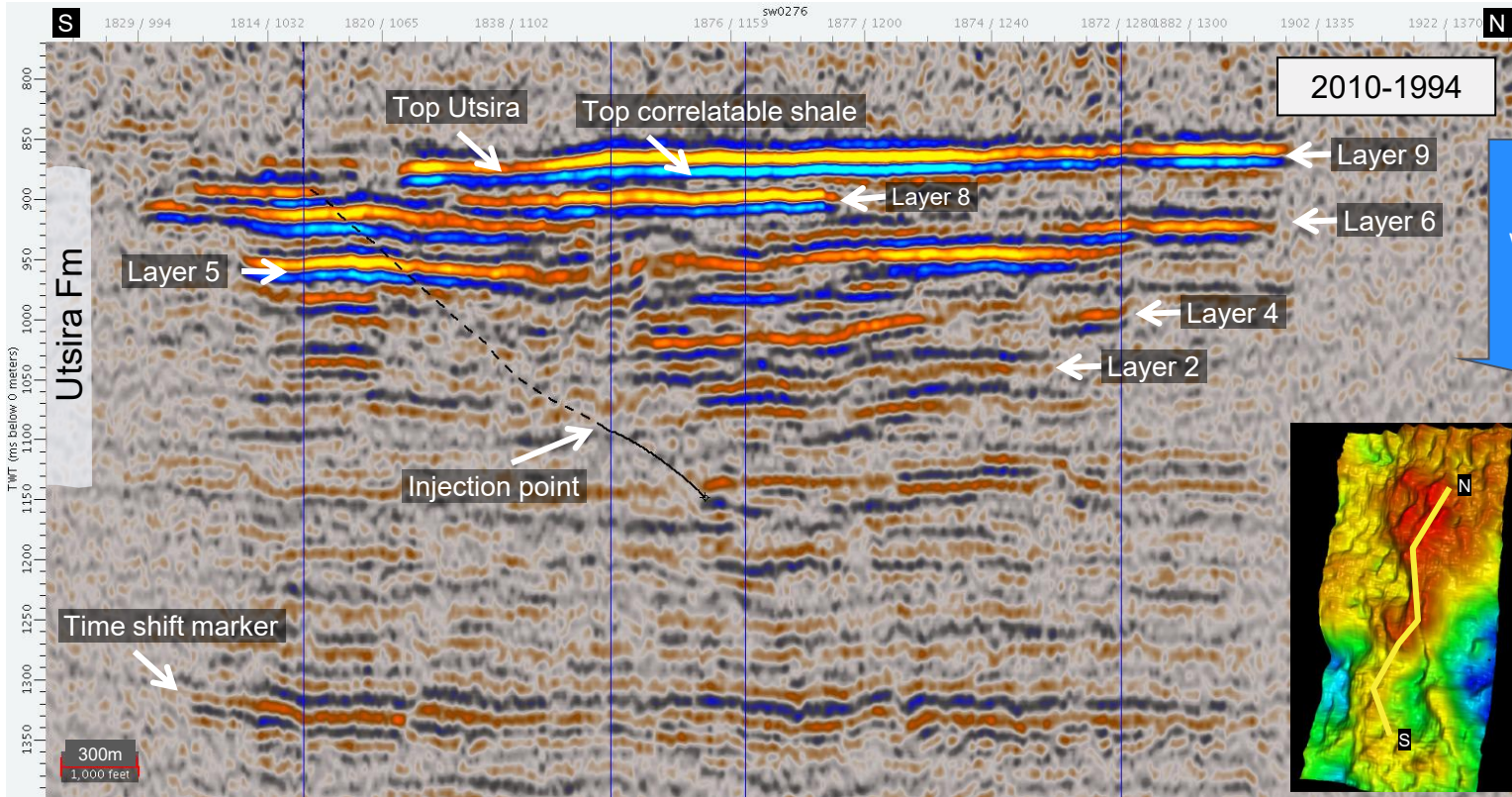
The logo for Viridien, featuring the word "VIRIDIEN" in a stylized font with a color gradient from purple to green.The logo for CGF, consisting of the letters "CGF" in a bold, sans-serif font.

SFI Centre for
Geophysical
Forecasting



International Workshop on Offshore Geologic CO₂ Storage, 20-21 April 2026, Bergen

4D seismic section at Sleipner (amplitude difference)



More challenging detection due to wave interference and velocity pull-down effects for deeper layers

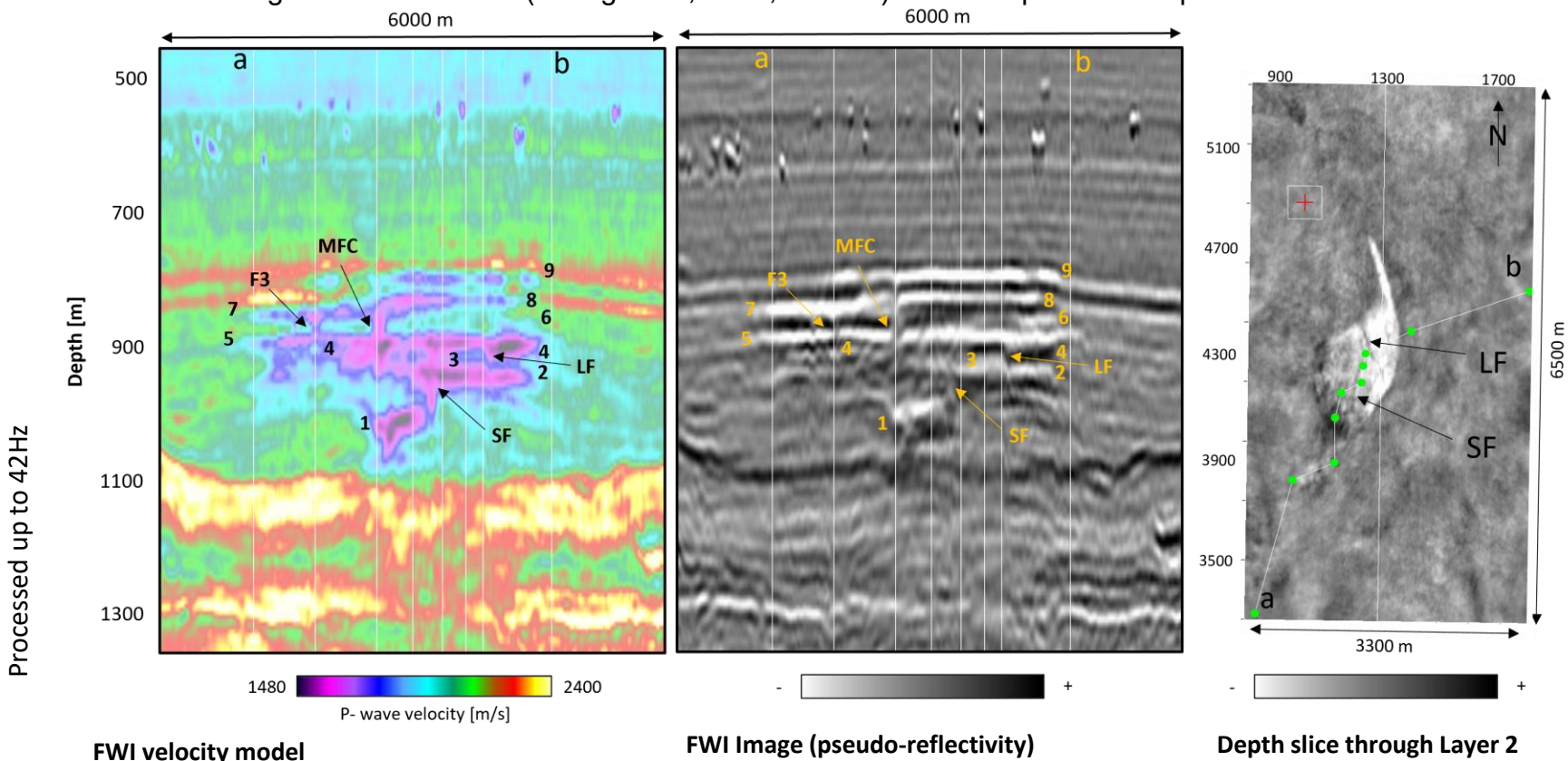
4D amplitude-difference data when comparing 2010 and 1994 surveys.

Modified from Furre et al. (2015). Data published with permission of the Sleipner Group of companies

FWI for CO₂ plume monitoring: 2010 dataset using time-lag FWI

Full-waveform inversion (FWI) of the 3D seismic data using 2010 marine-streamer acquisition (Martinez et al. 2025)

- Uses the Time-lag FWI cost-function (Zhang et al., 2018, Viridien) with data processed up to 42 Hz

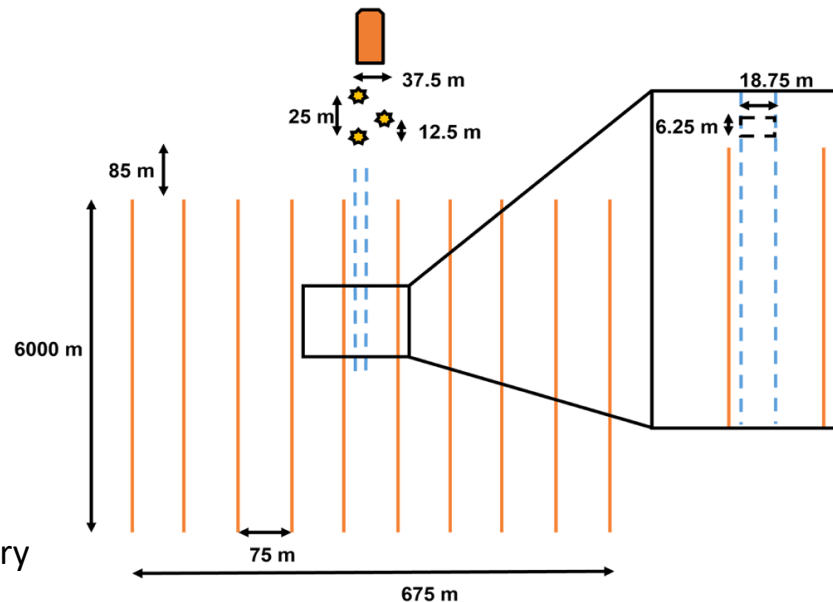


Time-lag acoustic FWI workflow summary

Martinez et al. (2025) study using 2010 marine streamer data

- Uses an acoustic, vertical transverse isotropic (VTI), finite-difference solution:
 - The anisotropy models for epsilon and delta were assumed to be 1D
 - Modeling used a reflective free-surface to capture the full-wavefield, including ghosts and multiples.
- 2010 acquisition parameters:
 - Source spacing = 37.5 m, cable spacing = 75 m
 - The shooting interval (flip-to-flip) = 25 m; receiver spacing = 12.5 m; **bin size = 6.25 × 18.75 m.**
 - The streamers are 6 km long, giving the longest offsets recorded at that time.
(Recent towed-streamer seismic has ~8 km max offset)

Sleipner 2010 acquisition geometry

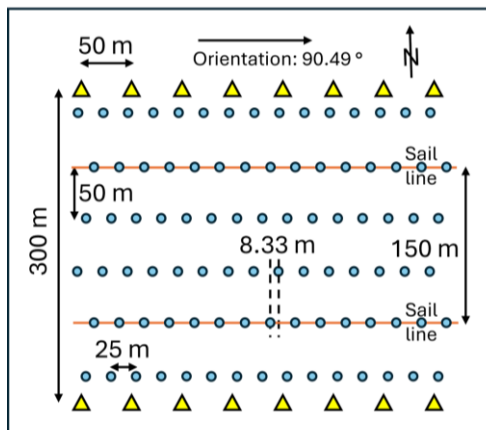


Latest FWI inversion of the CO₂ plume at Sleipner (2023 OBN data)

▲ OBN Receivers

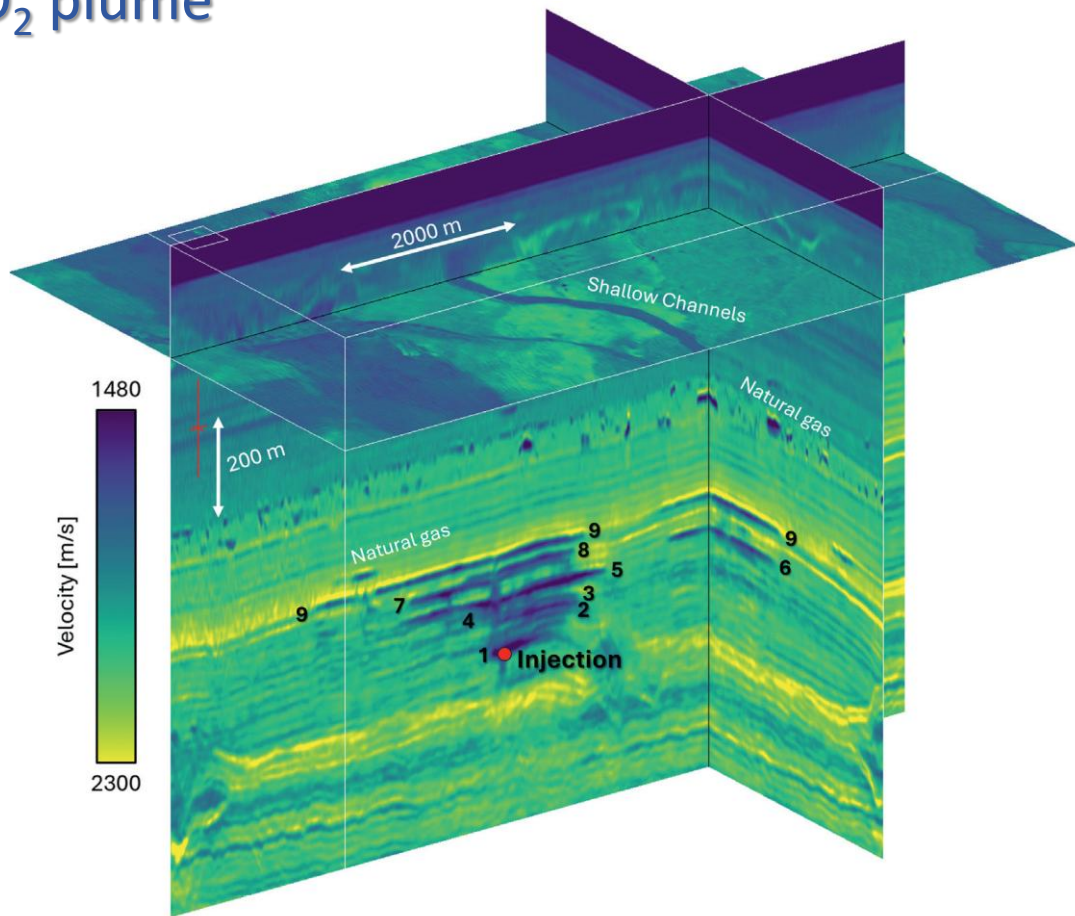
● Shots

Bin size =
12.5 × 25 m



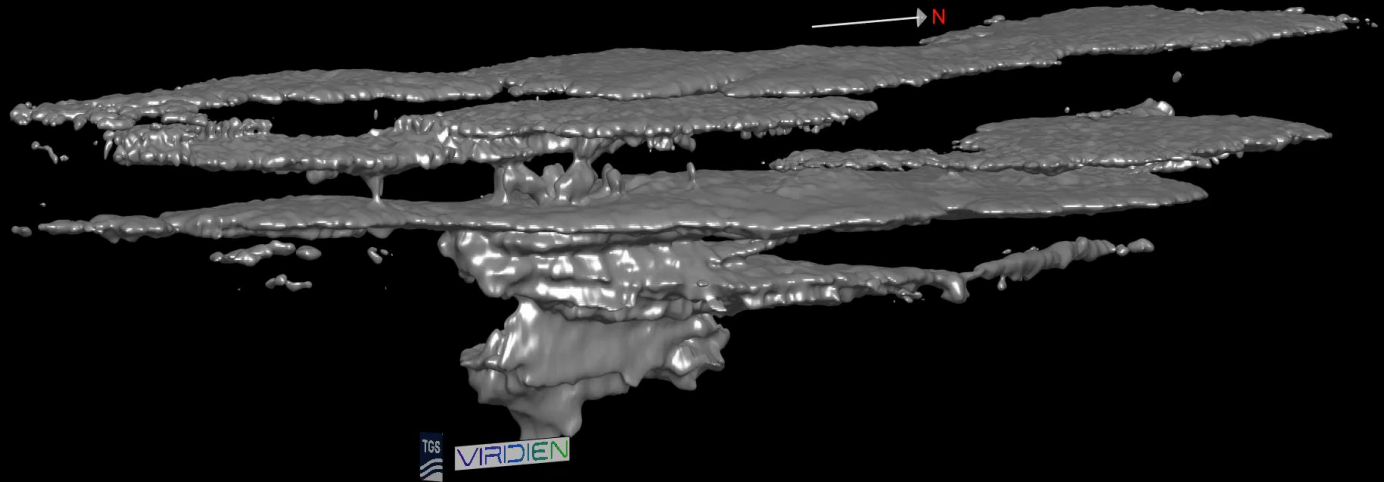
Velocity cube from FWI using the 2023 OBN data at Sleipner showing imaging of the multi-layer CO₂ plume, and shallower natural gas pockets and channels.

Vinje V, Martinez R, Ringrose P., 2025
First Break. 43(6):83-7.



Latest FWI inversion of the CO₂ plume at Sleipner (OBN data)

From Martinez, R. et al. (2026), *Interpretation*, and Vinje, V. et al (2025), *First Break*



Iso-velocity model (1762.5 m/s) of the CO₂ plume at Sleipner 2023

Derived from FWI analysis the 2023 4-component OBN 3D seismic survey acquired by TGS and Viridien

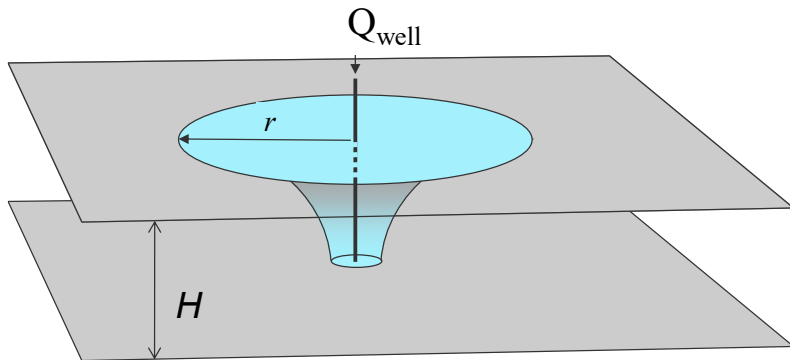
Processed up to 70Hz

Estimating the distribution of CO₂ from seismic data

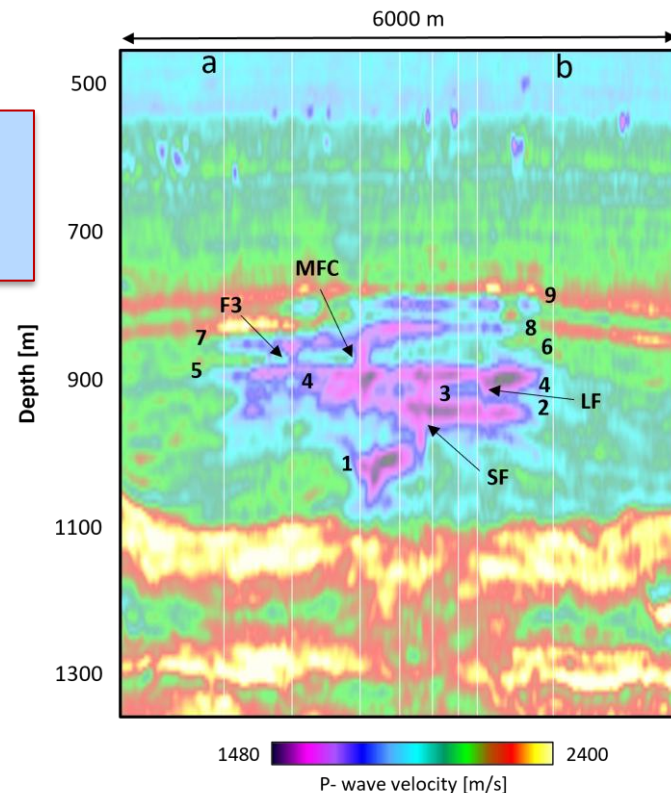
- We can apply a series of CO₂ storage efficiency coefficients using the geometry data from seismic

Viscous dominated analytical solution
(Nordbotten & Celia, 2006)

$$r_{max} = \sqrt{\frac{\lambda_c}{\lambda_b} \frac{Q_{well} t}{\pi H \phi (1 - S_{bir})}}$$



From velocity
model to fluid
distribution

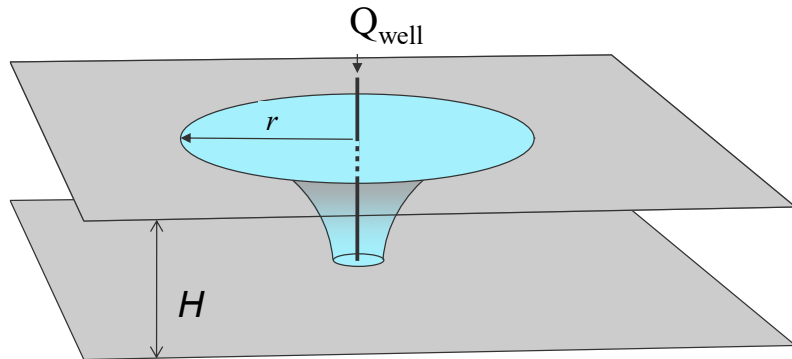


Estimating the distribution of CO₂ from seismic data

- We can apply a series of CO₂ storage efficiency coefficients using the geometry data from seismic

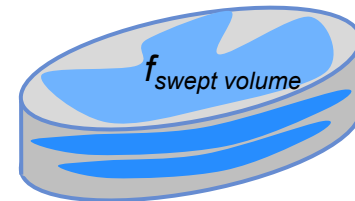
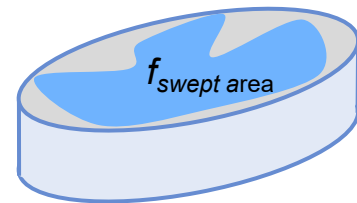
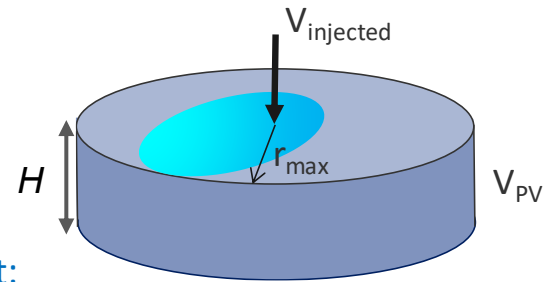
Viscous dominated analytical solution
(Nordbotten & Celia, 2006)

$$r_{max} = \sqrt{\frac{\lambda_c}{\lambda_b} \frac{Q_{well} t}{\pi H \varphi (1 - S_{bir})}}$$



CO₂ storage efficiency coefficient:

$$E_c = \frac{V_{injected}}{V_{PV}} = \frac{Q_{well} t}{\varphi H \pi a b}$$

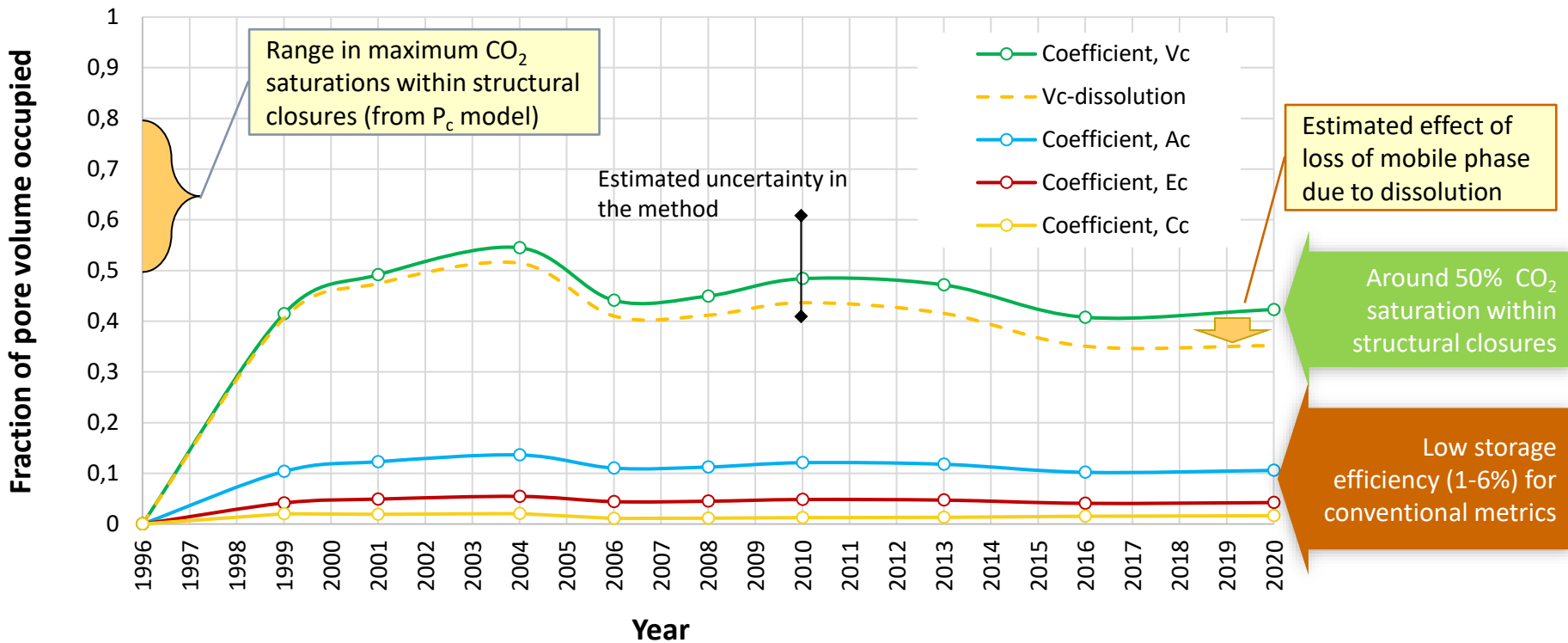


E_c scaled by swept area
or swept volume

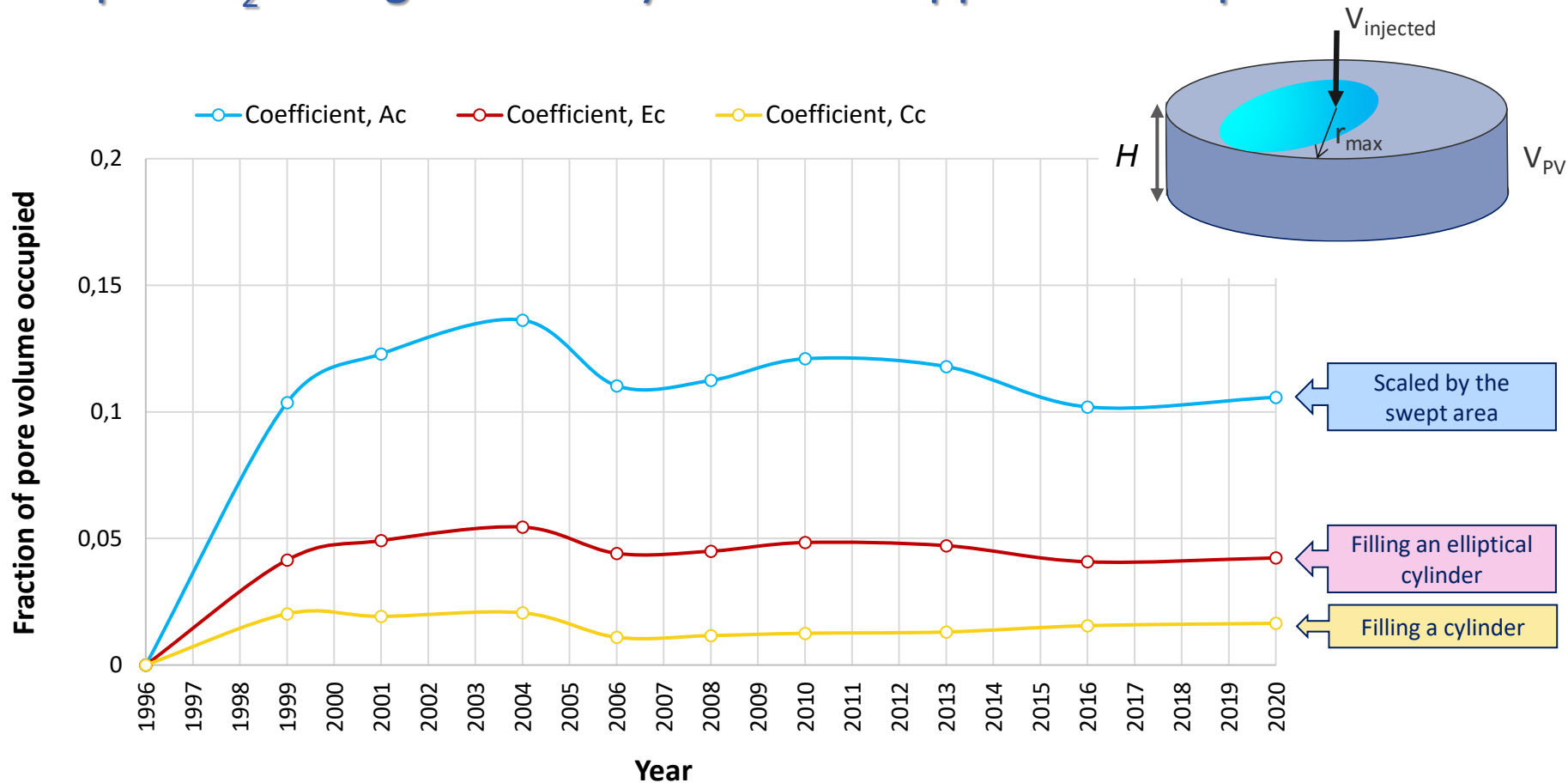
$$V_c = \frac{Q_{well} t}{\varphi H \pi a b} \frac{1}{f_{vol}}$$

Results for the whole plume analysis

Ringrose et al. 2026, Estimating the Multi-Scale Distribution of CO₂ Using Seismic Data at Sleipner. IJGGC



Simple CO₂ storage efficiency measures applied to Sleipner



CO₂ saturation at the pore scale

Pore-scale saturation will be controlled by the capillary pressure function (under gravity-capillary equilibrium):

$$P_c = C\gamma S_e^{-\frac{1}{\lambda}} \left(\frac{\phi}{k}\right)^{\frac{1}{2}}$$

We can then estimate the saturation for different CO₂ column heights:

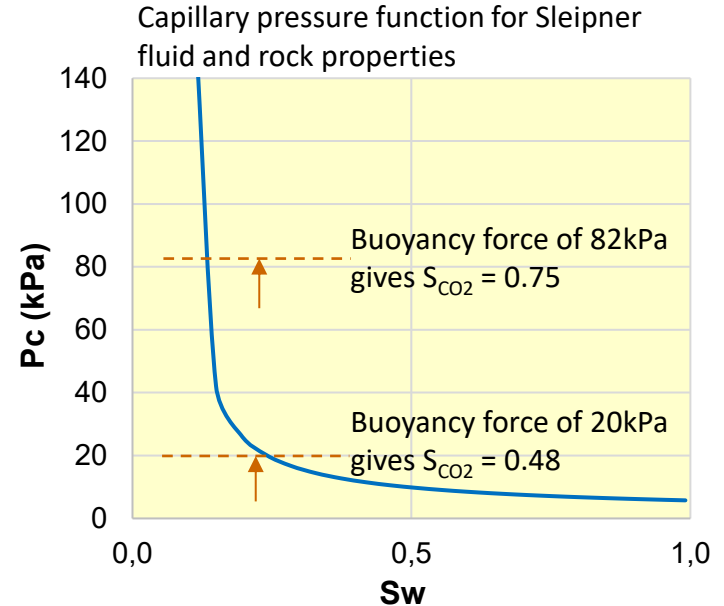
- 5m thick column has **S_{CO2} = 0.48**
- 20m thick column has **S_{CO2} = 0.75**
(CO₂ density assumed to be 600 kg/m³)

These are maximum estimates assuming no internal heterogeneities and a gravity-stable state.

This also gives us an analytical relationship between layer thickness and saturation

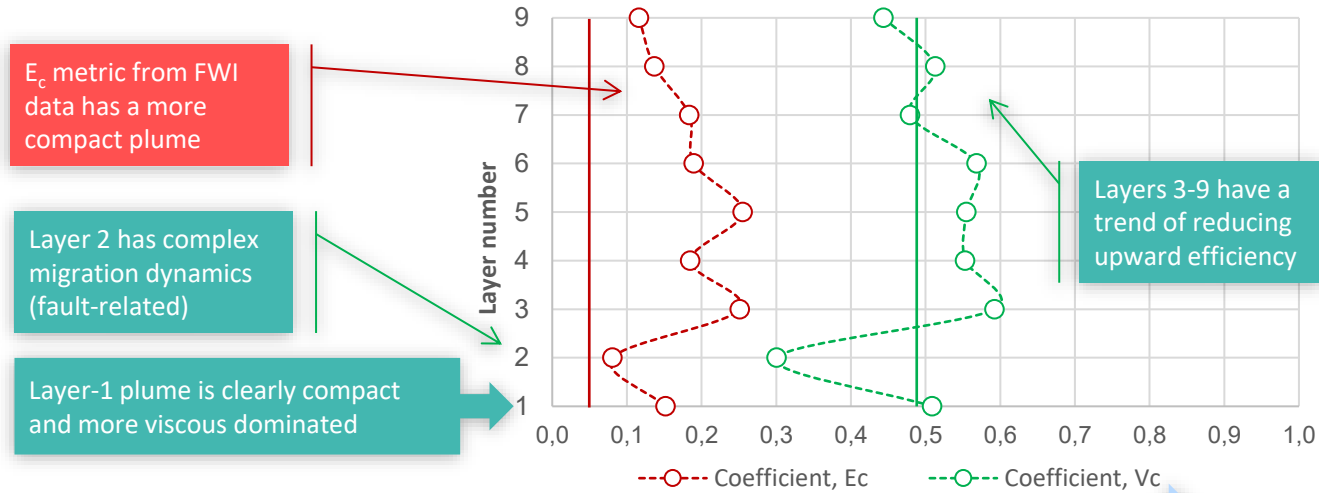
$$S_e \propto \frac{1}{\sqrt{h}}$$

Useful for quantitative seismic inversion



Results using the 2010 FWI 3D velocity model

Estimates for E_c and V_c from the FWI-based analysis are consistent with the whole plume analysis but reveal the nature of the layer-by-layer trends.



Layer-1 plume is clearly compact and more viscous dominated

Layer 2 has complex migration dynamics (fault-related)

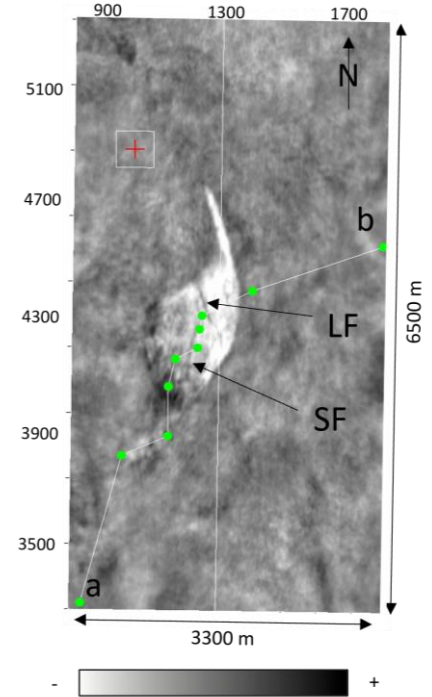
E_c metric from FWI data has a more compact plume

Layers 3-9 have a trend of reducing upward efficiency

FWI-velocity model reveals layer-by-layer trends showing:

- Viscous-forces quickly decay, followed by gravity-dominated migration
- Feeders and faults (detected by FWI) play an important role

Depth slice through Layer 2



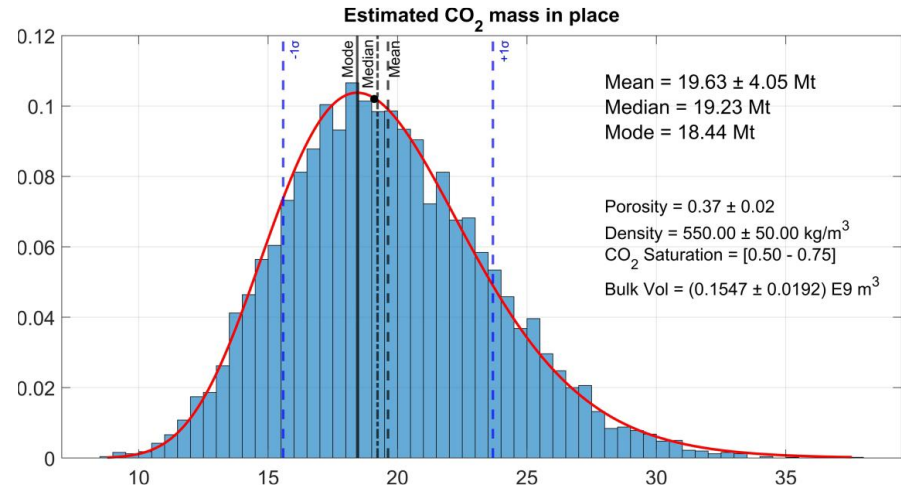
Mass in place estimate from the 2023 OBN FWI dataset

- Reference velocity model gives a **CO₂ volume estimate of 145 million m³ = 0.145 km³**
- Allowing for uncertainty in the velocity cut-off, we get: $V_{CO_2} = 0.155 \times 10^9 \pm 0.019 \times 10^9 \text{ m}^3$
 - We assume an average porosity of $\phi = 37 \pm 2 \%$ (core and well data)
 - For CO₂ saturation in the plume, we assume S_{CO_2} varies between 0.5 and 0.75 (from the P_c model)
 - We assumed an average CO₂ density of $550 \pm 50 \text{ kg/m}^3$ (gravity data and thermal modelling)

- The resulting mass = $19.63 \pm 4.05 \text{ Mt}$
- Compares with reported mass of: **19.1 Mt CO₂ injected by August 2023**

Since we know the mass injected, we can also estimate that **S_{CO₂} is between 0.38 and 0.65** (in the 'velocity object' detected by FWI).

From Martinez, R. et al. (2026), *Interpretation*



Summary

1. Many benefits from applying FWI for imaging the multi-layer CO₂ plumes at Sleipner:
 - Discovery of new feeders and confirmation of other feeders and small accumulations that were suspected from previous 4D reflection studies
2. FWI using a dense, full azimuth, 4C OBN survey acquired in 2023, shows:
 - High-frequency FWI can bring significant value for improved conformance monitoring
 - Provides estimates of the CO₂ bulk volumes/mass in place.
3. Pore-volume occupancy analysis shows that:
 - The macroscopic storage efficiency at Sleipner is in the range of 1-6%
 - The CO₂ saturation within each filled layer is in range of 30% to 60%.
4. Analysis of the FWI-velocity model reveals layer-by-layer trends showing:
 - Viscous-forces quickly decay, followed by gravity-dominated migration
 - Vertical feeders play an important role (faults and sedimentary features)
5. These insights have the potential to significantly improve the quantitative analysis of seismic data used for monitoring CO₂ storage sites.

Acknowledgements

- Funding from the Norwegian Research Council (NRC) via the 'Research-based Innovation' (SFI) Centre for Geophysical Forecasting (CGF) (grant no. [309960](#)).
- Viridien and TGS for FWI software and access to the 2023 OBN seismic dataset
- Equinor and the Sleipner license partners for the Sleipner CO₂ Reference datasets



Main references

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