Quantitative analysis of CO_2 saturation at the Snøhvit field from analytical solutions and time lapse seismic data

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BIGCCS International CCS Research Centre

Statoil

NTNU – Trondheim
Norwegian University of Science and Technology

Objective

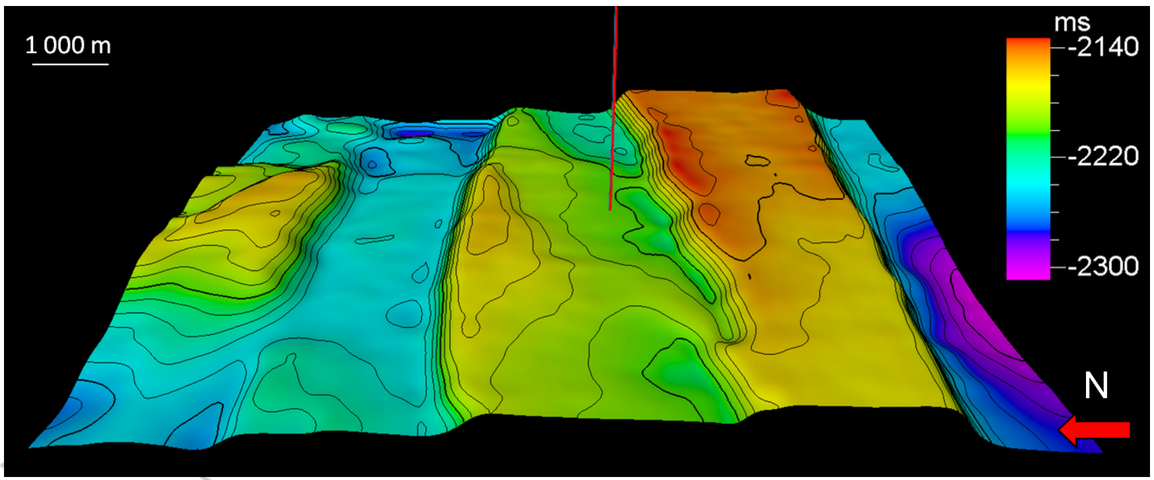
Quantify initial 400 ktons of CO_2 injected in the Tubåen 1 sand layer based on analytical solution and two time lapse seismic methods

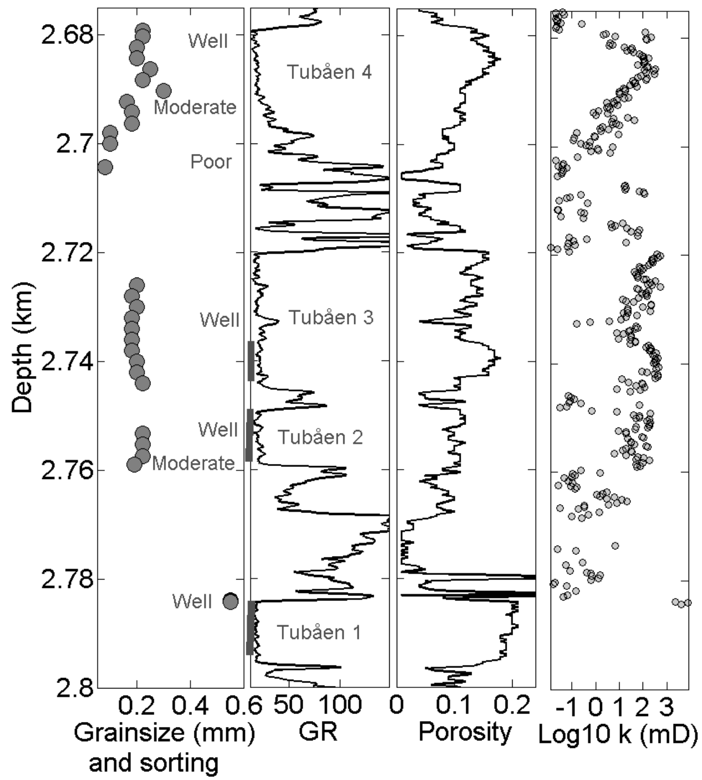
Outline

- Reservoir fluid flow
- Analytical estimate of CO_2 plume
- CO_2 plume quantification from time lapse seismic data
  - Inverted from amplitude versus offset (AVO)
  - Spectral decomposition
- Conclusions

Tubåen formation, Snøhvit field

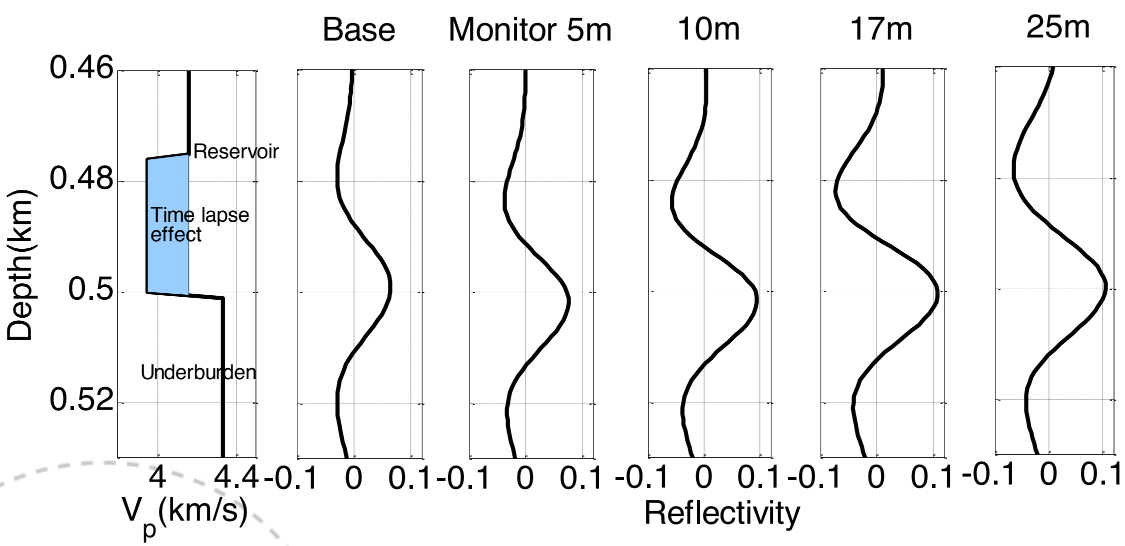
- Faults East-West, injection zone ~2 500 m wide
- 2.67 km depth, ~110m thick
- 500 ktons injected from April 2008 to Sept 2009
- Tubåen 1-4 sand layers, separated by shale
- CO_2 migrated into Tubåen 1 sand (80%), and Tubåen 2 and 3 sand layer (20%)
- Will focus on the Tubåen 1 sand layer

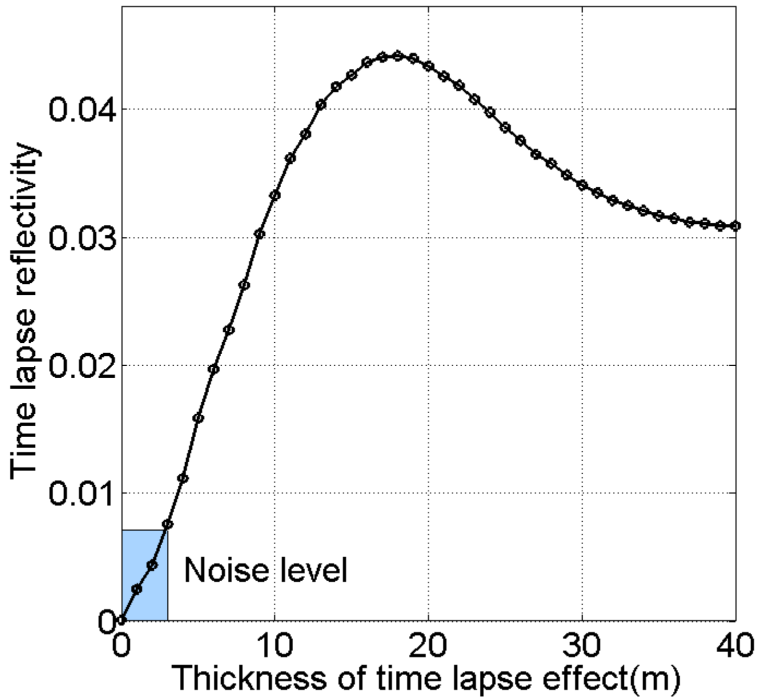




Time lapse reflectivity and noise level

- 1D Synthetic seismograms for increasing thickness of time lapse effect
- Time lapse seismic reflectivity noise level approximately 0.007
- CO_2 layer above ~3m detectable





Multiphase CO_2 flow on a short time scale

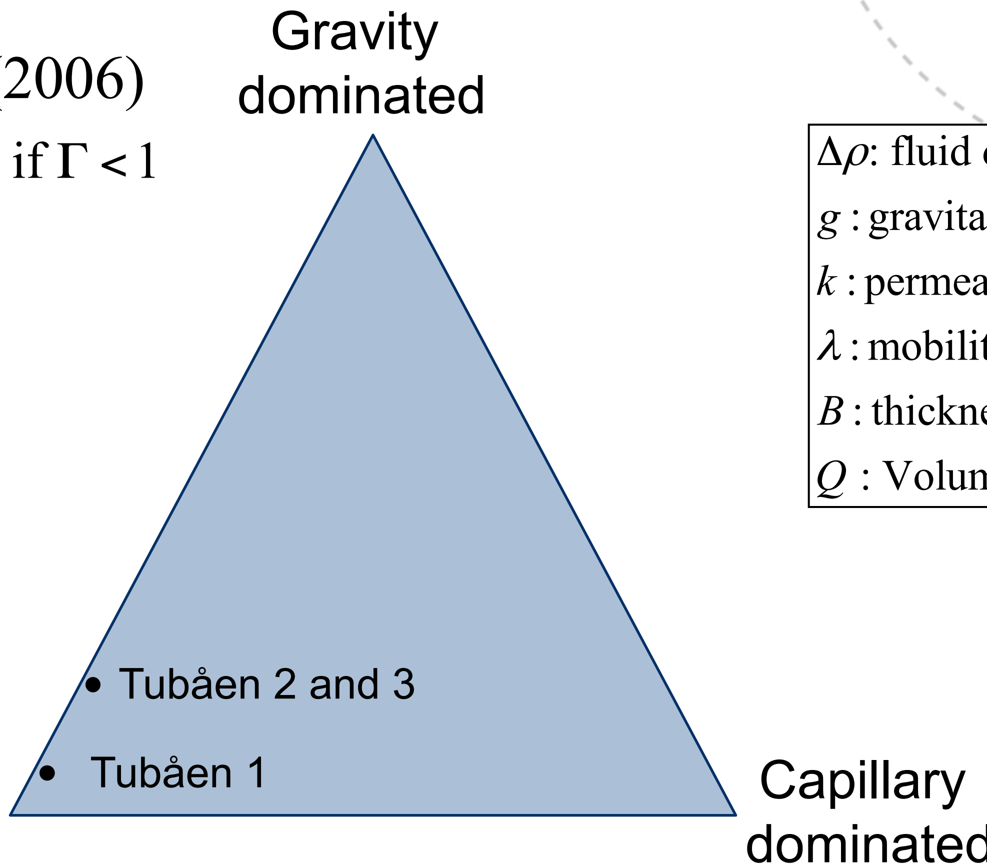
Nordbotten & Celia (2006)

Gravity factor: Ignorable if $\Gamma < 1$

$$\Gamma = \frac{2\pi \Delta\rho g k \lambda_b B^2}{Q_{well}}$$

Mobility ratio:

$$\lambda = \frac{\lambda_{CO2}}{\lambda_{Brine}}$$

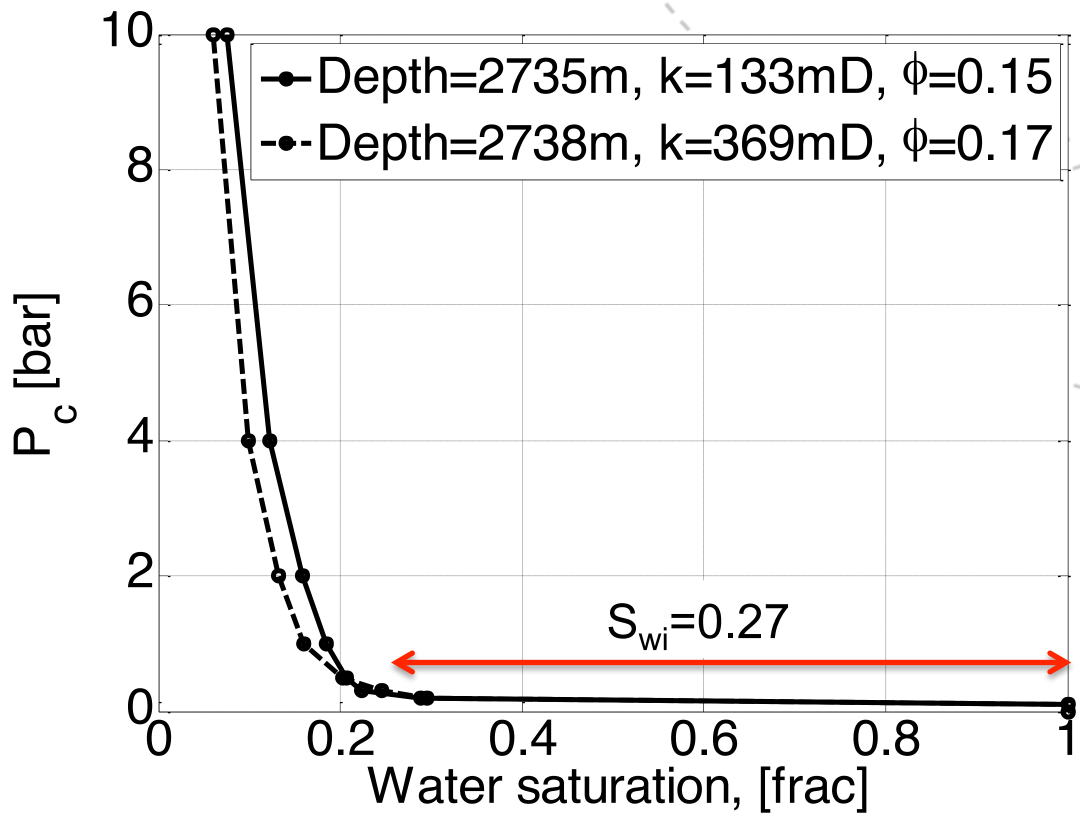


$\Delta\rho$: fluid density difference
g : gravitational acceleration
k : permeability
λ : mobility
B : thickness of formation
Q : Volumetric flow rate

Modified from Philip Ringrose's presentation at the CLIMIT & BICCCS PhD Seminar

Capillary pressure

- Laboratory measurements on core plugs from the Tubåen 3 sand layer (courtesy Statoil)
- Low capillary entry pressure
- Low capillary pressure at residual water saturation



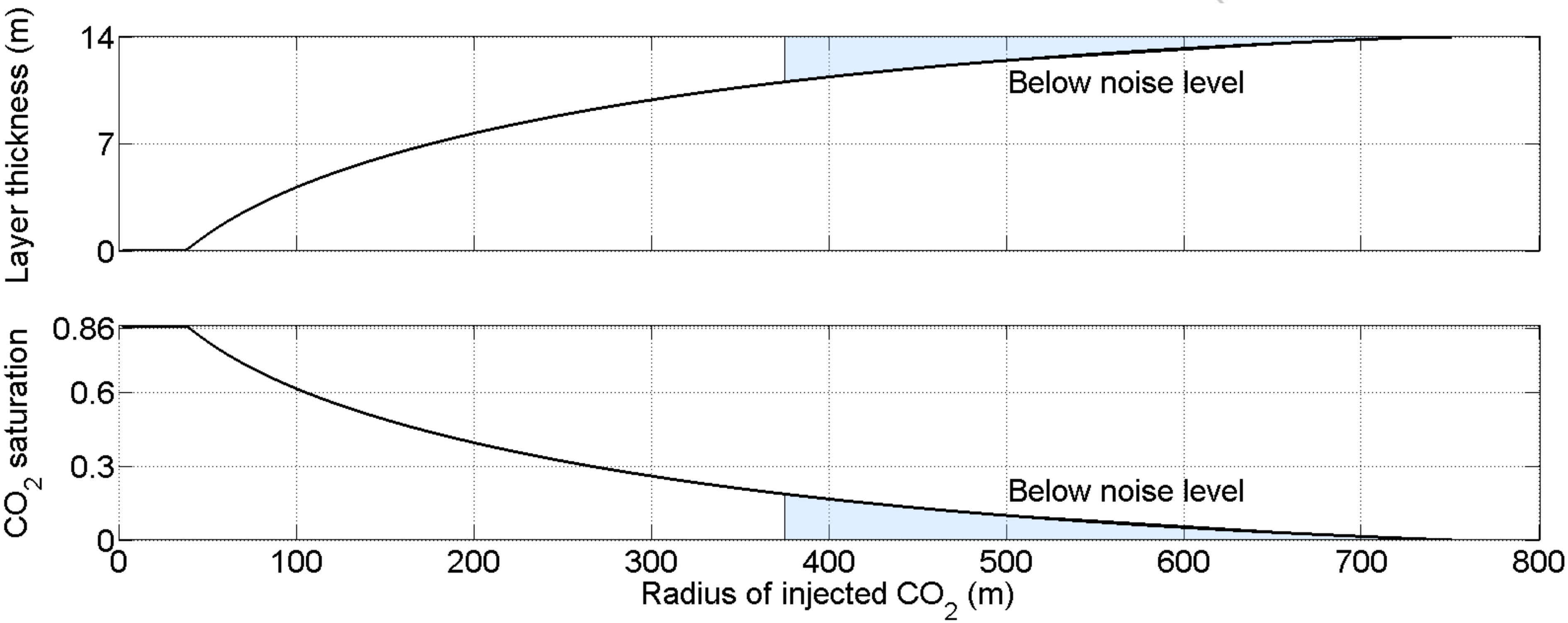
Analytical estimate of the CO_2 plume

		Tubåen 1	
Thickness	h	14	m
Porosity	Φ	0.19	fraction
Permability	k	750	mD
Relative permeability of CO_2	$k_{r,CO2}$	0.7[1]	fraction
Residual water saturation	S_{wi}	0.13 [2]	fraction
Injected volume	$Q \times t$	400	ktons
Mobility ratio	λ	6	
Gravity factor	Γ	0.6	

[1] No laboratory measurement available from Tubåen 1. Based on comparison with laboratory measurements of the relative permeability on three composite cores from 2735m measured depth (mD) and published literature (Bennion and Bachu, 2008)

[2] Estimated from (Sengupta, 2000)

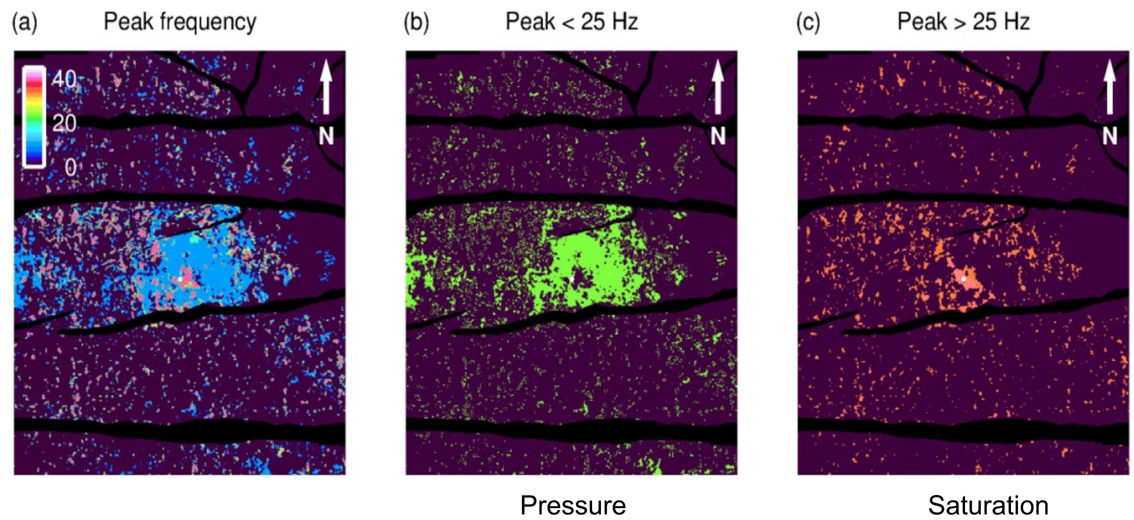
Analytical estimate of the CO_2 plume

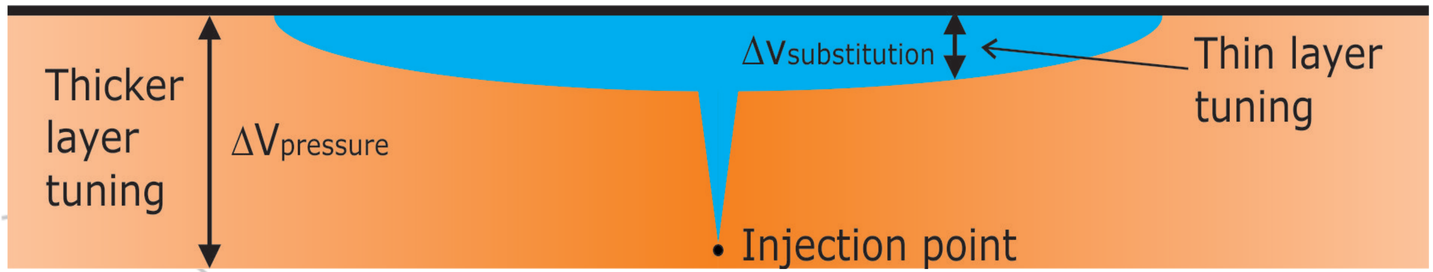


Link saturation vs thickness: CO_2 Layer thickness $= 16 \cdot S_{CO2,effective}$

Pressure-saturation discrimination from spectral decomposition

- Assume CO_2 thin layers, pressure more extensively
- Different vertical extents tune different frequencies in seismic wavelet
- 25 Hz cut-off separate the pressure and saturation changes

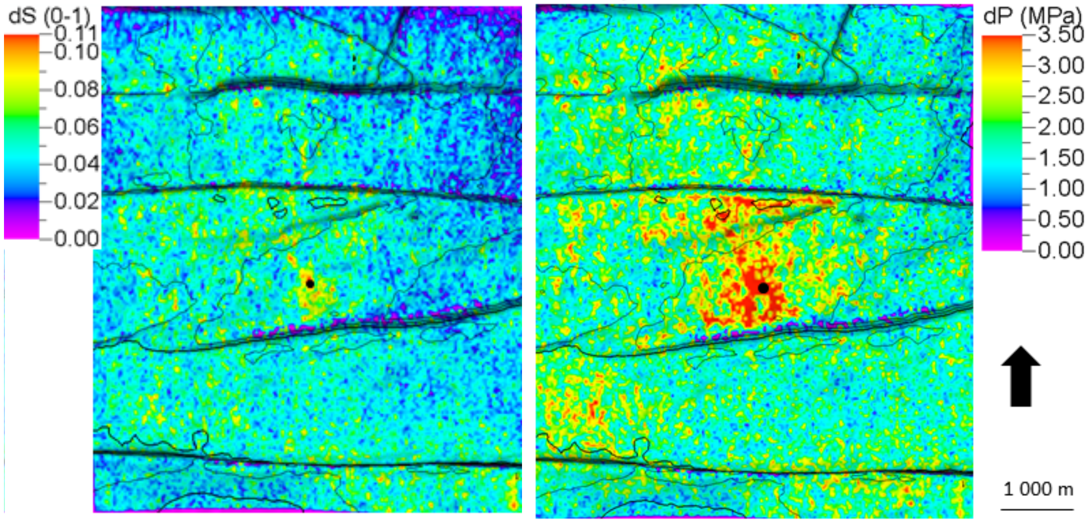


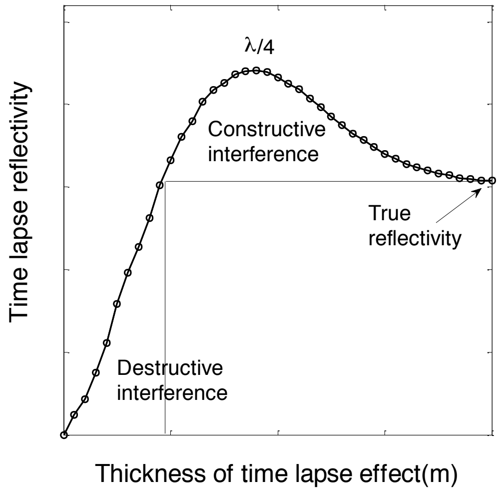


White et al., 2014

Pressure-saturation discrimination from time lapse AVO seismic

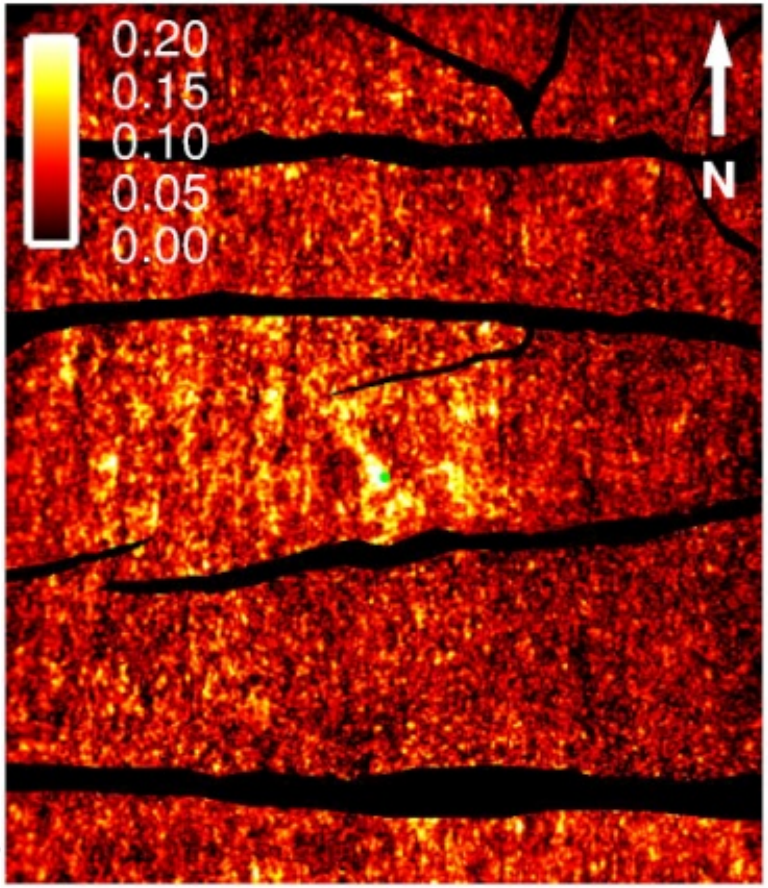
- Introduced by Landrø (2001)
- Exploits time-lapse near- and far offset seismic stacks as independent measurements
- Invert for fluid- and pressure related changes in seismic amplitude
- Thin layer tuning correction of saturation effect



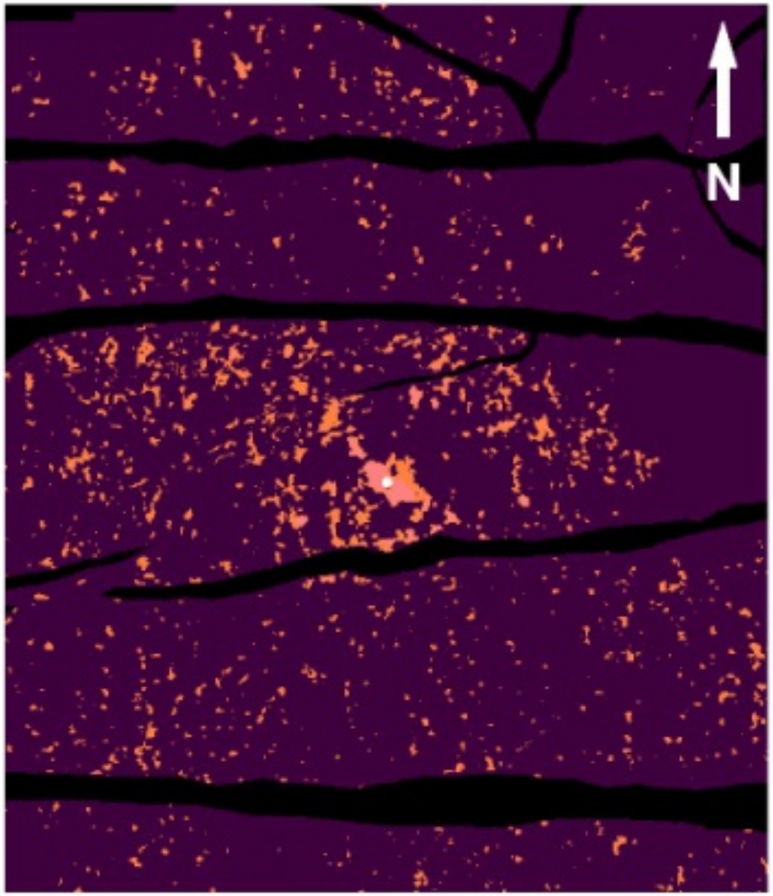


CO_2 saturation from time lapse seismic

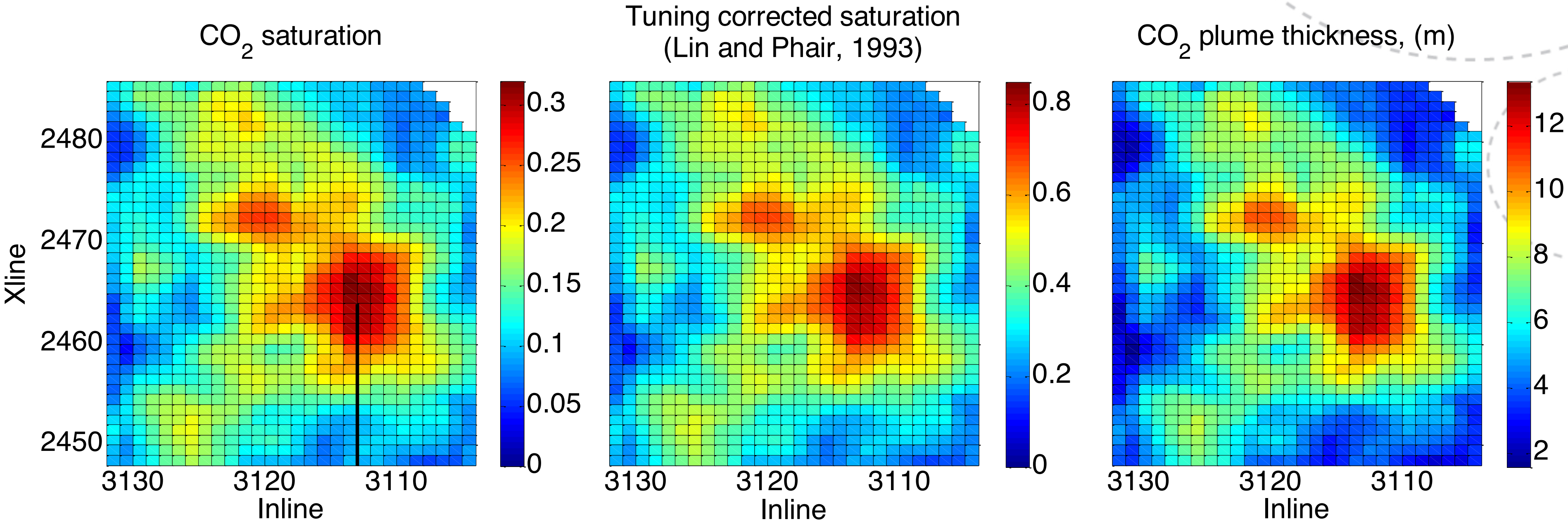
AVO



Spectral decomposition

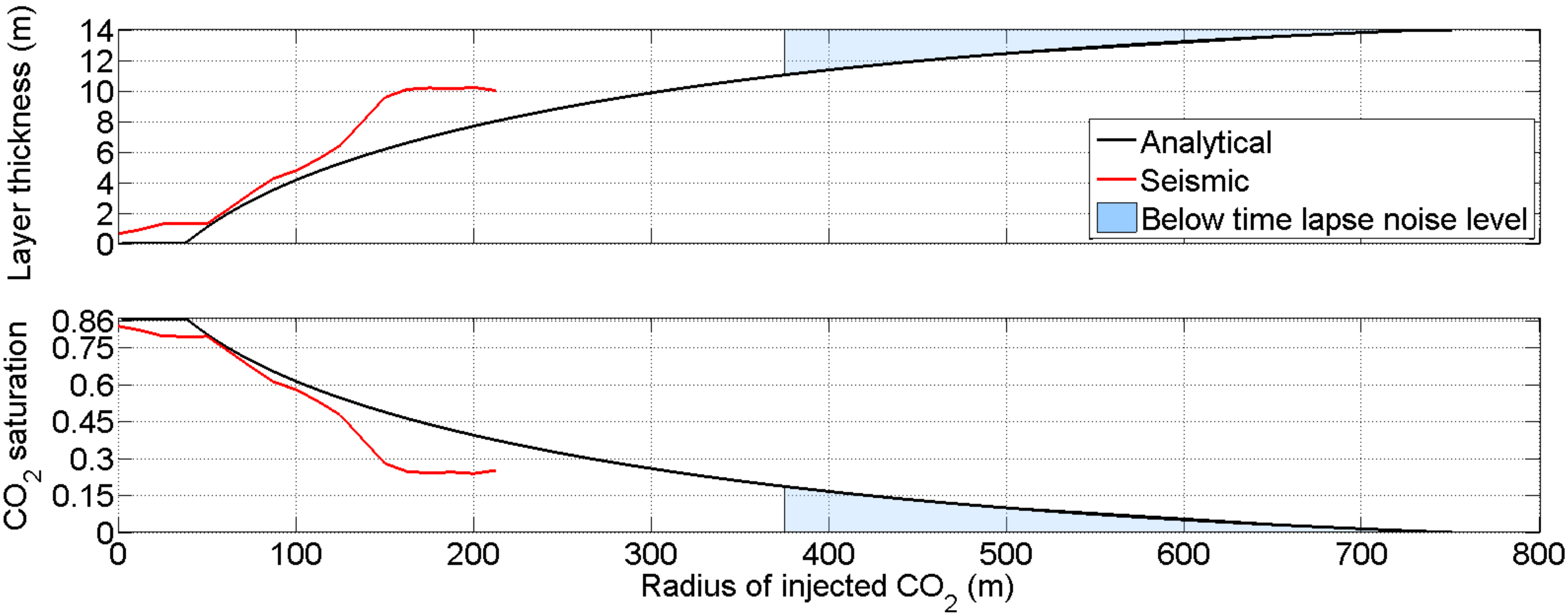


CO_2 saturation inverted from time lapse AVO seismic



12.5*12.5m grid cells

Comparions with analytical estimates



11% of injected CO_2 below noise level

Summary CO_2 saturation and radius of plume

	Maximum observable radius, m	*Maximum CO_2 saturation, [frac]*
Analytical solution	*375*	*0.87*
Time lapse AVO	*363*[1]	*0.83*[2]
Time lapse Spectral decomposition	*470*[1]	

[1] *In channel direction (SE-NW)*
[2] *After thin layer tuning correction*

Discussion

- Early injection times, stratigraphic and structural trapping
- Later: Dissolution of CO_2 in brine, evaporation of brine into the dry CO_2 and mineral trapping dominant trapping mechanisms
- Assume constant injection-rate into confined, homogeneous, isotropic and saline aquifer, wrong for fluvial environment?
- Uncertainty in capillary pressure (core plug measurements representative for large scale?)

Conclusions

- Viscous dominated fluid flow
- Wedge shaped CO_2 plume
- Thinning of wedge below time lapse noise level (<3m CO_2)
- Spectral decomposition indicate tuning of time lapse saturation effect, and pressure communication with the surroundings
- Plume radius from analytical solution comparable to average radius from time lapse seismic
- CO_2 saturation from time lapse seismic in good agreement with analytical solution after thin layer scaling, with a partially patchy fluid distribution in the pore space

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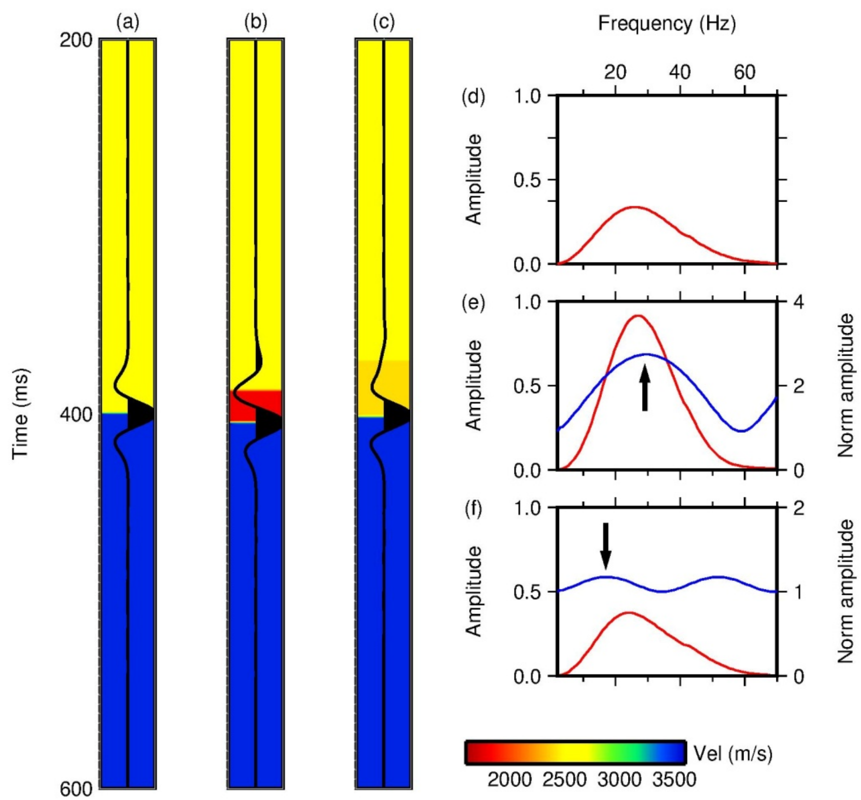
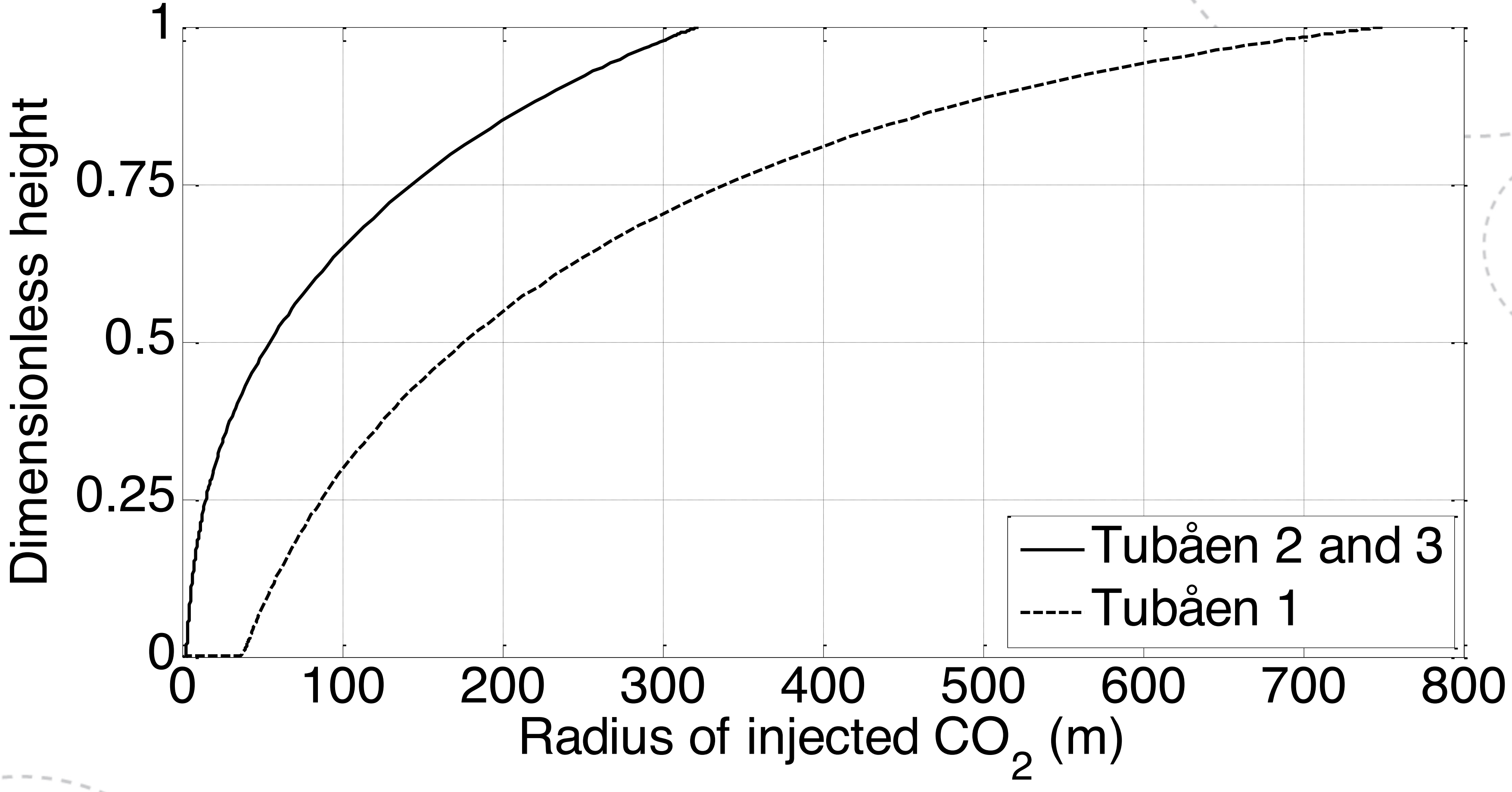
Backup-slides

Spectral decomposition: Pore pressure and fluid substitution changes generated during CO_2 injection



a) Baseline wavelet
b) 15 m layer where CO_2 has replaced brine
c) 36 m thick pore pressure anomaly
d) Baseline spectral response
e) Red line- spectral content of the reflected energy following fluid substitution changes. Blue line- the same spectra normalised by the baseline response. The peaks define the tuning frequency for the top and base reflection. Peak frequency of ~29 Hz. Corresponds to a temporal thickness of 17 ms.
f) Red line- spectral content of the reflected energy following pore pressure changes. Blue line- the same spectra normalised by the baseline response. The peaks define the tuning frequency for the top and base reflection. Peak frequency ~17 Hz, equivalent to temporal thickness of 30 ms. The second peak frequency at 51 Hz corresponds to the 2^{nd} tuning harmonic.

Analytical estimate of the CO_2 plume



Comparions with analytical estimates

Opposite direction in blue