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Borehole Wavefield Monitoring in CO_2 Wells

Ensuring well Integrity and leakage detection at near-well

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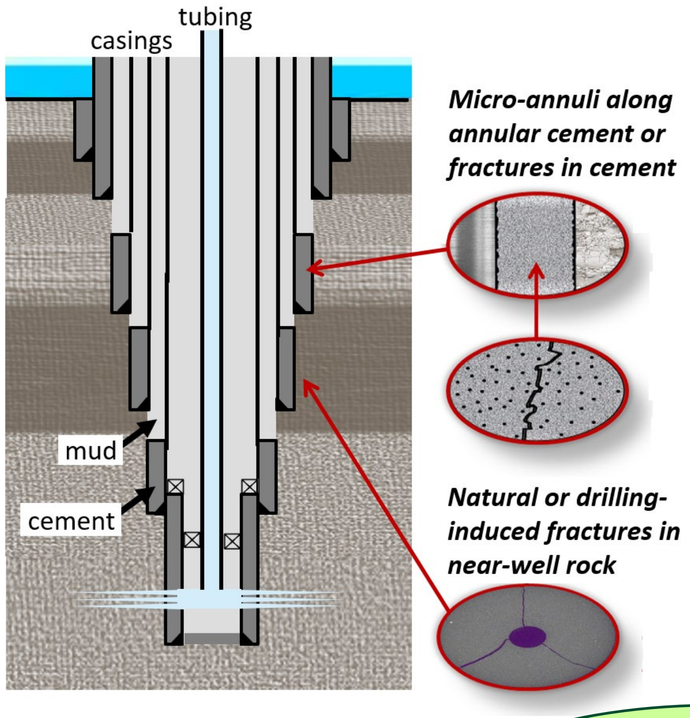
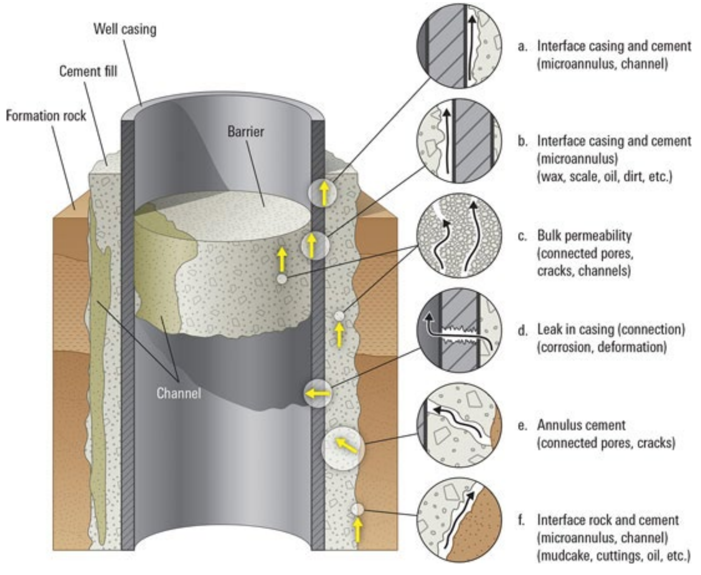
Background & Motivation

- Well integrity / leakage is a risk element for future storage projects
- Conventional monitoring will likely not be efficient
- For P&A'd wells, non-invasive monitoring most realistic
- For active wells and wells to be plugged, downhole seismic (VSP) senses much closer to the targets of interest
  - DAS promising
- A detailed understanding of more complex wave modes and novel acquisition layouts is SINTEF's suggested approach





Securing Storage of CO_2 or Energy

Well integrity and potential leakage risks, for active and legacy wells

Where and why does it occur and how to deal with it

Borehole wavefields sensitivity to near well changes

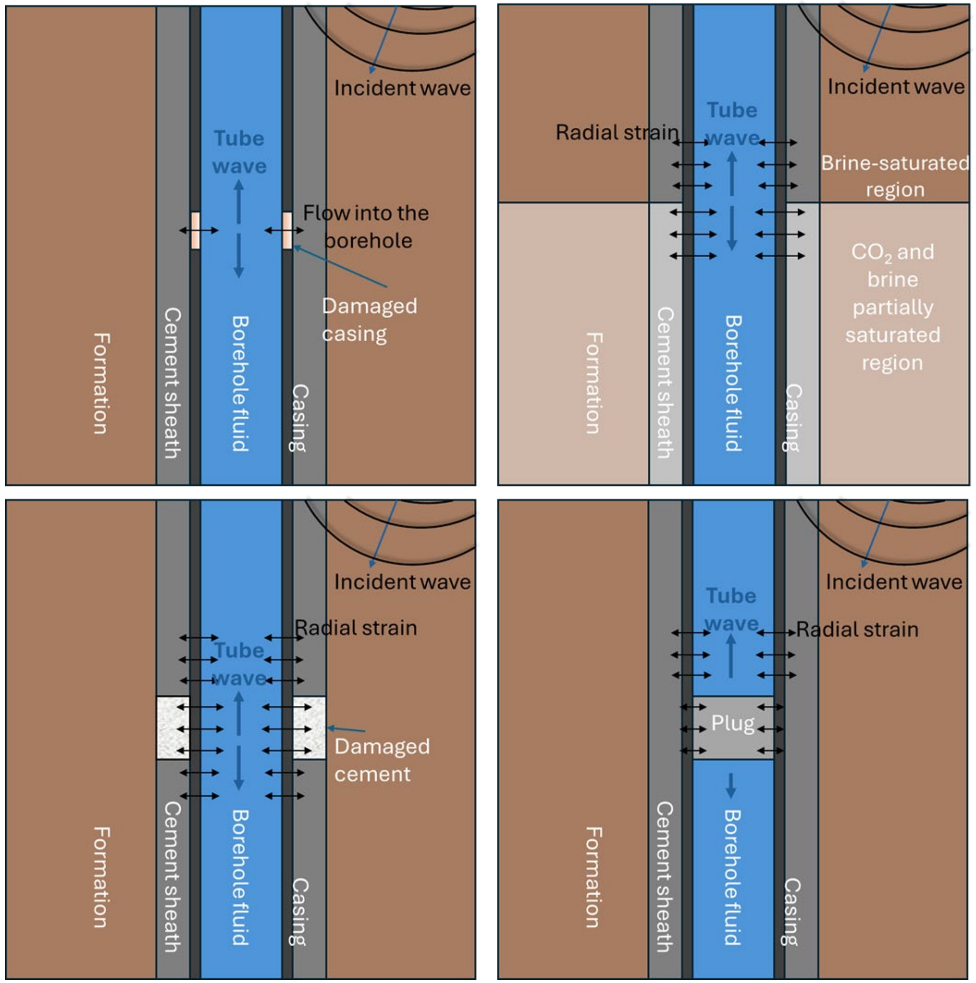
Borehole wavefields:

- Usually considered as noise and removed from seismic recordings
- But actually, carry lots of information on well architecture and near-well properties (and changes)
- The fluid pressure in the borehole can be affected by externally propagating surface and body waves due to a distant seismic source.

Physical mechanisms that can create pressure perturbations due to an incident wavefield:

- **Fluid infiltration** from a porous formation
- Differences in radial strain at the borehole wall at an **elastic boundary**
- Local changes in fluid volume at a **borehole irregularity**

➔ The sensitivity of **tube waves** to the acoustic-poroelastic coupling between the borehole fluid and the surrounding solid holds the potential as a **tool for near wellbore monitoring.**



Examples of mechanisms (Barbosa et al., submitted)

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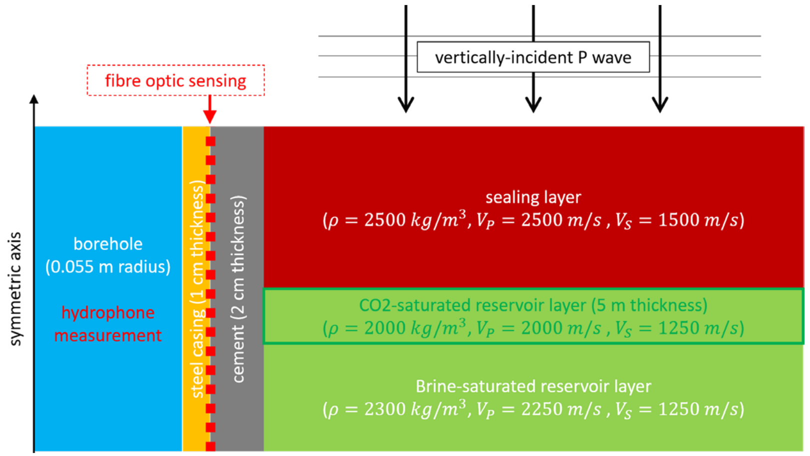
3-layer model

not-cased, without CO_2; Ricker of 200 Hz



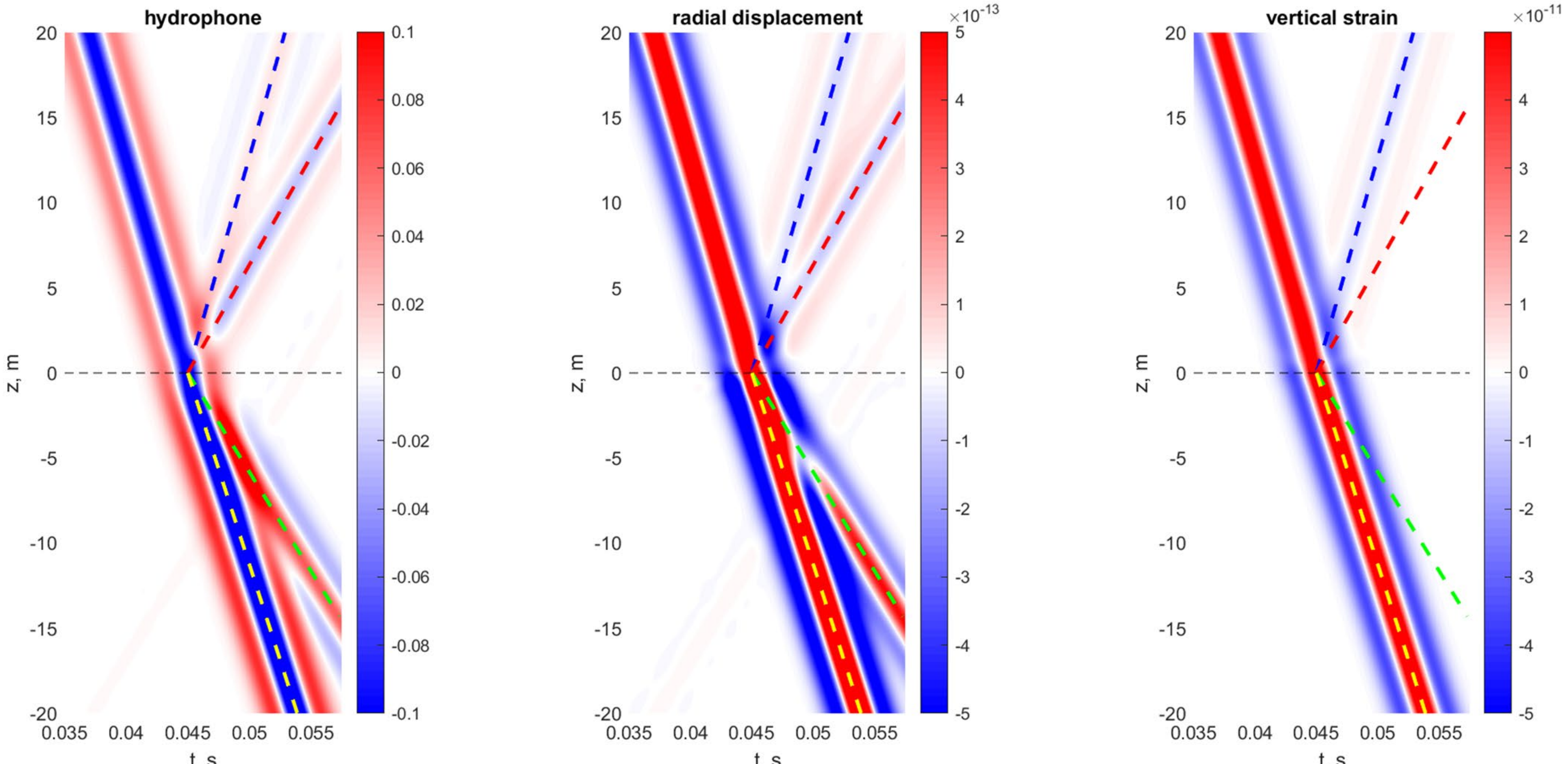
four dashed lines for Model 1:

- reflected P-wave (blue);
- reflected tube wave (red);
- transmitted P-wave (yellow);
- transmitted tube wave (green).

Numerical models

Generation of tube wave at the elastic interface

not cased, without CO2 (done axis sym 11 AE run 20250622 155626)



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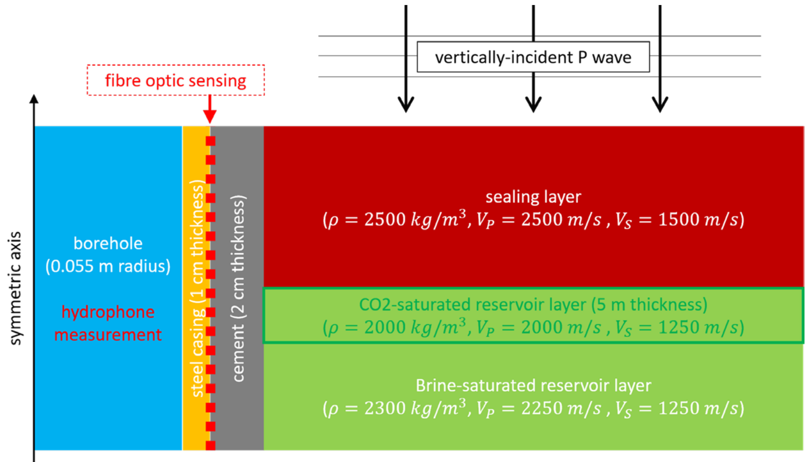
3-layer model

cased without CO_2; Ricker of 200 Hz



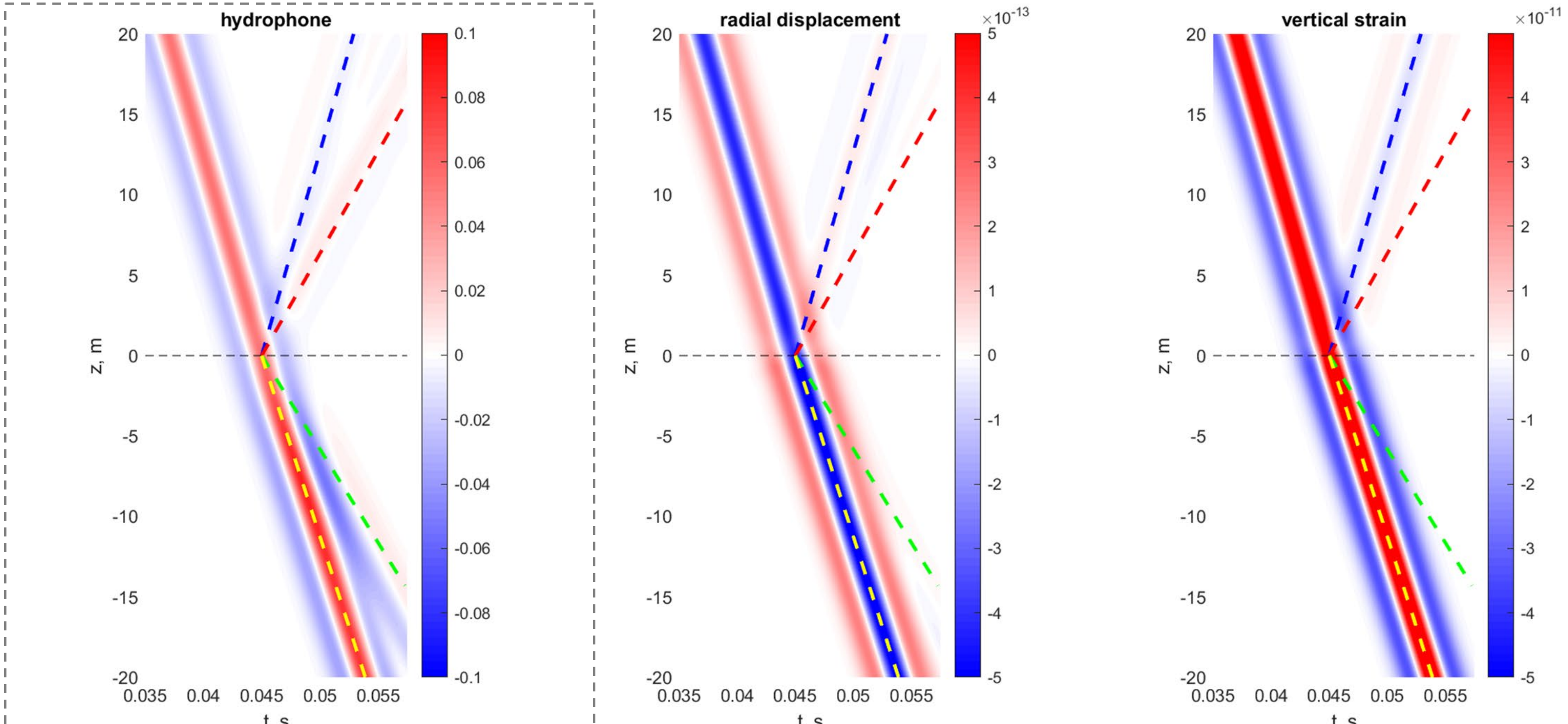
four dashed lines for Model 1:

- reflected P-wave (blue);
- reflected tube wave (red);
- transmitted P-wave (yellow);
- transmitted tube wave (green).

Numerical models

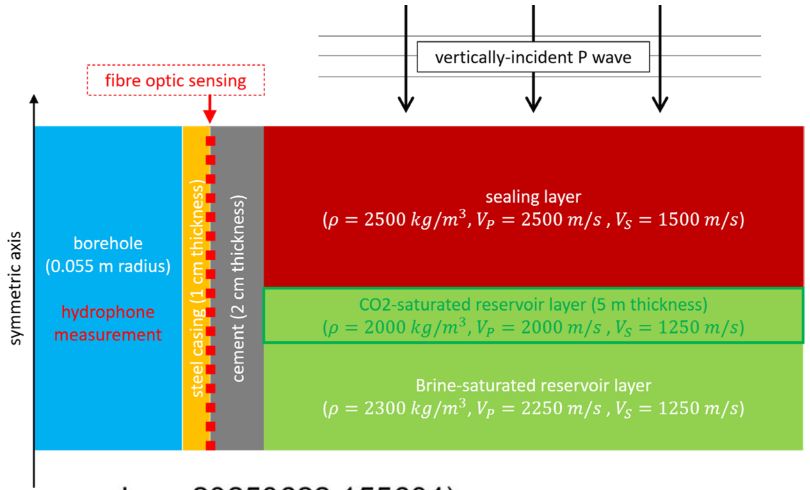
Changes in amplitudes and phase velocities due to presence of the casing

cased, without CO2 (done axis sym 11 AE cased run 20250622 155647)



3-layer model

cased with CO_2; Ricker of 200 Hz



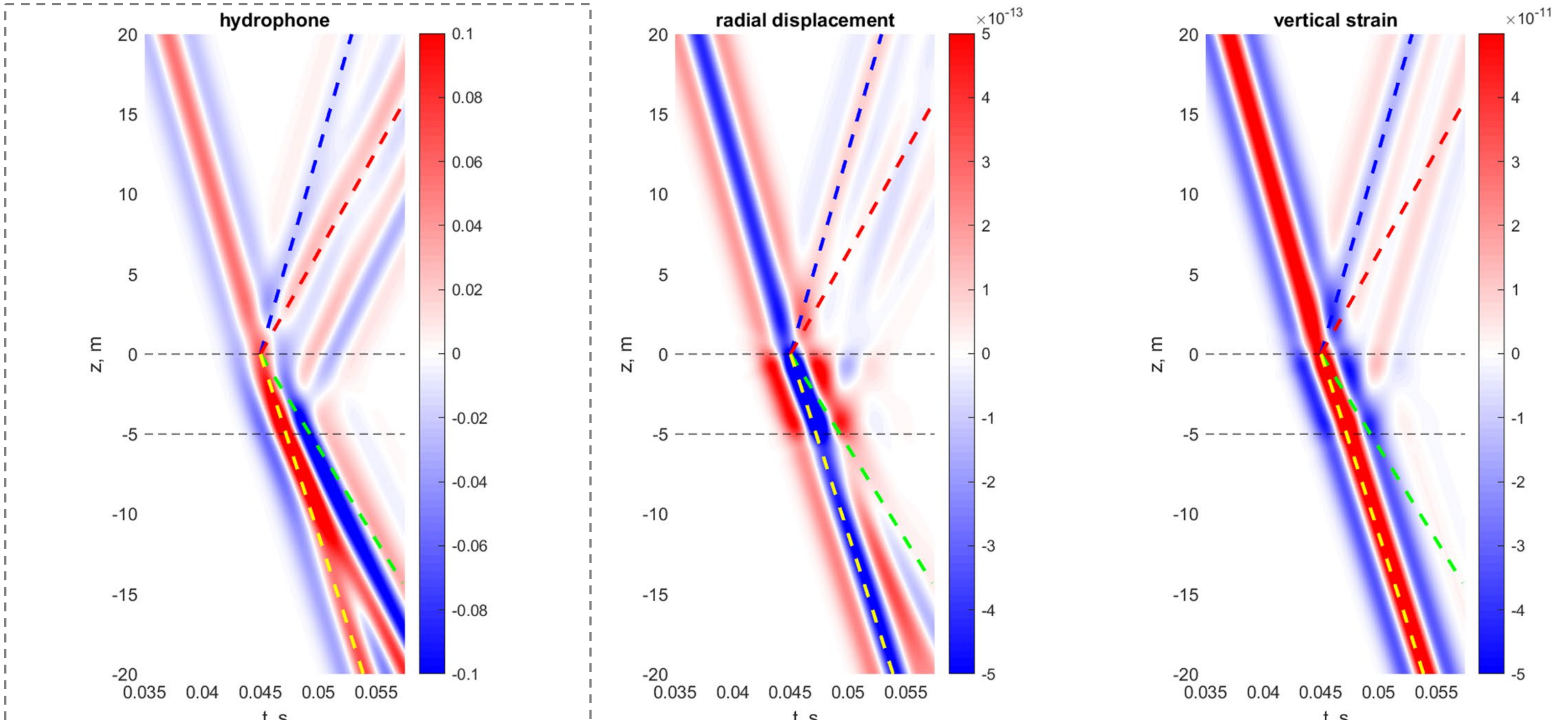
four dashed lines for Model 1:

- reflected P-wave (blue);
- reflected tube wave (red);
- transmitted P-wave (yellow);
- transmitted tube wave (green).

Numerical models

Changes in the amplitude of the transmitted tube wave due to the presence of CO_2

cased, with CO2 (done axis sym 11 AE res cased run 20250622 155604)



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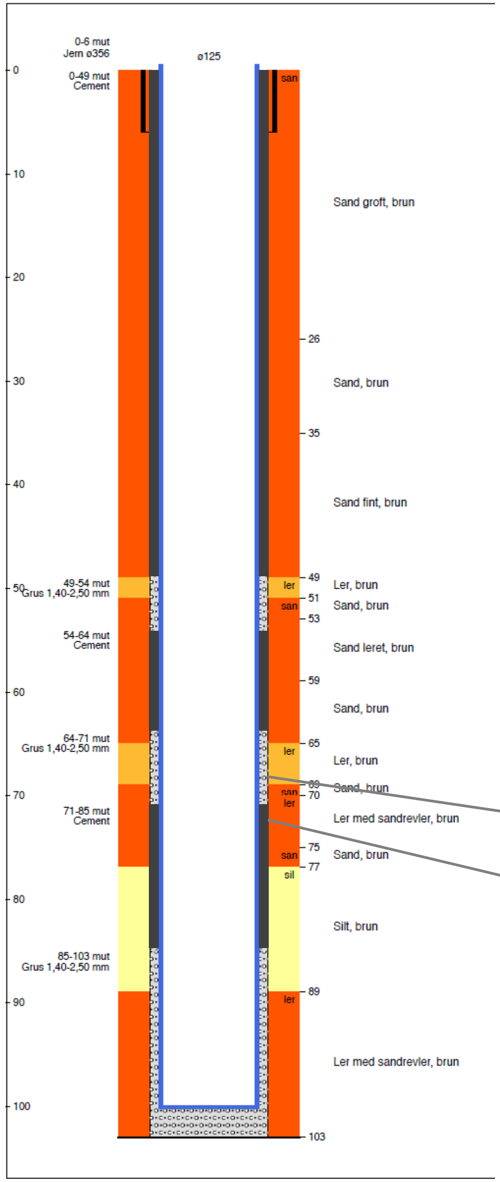
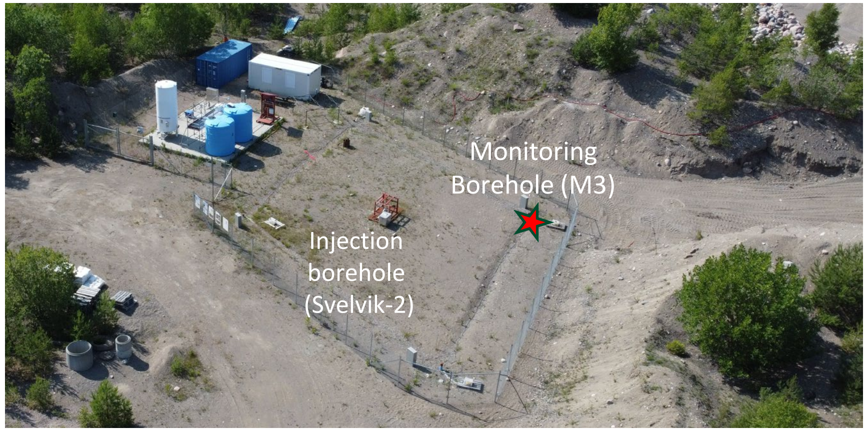
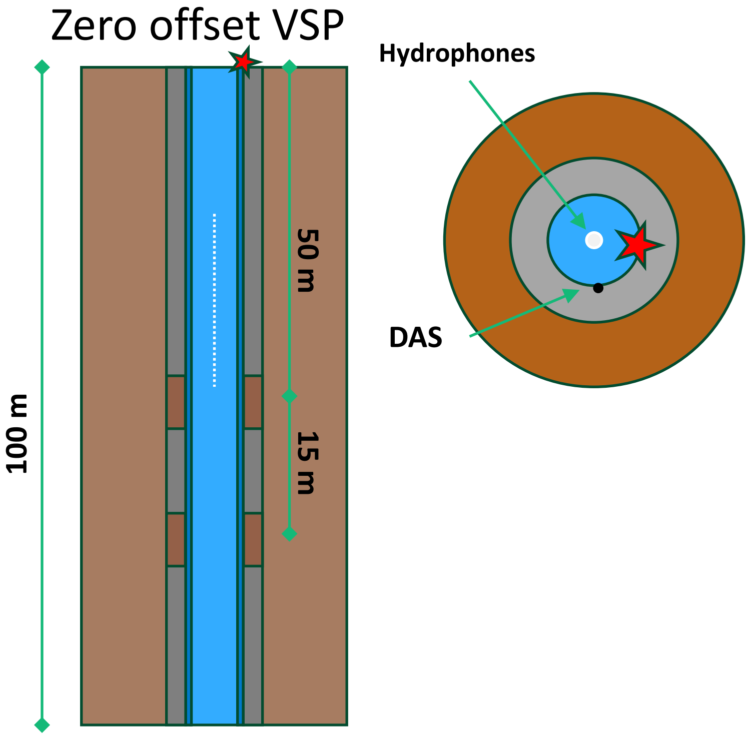
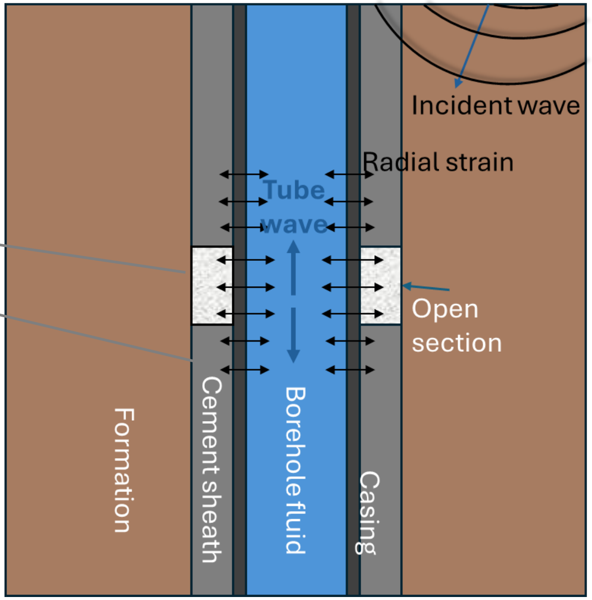
CASE 1: Tube waves sensitivity to cement integrity behind casing – Svelvik experiment





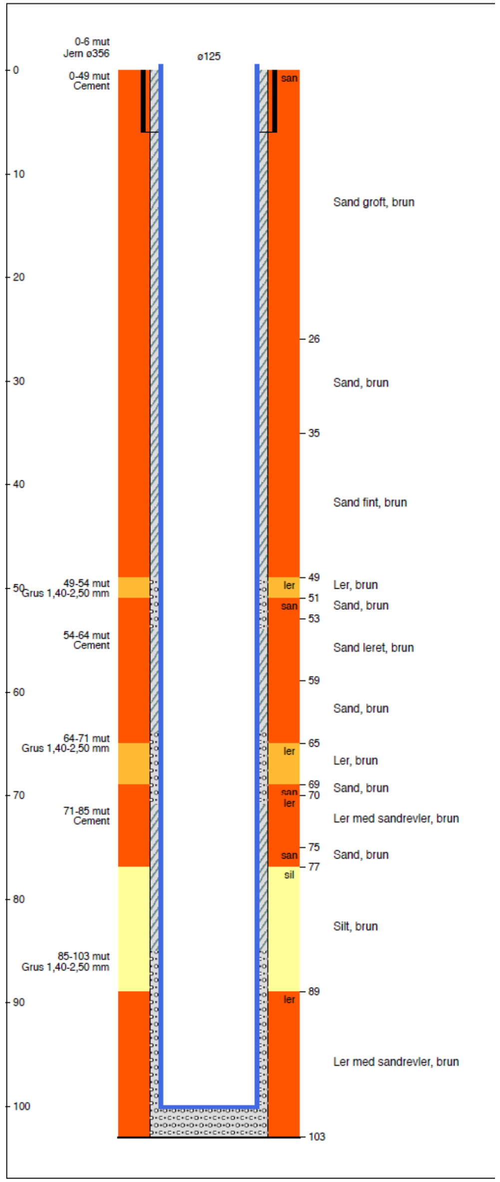
Zero offset VSP data for tube wave analysis was collected before ("Baseline") and during CO_2 injection ("Monitor").

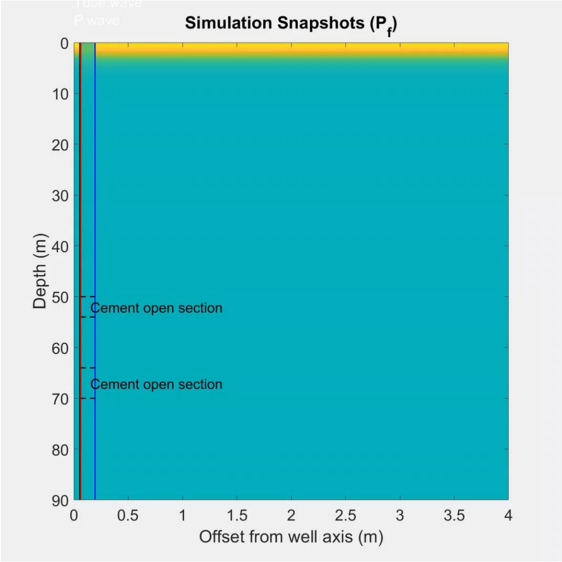


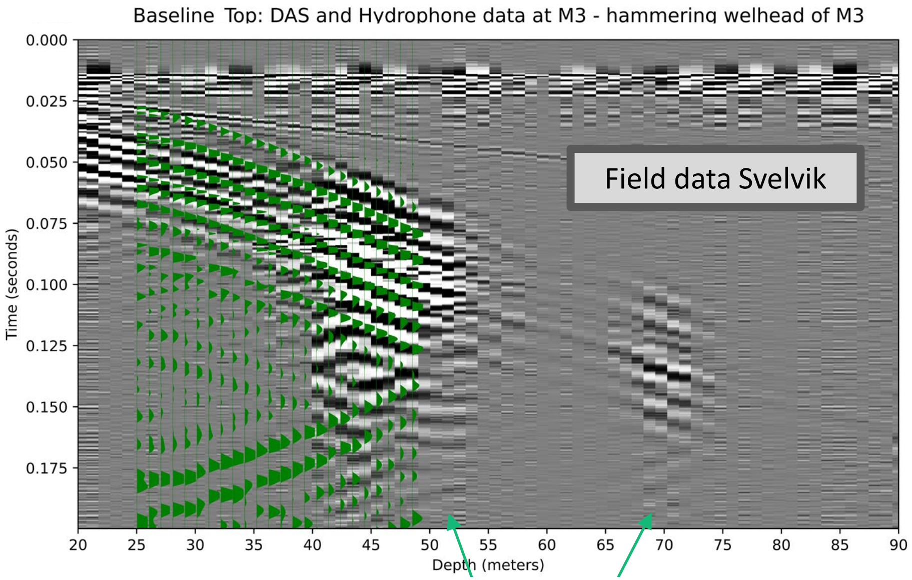


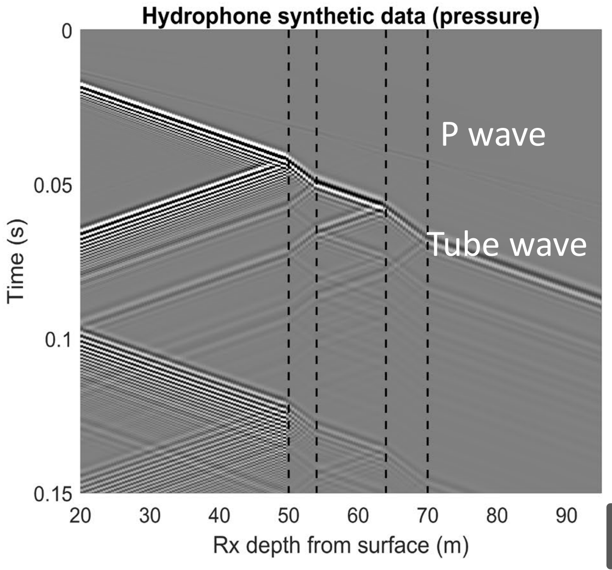
Differences in the elastic properties of the cement annulus surrounding the borehole ➔ *affect the wave-induced strain along depth and generates tube waves at the boundary*

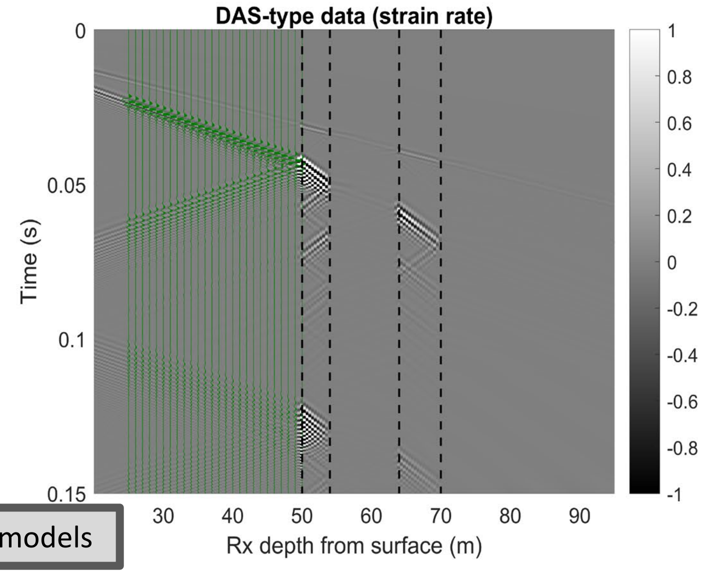
CASE 1: Tube waves sensitivity to cement integrity behind casing – Svelvik experiment







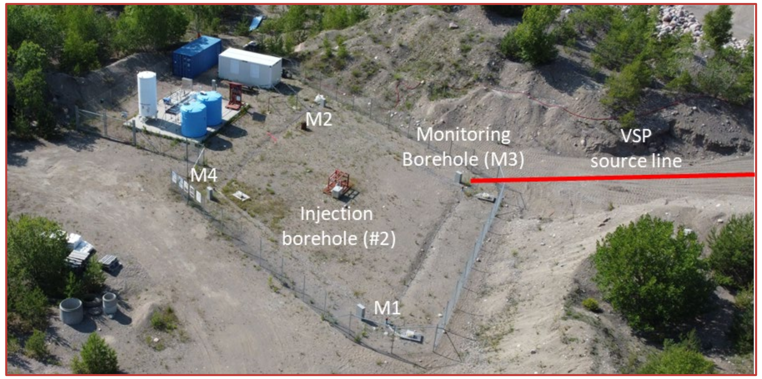




Numerical models

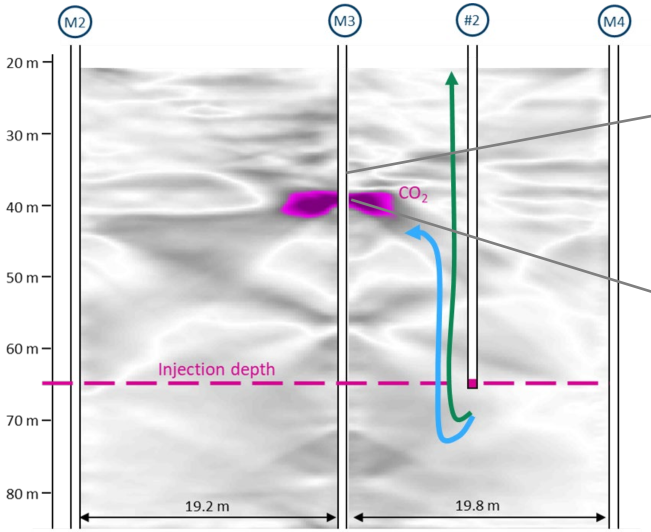
FDModBiotCyl.jl: A Julia implementation of 2.5-D seismic wave simulation using a finite-difference method in a cylindrical coordinate system. Minato (2021)

CASE 2: Tube waves sensitivity to CO_2 behind casing – Svelvik experiment



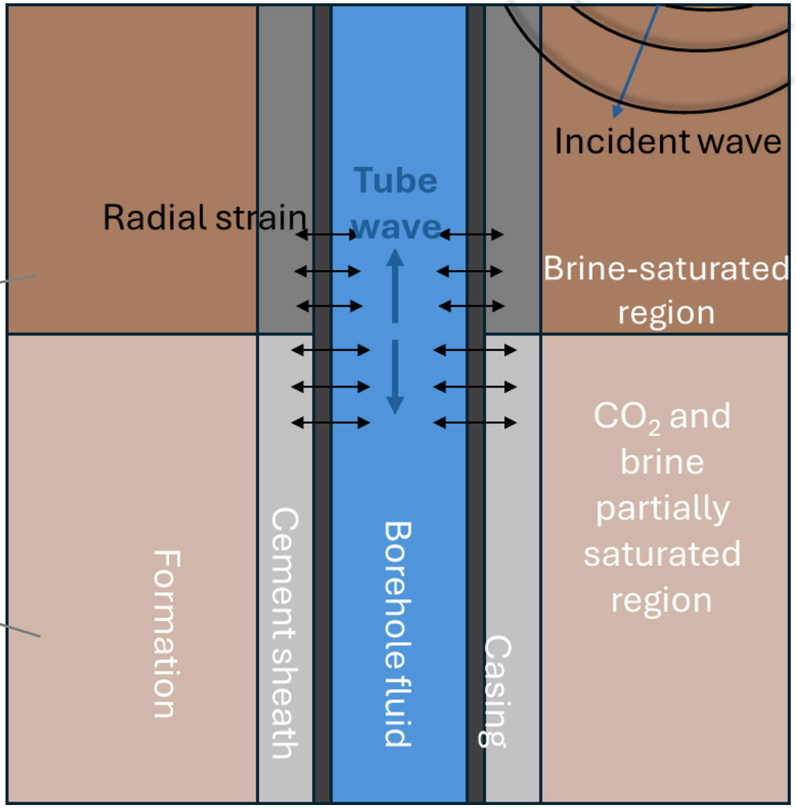
VSP data for tube wave analysis was collected before ("Baseline") and during CO_2 injection ("Monitor").

PRE-ACT PROJECT



Jordan et al. (2022)

Elastic boundary between the CO_2- and water-saturated regions around the borehole ➔ *affects the wave-induced strain along the well and generates tube waves at the boundary*



CASE 2: Tube waves sensitivity to CO_2 behind casing – Svelvik experiment

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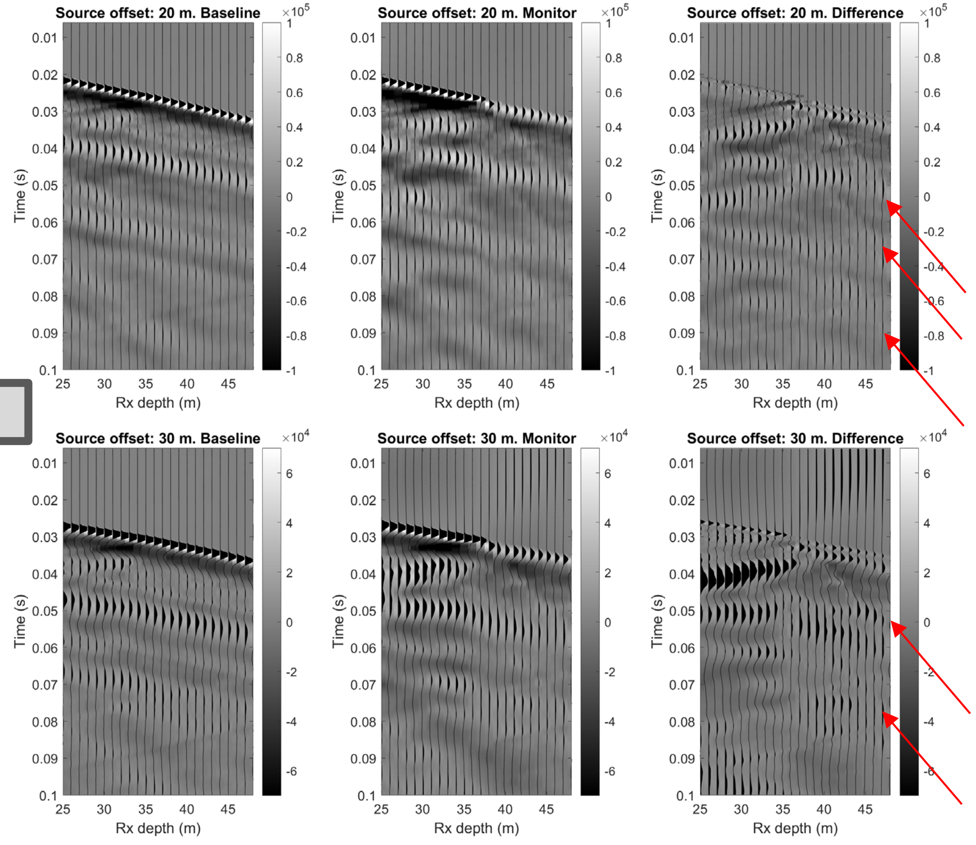
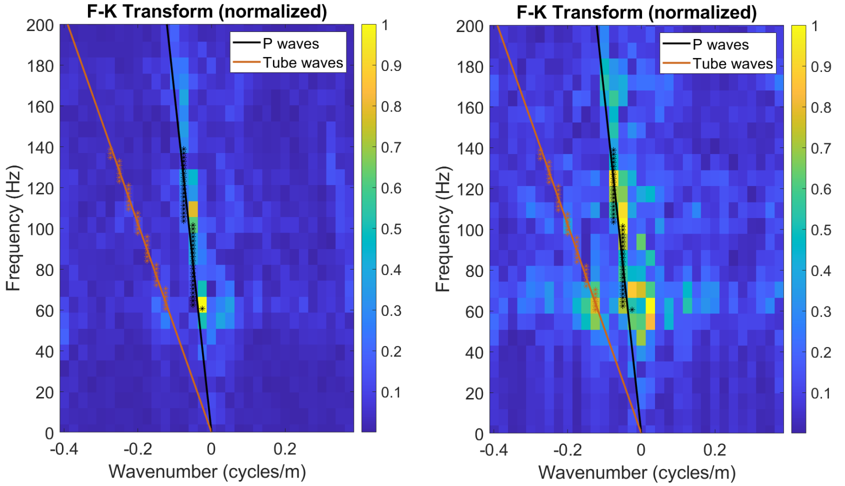
Field data Svelvik



VSP data for tube wave analysis was collected before ("Baseline") and during CO_2 injection ("Monitor"). Source offsets equal to 20 m (top) and 30 m (bottom). Tube waves (red arrows) generated due to CO_2 accumulation at 38 m around M3.

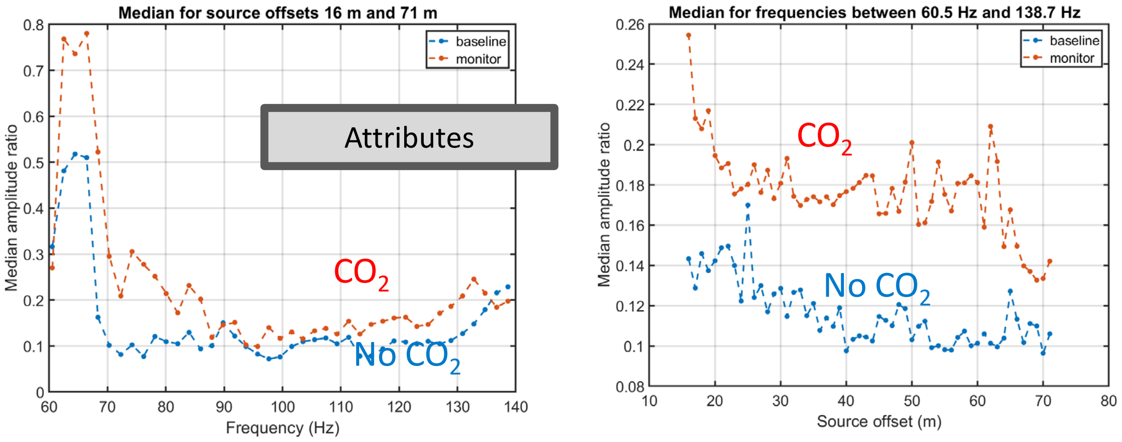
Baseline

Monitor



Amplitude analysis in FK-domain: Pick the amplitude lying along the lines defined by the tube and P- wave velocities using the expected wave velocities.

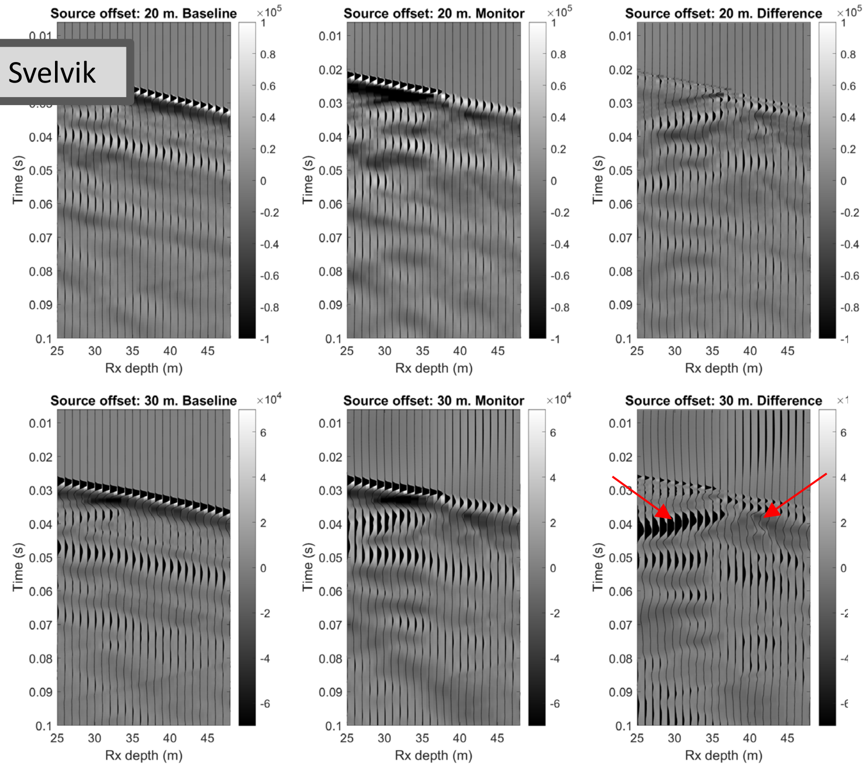
Attributes



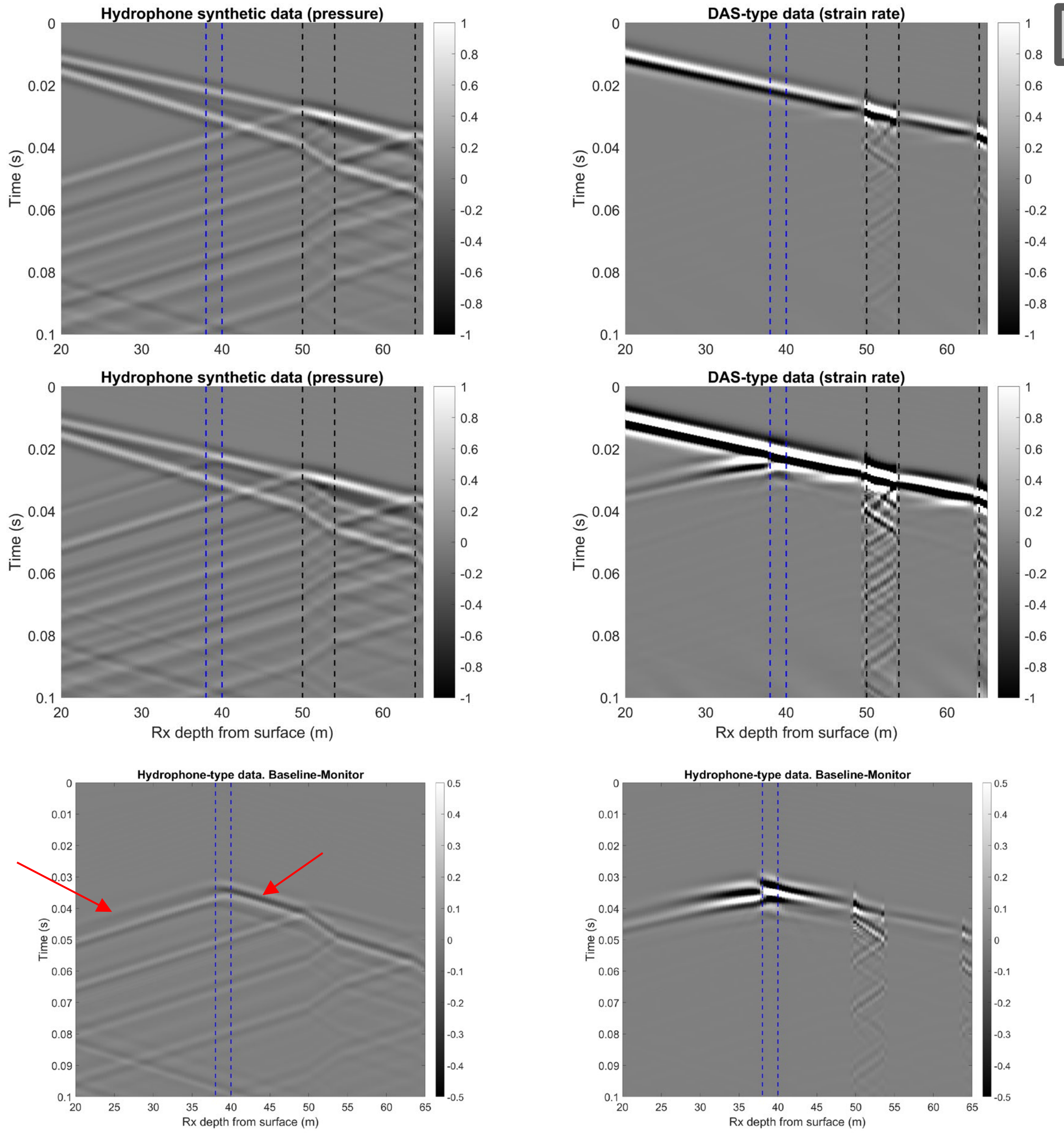
Sensitivity of ratio between tube wave and P-wave spectral amplitudes as a function of source offset and frequency to presence of CO_2 behind casing.

CASE 2: Tube waves sensitivity to CO_2 behind casing – Numerical verification

Field data Svelvik



Numerical models



No CO_2

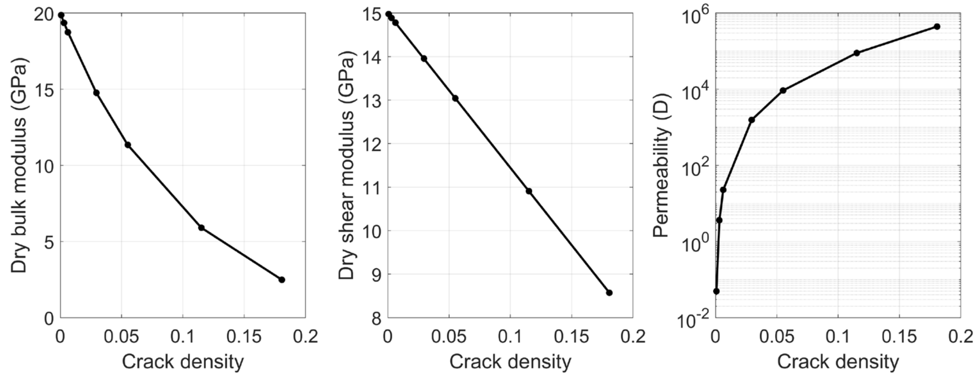
CO_2

Differences

- We focus on the direct P-waves as the source of tube wave generation
- Visible increase in tube wave amplitudes during CO_2 injection
- Sensitivity of both DAS and hydrophone data

CASE 3: Tube waves sensitivity to plug integrity– Numerical study

- **Simple borehole structure with multiple scales**: cm-scale (casing, cement sheath), m-scale (plug, wavelength)
- **Rock physics modeling**: poroelastic approach, inclusion-based model for elastic and hydraulic properties
- **Acquisition setup**: zero-offset VSP. Source frequency tens to hundreds of Hz. Plane-wave approximation.

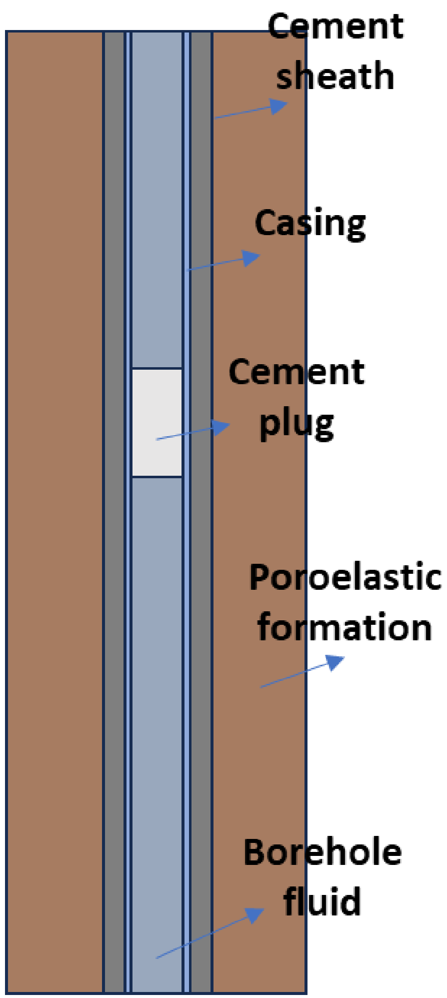


We follow an approach based on the linear slip theory to estimate the effective dry moduli of a cracked cement as a function of crack density. Permeability is computed from crack density, aspect ratios, and apertures (Benson et al., 2006).

	Radius (m)	Height (m)
Borehole	0.12	500
Cement casing	0.08 (thickness)	500
Steel casing	0.04 (thickness)	500
Plug	0.12	40

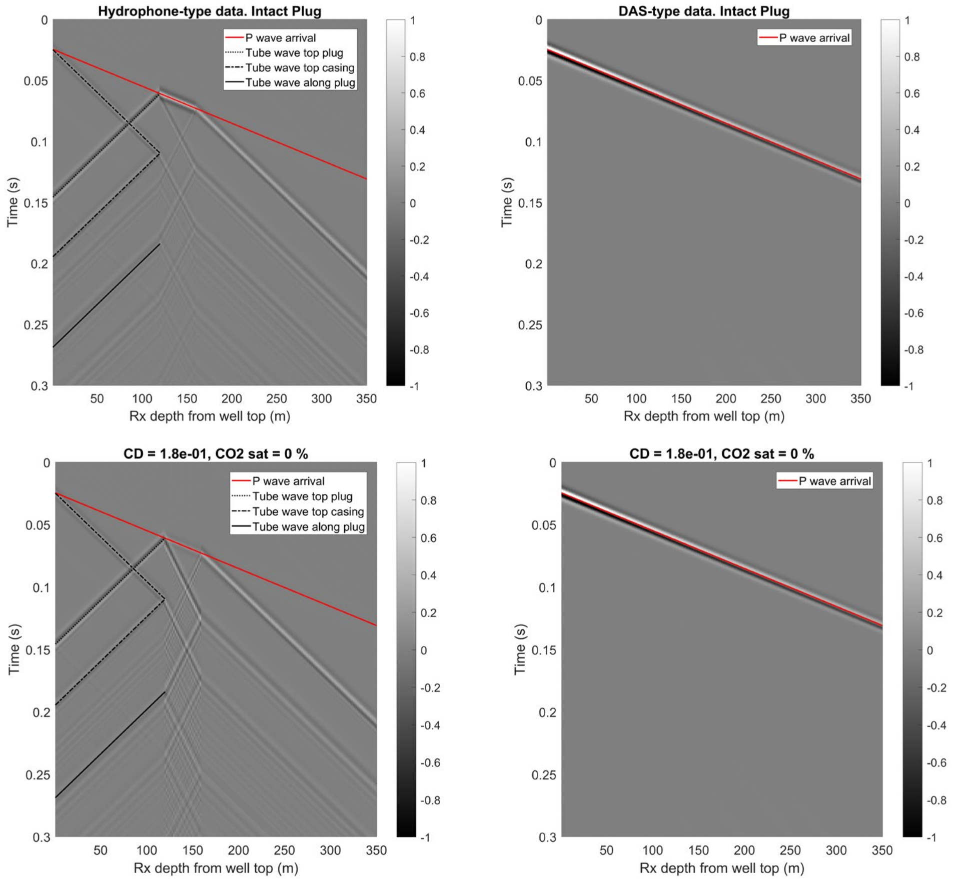
Material	Poroelastic properties representative of
Brine	Smeaheia reservoir conditions
Formation	Sandstone
CO_2	Smeaheia reservoir conditions
Cement	Portland
Casing	Steel

We follow a poroelastic approach to represent the different borehole elements



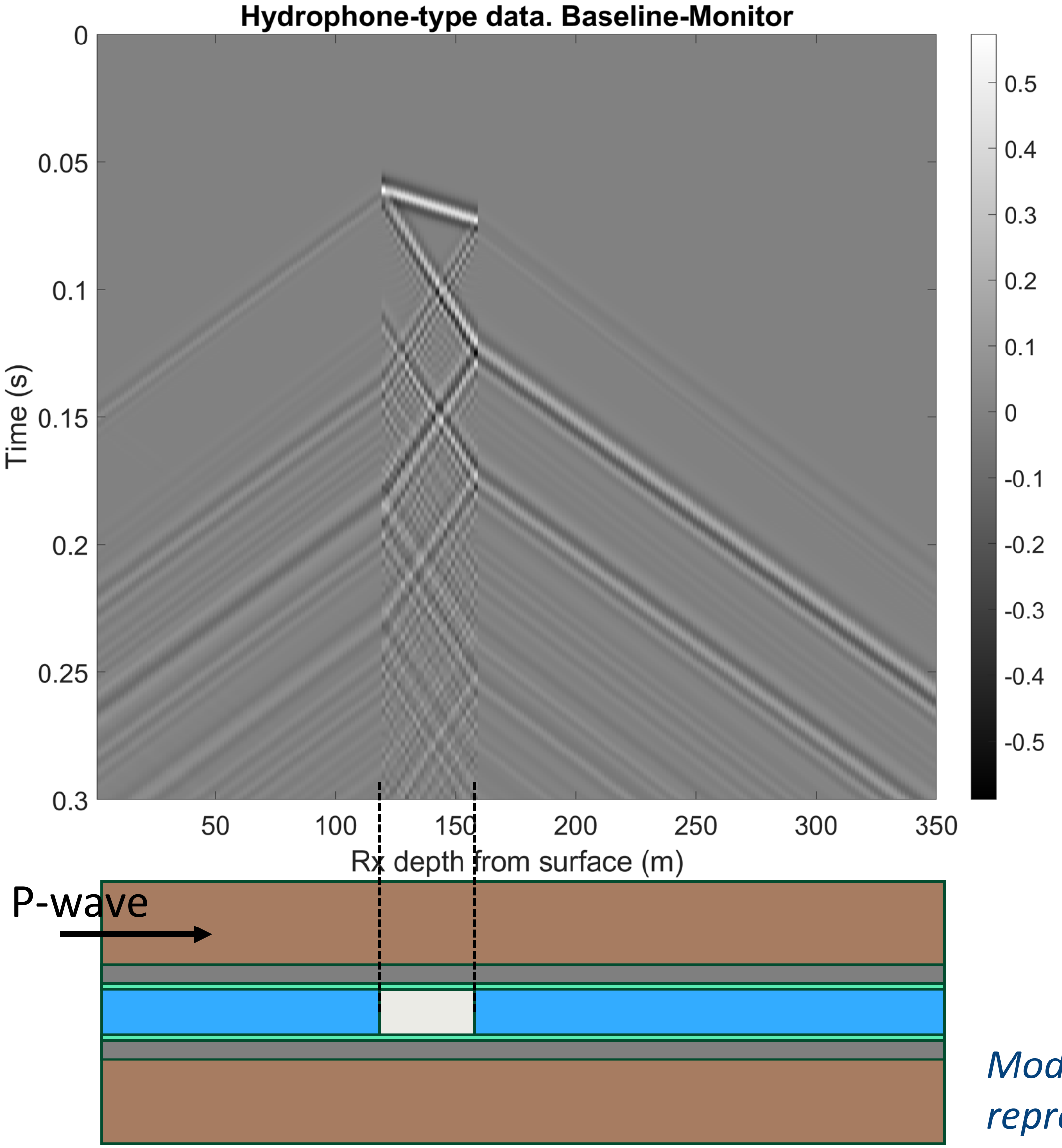
Simple borehole structure with multiple scales

CASE 3: Tube waves sensitivity to plug integrity– Synthetic data



Zero-offset VSP profiles along the well for ***intact*** *(top) and* ***damaged*** *(bottom)* ***cement plug*** *(depth range from 280 to 320 m). Traces correspond to fluid pressure measured at the centre of the well (left) and vertical strain rate along the borehole wall (right).*

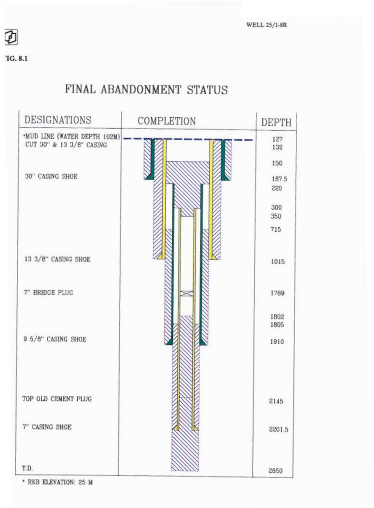
Numerical models



VSP profile changes for hydrophone data

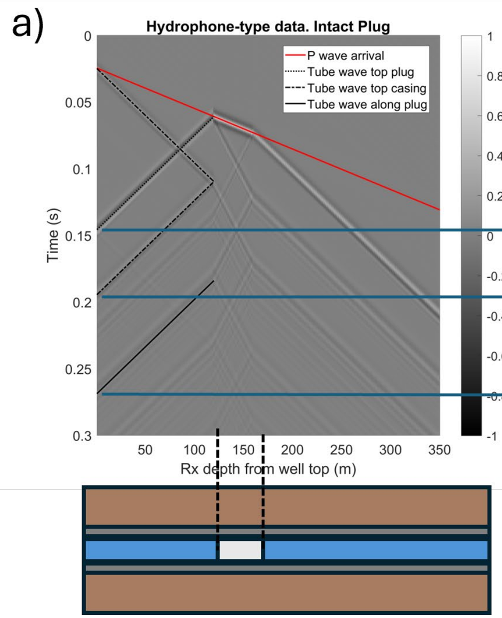
Model representation

CASE 3: Tube waves sensitivity to plug integrity– Synthetic data

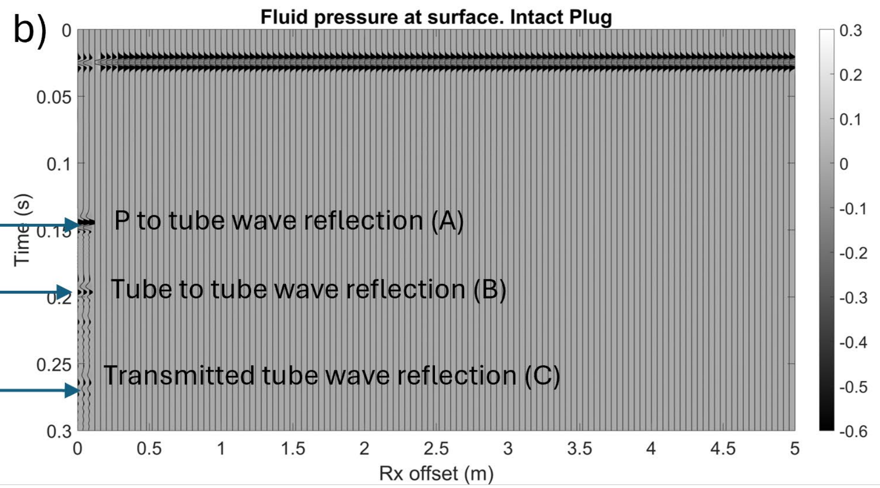


Next step: Identify and characterize the most relevant arrivals observed at the top of the well → assuming we cannot access the well

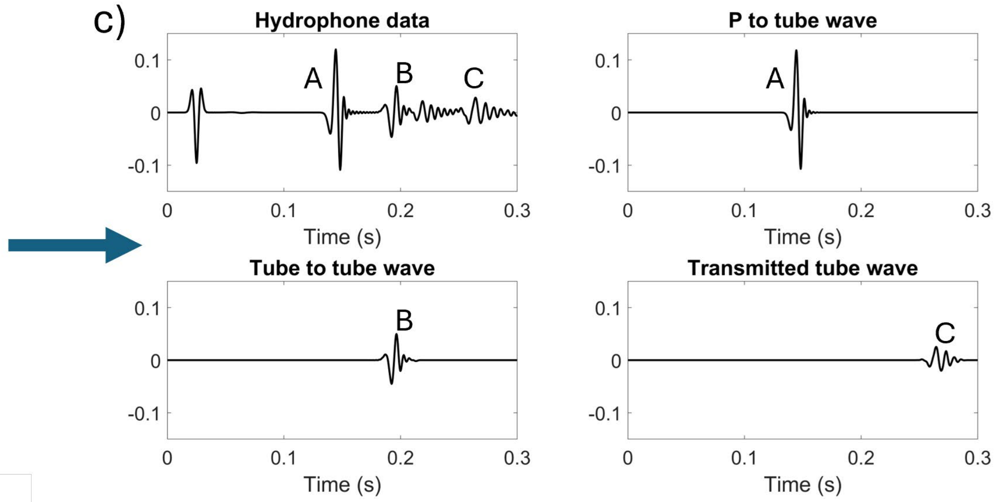
Numerical models



Synthetic VSP profile ***along well***

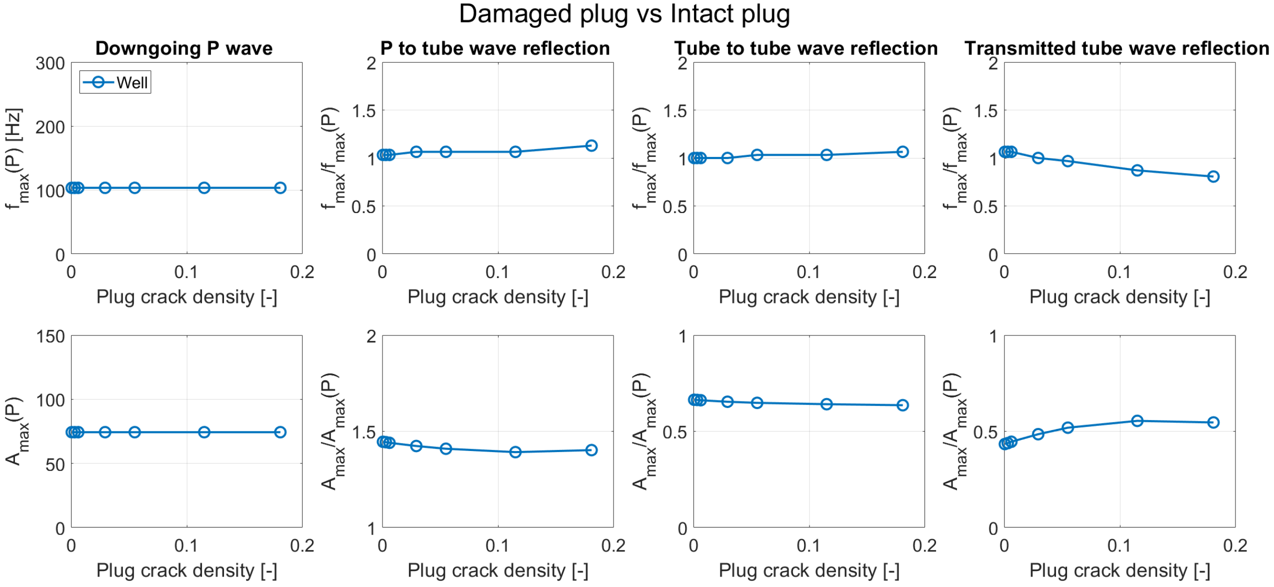


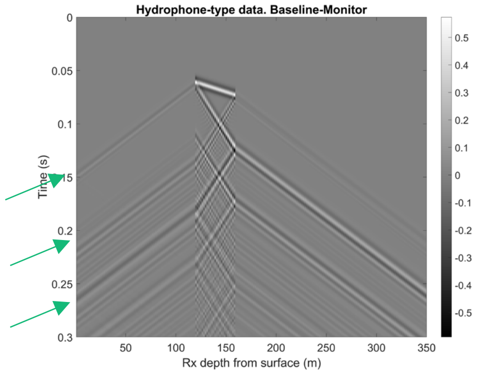
Scattered wavefields at the ***top of the well***



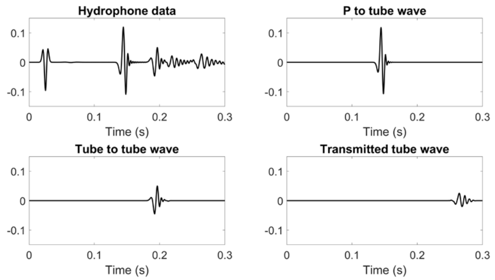
Identify and isolate ***arrivals*** *associated with the* ***plug***

CASE 3: Tube waves sensitivity to plug integrity
Seismic attributes sensitivity to crack density



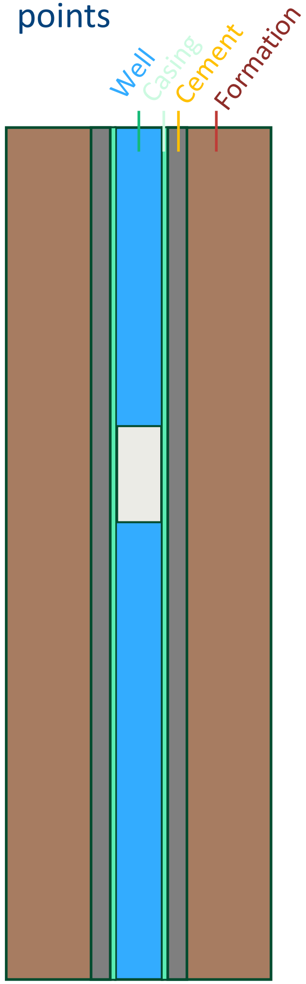


Difference between baseline and monitor shots



Extracted backscattered wavefields for frequency analysis

Wavefields at the top of the well are recorded at four measurement points

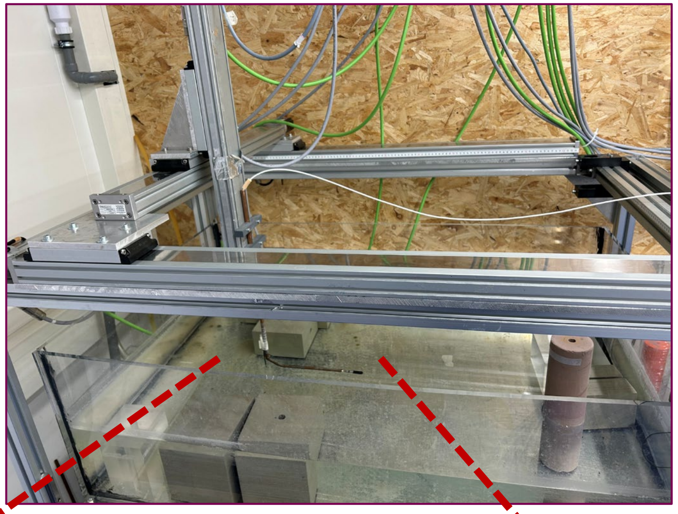


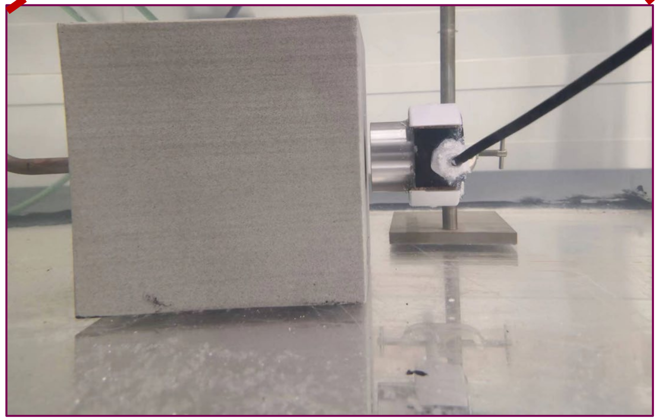
- Pressure sensors located in the well fluid are most sensitive to backscattered wavefields.
- Dominant frequency and amplitude sensitivity depends on which arrival we consider.

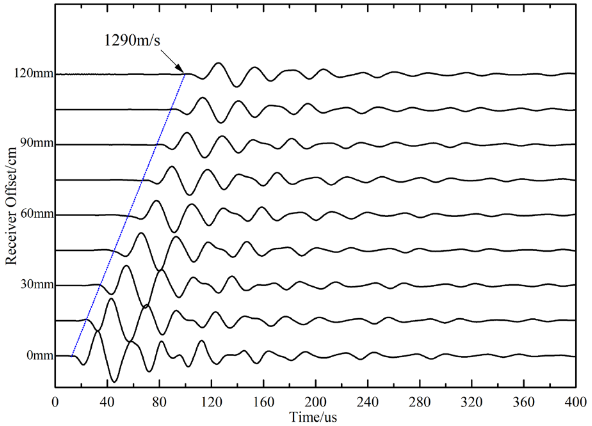
Planned activities

Controlled laboratory scale studies

Borehole wavefields in various configurations of casing and annulus cement embedded in formation rock

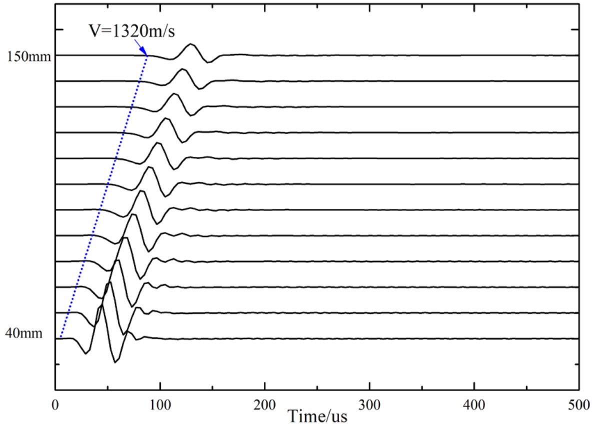




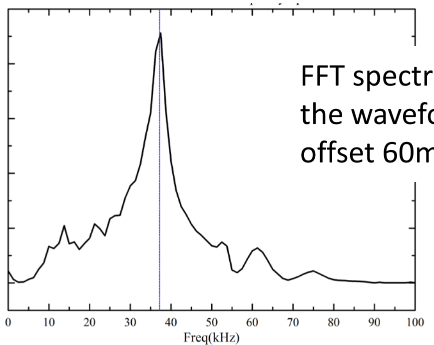


Measured waveforms

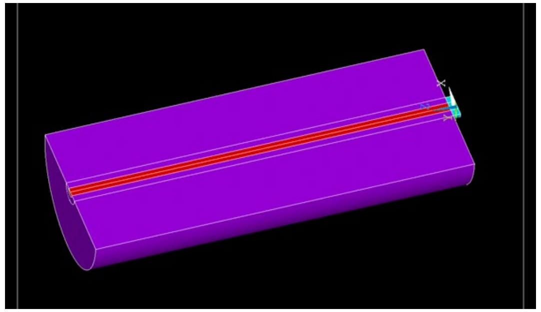
Stoneley wave in non-cased borehole



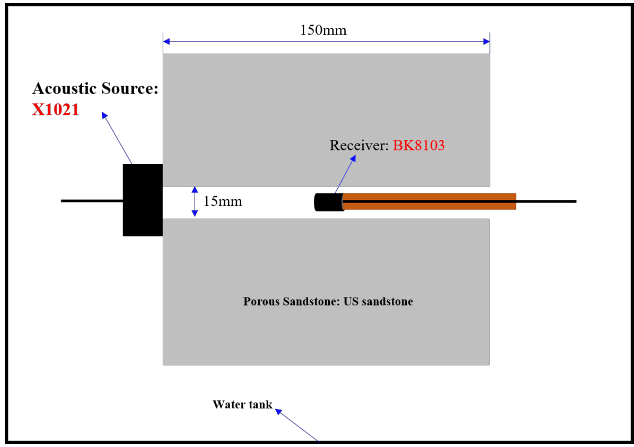
Modelled waveforms



FFT spectrum for the waveform at offset 60mm

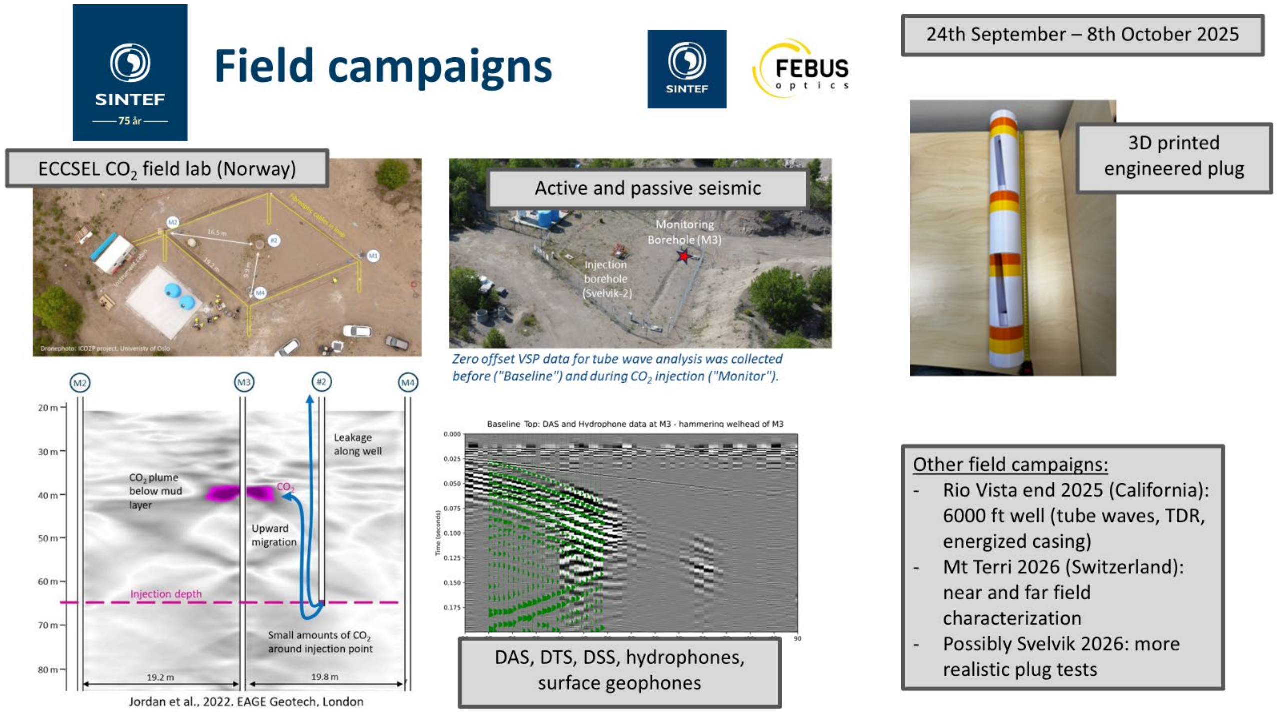


Collaboration with Eindhoven University of Technology



Summary

- **Borehole wavefields** are sensitive to wellbore geometry and near wellbore properties (modelling of complex wave modes for improved understanding)
  - Status/condition of casing
  - Cement plug condition
  - Presence/absence of CO_2
- Acquisition layout:
  - Hydrophone / DAS / geophone at surface, source positions
  - In-well sensors / VSP for future wells
- Repeatability, time-lapse
- Quantitative interpretation



Acknowledgements:

- CETP LEGACY project
- **CHARISMA project** (RCN #344541)
- Thanks to
  - **SINTEF's Svelvik CO_2 Field Lab** (part of ECCSEL RI) for access to the field and site facilities
  - Partial support from **LINCCS** (RCN #328738), **FME gigaCCS** (RCN#350370), **CETP Q-Fibre** (RCN #355463)

Thank You

75 år med teknologi for et bedre samfunn

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