Low-cost time-lapse seismic imaging of CCS with the joint recovery model

Ziyi (Francis) Yin, Mathias Louboutin
Philipp Witte*

* now at Microsoft Research



SLIM
Georgia Institute of Technology

Ziyi Yin, Mathias Louboutin, and Felix J. Herrmann, "Compressive time-lapse seismic monitoring of carbon storage and sequestration with the joint recovery model". 2021.

Energy transition

CCS – viable technology to combat climate change

For successful adaptation of CCS, there is a need to

- convince general public, insurers, regulators of safety (liability transfer)
- build scalable capability to de-risk
  - by establishing baselines
  - via seismic monitoring technology that mitigates hazards & accounts for mass of injected CO_2
- be transparent / accountable to increase public's & regulator's confidence in CCS (monitoring)
- reduce costs to sustain continuous monitoring over long periods of time

Solution – create an open platform modeled after openAI

- avoid replication of de-risking monitoring capabilities via open source software (OSS)
- accelerate innovation via access to data & compute

Challenges

appeasing general public & regulators

CCS is difficult because it requires

- monitoring over *large* areas over *long* periods of time
- de-risking in *different* geological environments
- errors in earth model impact much more than bottom line only
- *coupling* of complex multiphysics & chemistry
- flow simulations & seismic imaging to detect leakage
- must include uncertainty quantification to mitigate risk

Calls for *open* sharing of best practices, transparency, & accountability…

Answers

simulation-based seismic monitoring design

Address questions like

“What is the seismic detectability of CO_2 -plume dynamics, impact of source strength, acquisition density, and need to replicate surveys?”

and

“How often & when (early/late) do we need to shoot seismic to mitigate long-term risks? Can we adaptive as CCS project matures?”

and

“What are feasible acquisition scenarios OB DAS and/or DAS in wells?”

Different settings

Saline aquifers:

- pro: massive storage potential
- cons: many unknowns; easy to exceed virgin pressure

Depleted Oil & Gas reservoirs:

- pros: well studied; larger storage potential when safely repressurized
- cons: residual hydro-carbons; reactivation faults; integrity legacy wells

Basalt:

- pros: CO_2 binds chemically
- cons: difficult to image / monitor seismically; challenging to drill

Salt:

- pros: create caverns; extreme low permeability; chemically inert; self healing; easy to drill
- cons: difficult to image / monitor seismically

Subject to fault activation, porosity waves, etc.

No issue w/ seals

Goulart, et al. "Technology readiness assessment of ultra-deep Salt caverns for carbon capture and storage in Brazil." *International Journal of Greenhouse Gas Control* 99 (2020): 103083.

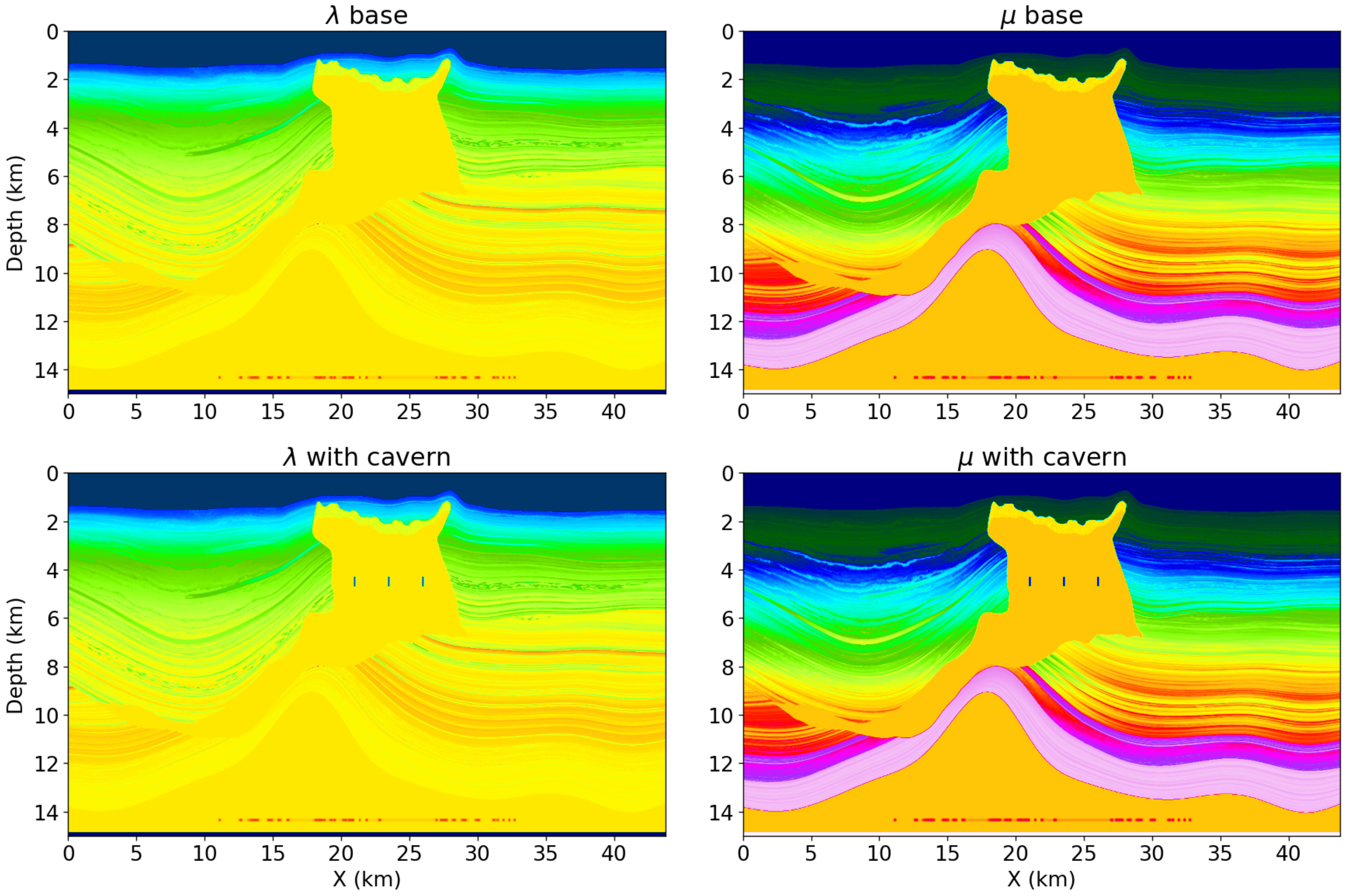
Example

Salt – SEAM model

CCS in Salt:

- 5 km m deep rock + 1.2 km water
- permeability of rock salt is about $10^{-21} - 10^{-24}$
- great seal & self healing
- high pressure
- robust w.r.t pressure changes
- Salt is abundant
  - Brazil
  - GOM
  - North Sea

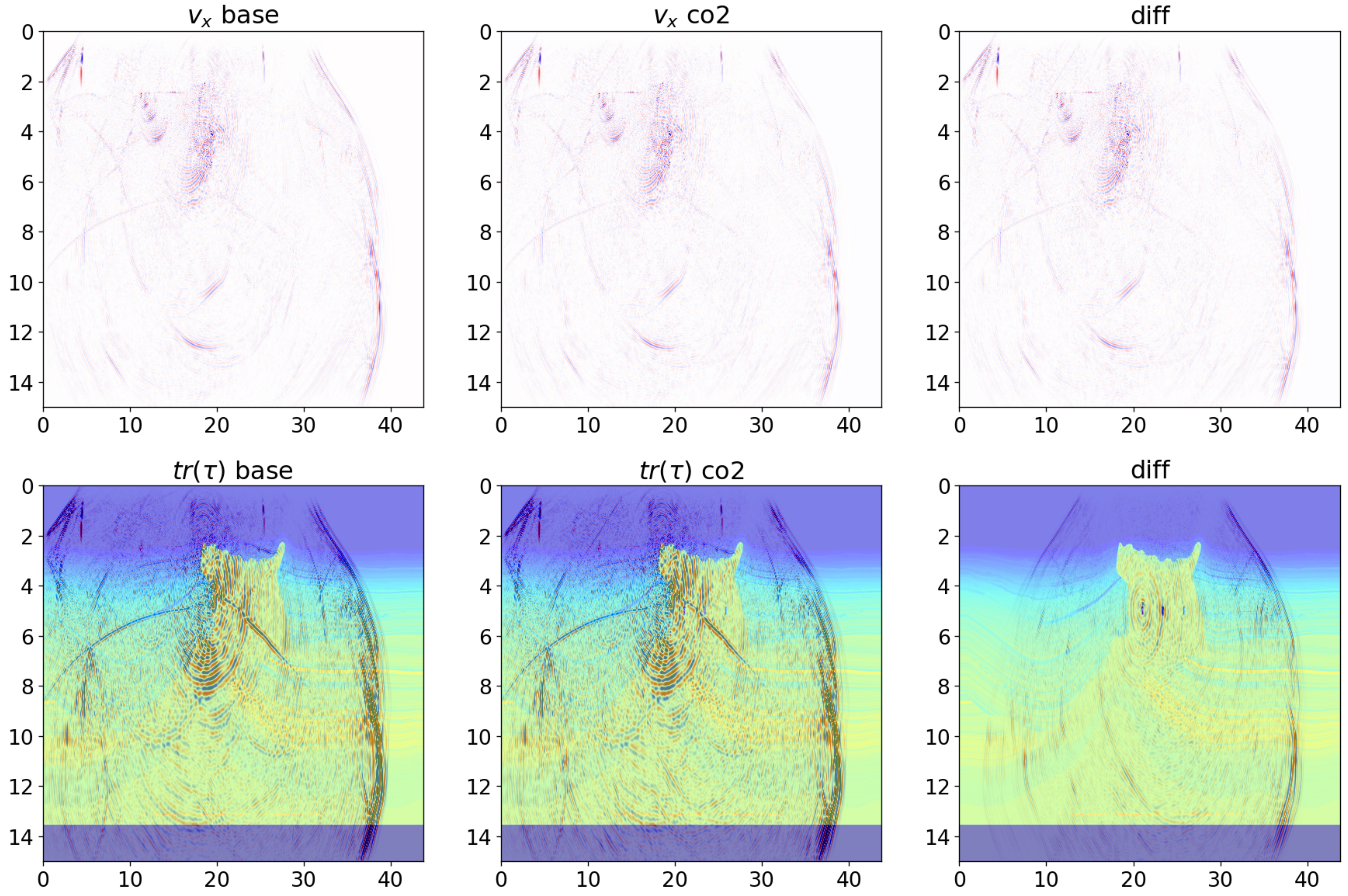
Stores at least 43.8 MT of CO_2



Salt Cavity
elastic modeling

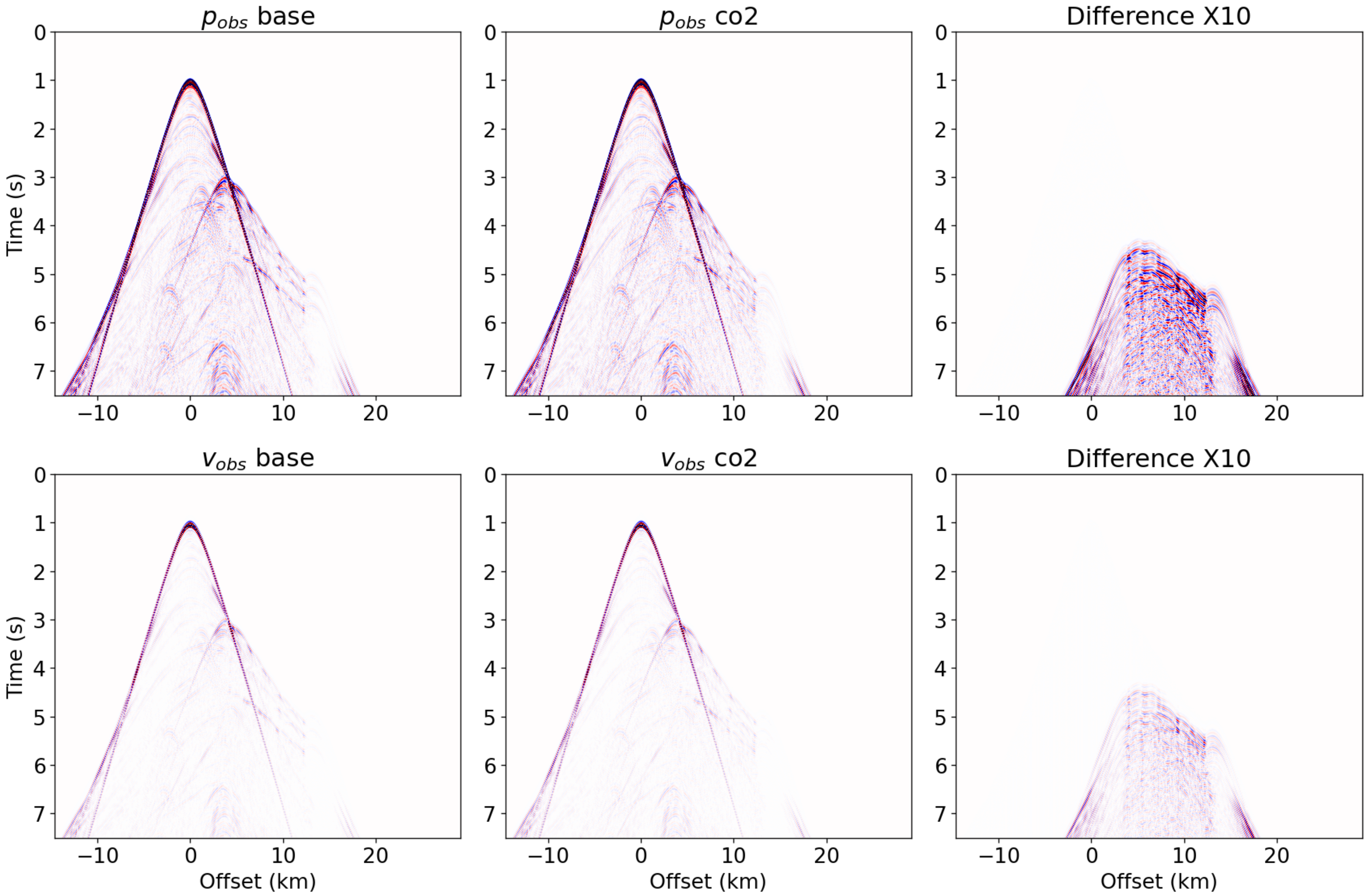
Modeling:

- 2D SEAM
- Single OBN experiment (OBN as source, receiver at 6m depth every 25m)
- 10Hz ricker wavelet
- 3 caverns 4.5km depth (400m x 50 x 50m)
- 7.5 sec recording
- elastic modelling w/ DEVITO

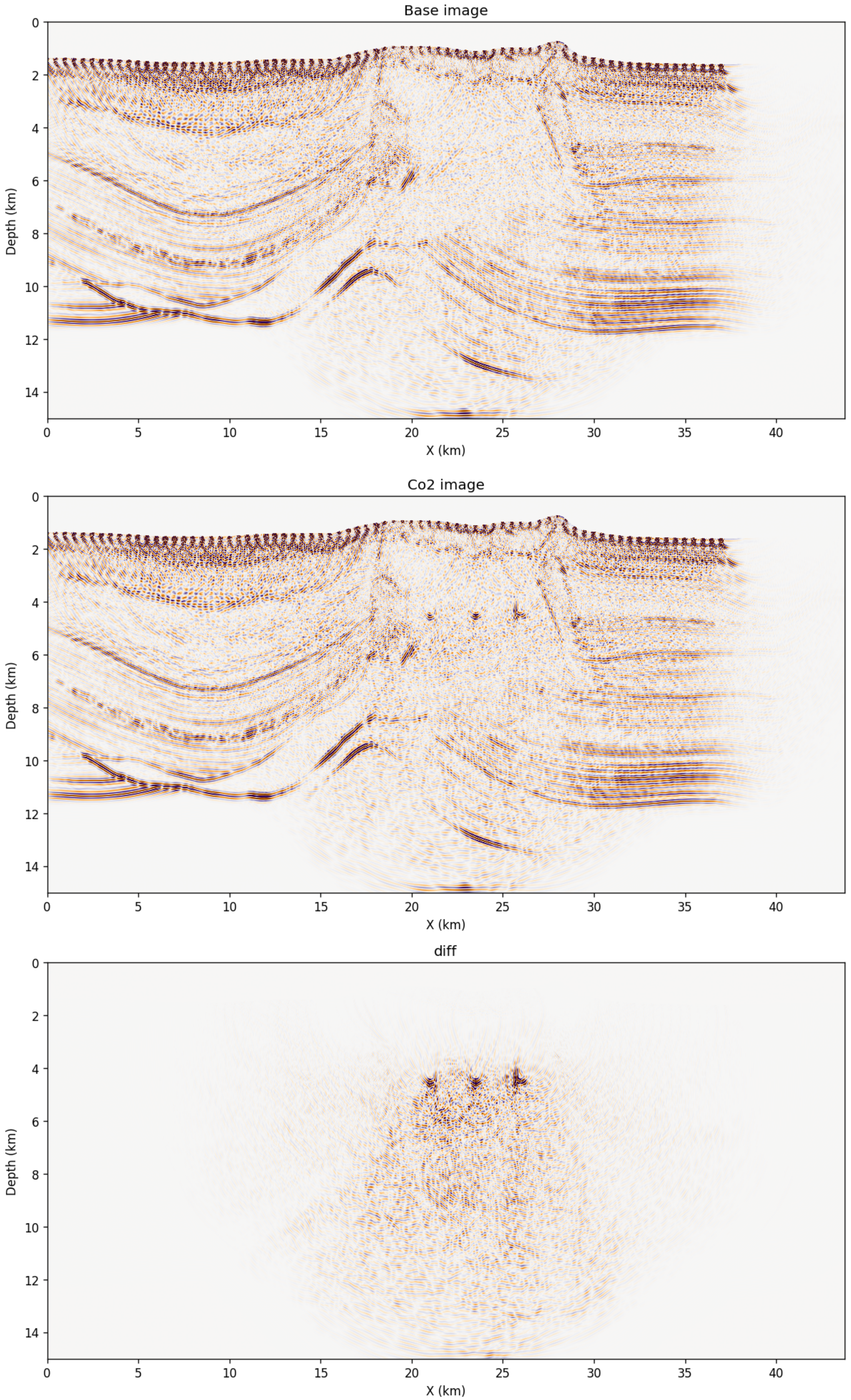


RTM

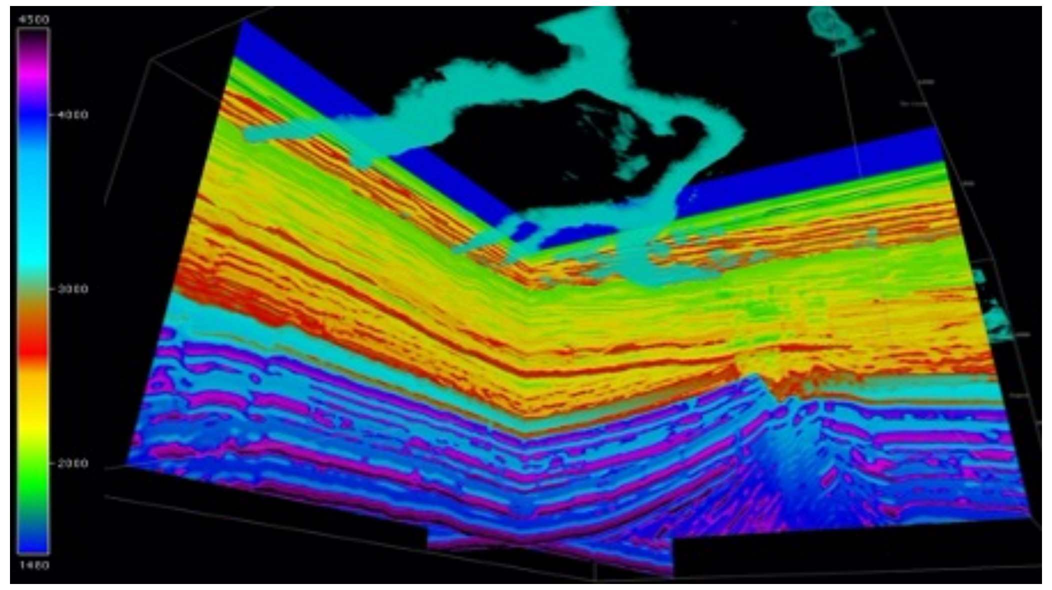
elastic data OBN spacing 500m



- CO2 filled cavities seismically detectable
- sparse OBN array
- dense source sampling

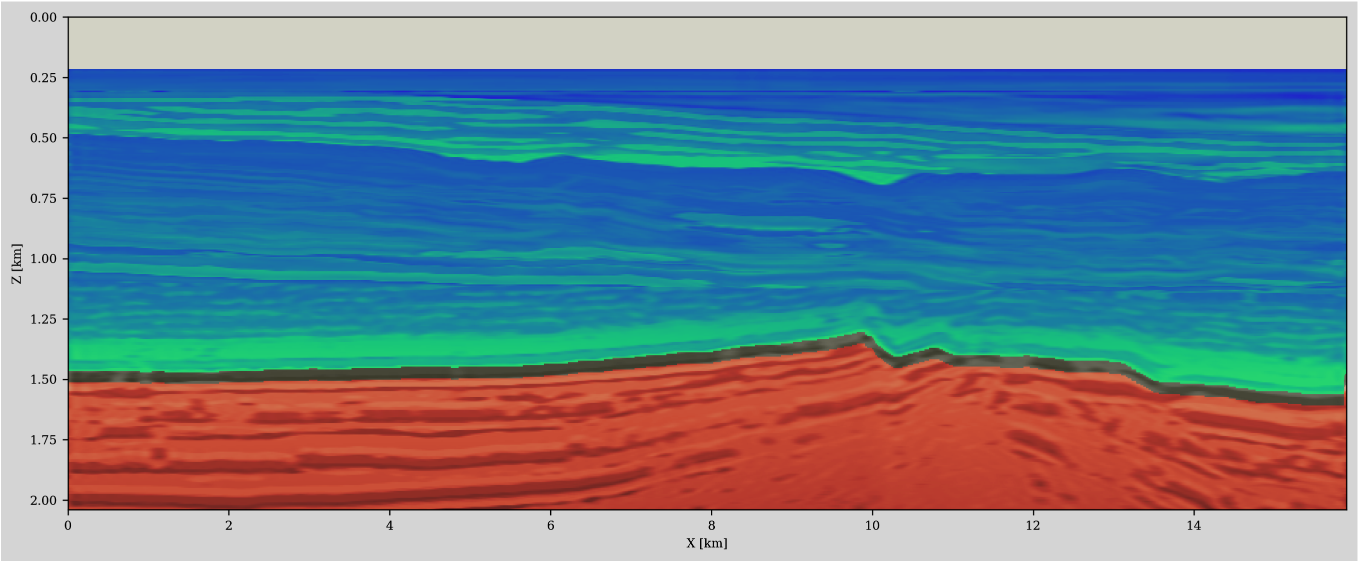


Seismic4CCS – Simulation-based seismic monitoring for CCS workflow



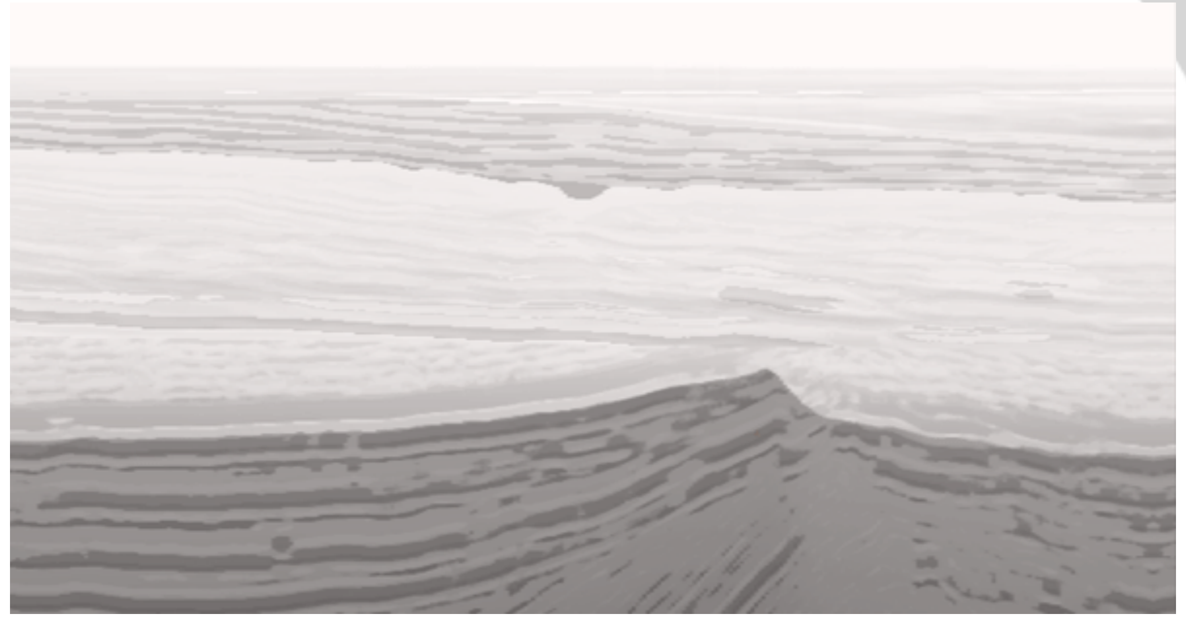
Seismic model
wave speed (c_p), density (ρ)

Conversion
$(\rho, c_p) \longrightarrow (\kappa, \phi)$



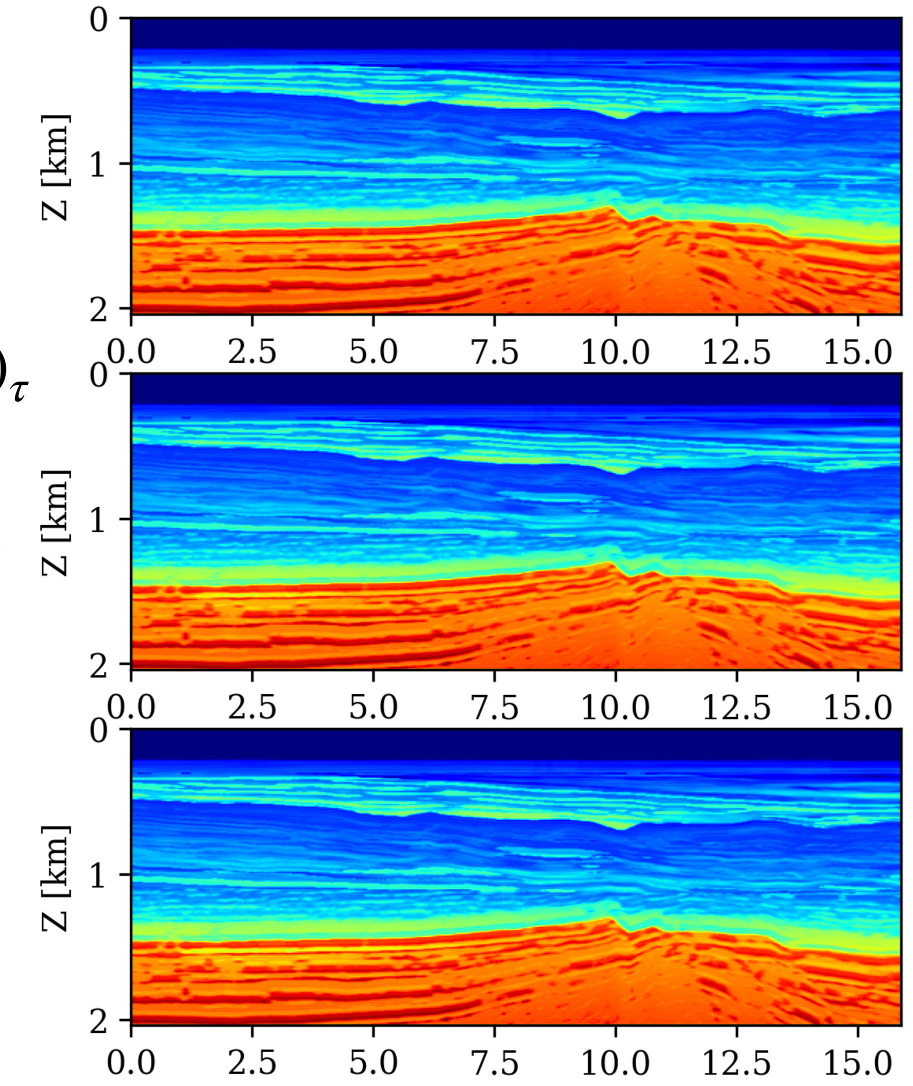
Fluid model
permeability (κ), porosity (ϕ)

Proxy Flow
$(\kappa, \phi) \longrightarrow S_\tau$



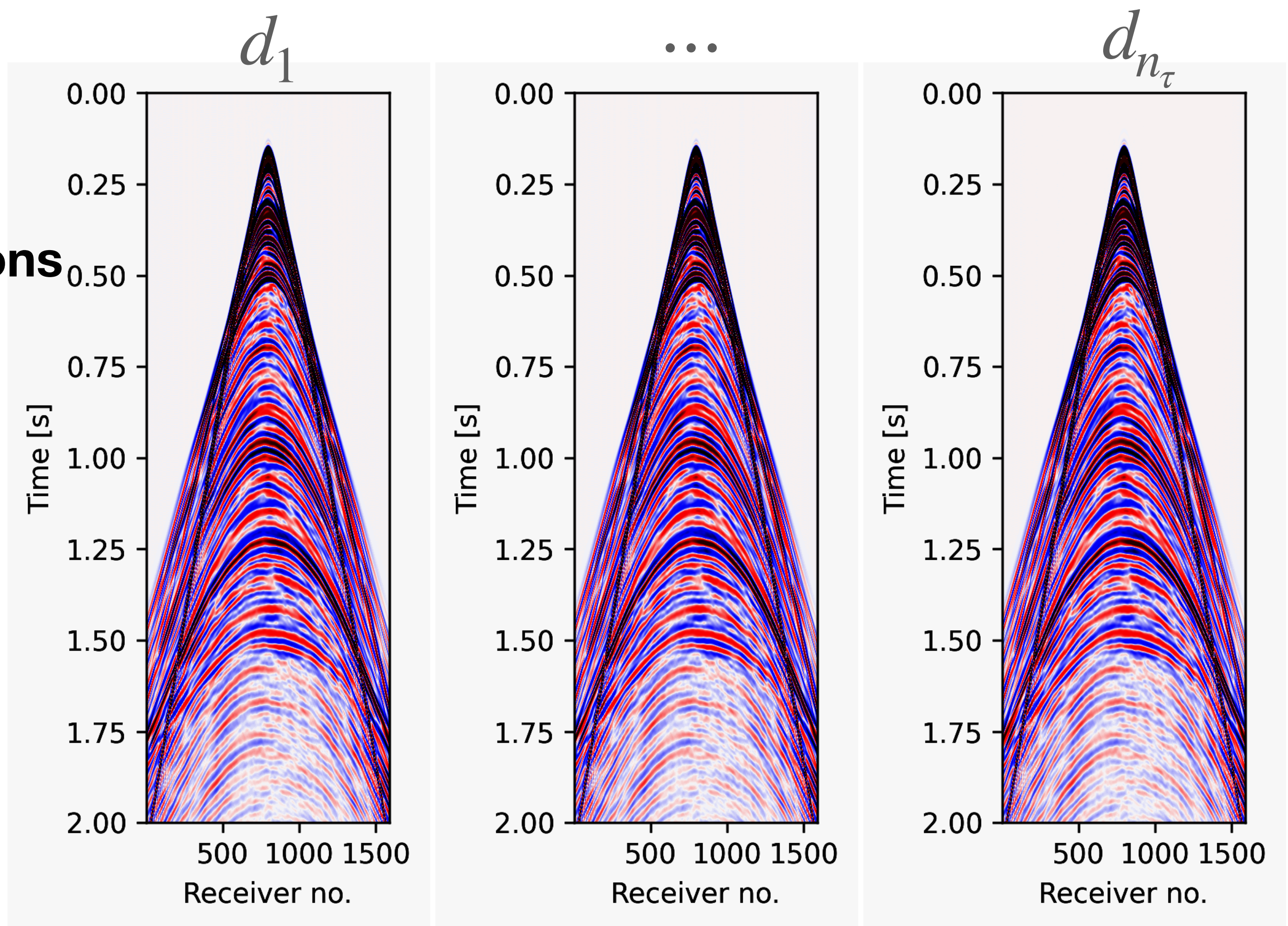
CO_2 dynamics
saturation, pressure

Conversion
$S_\tau \longrightarrow (\rho, c_p)_\tau$



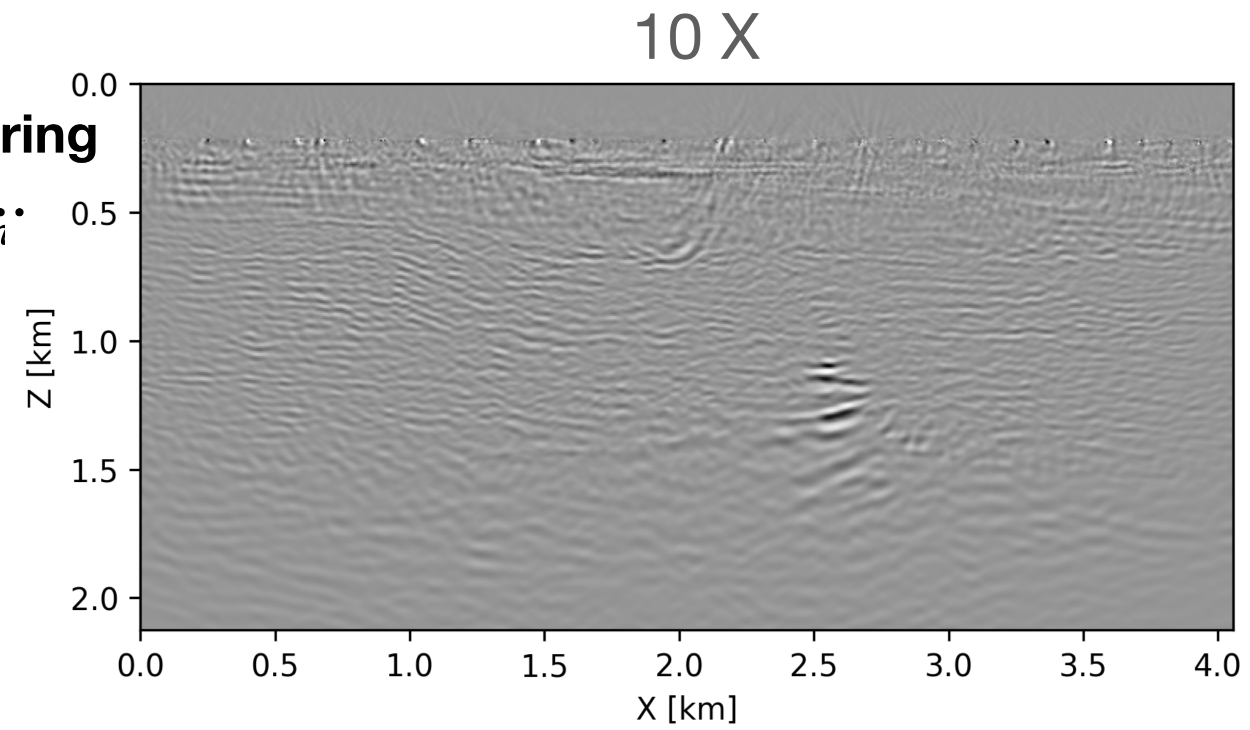
Time-lapse seismic model
wave speed, density

Seismic simulations
$(\rho, c_p)_\tau \longrightarrow d_\tau$



Time-lapse seismic
pressure data

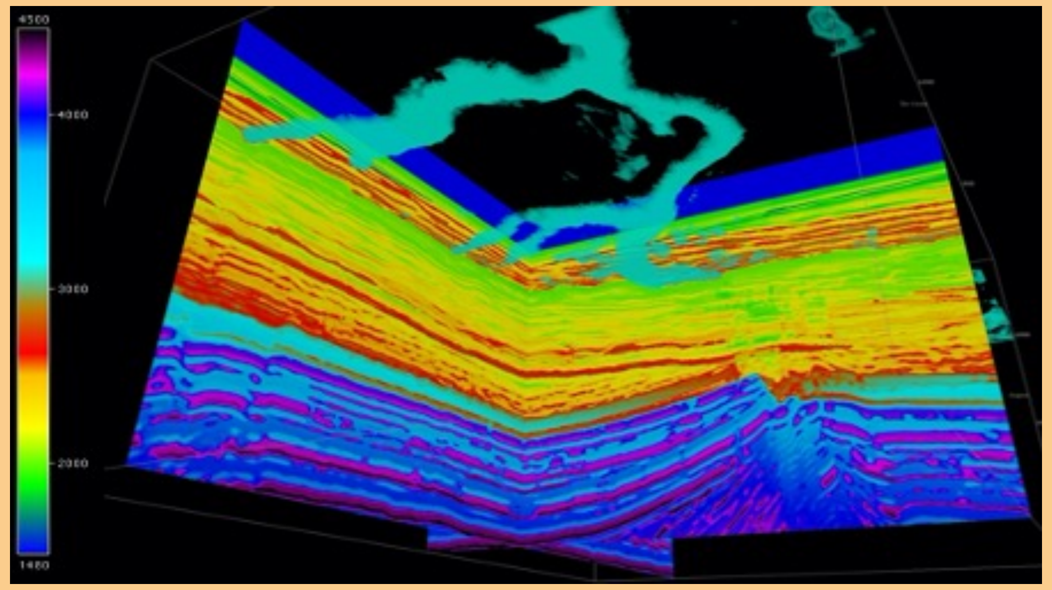
Seismic monitoring
$\delta m_1 \longrightarrow \delta m_{n_\tau}$



Time-lapse seismic images
impedance contrast

Proxy Reservoir Module

seismic to fluid



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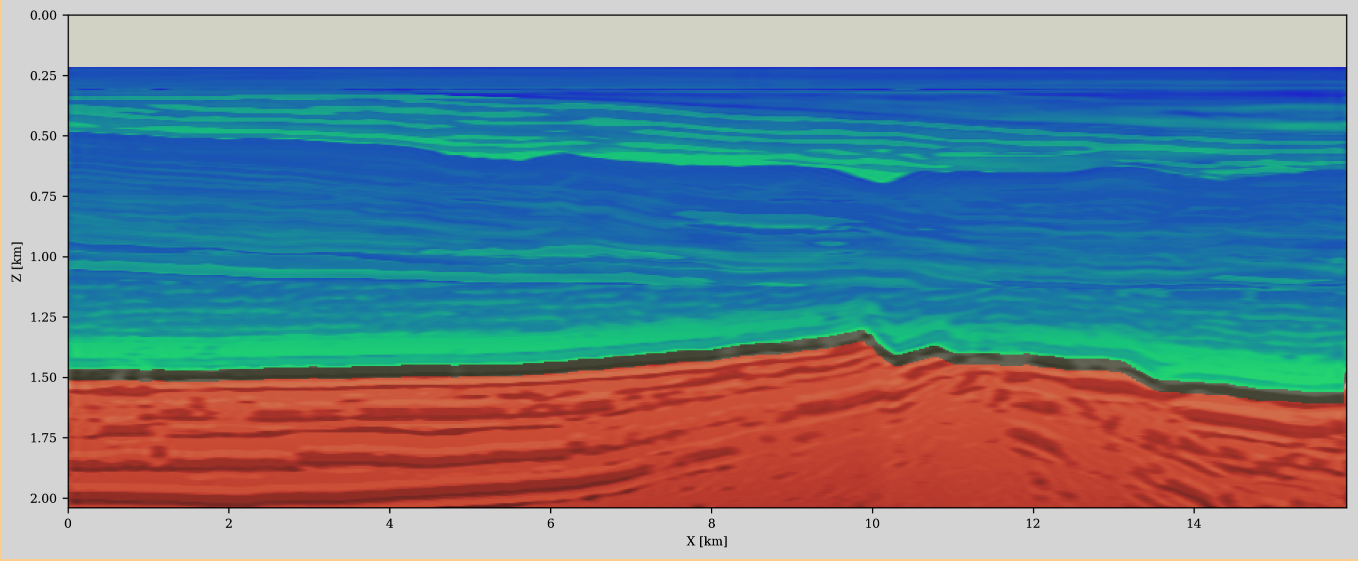

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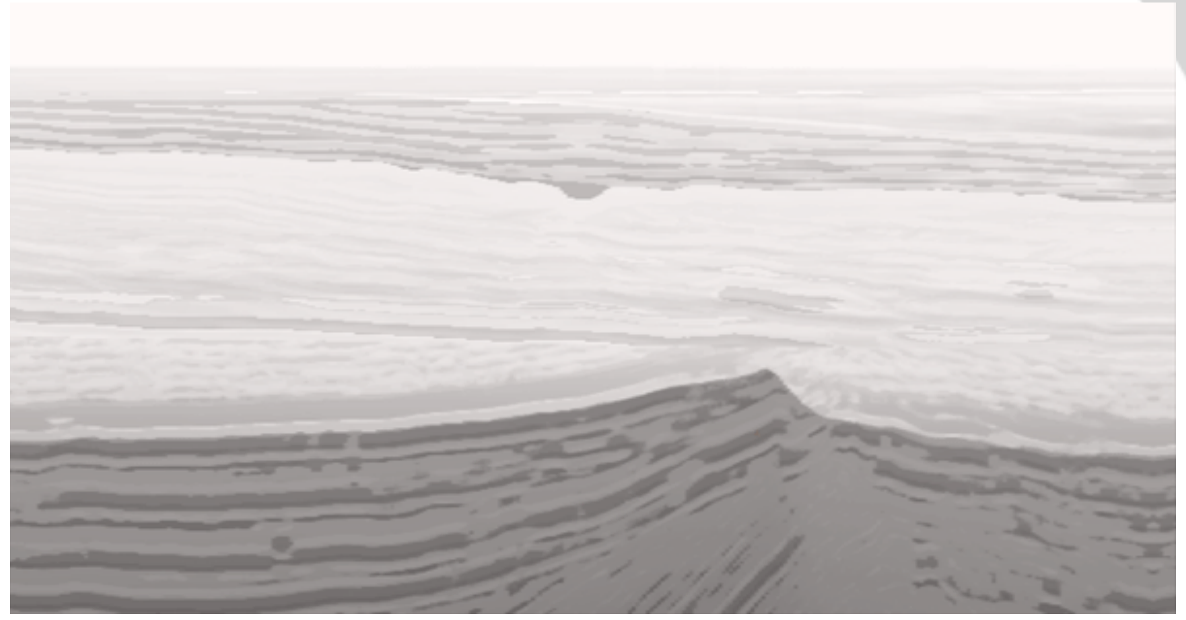

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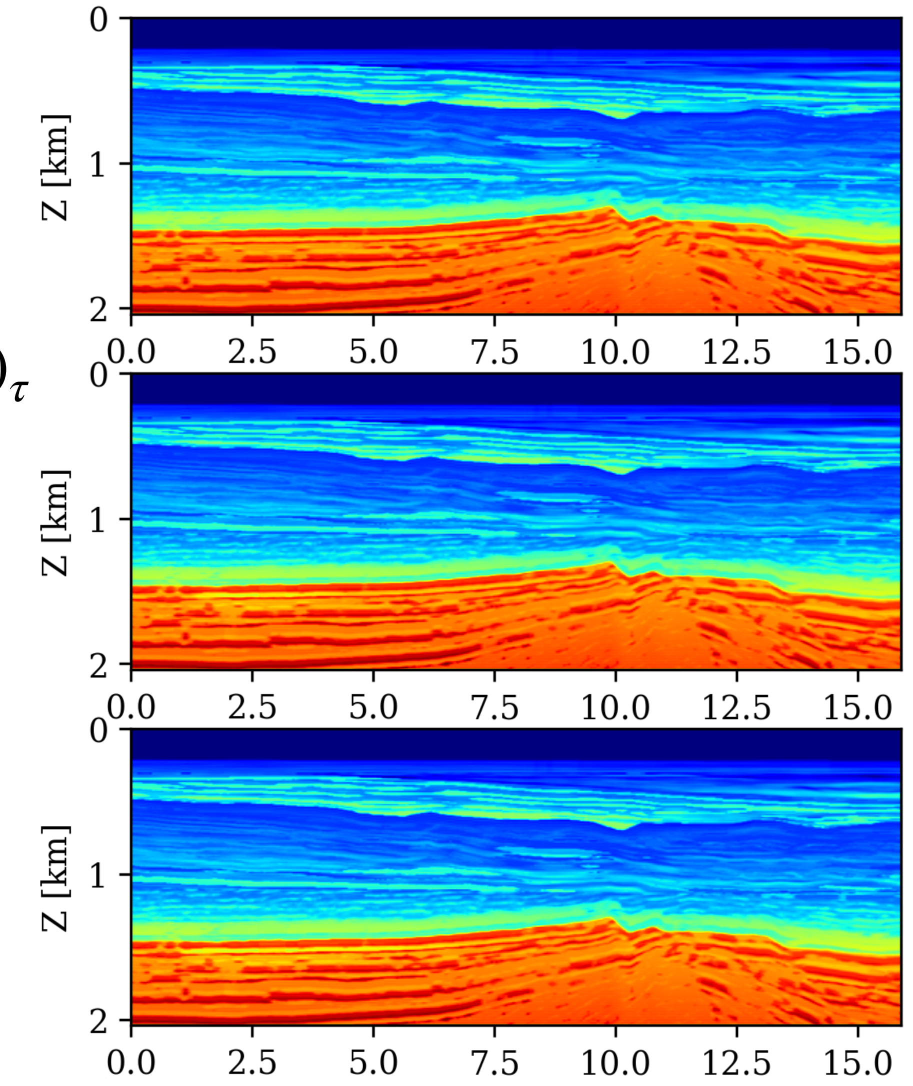

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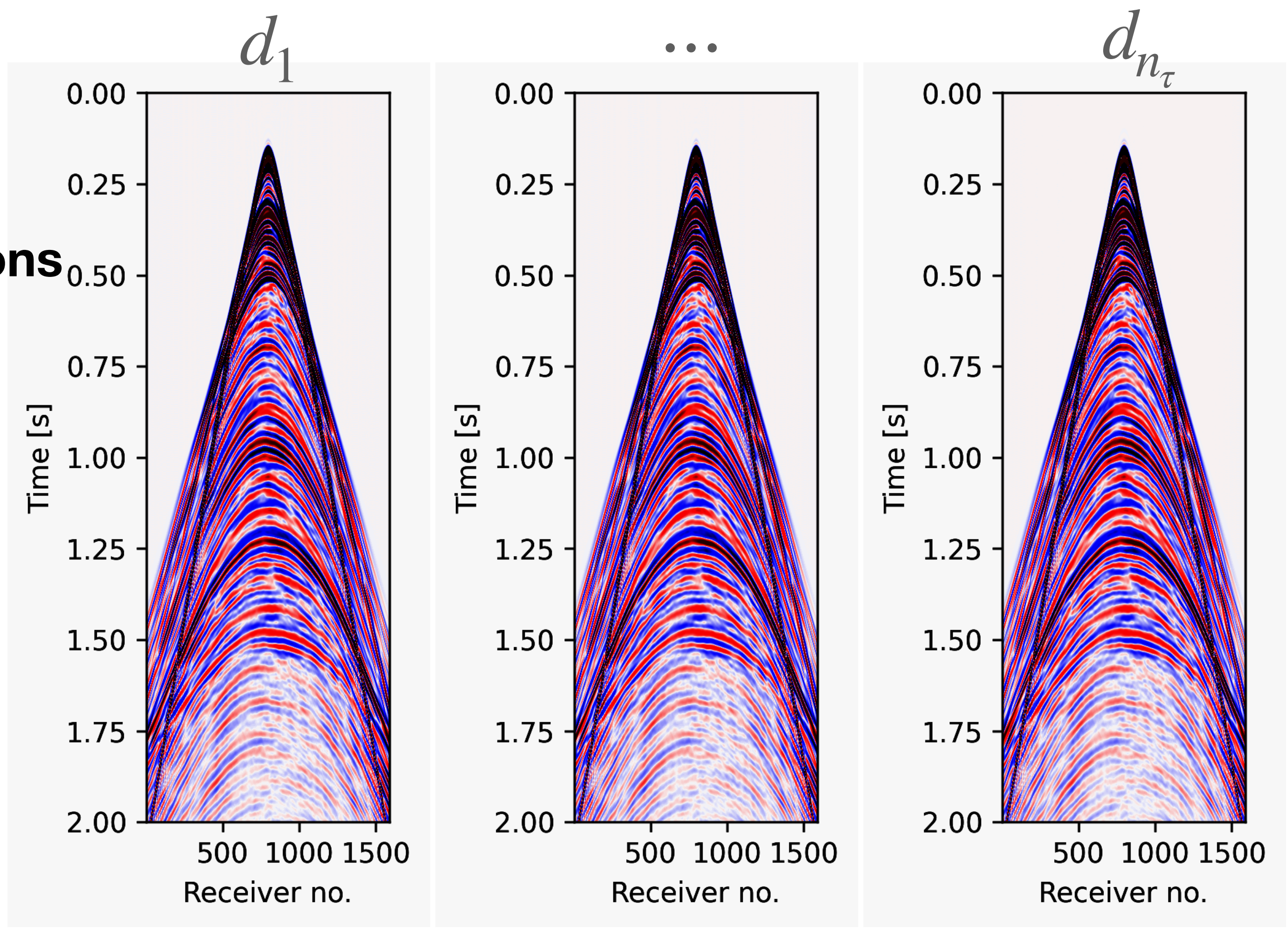
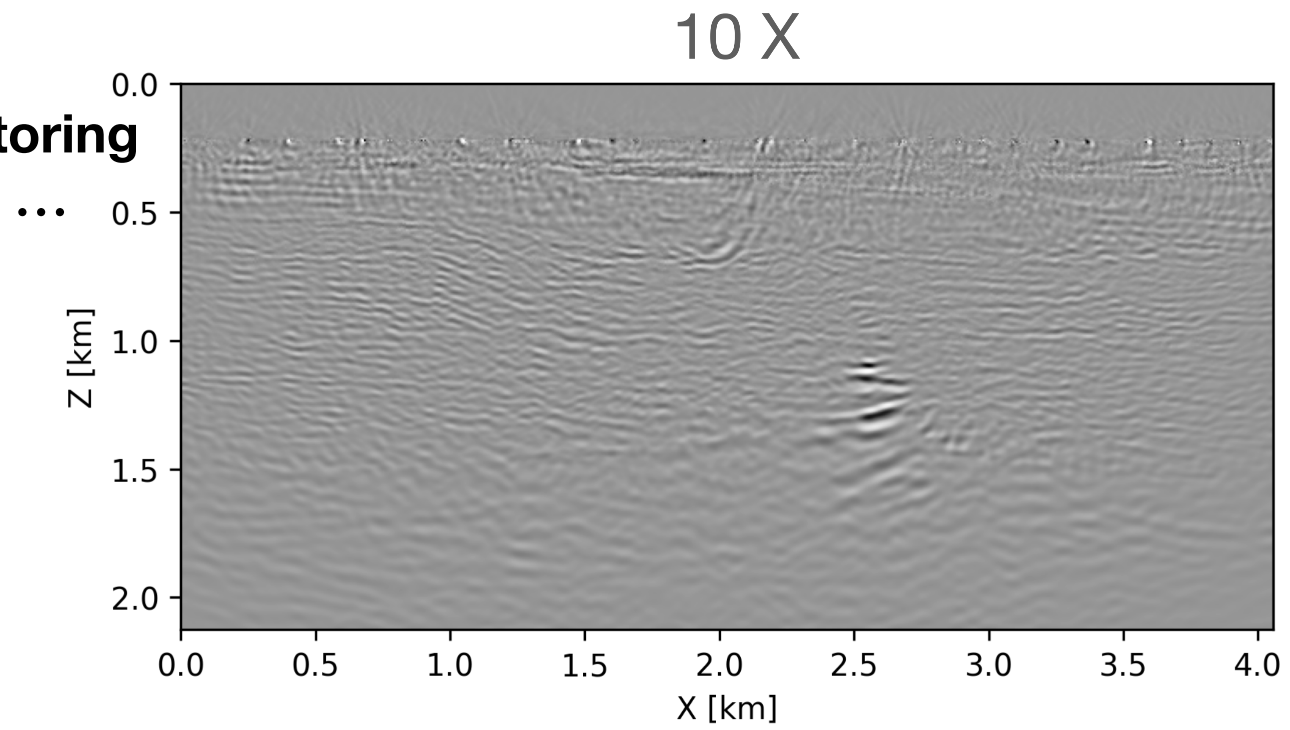


Time-lapse seismic
pressure data

Seismic monitoring
$\delta m_2 - \delta m_1, \cdots$

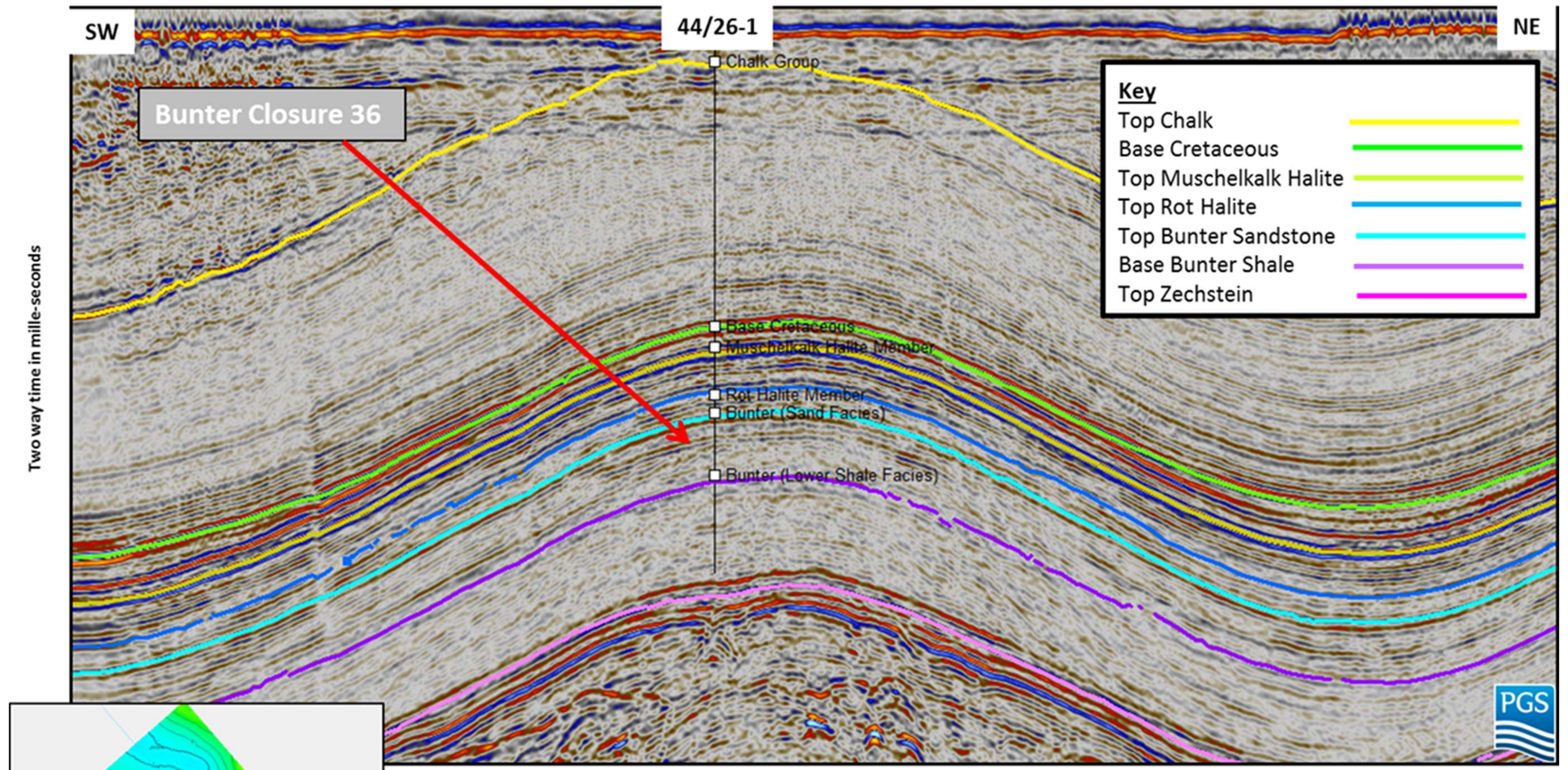


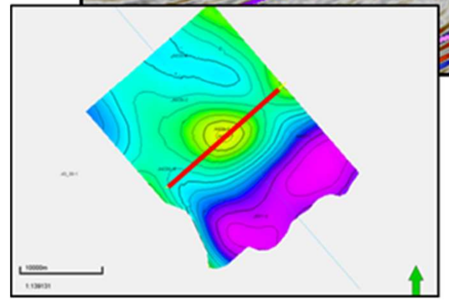
Time-lapse seismic images
impedance contrast

Proxy Reservoir Module – Saline Aquifers

heterogeneity constrained by 3D seismic & well-data

Jones, C. E., et al. "Building complex synthetic models to evaluate acquisition geometries and velocity inversion technologies." European Association of Geoscientists & Engineers, 2012.

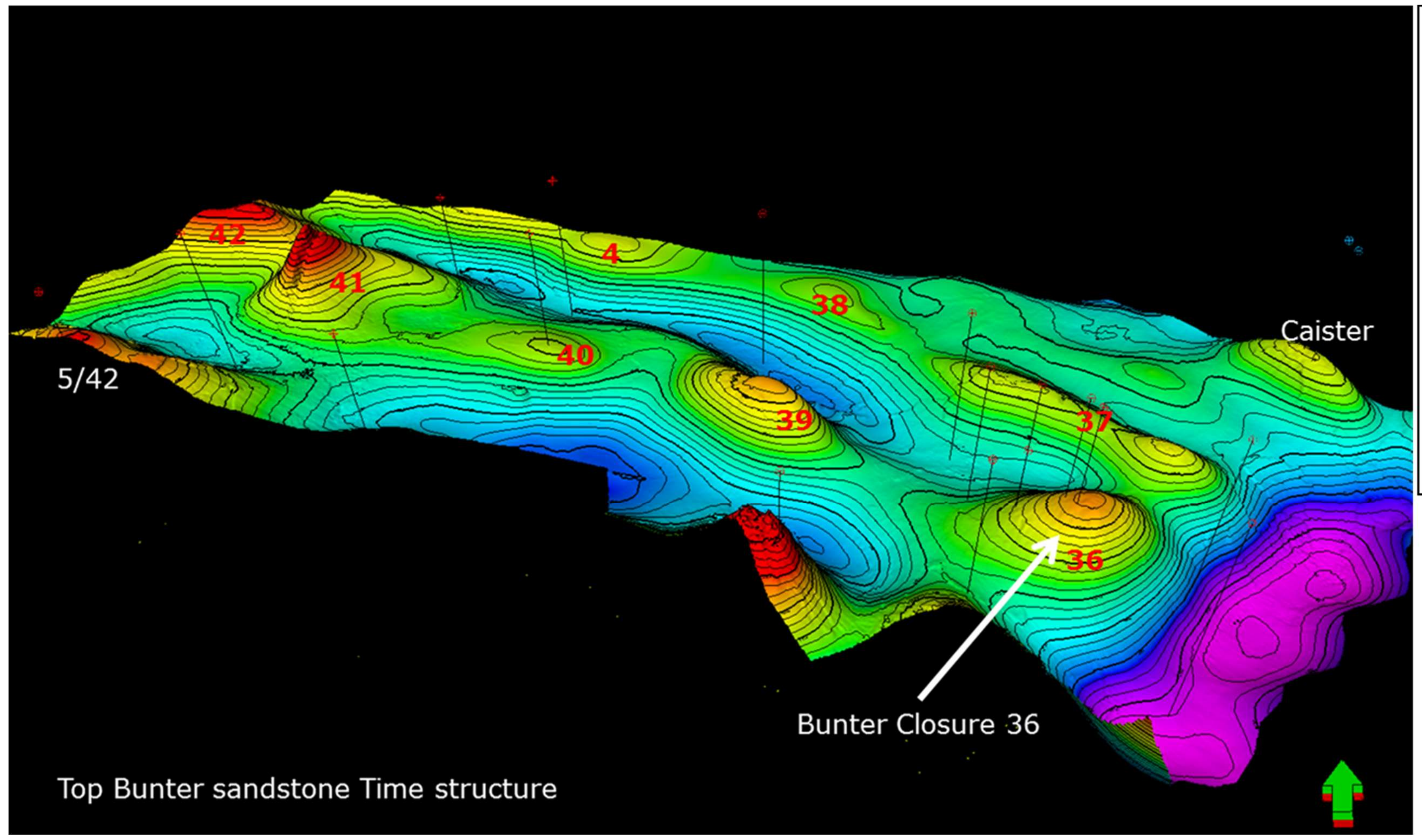




SW-NE seismic line from PGS Megasurvey showing horizons interpreted.

Bunter Closure 36 is highlighted.

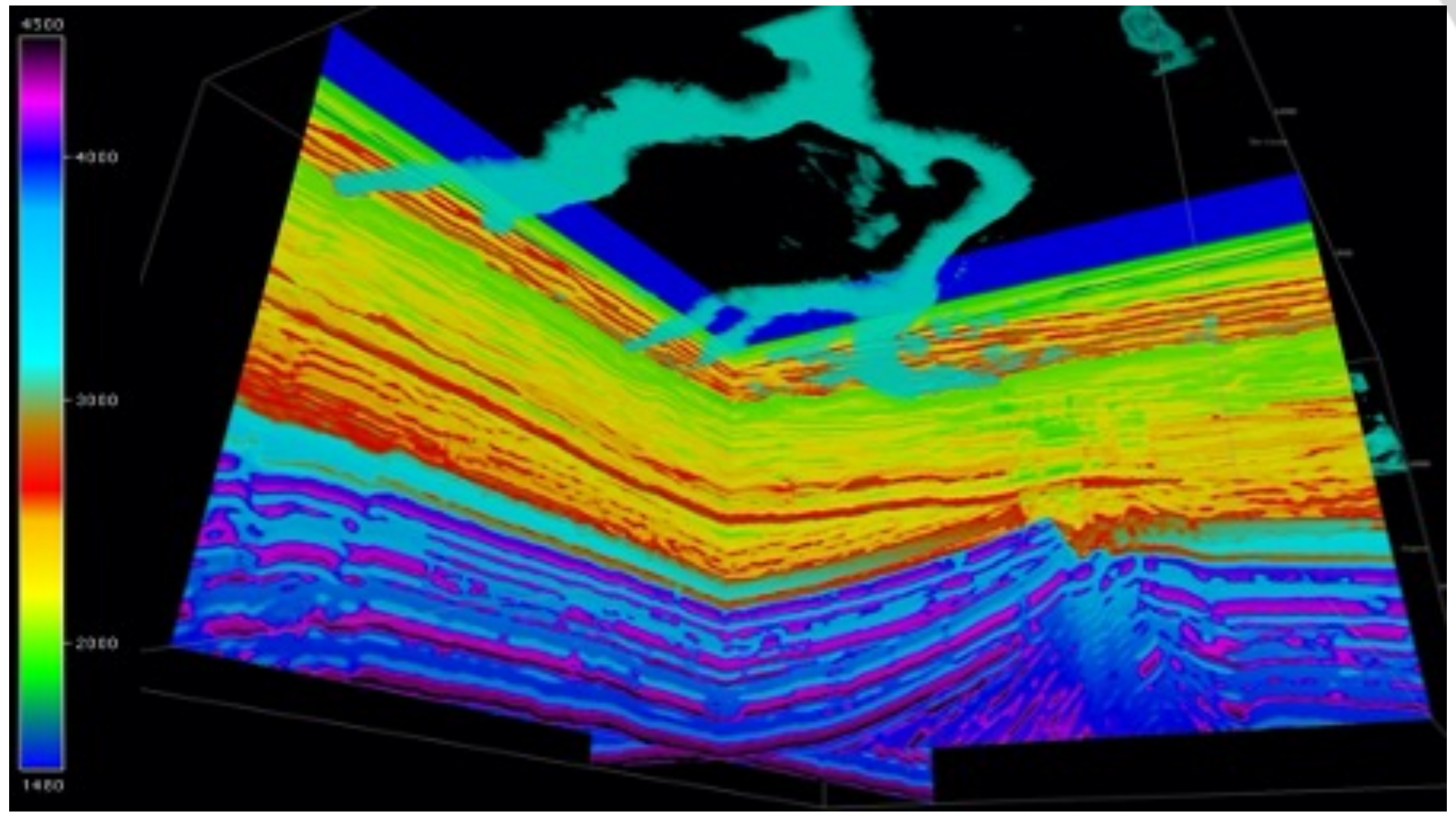
from: Strategic UK CCS Storage Appraisal Project



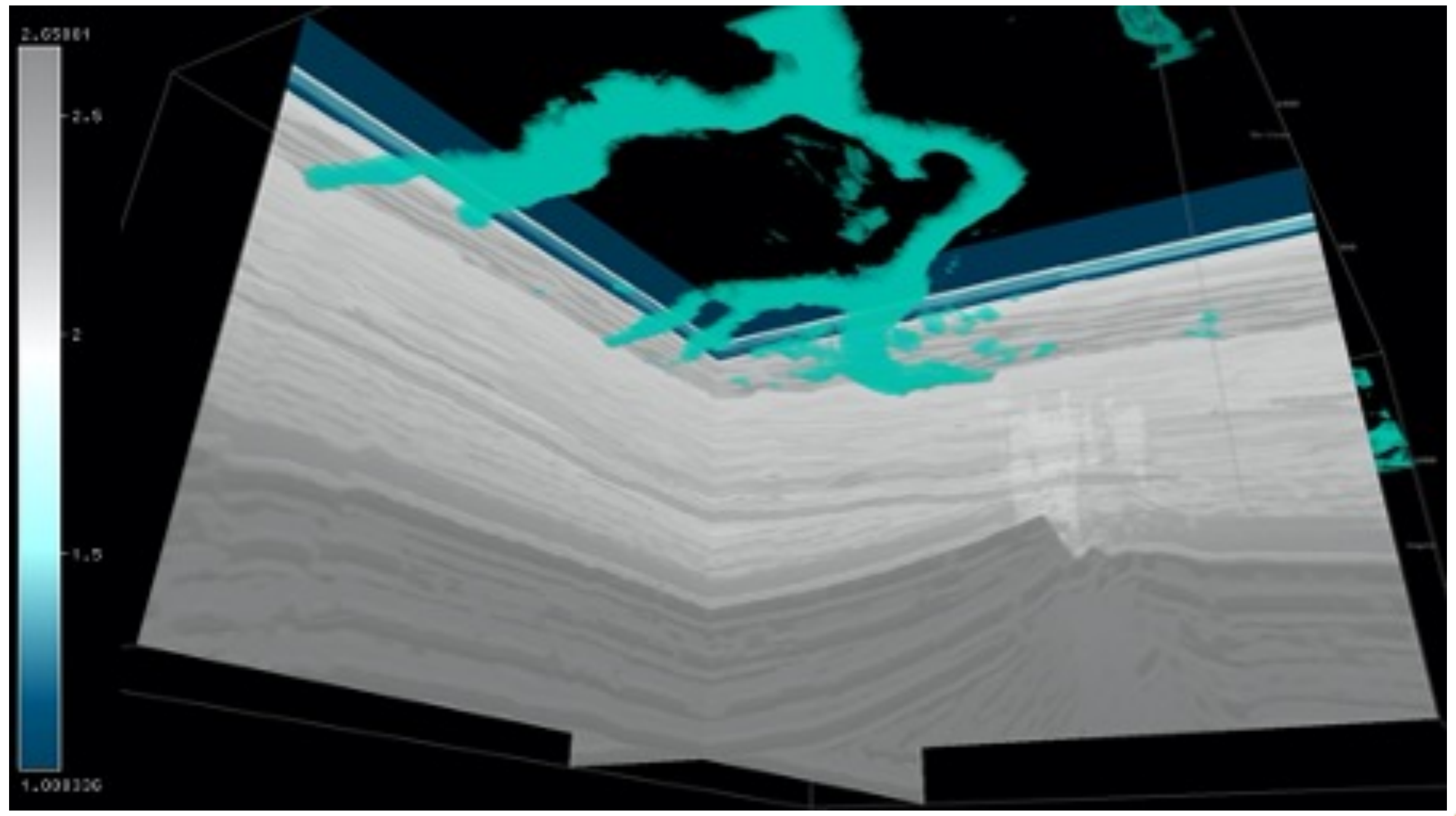
3D view of Top Bunter Sandstone two-way time structure over the Fairway and Closure 36.

Shows 8 anticlines with the UKSAP numbers plus 5/42 and Caister.

translate 3D post-stack seismic + well data into *full-scale* 3D proxy *reservoir* models for velocity & density



compressional wavespeed
≫15km



density

Rock physics

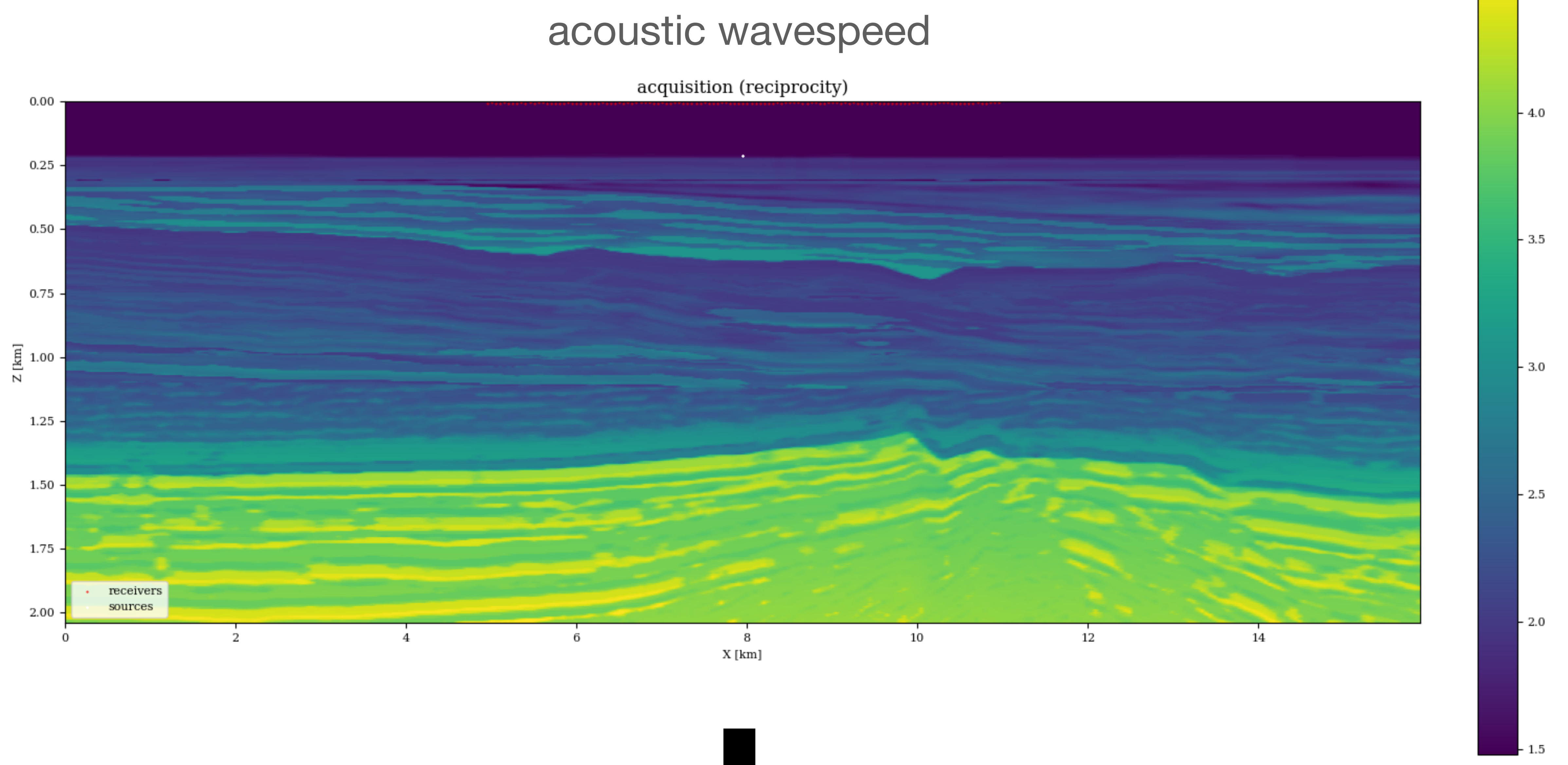
velocity ⟶ permeability

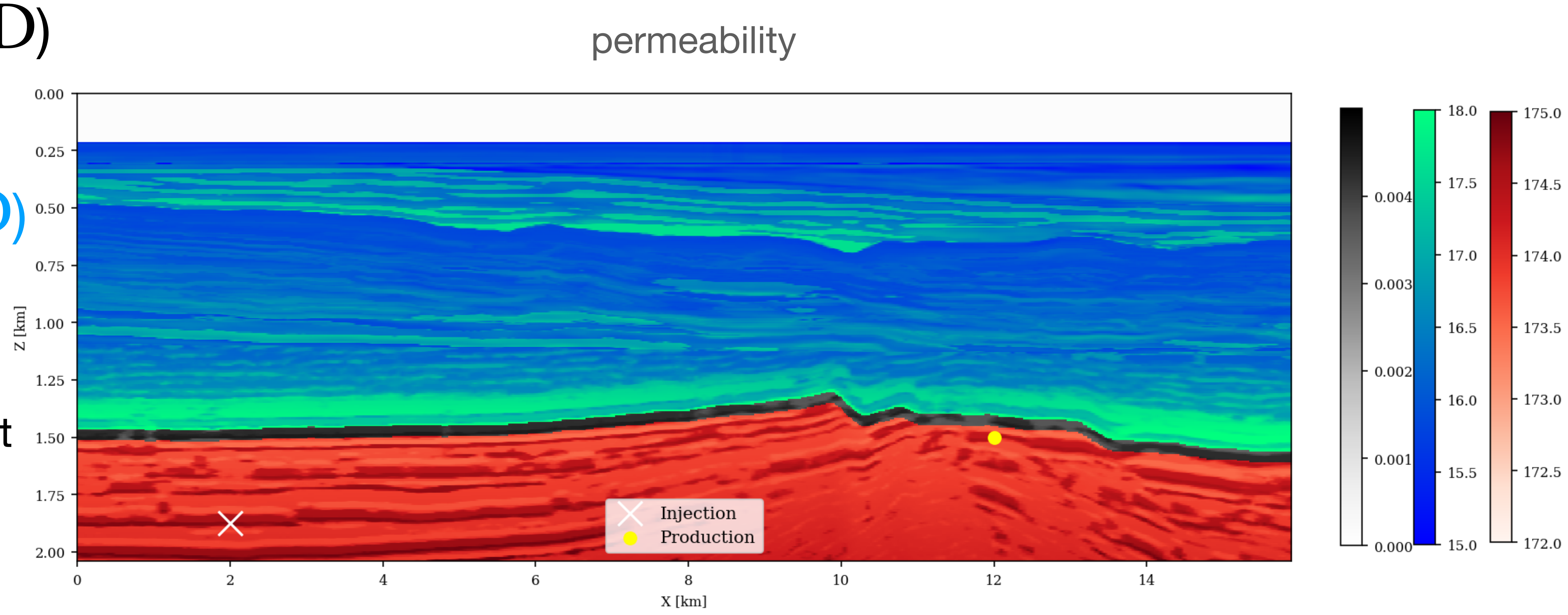
Conversion* with $\Delta \mathbf{K} = 1.63 \Delta \mathbf{V}_p$

Three main geologic sections:

- Saline aquifer – Bunter sandstone (red, $300-500\text{m}$, permeability $>170\text{mD}$)
- Primary seal – Rote Halite member (black, 50m, permeability $10^{-4}-10^{-2}\text{mD}$)
- Secondary seal – Haisborough group (blue, $>300\text{m}$, permeability $15-18\text{mD}$)

*values taken from Strategic UK CCS Storage Appraisal Project





Costa, Antonio. "Permeability-porosity relationship: A reexamination of the Kozeny-Carman equation based on a fractal pore-space geometry assumption." Geophysical research letters 33.2 (2006).

Rock physics

permeability ⟶ porosity

Kozeny-Carman relationship:

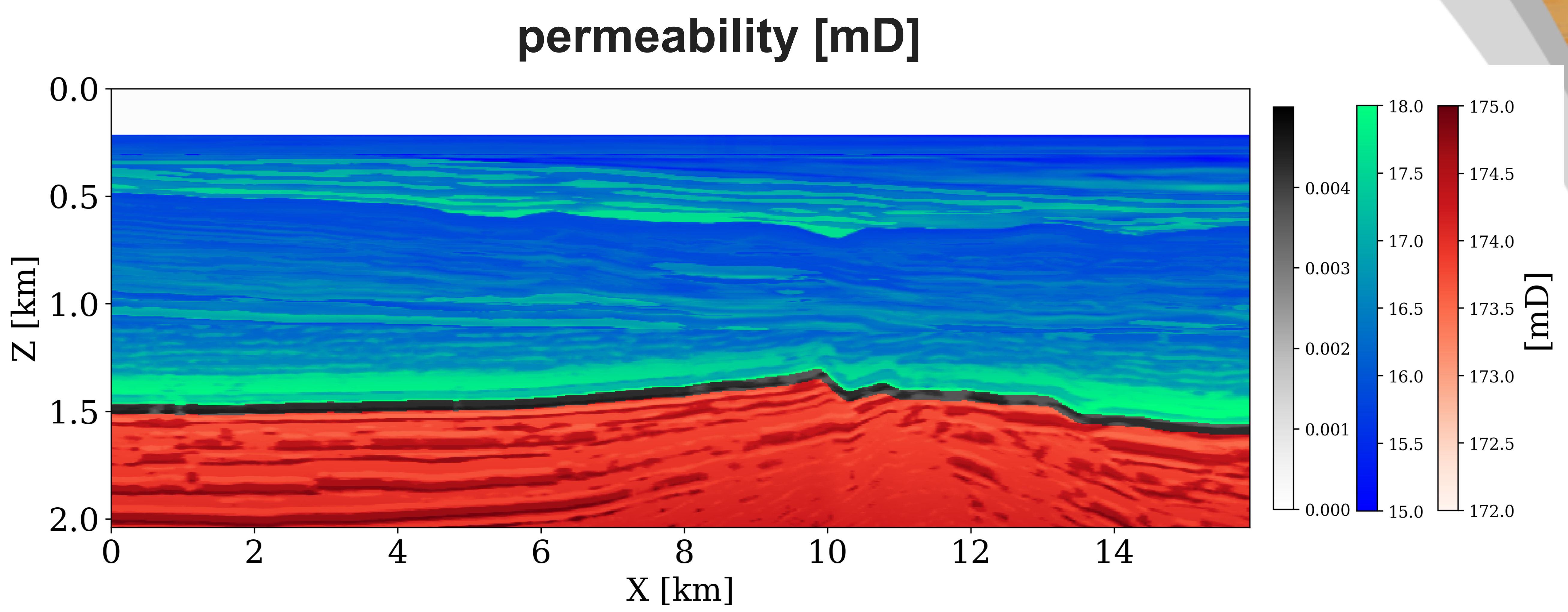
$$K = \phi^3 \left(\frac{1.527}{0.0314 * (1 - \phi)} \right)^2$$

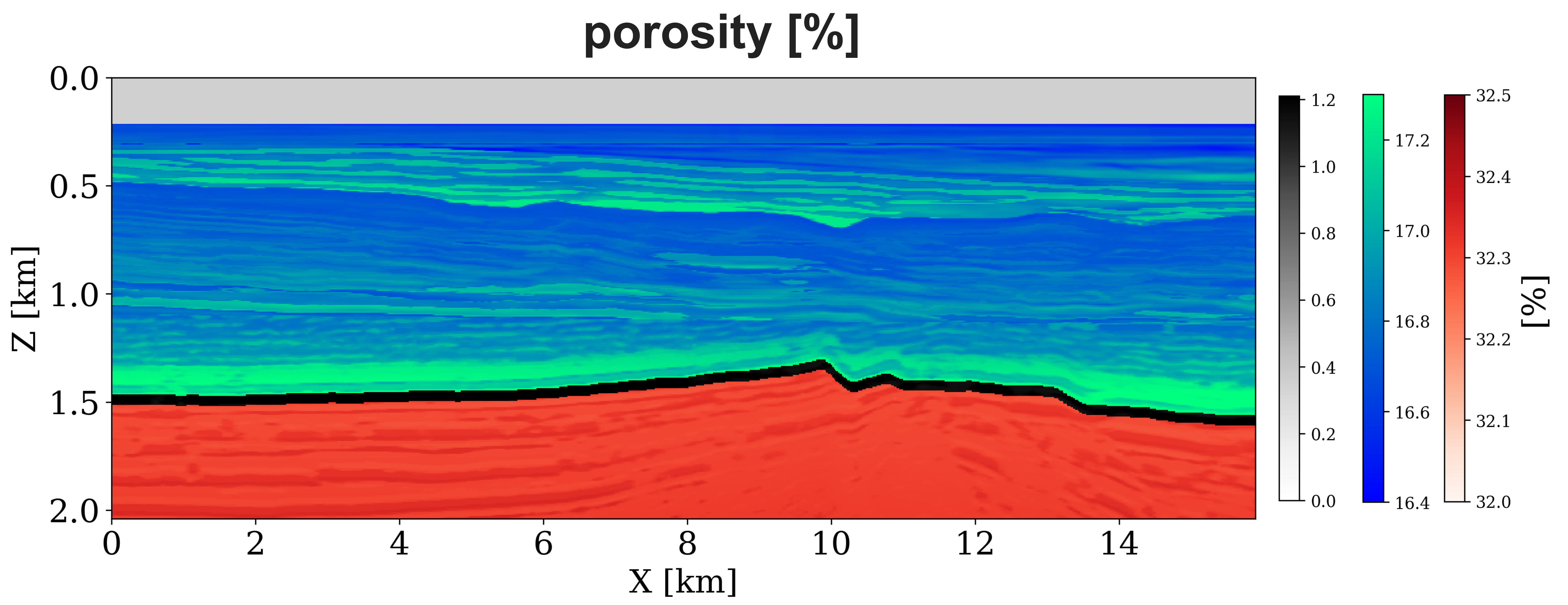
- K permeability
- ϕ porosity

Permeability & porosity models:

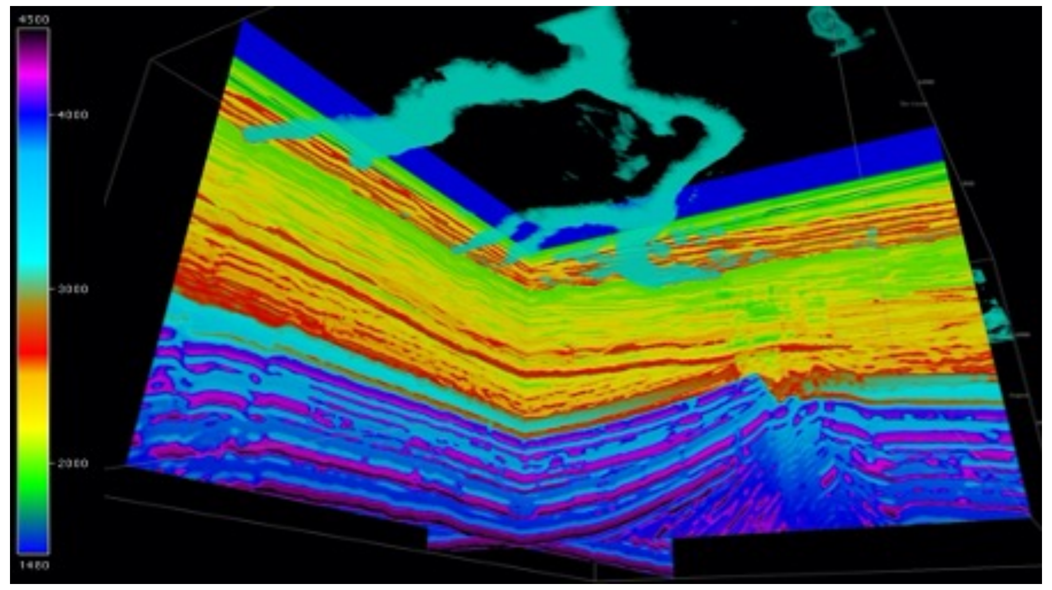
- **input for two-phase fluid flow simulations**

*values taken from Strategic UK CCS Storage Appraisal Project





Flow Simulation Module



Seismic model
wave speed (c_p), density (ρ)

Conversion
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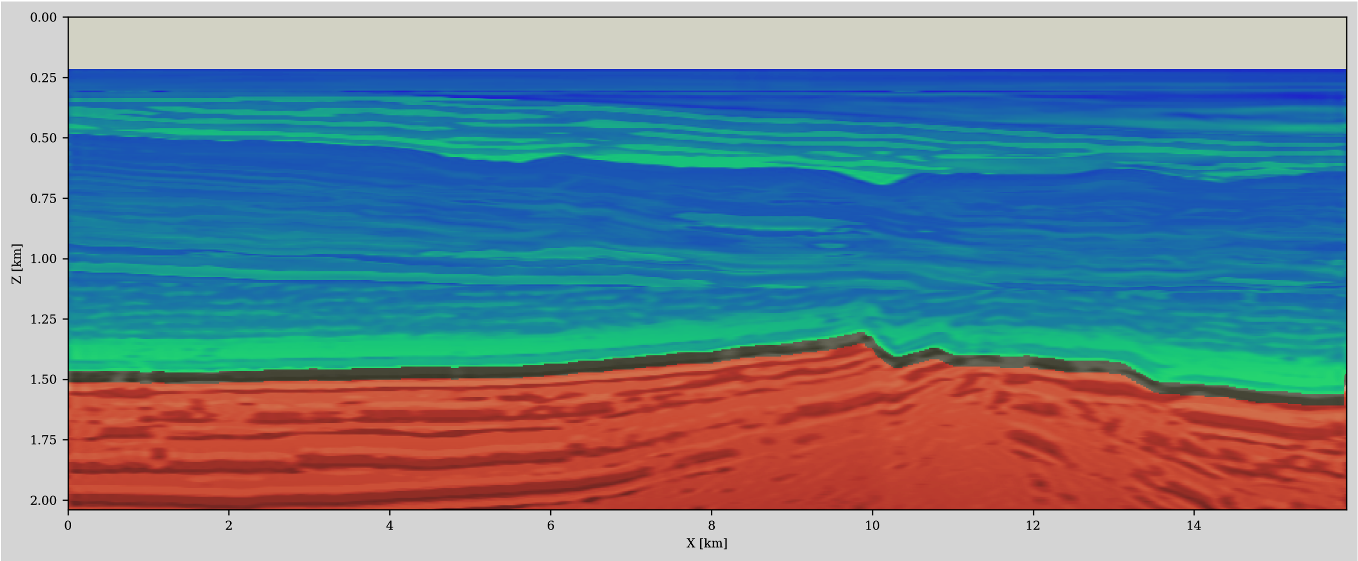
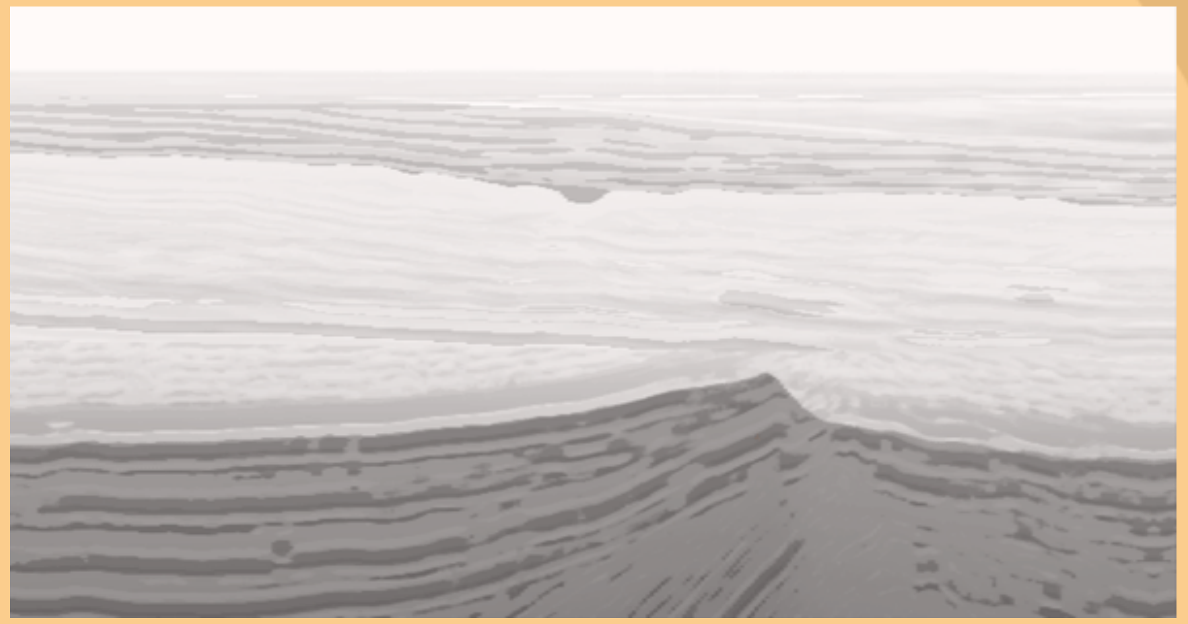


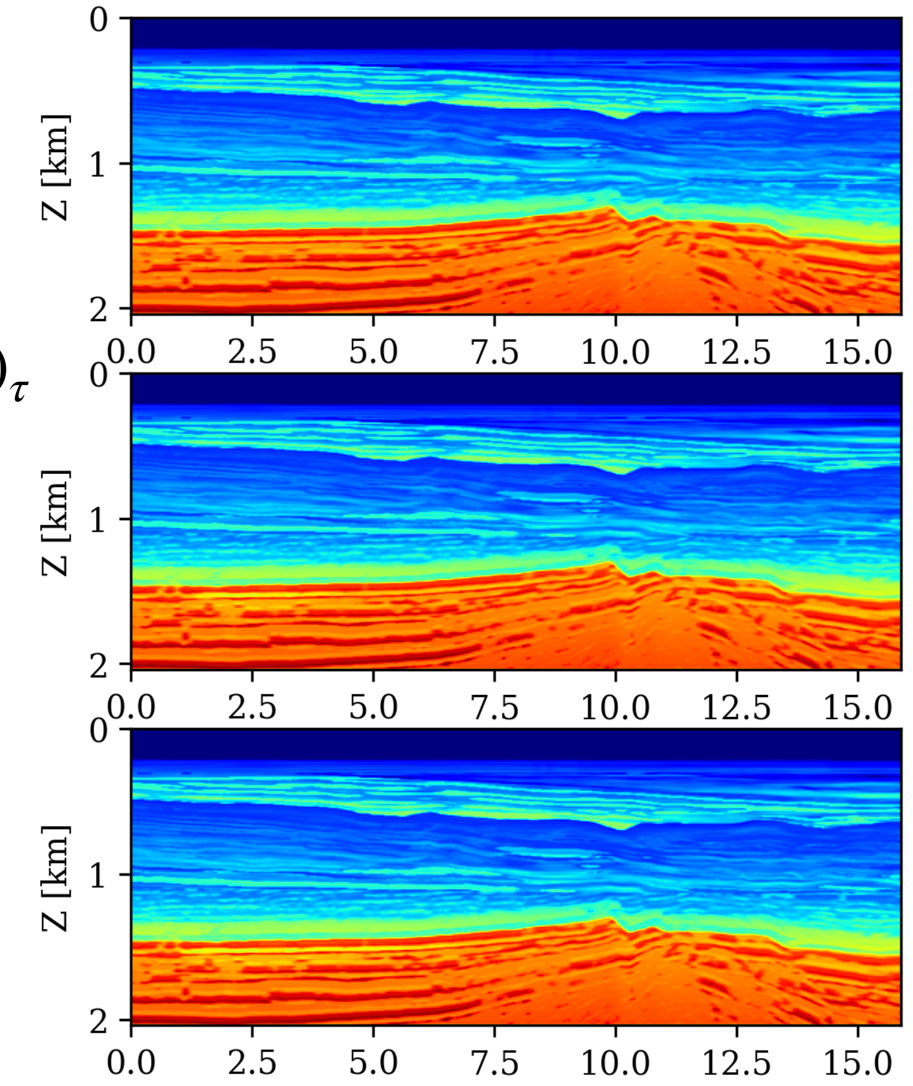
Fluid model
permeability (κ), porosity (ϕ)

Proxy Flow
$(\kappa, \phi) \longrightarrow S_\tau$



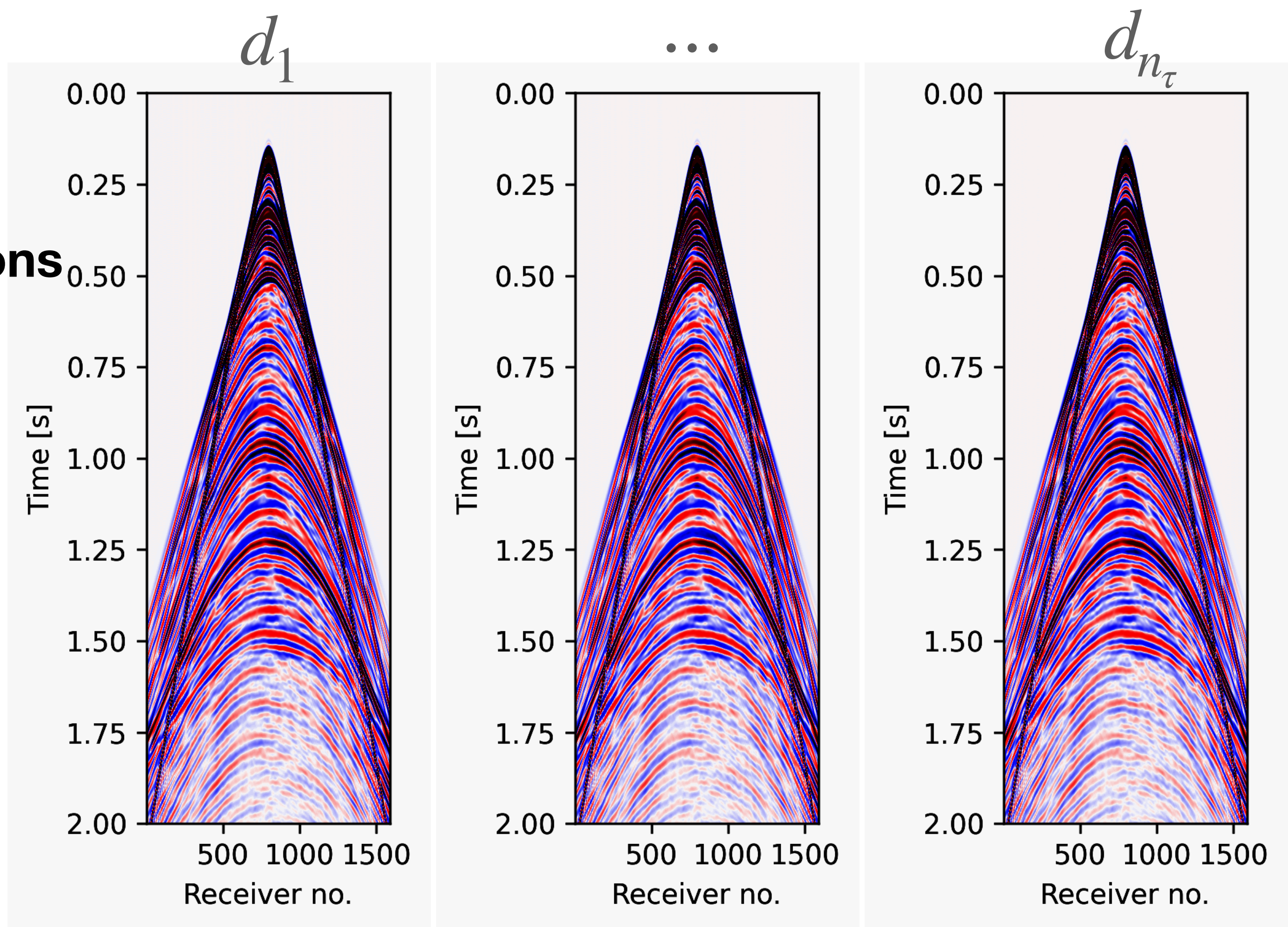
CO_2 dynamics
saturation, pressure

Conversion
$S_\tau \longrightarrow (\rho, c_p)_\tau$



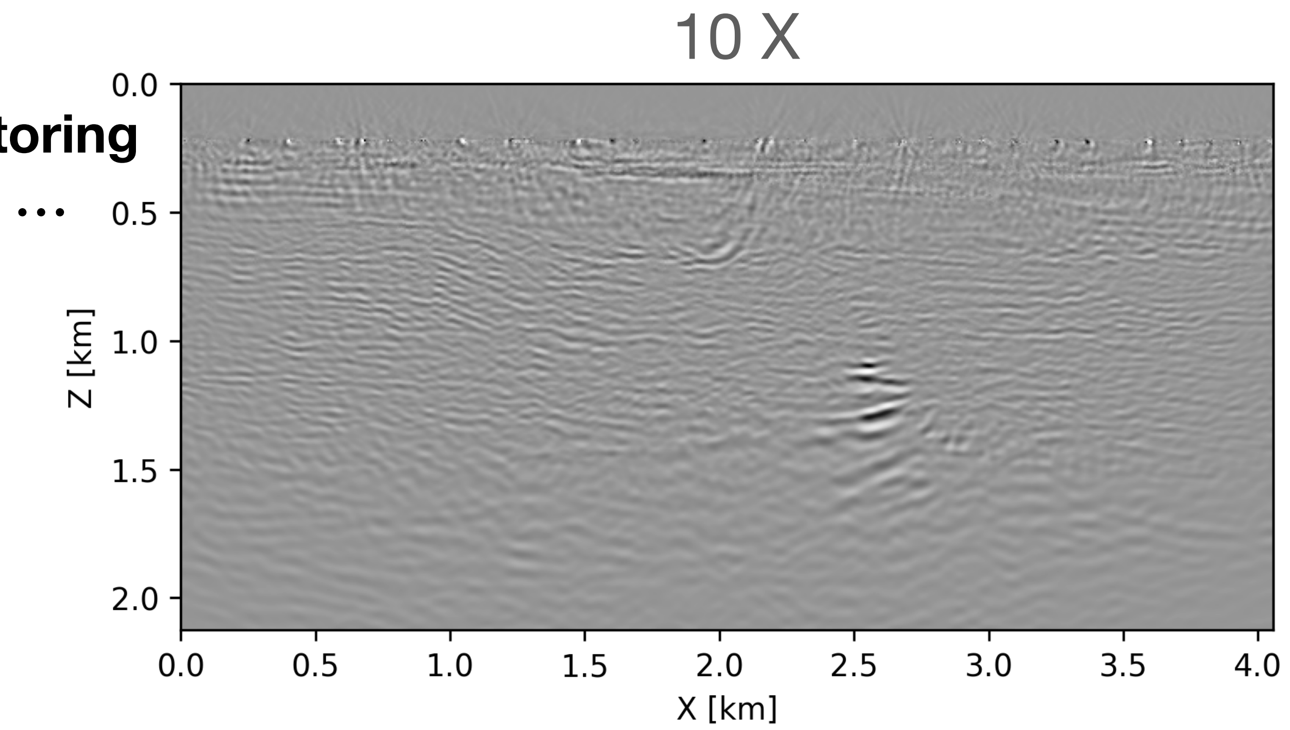
Time-lapse seismic model
wave speed, density

Seismic simulations
$(\rho, c_p)_\tau \longrightarrow d_\tau$



Time-lapse seismic
pressure data

Seismic monitoring
$\delta m_2 - \delta m_1, \cdots$

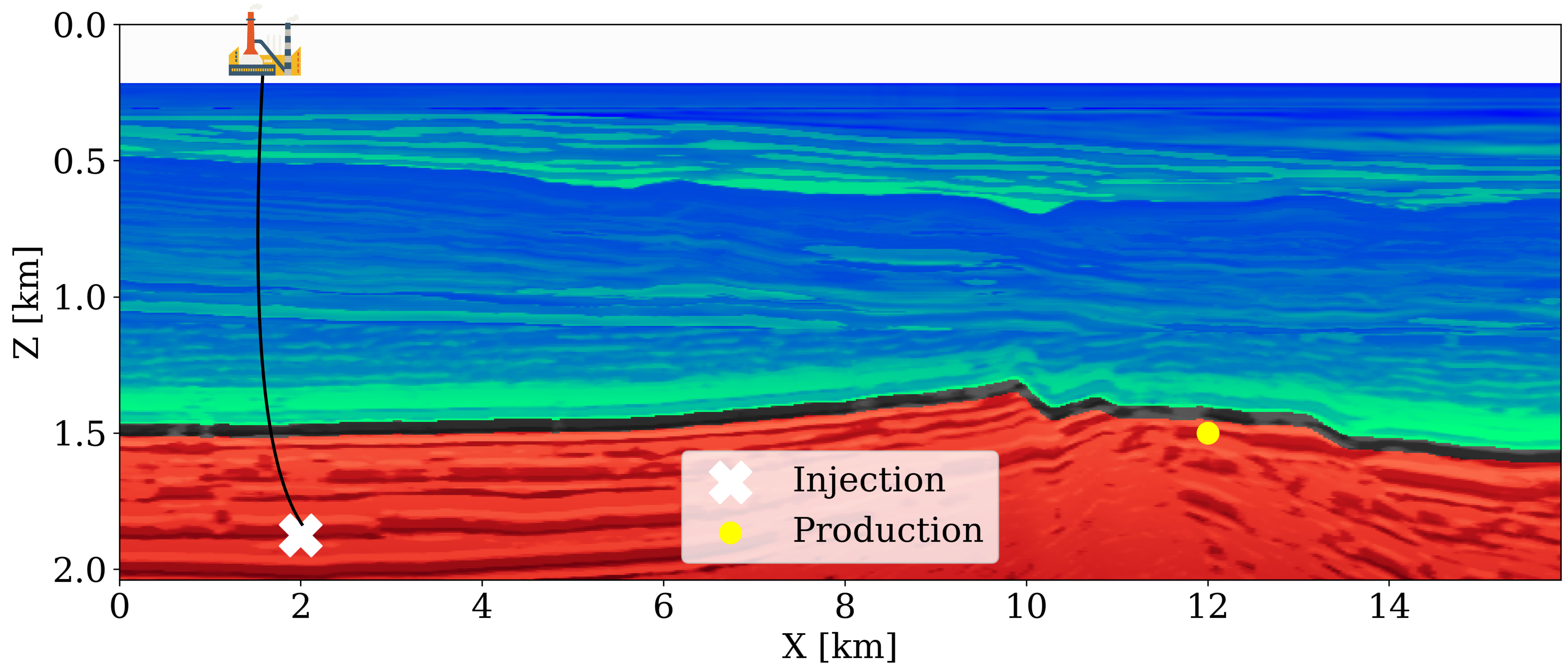


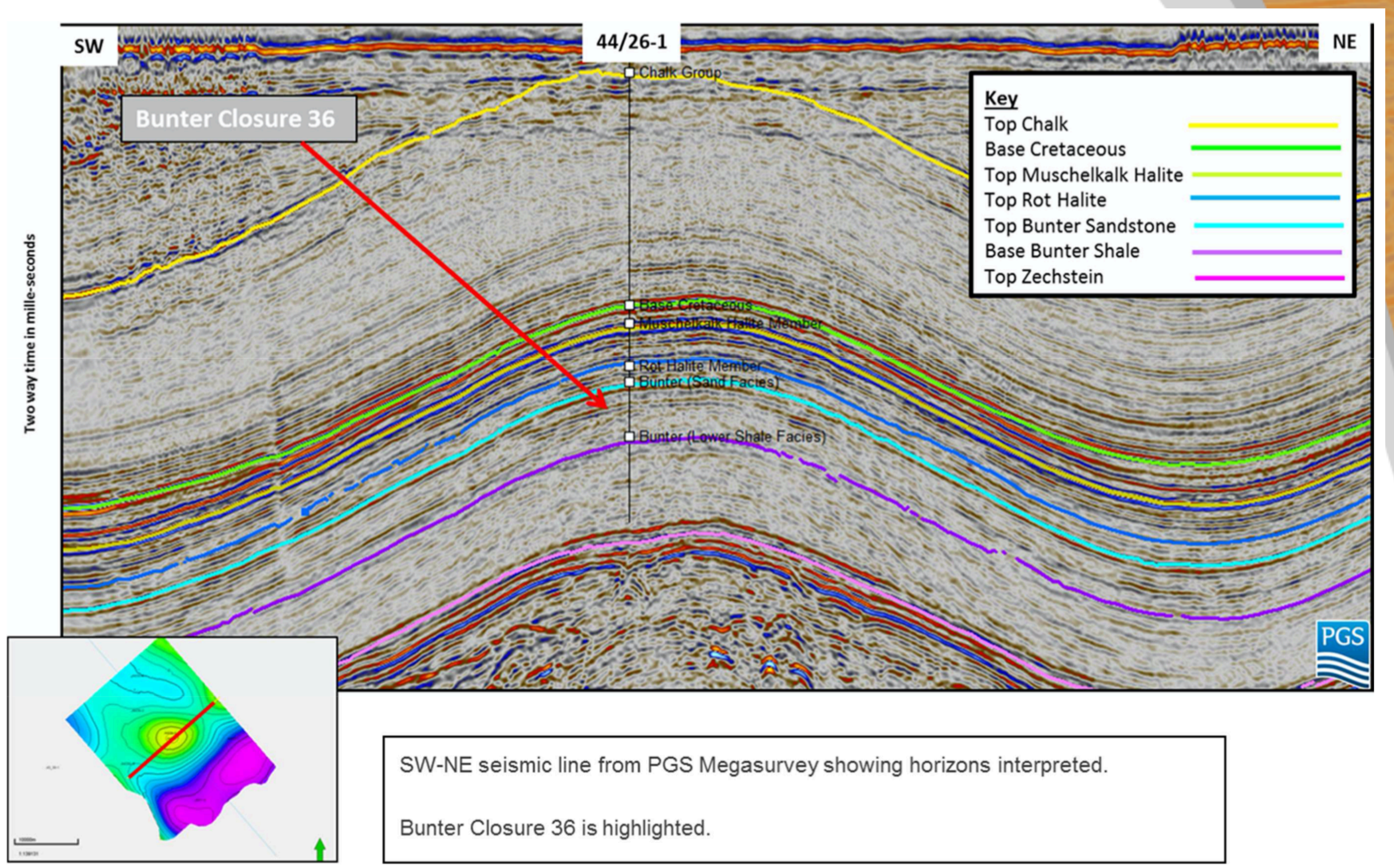
Time-lapse seismic images
impedance contrast

CO_2 injection
Compass proxy model

Synthetic 100-year CCS project in the North Sea

- inject 7Mt/y of CO_2 for 60 years
- monitor by active-source seismic imaging
- 5 seismic surveys: baseline & 15, 30, 45, 60 years after injection





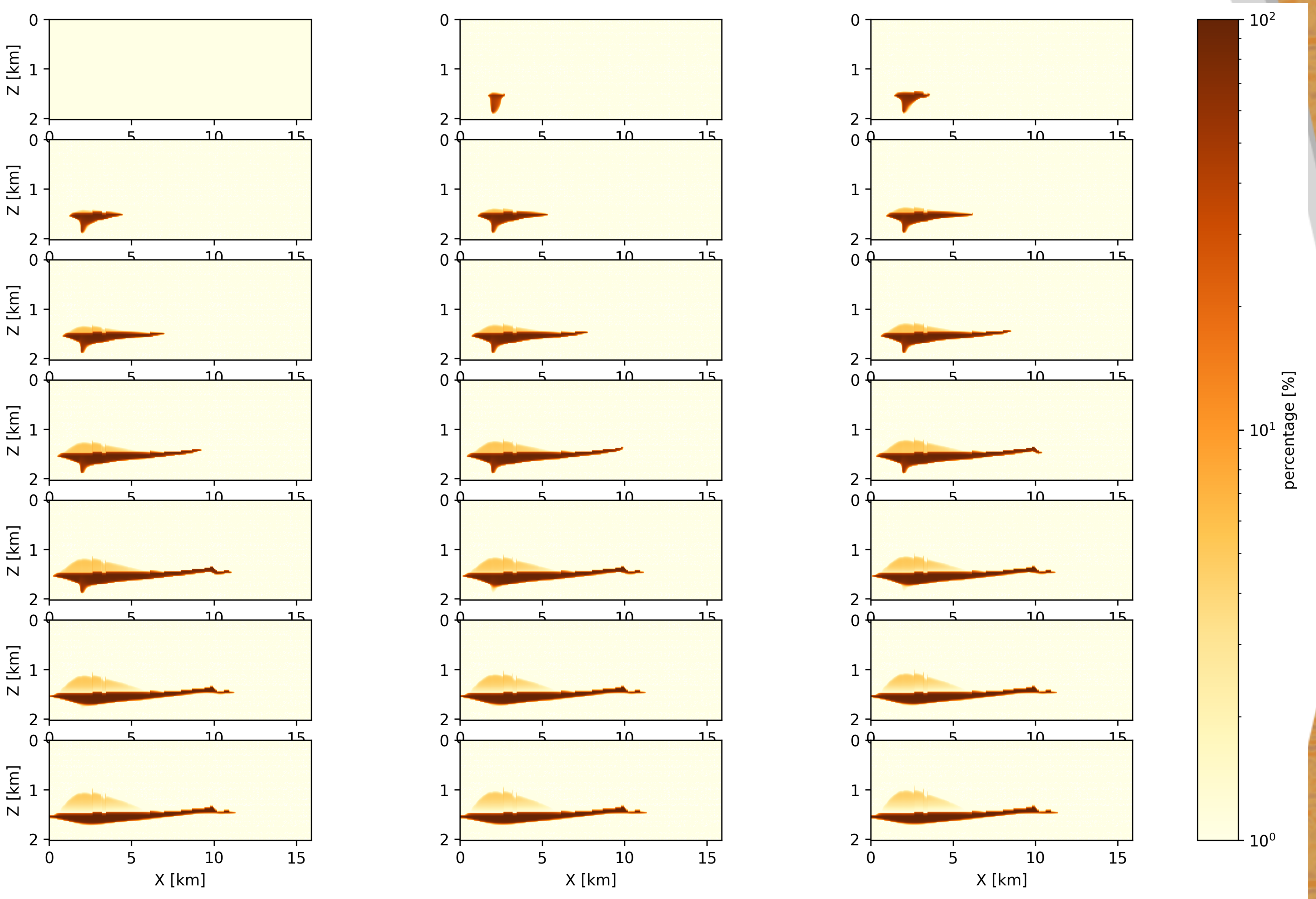
Strategic UK CCS Storage Appraisal Project

https://github.com/lidongzh/FwiFlow.jl

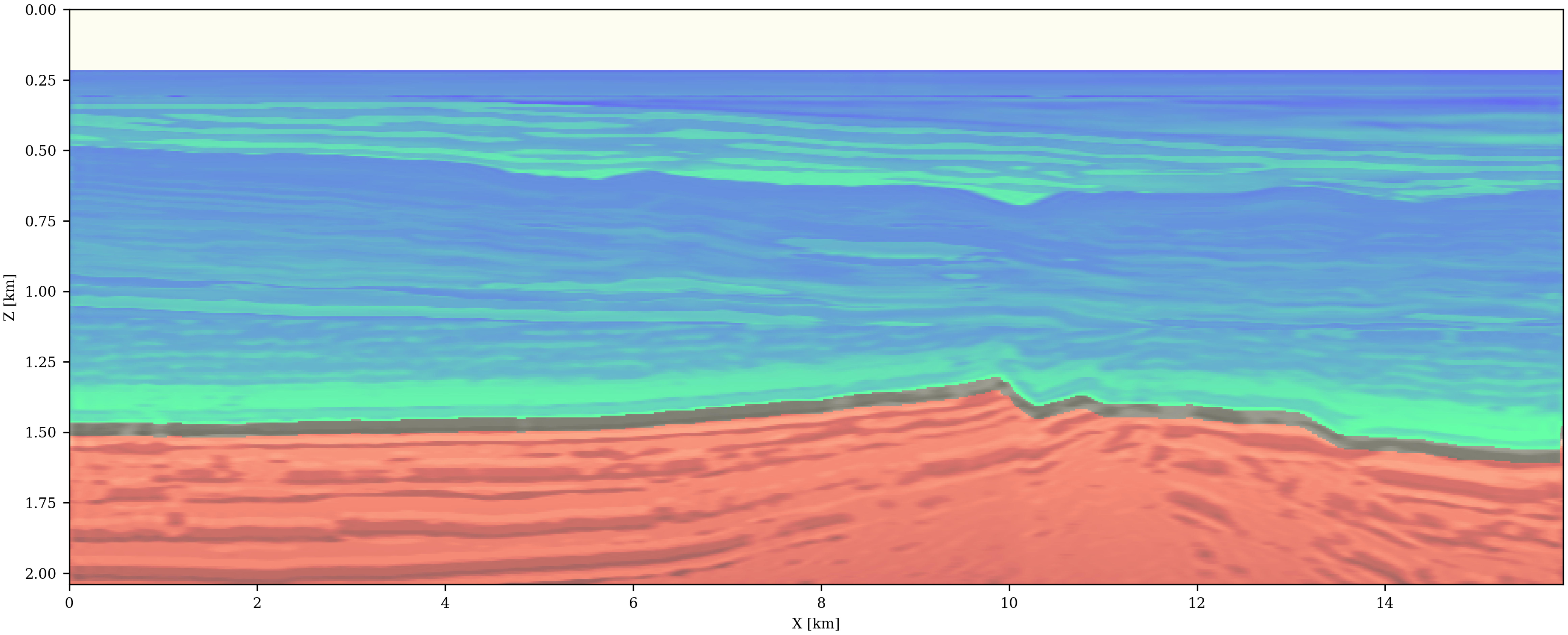
CO_2 dynamics
two-phase flow simulation

- grid spacing 25m, time step 20 days
- stop injection at 60th year model extends 1.6km in perpendicular direction
- CO_2 movement driven by buoyancy
- **420 Mt CO_2** injected during CCS project
- depleted gas reservoir

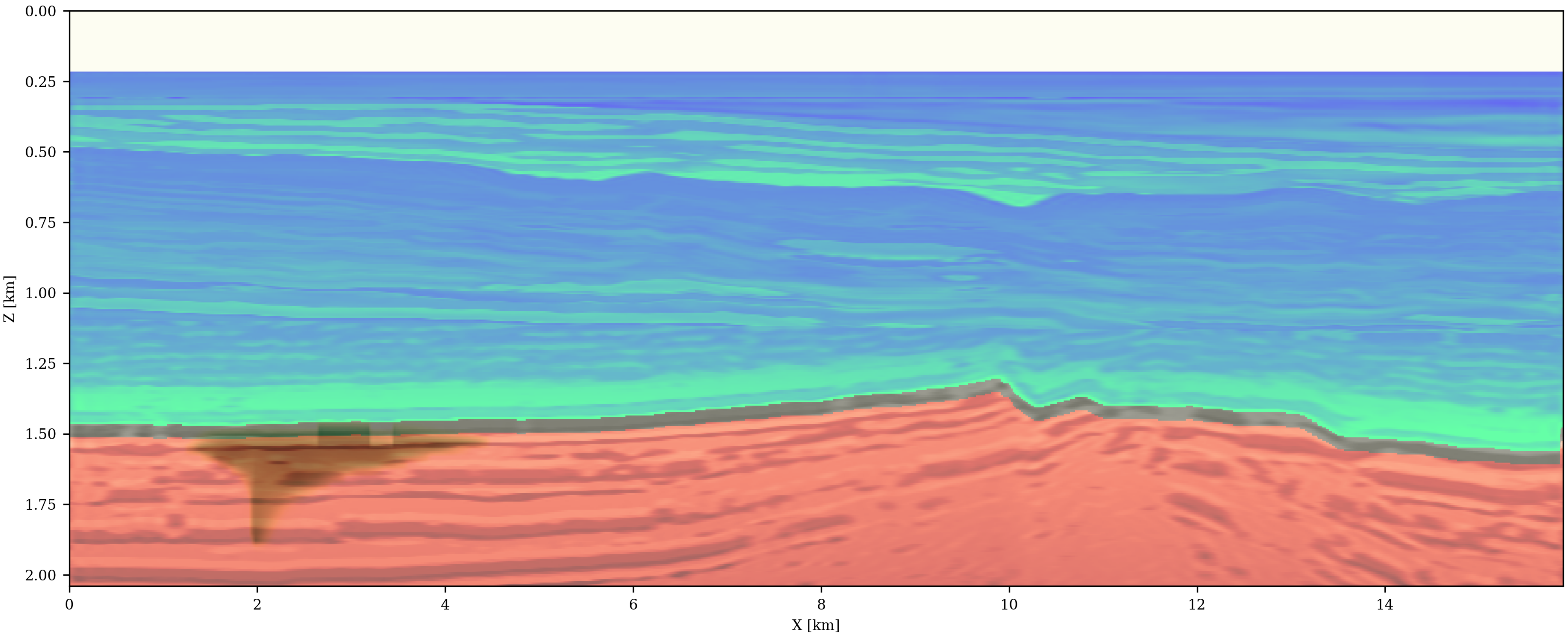
CO_2 concentration [%] for every 5 years



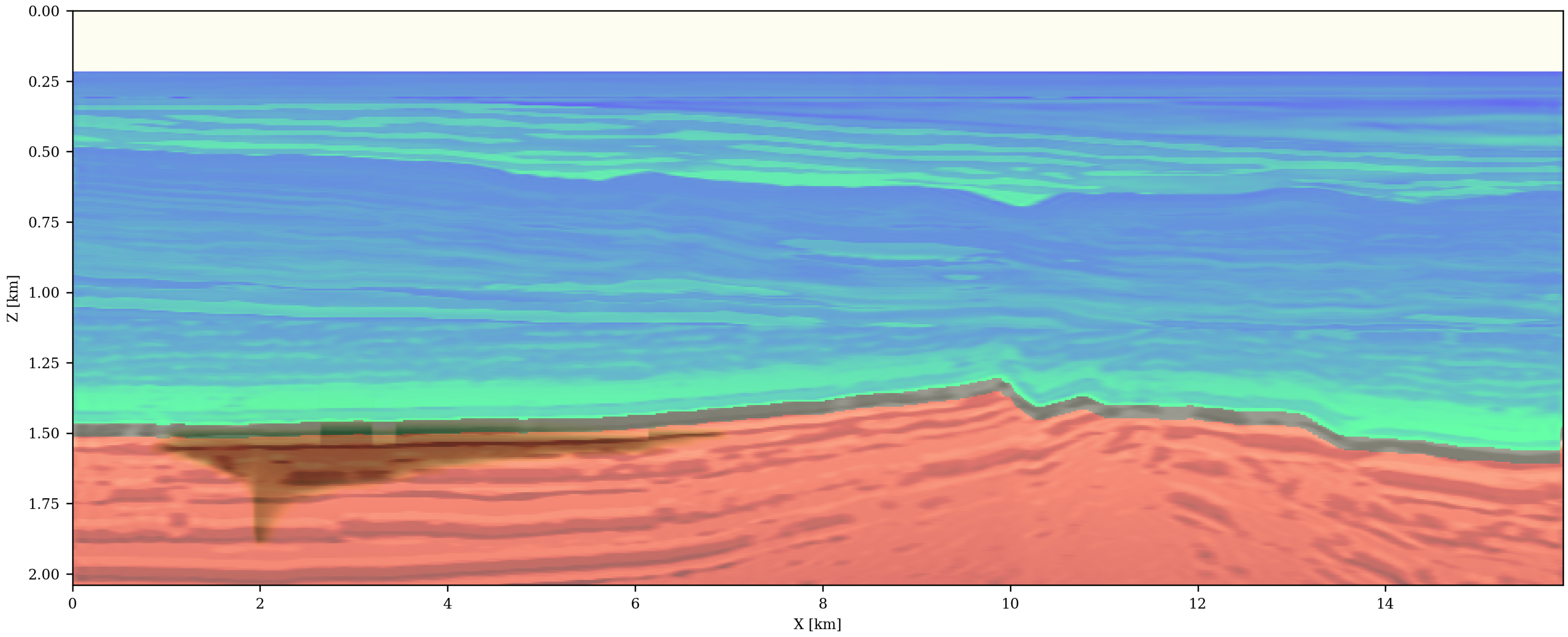
CO_2 saturation
baseline



CO_2 saturation
monitor 1 — 15 years after injection

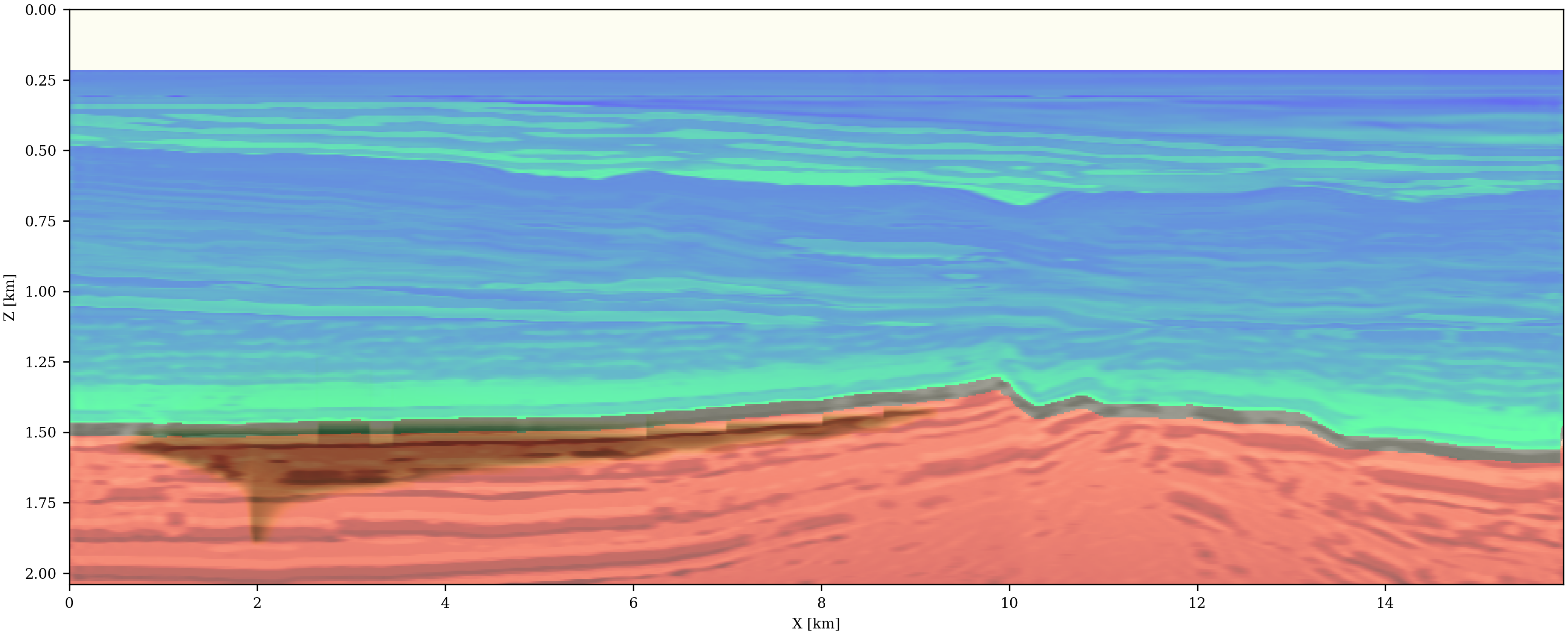


CO_2 saturation
monitor 2 — 30 years after injection

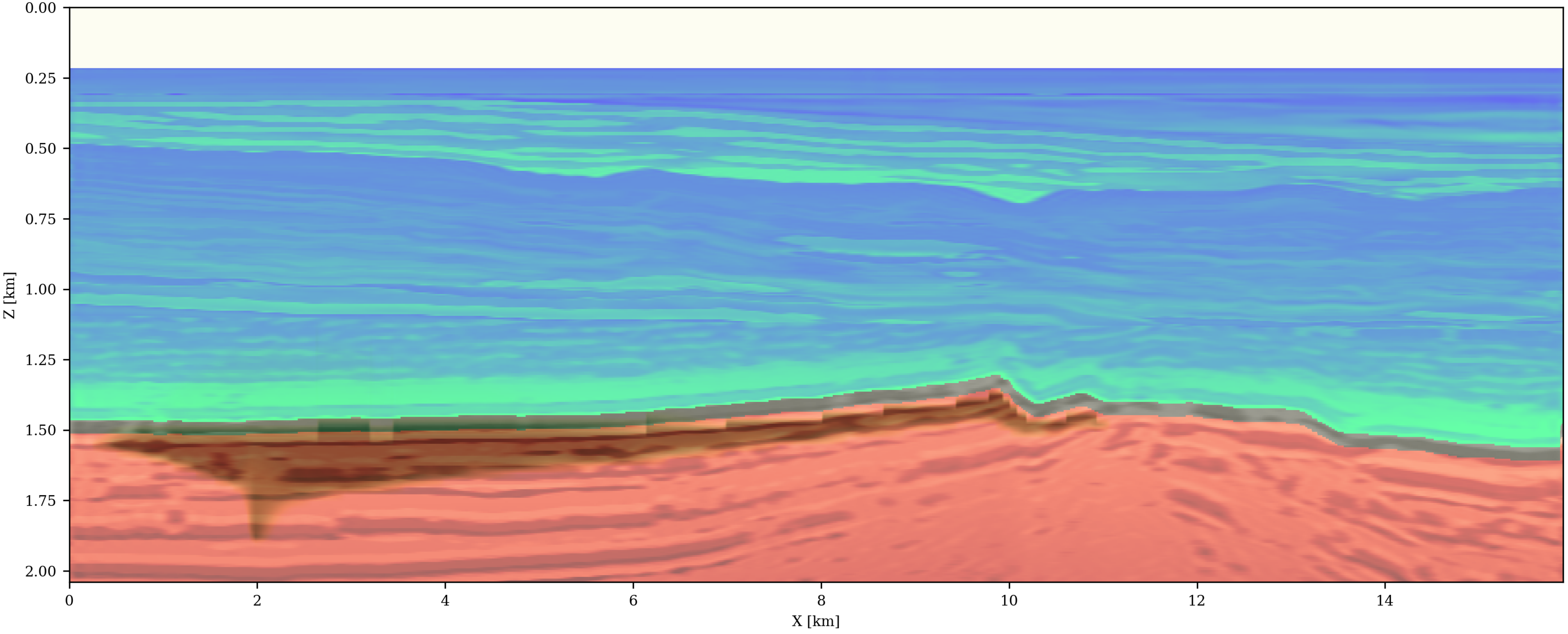


CO_2 saturation

monitor 3 — 45 years after injection

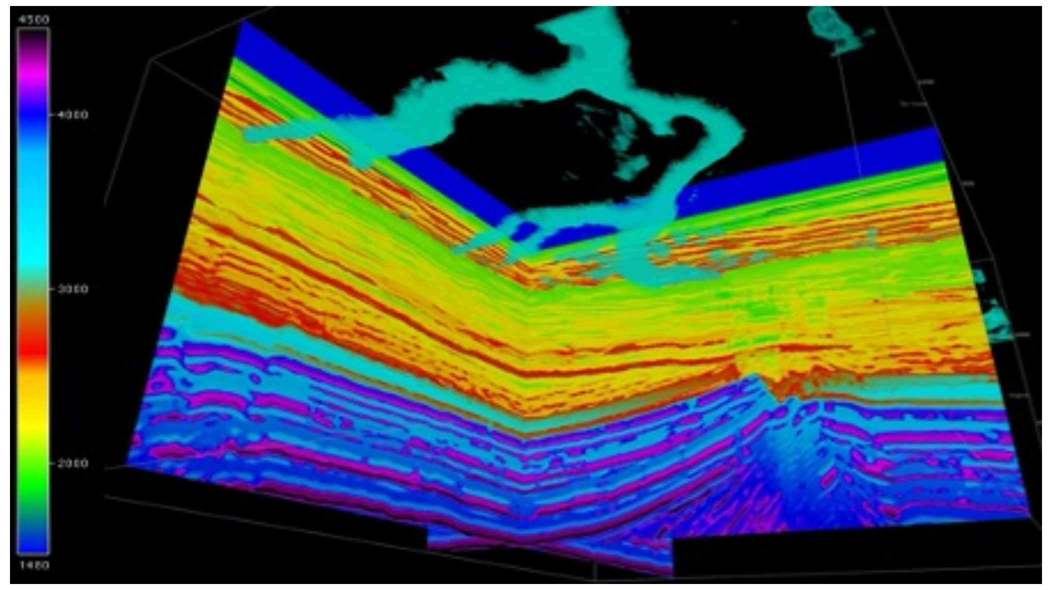


CO_2 saturation
monitor 4 — 60 years after injection



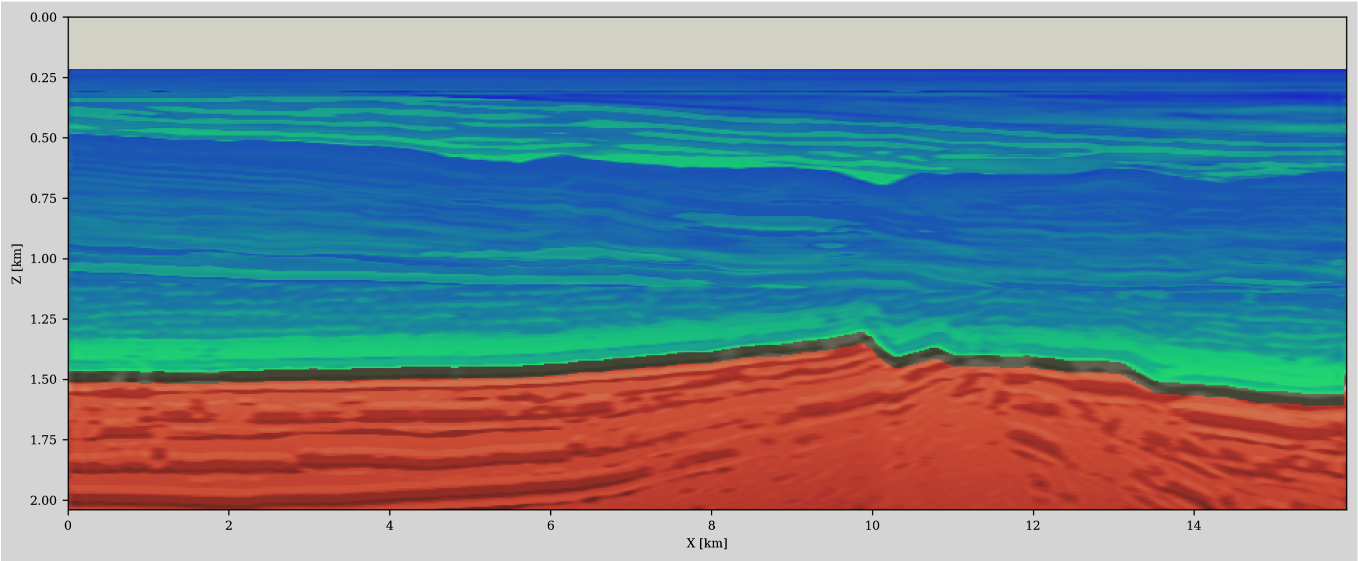
Proxy Reservoir Module

fluid flow to seismic



Seismic model
wave speed (c_p), density (ρ)

Conversion
$(\rho, c_p) \longrightarrow (\kappa, \phi)$



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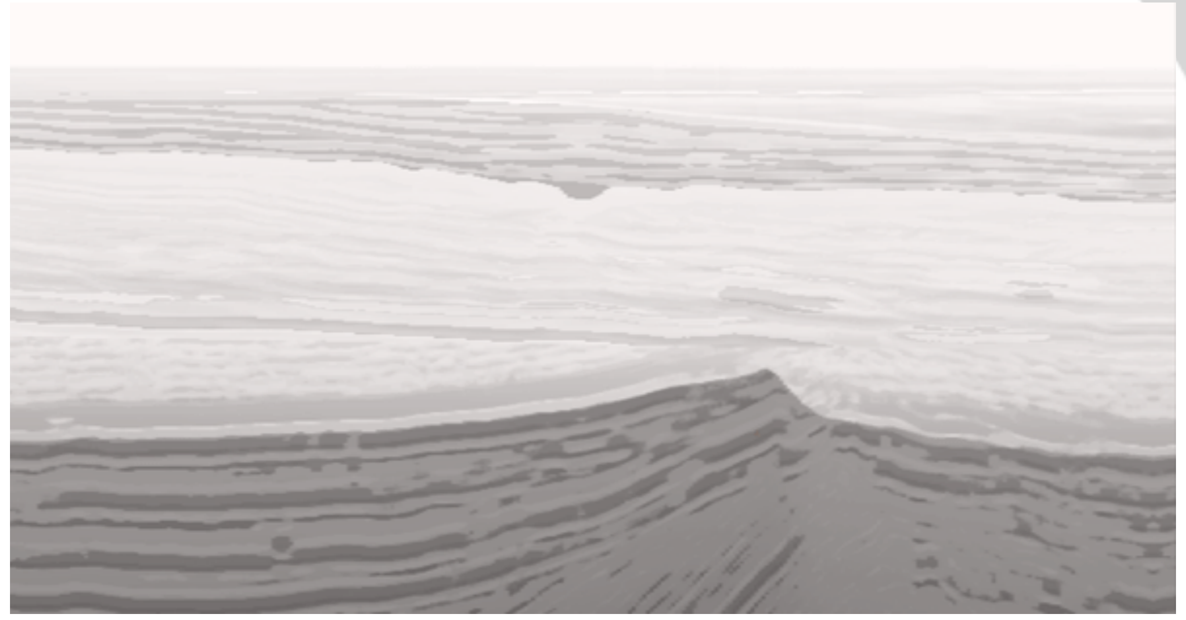

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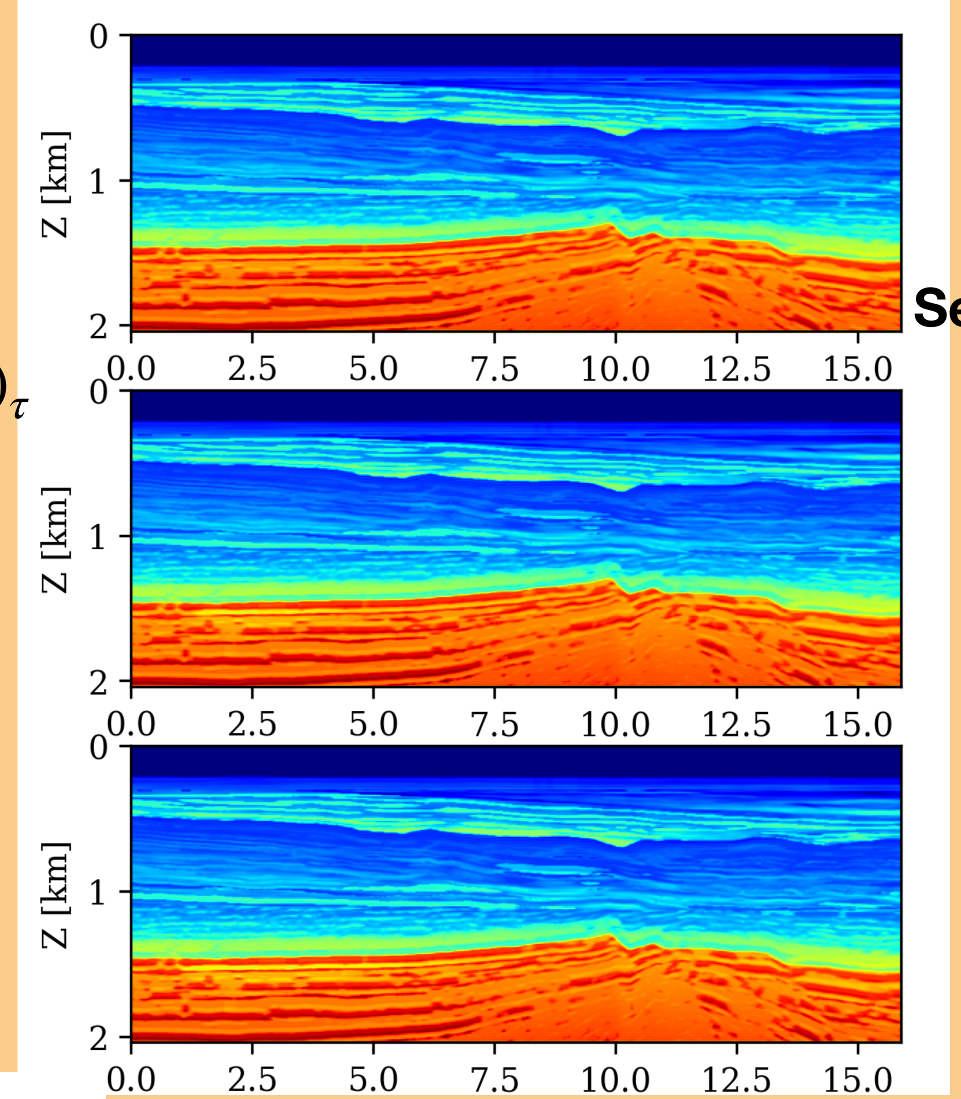
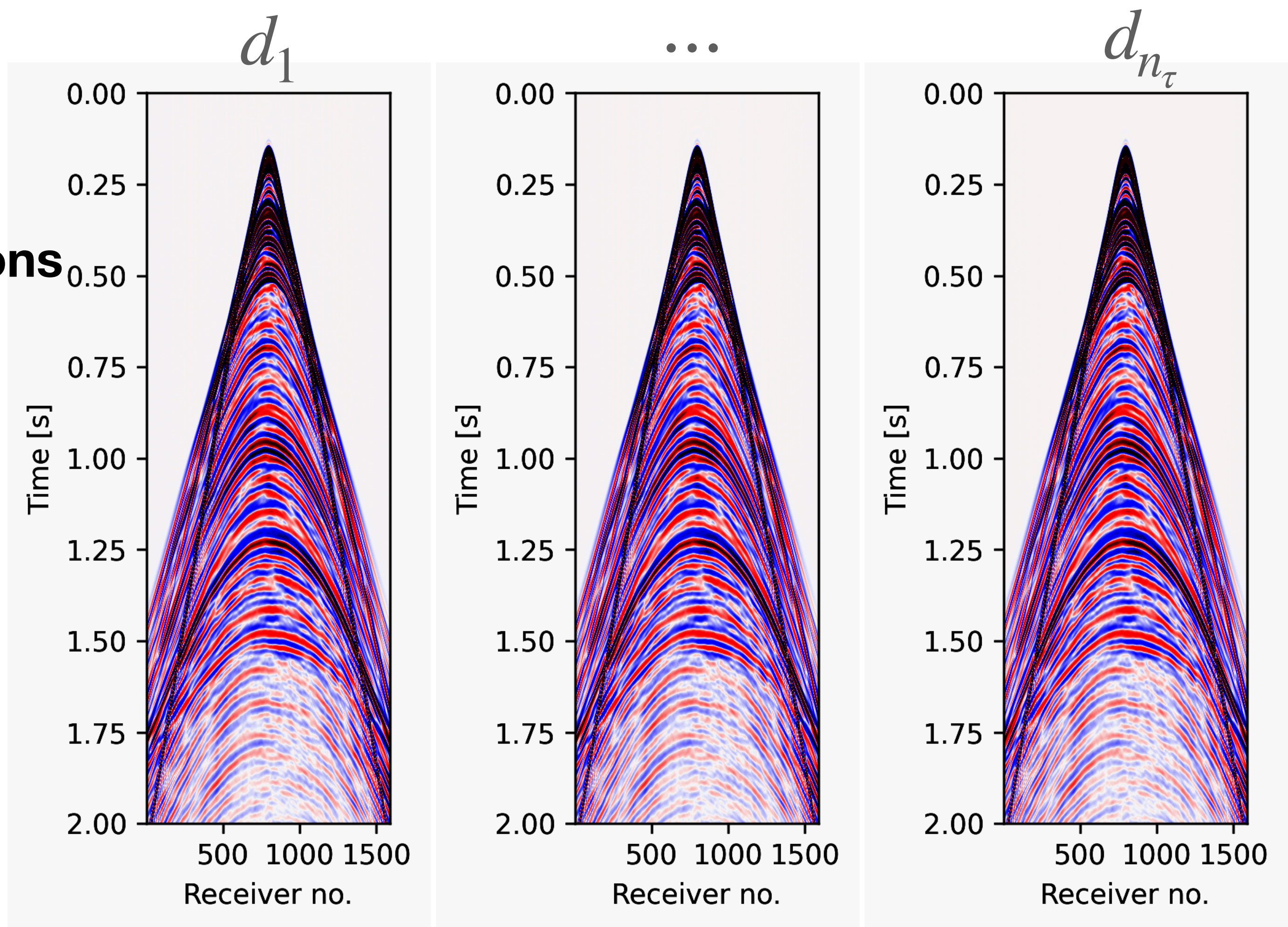


Time-lapse seismic model
wave speed, density

Seismic simulations
$(\rho, c_p)_\tau \longrightarrow d_\tau$



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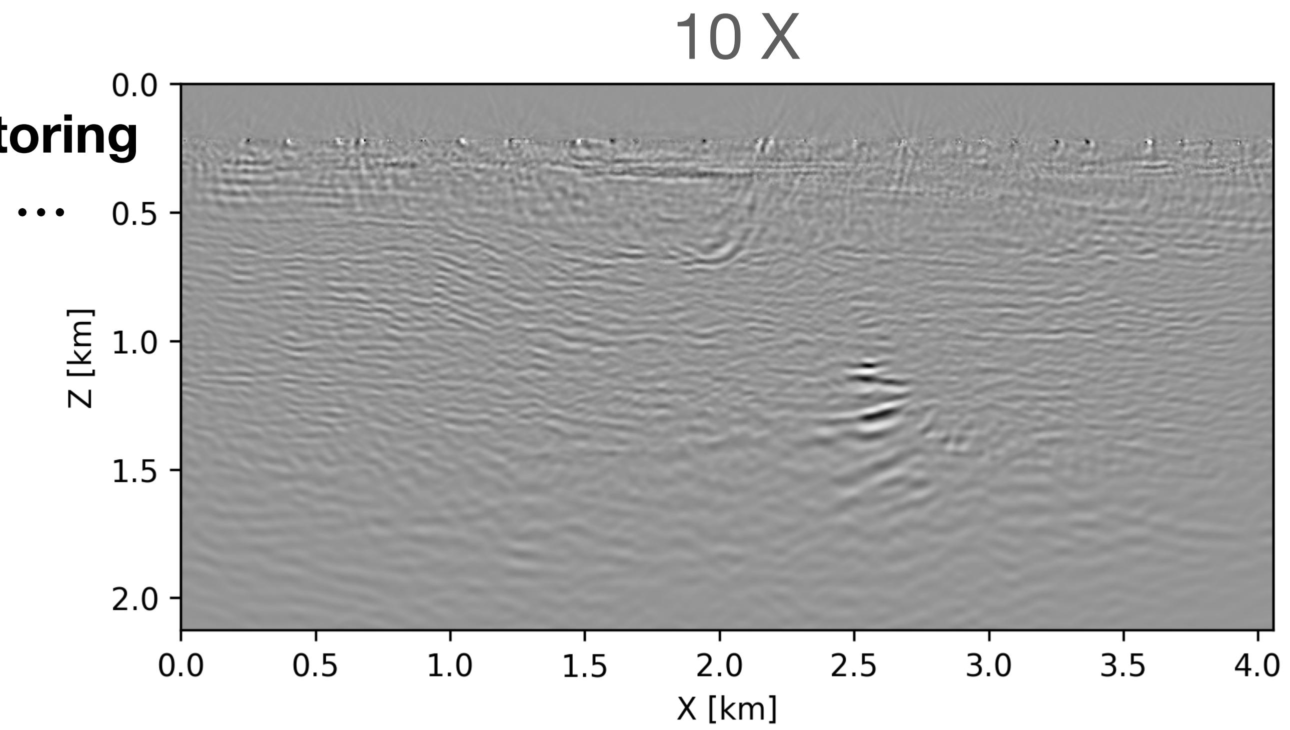
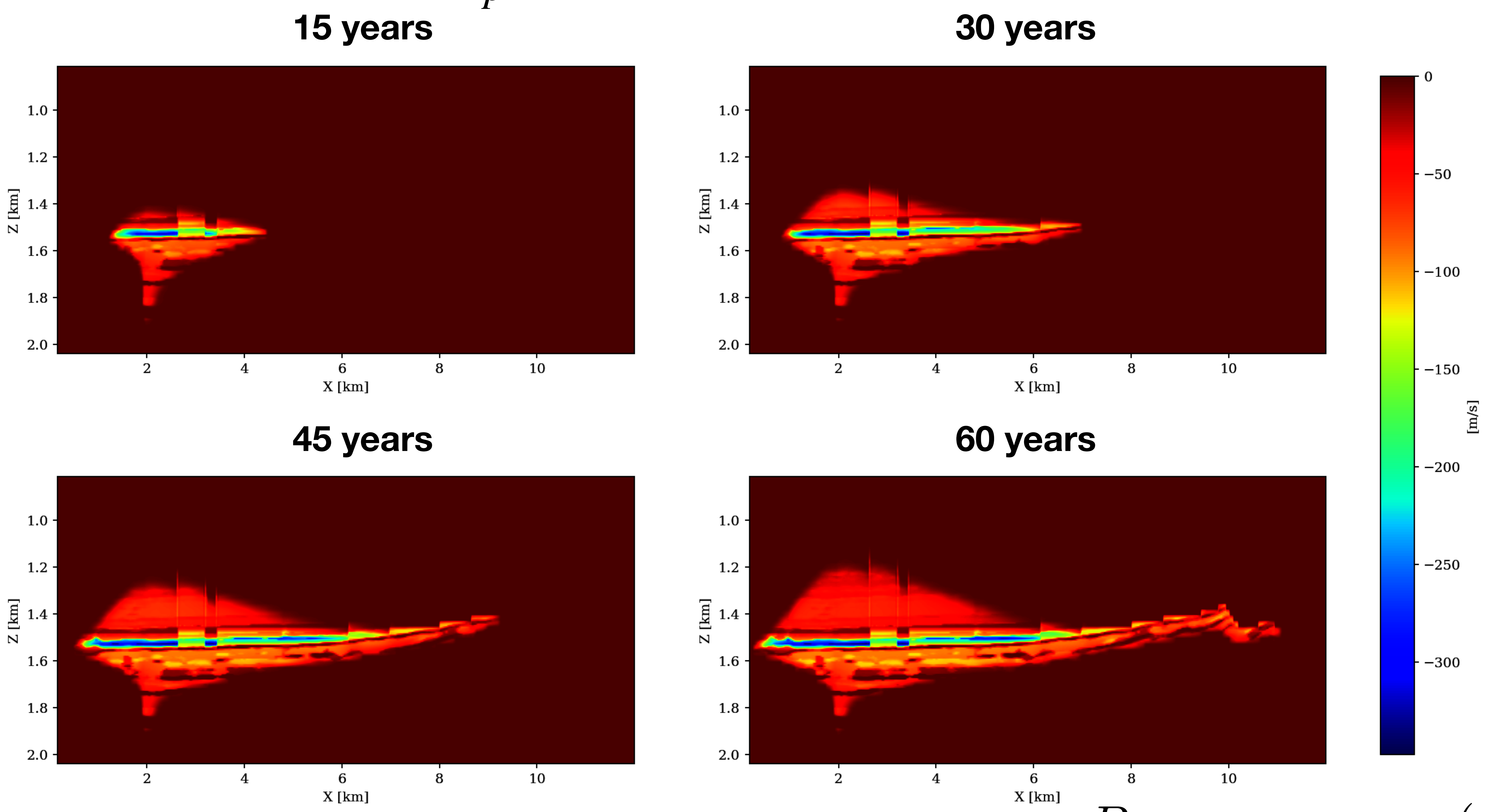


Time-lapse seismic images
impedance contrast

Rock physics
patchy saturation model

δv_p velocity changes



Symbol	Meaning
B_{r1}/B_{r2}	bulk modulus of rock fully saturated with fluid 1/2
B_{f1}/B_{f2}	fluid bulk modulus
ρ_{f1}/ρ_{f2}	fluid density
μ_r	rock shear modulus
v_p/v_s	rock P/S-wave velocity
B_o	bulk modulus of rock grains
ρ_r	rock density
ϕ	rock porosity
S	CO_2 saturation

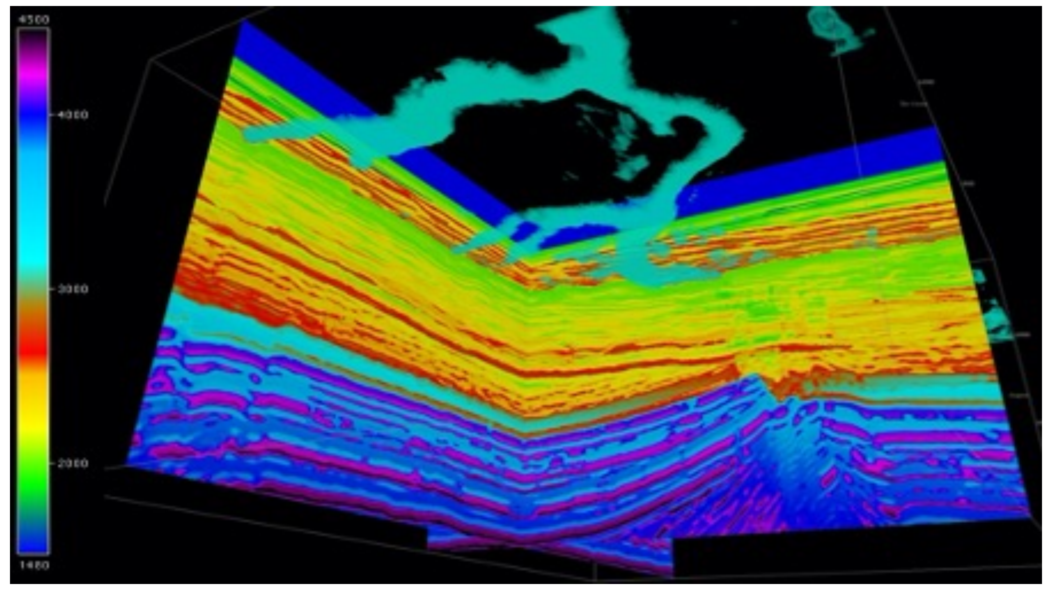
- CO_2 concentration ↑ ⟶ v_p ↓
- Decrease by 0-300 m/s
- Localized time-lapse changes
- v_p after 15, 30, 45, 60 years of injection

$$
\begin{aligned}
B_{r1} &= \rho_r(v_p^2 - \tfrac{4}{3}v_s^2) \\
\mu_r &= \rho_r v_s^2 \\
\frac{B_{r2}}{B_o - B_{r2}} &= \frac{B_{r1}}{B_o - B_{r1}} - \frac{B_{f1}}{\phi(B_o - B_{f1})} + \frac{B_{f2}}{\phi(B_o - B_{f2})} \\
\hat{B}_r &= [(1-S)(B_{r1} + \tfrac{4}{3}\mu_r)^{-1} + S(B_{r2} + \tfrac{4}{3}\mu_r)^{-1}]^{-1} - \tfrac{4}{3}\mu_r \\
\hat{\rho}_r &= \rho_r + \phi S(\rho_{f2} - \rho_{f1}) \\
\hat{v}_p &= \sqrt{\frac{\hat{B}_r + \frac{4}{3}\mu_r}{\hat{\rho}_r}}
\end{aligned}
$$

Per Avseth, et al. Quantitative seismic interpretation: Applying rock physics tools to reduce interpretation risk. Cambridge university press, 2010.

Seismic Simulation Module

from earth models to seismic data



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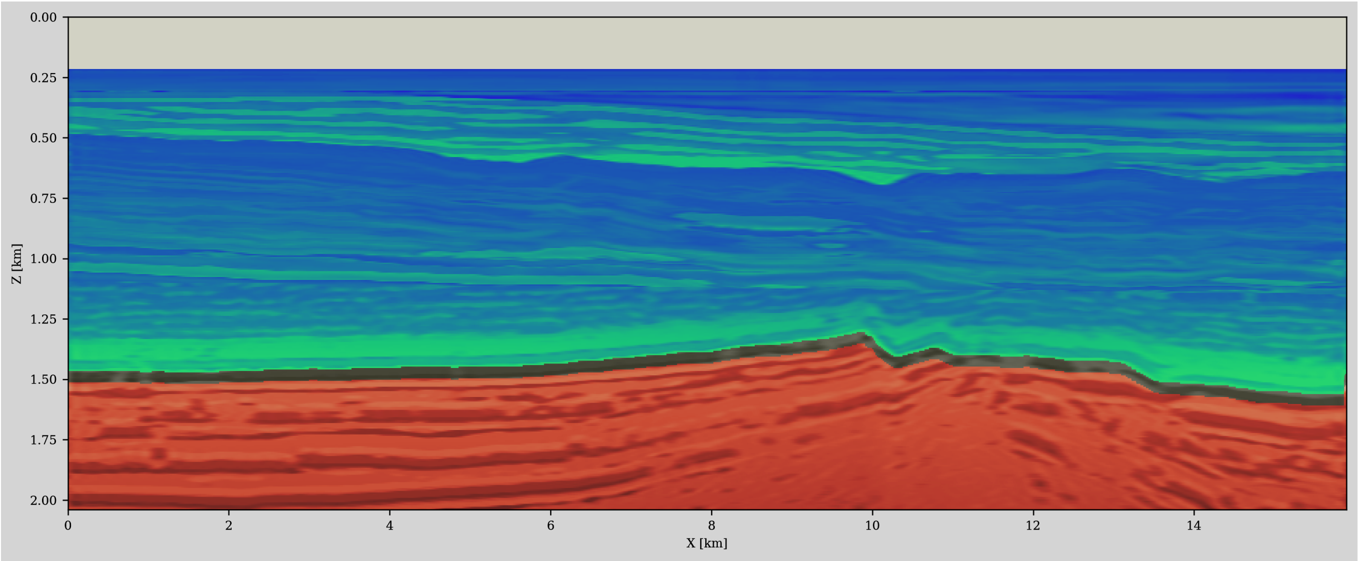

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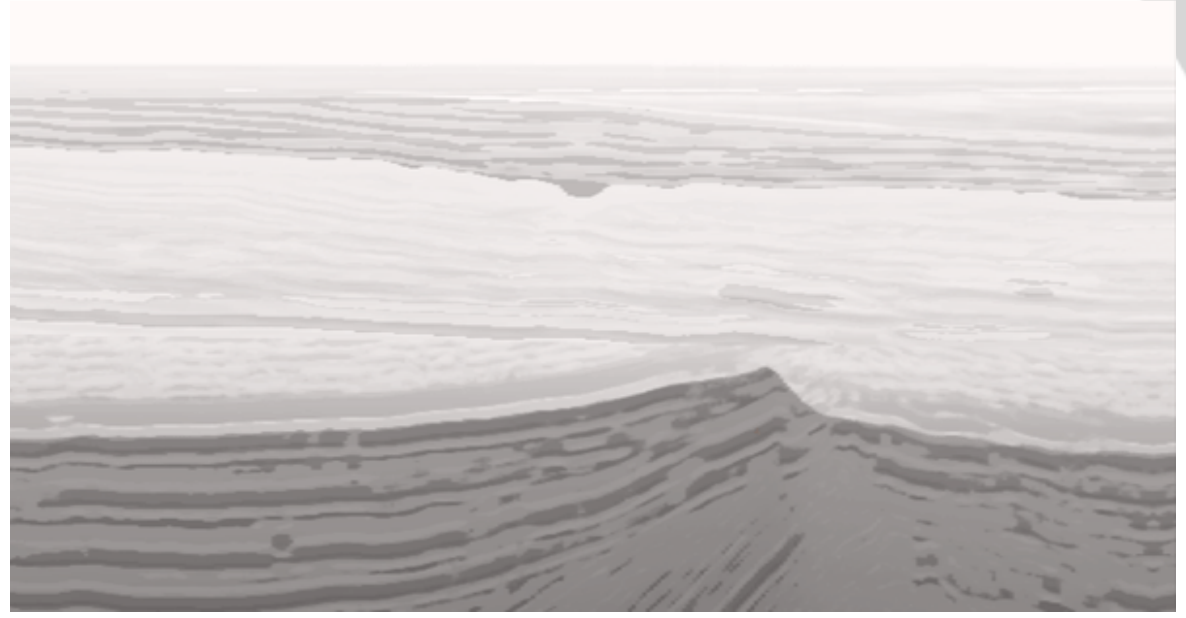
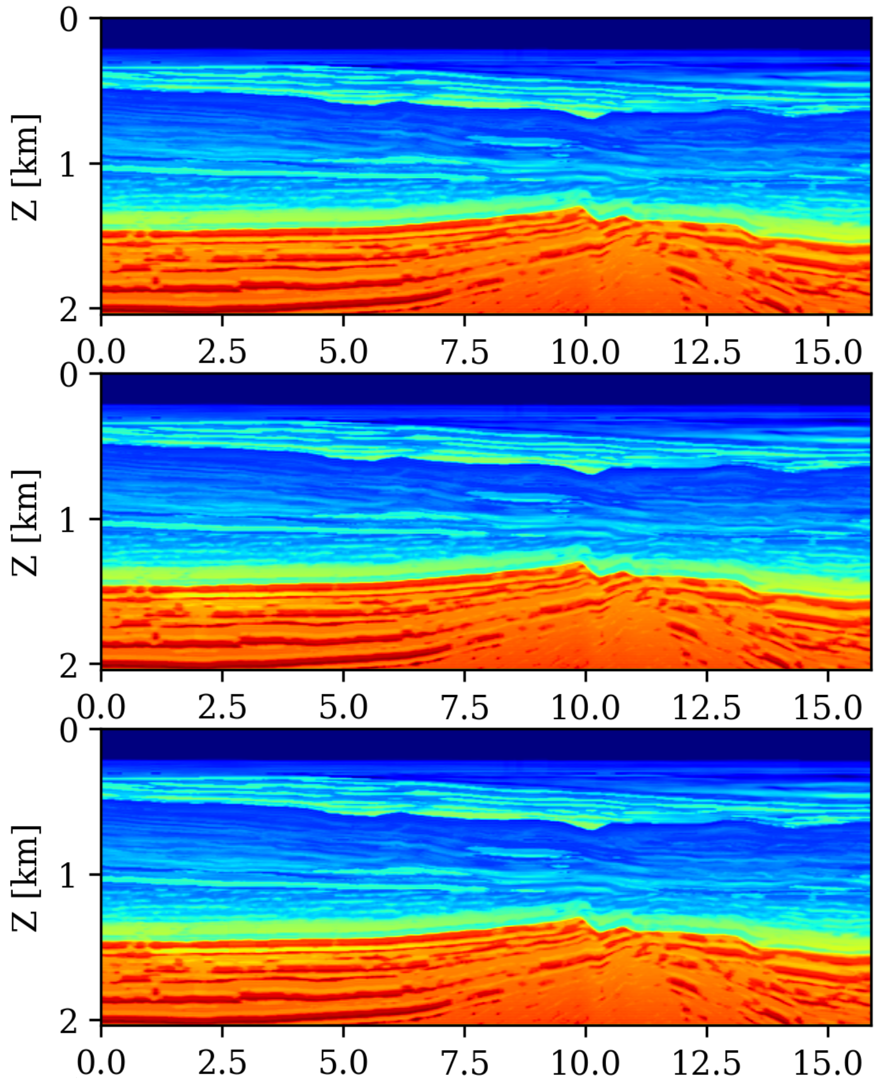
Proxy Flow
$(\kappa, \phi) \longrightarrow S_\tau$



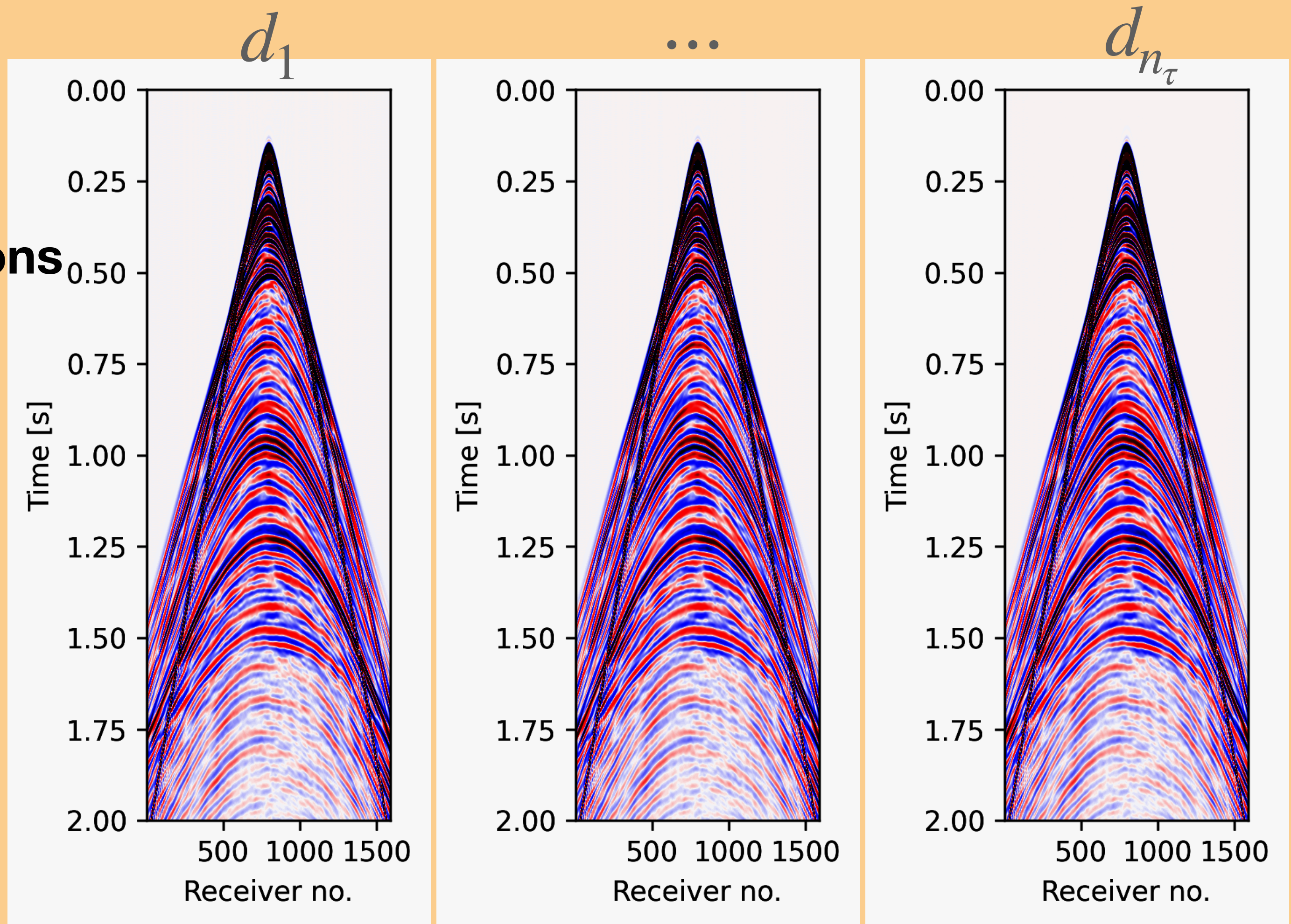
CO_2 dynamics
saturation, pressure

Conversion
$S_\tau \longrightarrow (\rho, c_p)_\tau$



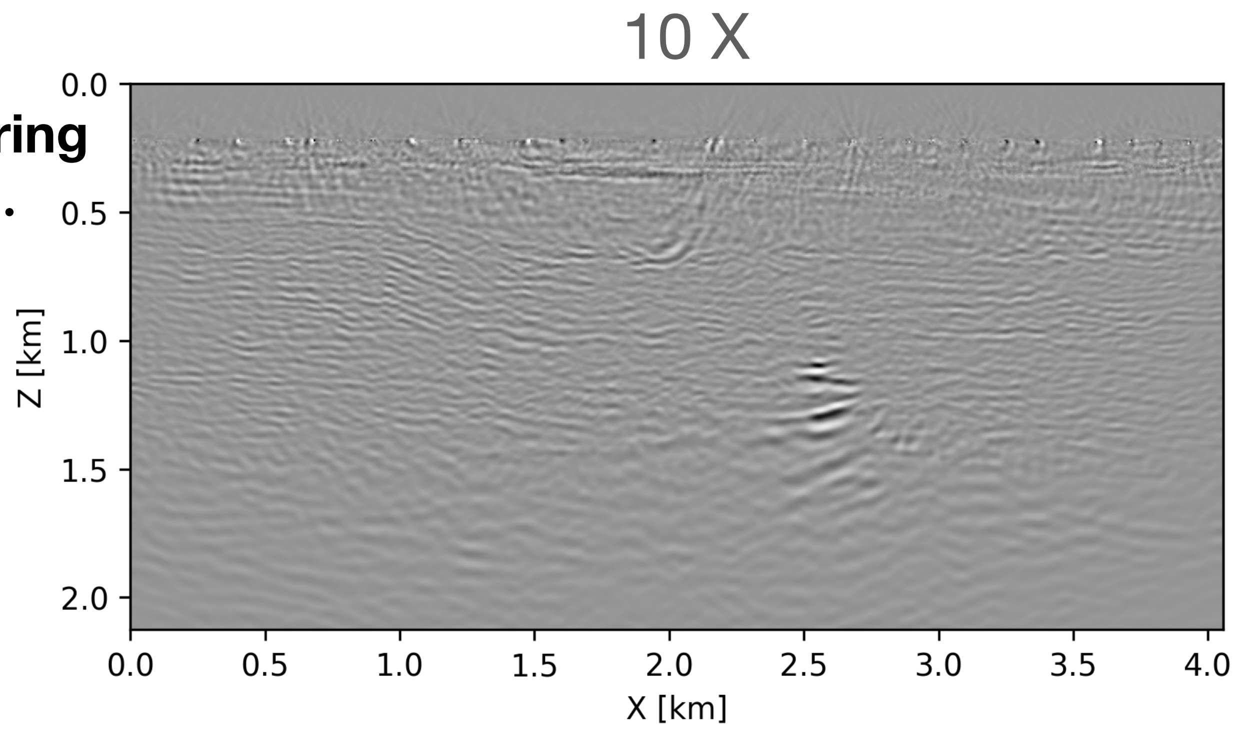
Time-lapse seismic model
wave speed, density

Seismic simulations
$(\rho, c_p)_\tau \longrightarrow d_\tau$



Time-lapse seismic
pressure data

Seismic monitoring
$\delta m_2 - \delta m_1, \cdots$



Time-lapse seismic images
impedance contrast

The Julia Devito Inversion framework (JUDI.jl & JUDI4Cloud.jl)

Julia

linear opeartors, data containers, IO

parallel modeling function

parallelization: distribute sources, data

serial modeling function

interface to Devito (Python)

Python

Devito: symbolic definition of PDE

automatic code generation
and JIT compilation

C

solve PDE w/ OpenMP parallelism

```
g = J'*(Pr*A_inv*Ps'*q - d_obs)
```

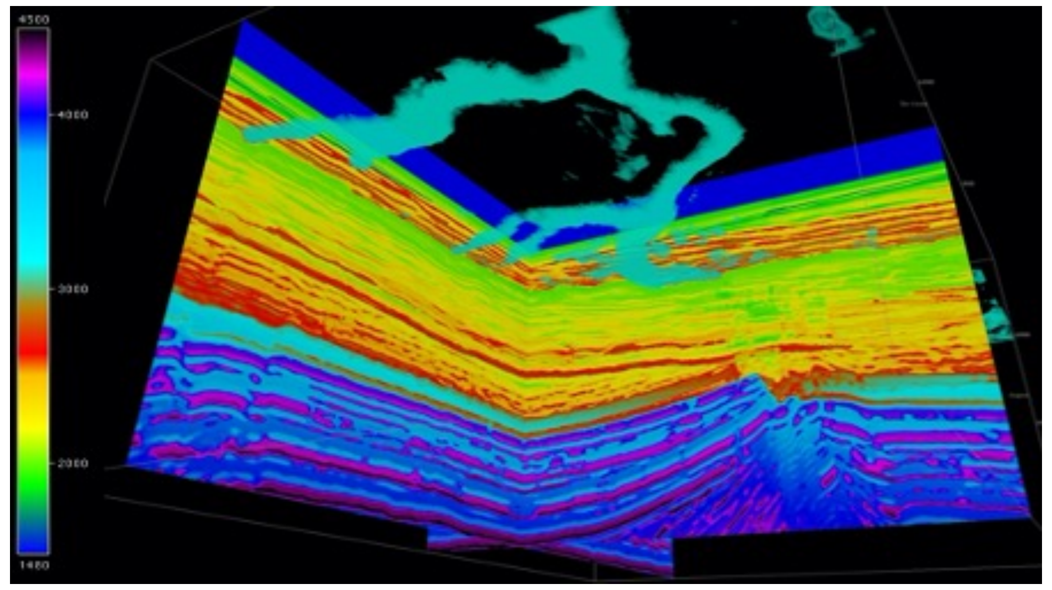
```
# Symbolic wavefield
u = TimeFunction(name='u', space_order=16)

# Acoustic wave equation
pde = model.m * u.dt2 - u.laplace
```

```
float (*rec_coords)[2] = (float (*)[2]) rec_coords_vec;
{
  struct timeval start_kernel, endkernel;
    gettimeofday(&start_kernel, NULL);
    int t0;
    int t1;
    int t2;
    ;
    for (int i3 = 0; i3 < 3; i3+=1)
    {
      flops->kernel += 2.000000;
      {
        {
          t0 = (i3)%(3);
```

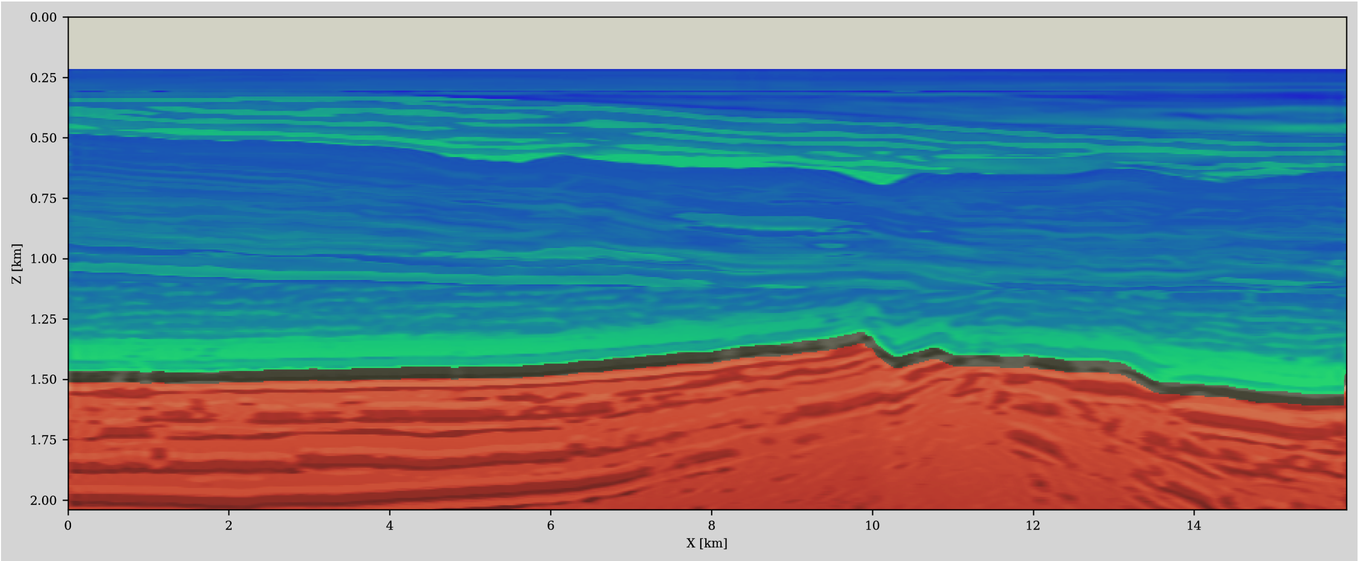
Seismic Monitoring Module

from baseline & monitor to time-lapse differences



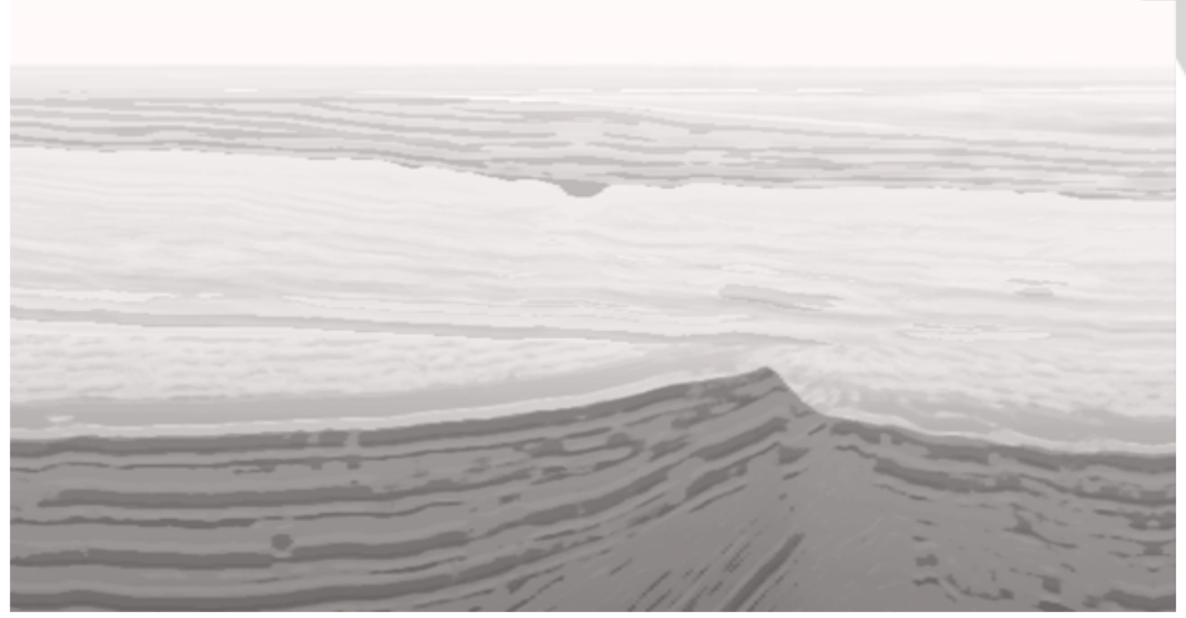
Seismic model
wave speed (c_p), density (ρ)

Conversion
$(\rho, c_p) \longrightarrow (\kappa, \phi)$



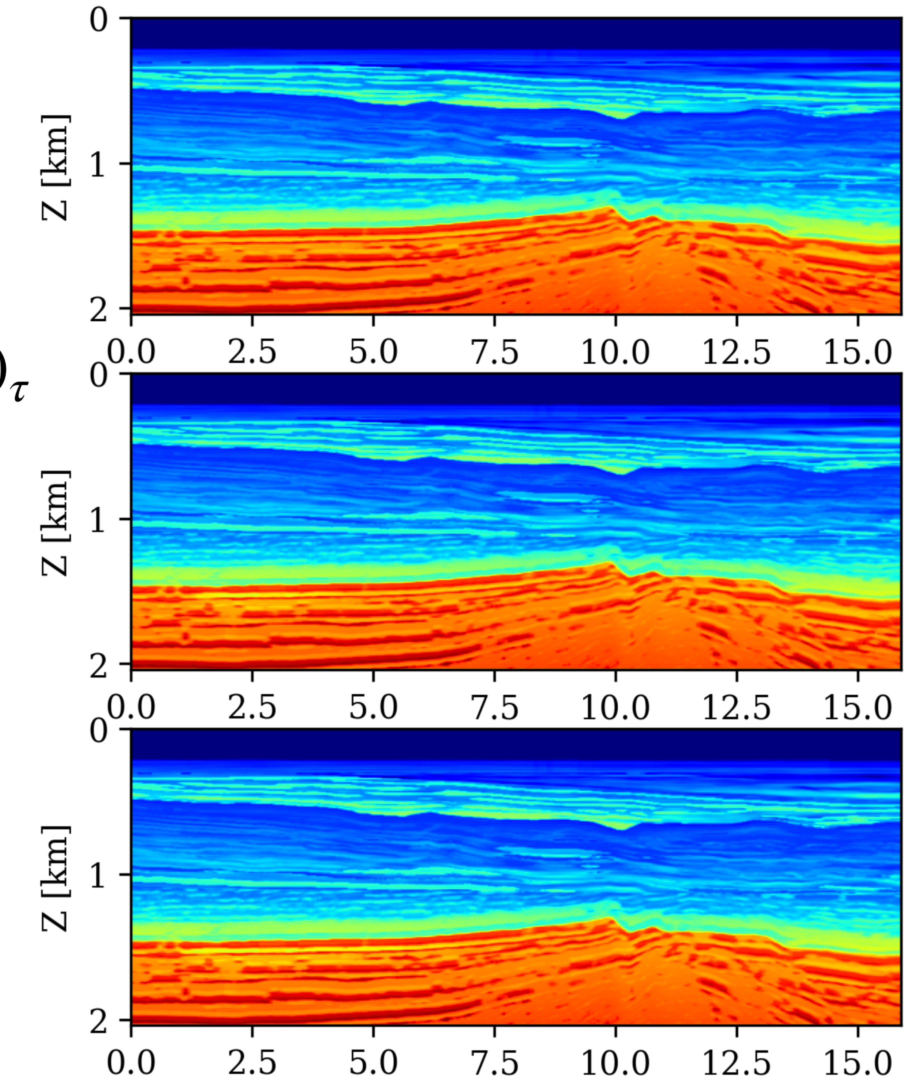
Fluid model
permeability (κ), porosity (ϕ)

Proxy Flow
$(\kappa, \phi) \longrightarrow S_\tau$



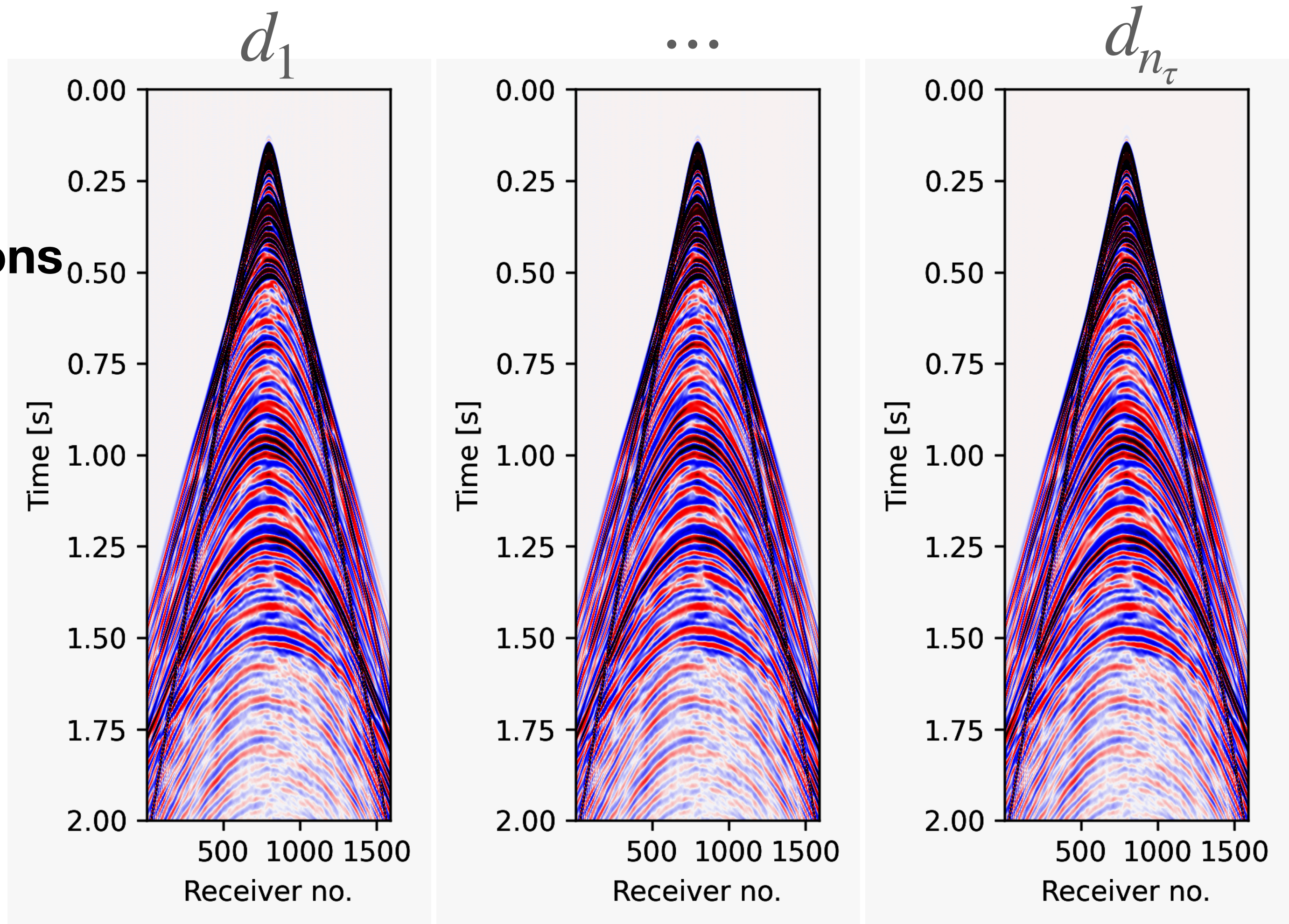
CO_2 dynamics
saturation, pressure

Conversion
$S_\tau \longrightarrow (\rho, c_p)_\tau$



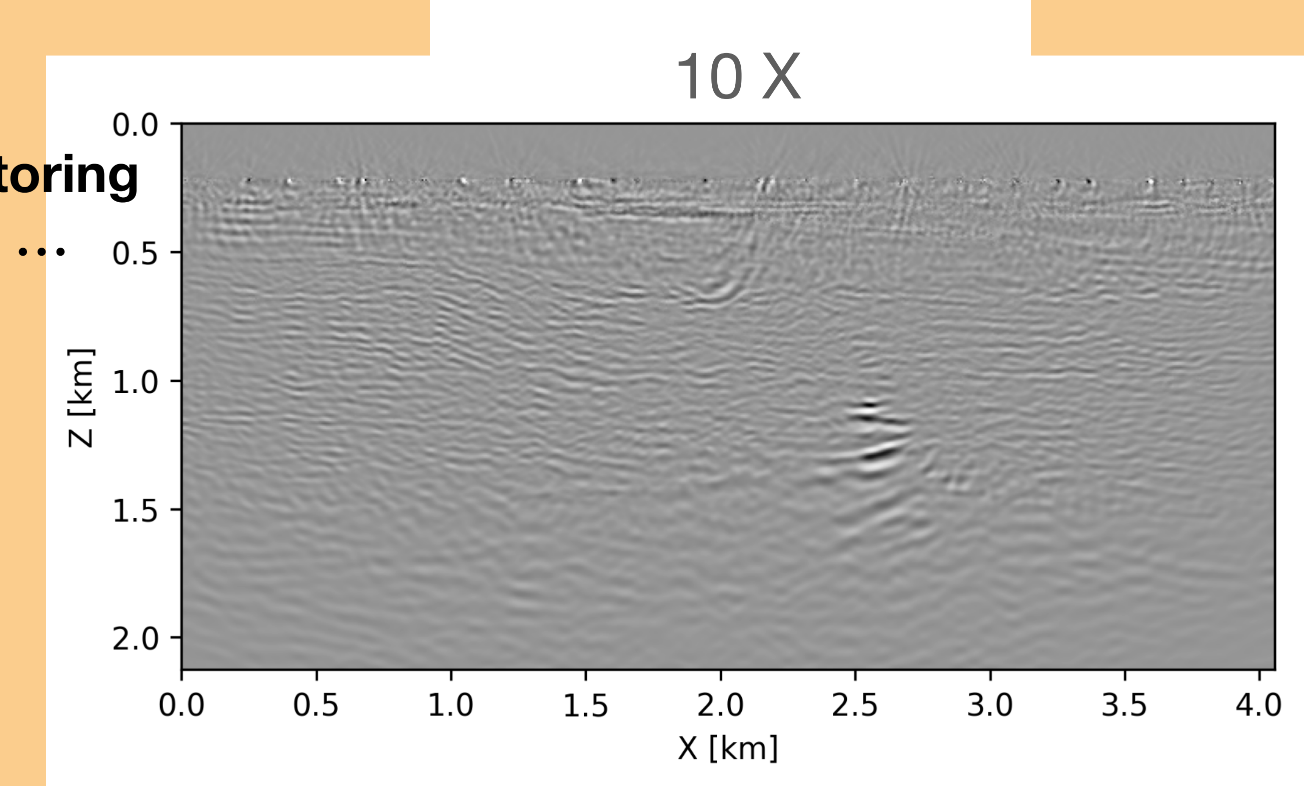
Time-lapse seismic model
wave speed, density

Seismic simulations
$(\rho, c_p)_\tau \longrightarrow d_\tau$



Time-lapse seismic
pressure data

Seismic monitoring
$\delta m_2 - \delta m_1, \cdots$

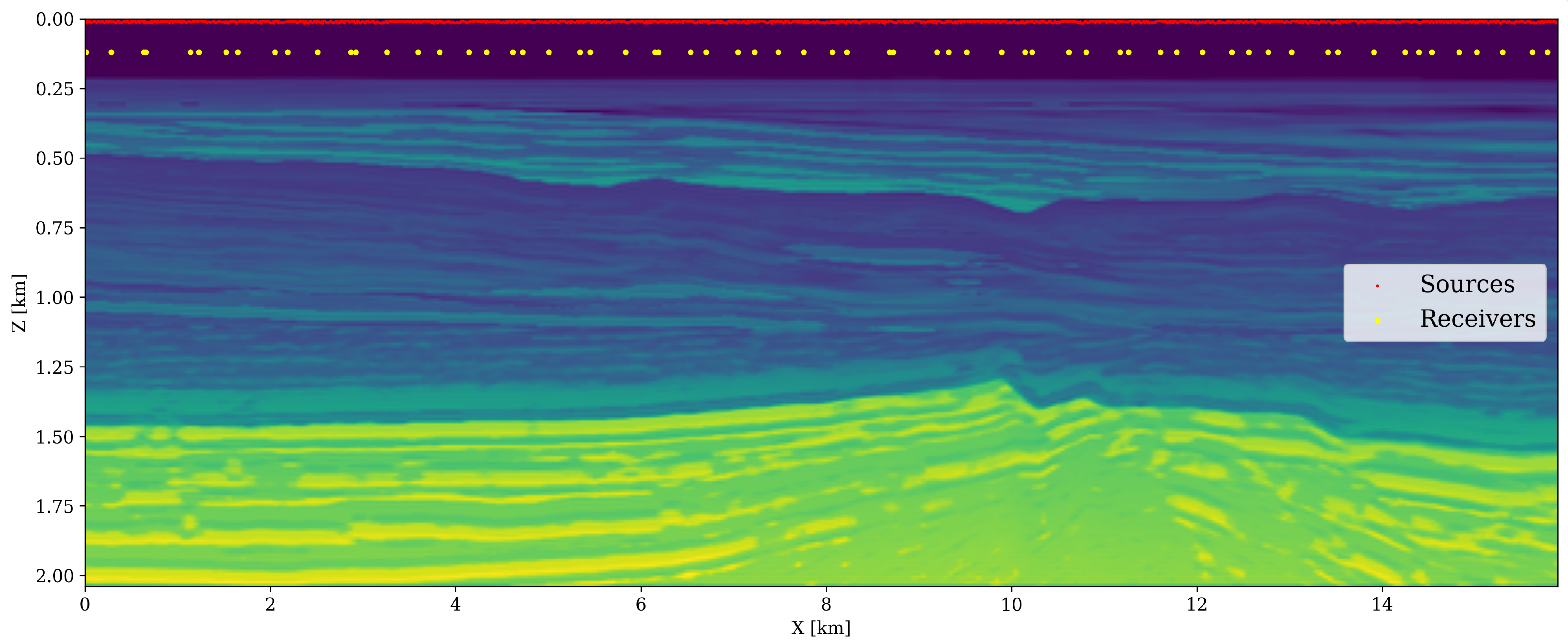


Time-lapse seismic images
impedance contrast

Seismic data simulation

low-cost time-lapse acquisition

- 64 coarse jittered ocean bottom hydrophones on buoys ($\Delta x_r = 250\text{m}$)
- 1272 non-replicated deblended sim. source data ($\Delta x_s = 12.5\text{m}$)
- non-replicated tow-depth
- 5 surveys 1 baseline & 4 monitor



Felix Oghenekohwo, Haneet Wason, Ernie Esser, and Felix J. Herrmann, “Low-cost time-lapse seismic with distributed compressive sensing–-Part 1: exploiting common information among the vintages”, Geophysics, vol. 82, pp. P1-P13, 2017.
Felix Oghenekohwo, Rajiv Kumar, Ernie Esser, and Felix J. Herrmann, “Using common information in compressive time-lapse full-waveform inversion”, EAGE, 2015.

SLIM

Seismic monitoring

joint recovery model

$$\mathbf{A} = \begin{bmatrix} \frac{1}{\gamma}\nabla\mathcal{F}_1(\overline{\mathbf{m}}_1) & \nabla\mathcal{F}_1(\overline{\mathbf{m}}_1) & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \frac{1}{\gamma}\nabla\mathcal{F}_2(\overline{\mathbf{m}}_2) & \mathbf{0} & \nabla\mathcal{F}_2(\overline{\mathbf{m}}_2) & \mathbf{0} & \mathbf{0} \\ \cdots & \mathbf{0} & \mathbf{0} & \cdots & \mathbf{0} \\ \frac{1}{\gamma}\nabla\mathcal{F}_{n_v}(\overline{\mathbf{m}}_{n_v}) & \mathbf{0} & \mathbf{0} & \mathbf{0} & \nabla\mathcal{F}_{n_v}(\overline{\mathbf{m}}_{n_v}) \end{bmatrix}$$

$$\mathbf{z} = \left[\mathbf{z}_0^\top, \mathbf{z}_1^\top, \cdots, \mathbf{z}_{n_v}^\top\right]^\top \qquad \mathbf{b} = \left[\delta\mathbf{d}_1^\top, \delta\mathbf{d}_2^\top, \cdots, \delta\mathbf{d}_{n_v}^\top\right]^\top$$

- common component observed & seen by all vintages $\longrightarrow$ improved images
- innovation components will also be well recovered

[1] P. A. Witte, M. Louboutin, F. Luporini, G. G. Gorman and Felix J. Herrmann, 2019, *Compressive least-squares migration with on-the-fly Fourier transforms* , Geophysics, 84, 5.

SLIM

Solution by Convex Optimization

Least-squares migration as an elastic net:[1]

$$\underset{\mathbf{z}}{\text{minimize}} \quad \lambda\|\mathbf{C}\mathbf{z}\|_1 + \frac{1}{2}\|\mathbf{C}\mathbf{z}\|_2^2$$

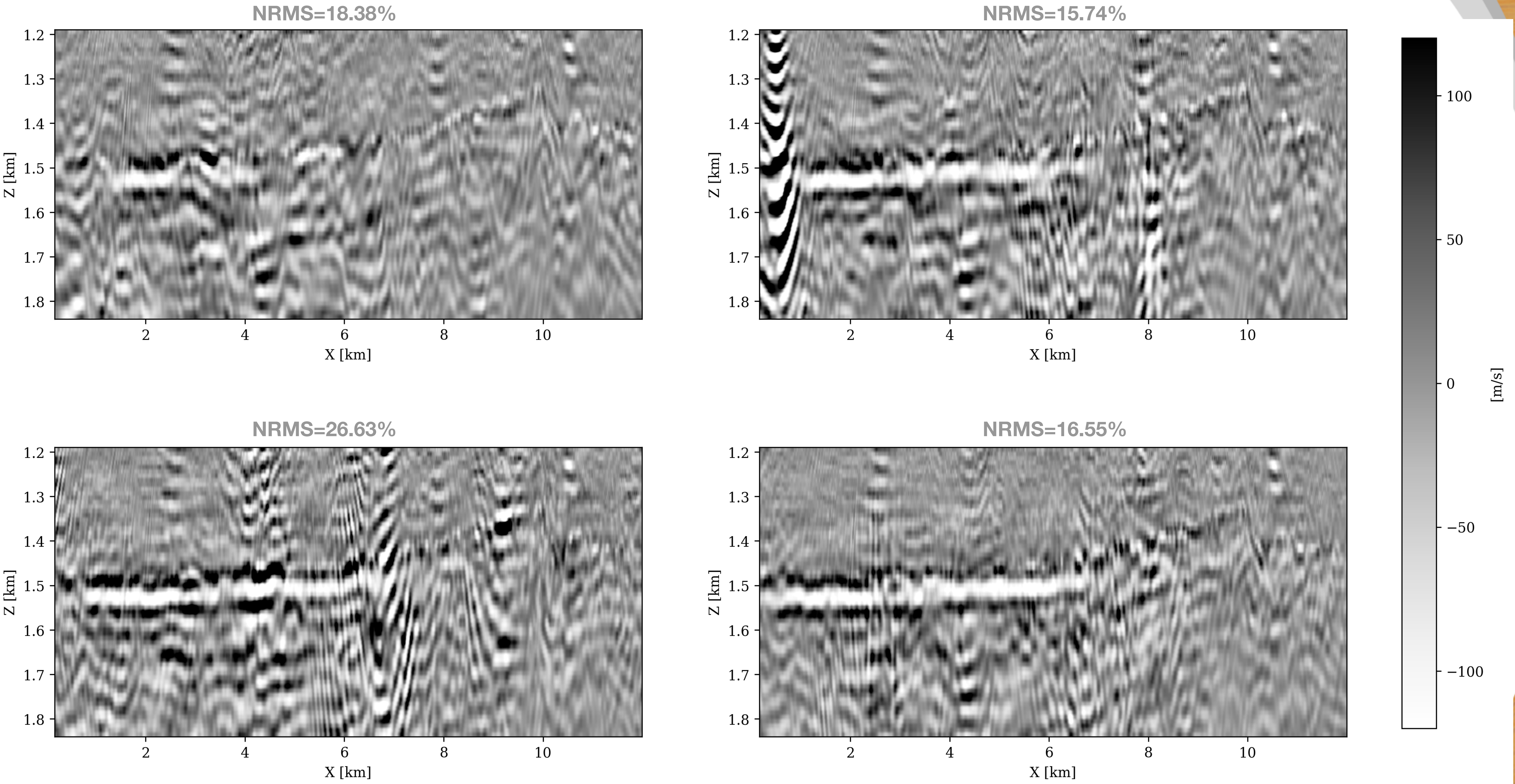
$$\text{subject to} \quad \|\mathbf{A}\mathbf{z} - \mathbf{b}\| \leq \sigma$$

Solve via the linearized Bregman method:

- at each iteration: random subsets of sources + randomly compressed state variables
- memory per source: $\mathcal{O}(\bar{n})$ with $\bar{n} \ll n_t$
- suitable for 3D GPU implementation

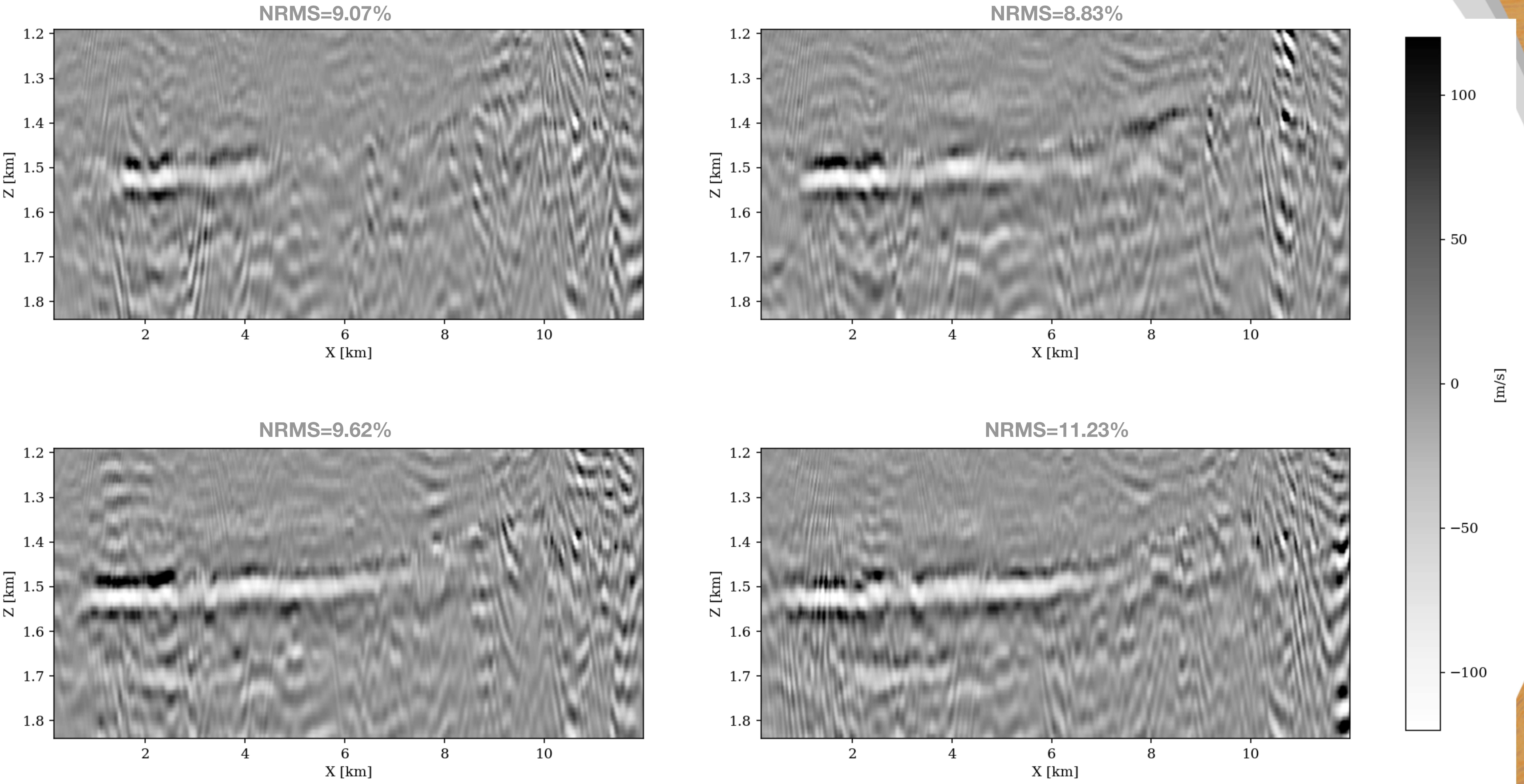
Independent recovery

poor repeatability (NRMS $> 15\,\%$)



Joint recovery

acceptable repeatability (NRMS $< 10\,\%$)

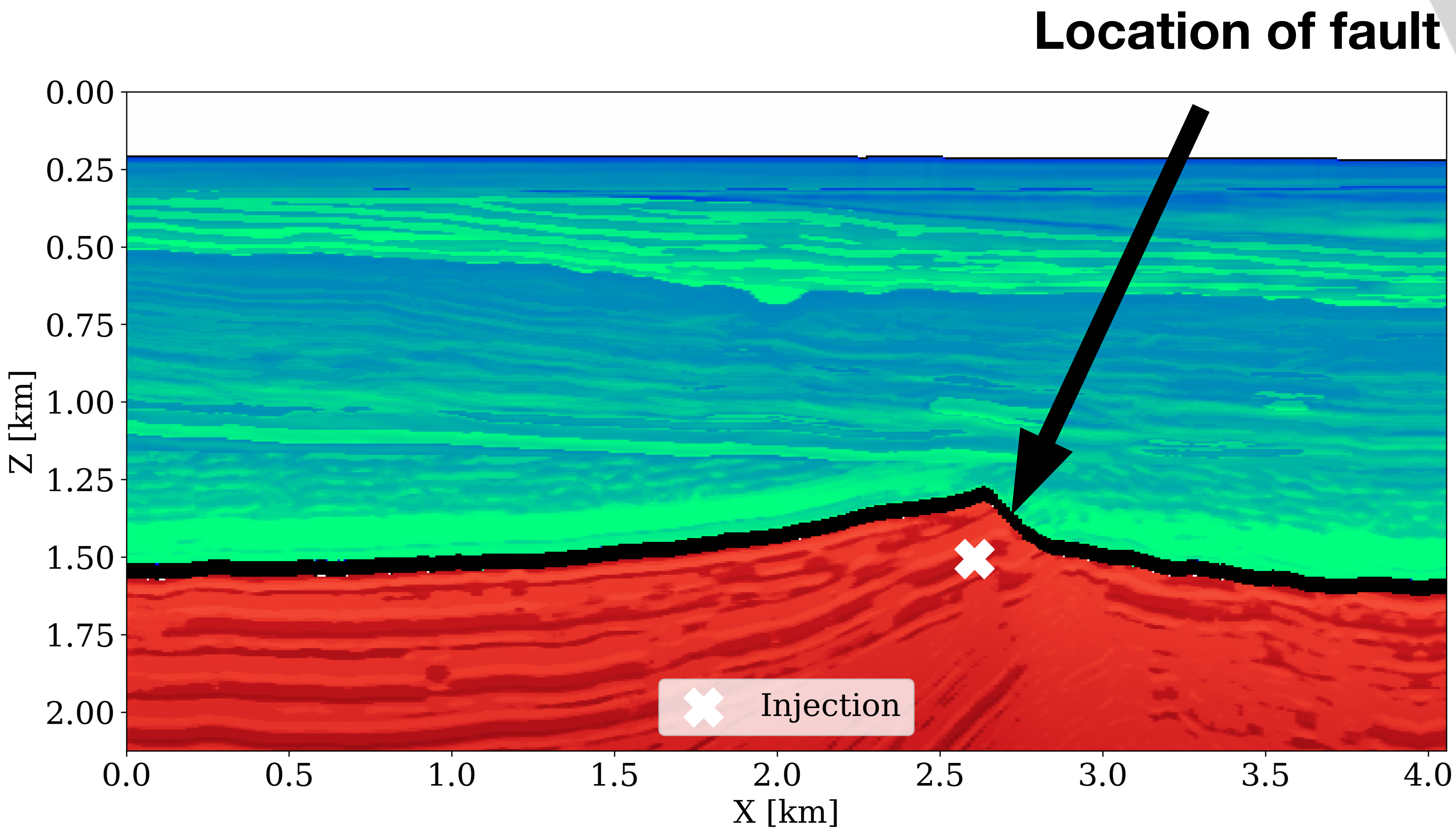


CO_2 plume monitoring

leakage through fault

12-year CCS project:

- fault above injection well w/ 12.5m width
- fault opens when pressure exceeds 10^9 Pa
- fault closes after 3 years when pressure drops under 10^7 Pa
- assess seismic detectability

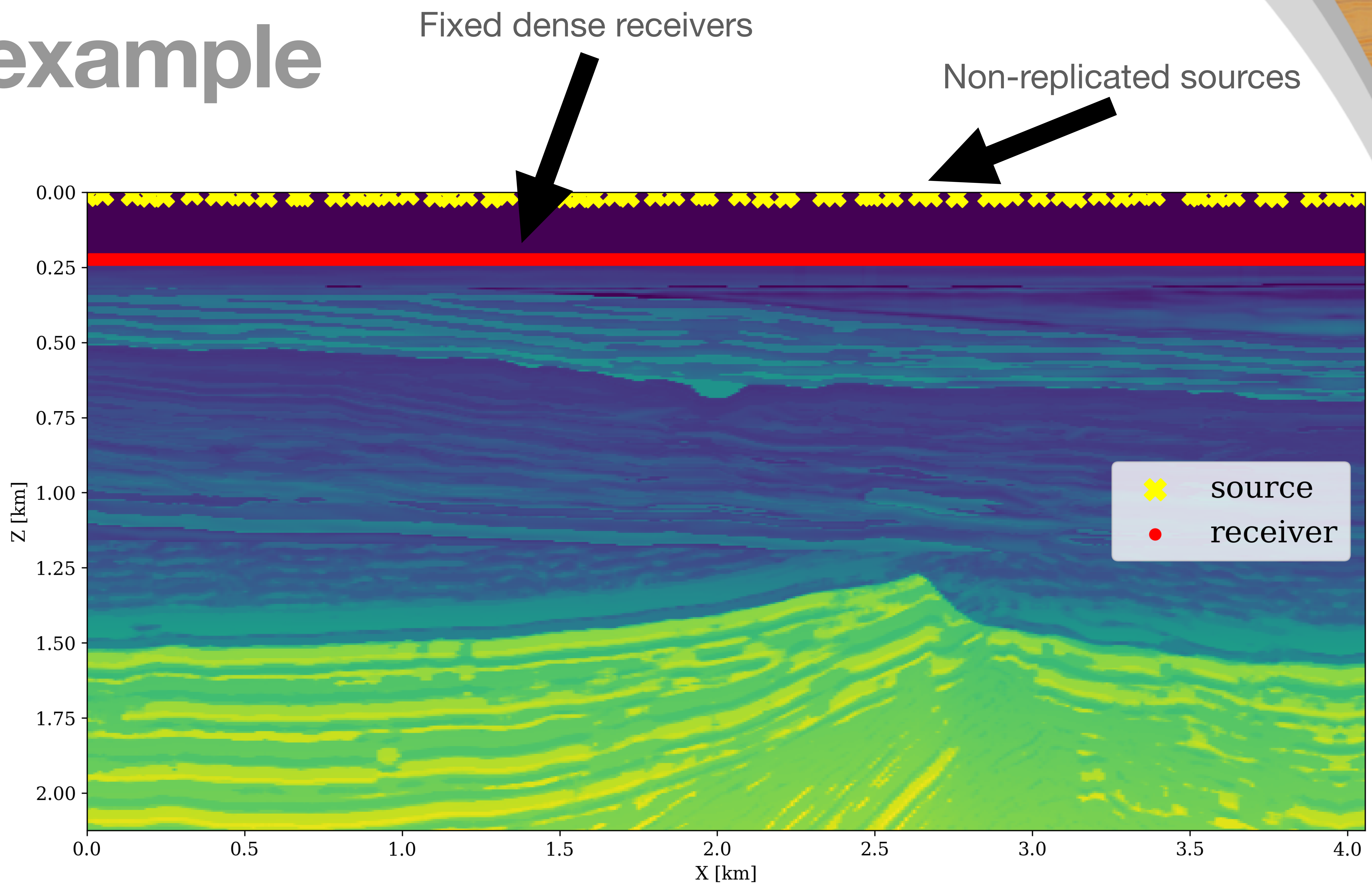


Leakage example

Fixed dense ocean bottom nodes (DAS)

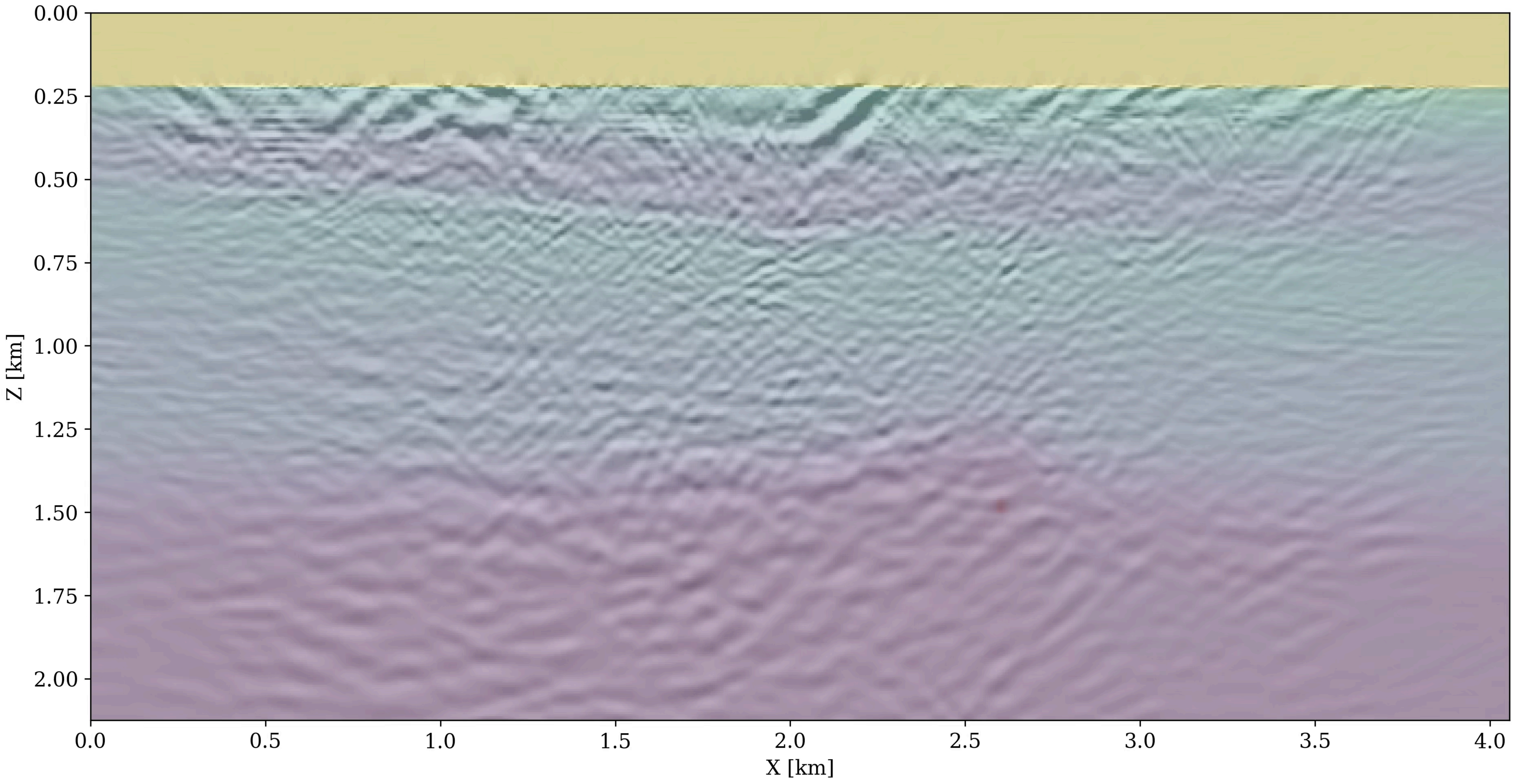
Non-replicated random *sparse* jittered sources (65.5 m)

64-vintage monitoring



Pressure induced CO2 leakage

1 data pass = 1 RTM



Observations

Making good progress w/ a small team towards development of a modular workflow

- assessment of low-cost seismic monitoring for CCS in realistic settings
- capable of working w/ non-replicated sparse & low-energy monitoring data
- well aligned w/ other CCS projects (NorthernLights)

More work needs to be done

- further develop modules & test in realistic 3D settings
- come up w/ different failure scenarios & systematic approach to UQ

To accomplish these we need access to major compute & training data…

Acknowledgement

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- The CCS project information is taken from the Strategic UK CCS Storage Appraisal Project, funded by DECC, commissioned by the ETI and delivered by Pale Blue Dot Energy, Axis Well Technology and Costain. The information contains copyright information licensed under ETI Open License.
- This research was carried out with the support of Georgia Research Alliance and partners of the ML4Seismic Center.