Velocity and Thickness Estimation of

Thin CO_2 Layers

with Patchy Saturations

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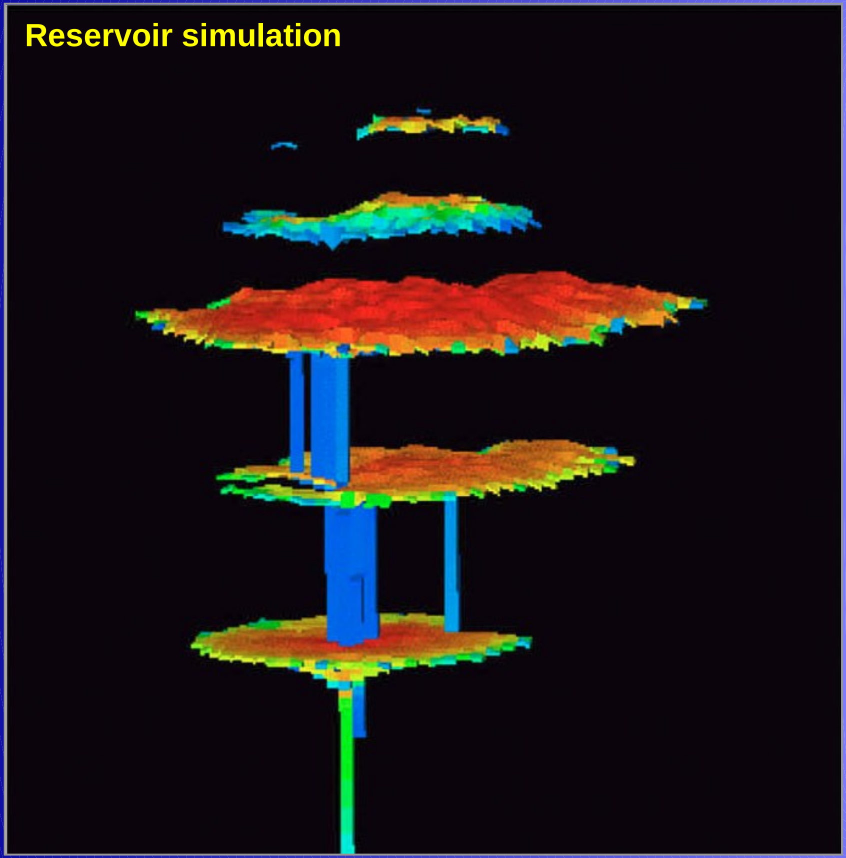
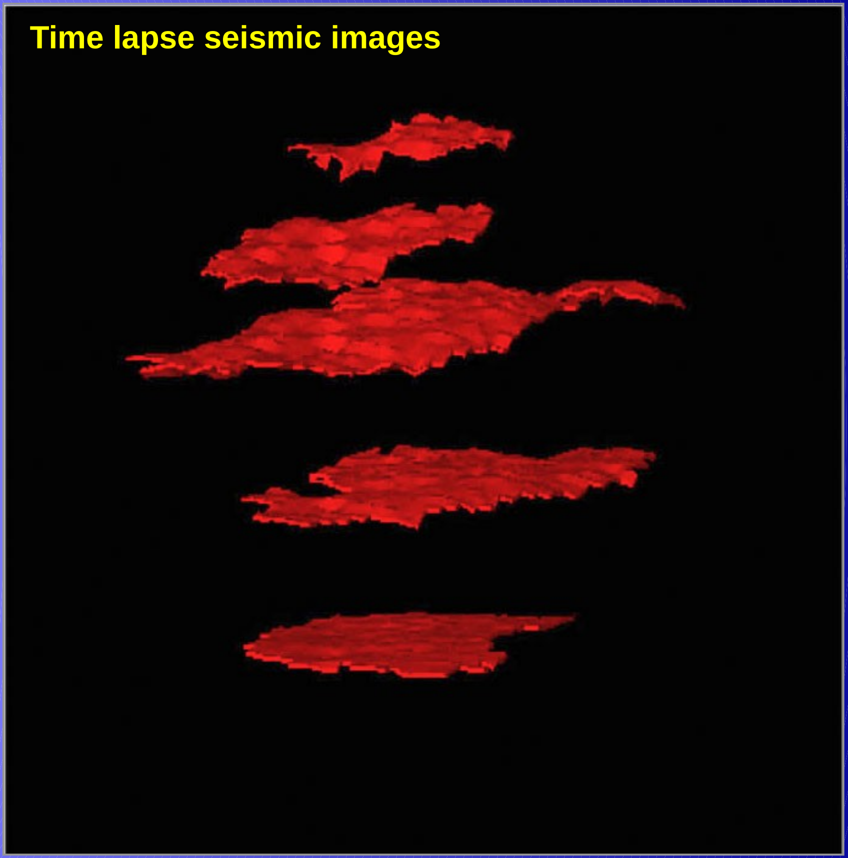
Outline

- Define the problem: thin CO_2 layers
  - Why of interest?
- The method by Ghaderi-Landrø (2009)
  - Outline the method for simultaneous estimation of 4D changes in velocity and thickness with application to real data
  - Test on synthetic data
- Show that the method is sensitive to saturation scales, accounting for
  - Patchy and uniform saturation

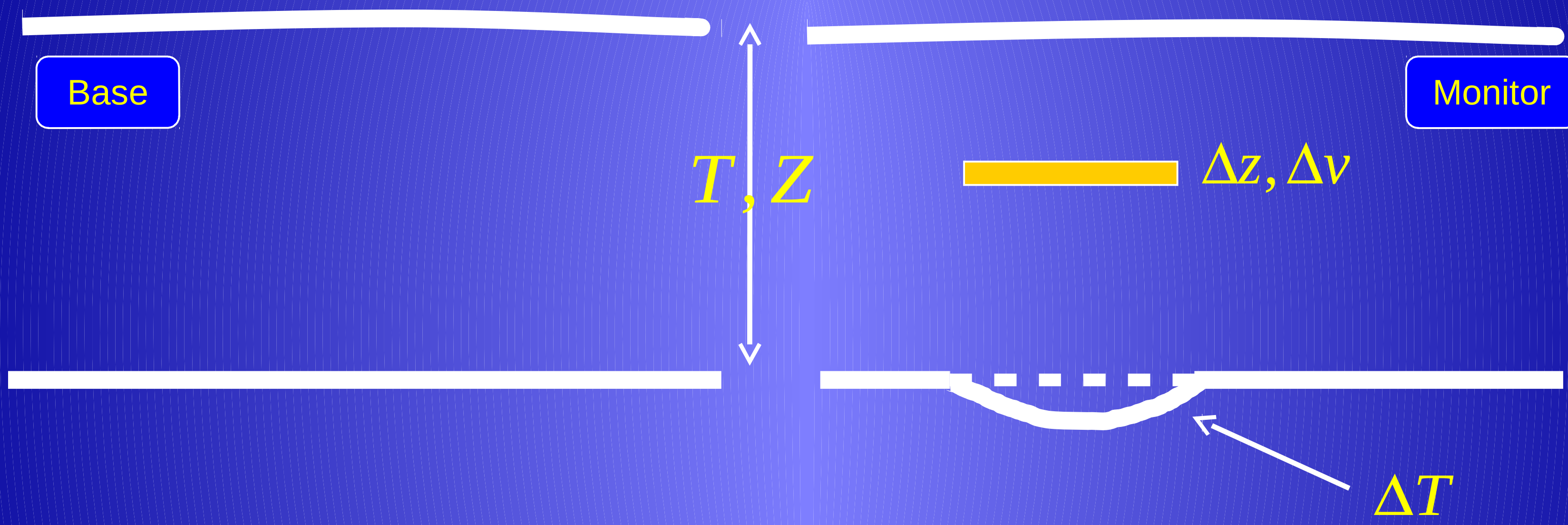
Layers of CO_2 - 3 years disposal in the Utsira





- CO_2 is injected at the base of the Utsira aquifer in Sleipner
- CO_2 rises due to buoyancy and accumulates under thin shale layers on its way up

The Problem



For the 4D seismic anomaly, we are interested in an estimate of

- thickness: ΔZ
- change in velocity : ΔV
- a quantitative measure of saturation $S_{anomaly}$

Estimation of thickness ΔZ, given ΔV

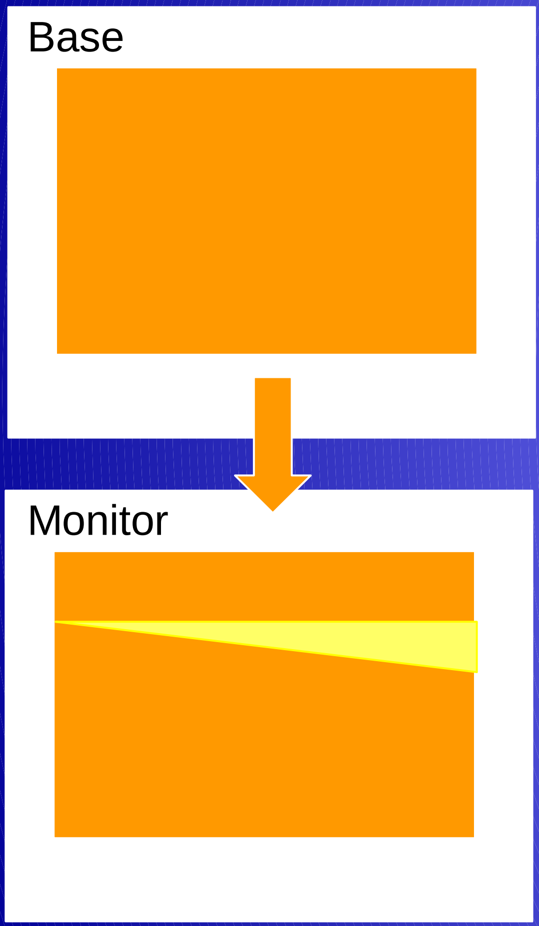
- One simple thickness estimate is based on direct picks and:

$$\Delta z = \left(t_2 - t_1 \right) \Delta v$$

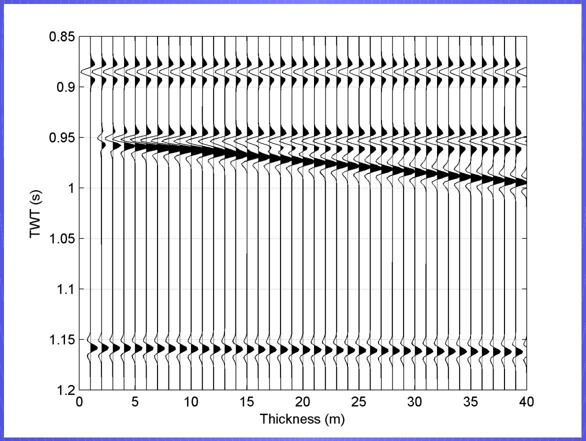
- Alternative method is using Ghaderi & Landrø (geophysics 2009),

$$\Delta z = -z \frac{v}{\Delta v} \frac{\Delta T}{T}$$

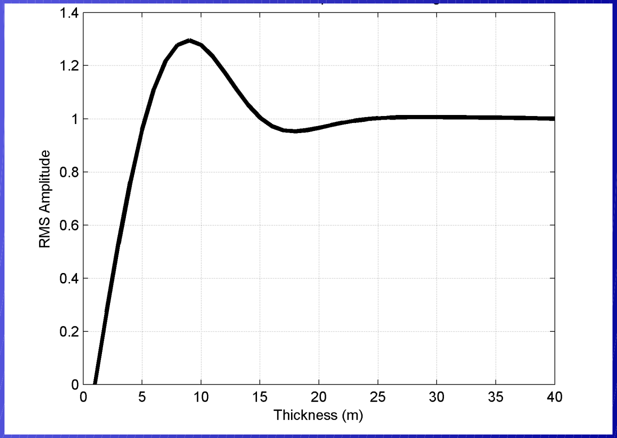
Synthetic test of the proposed methods



Wedge model

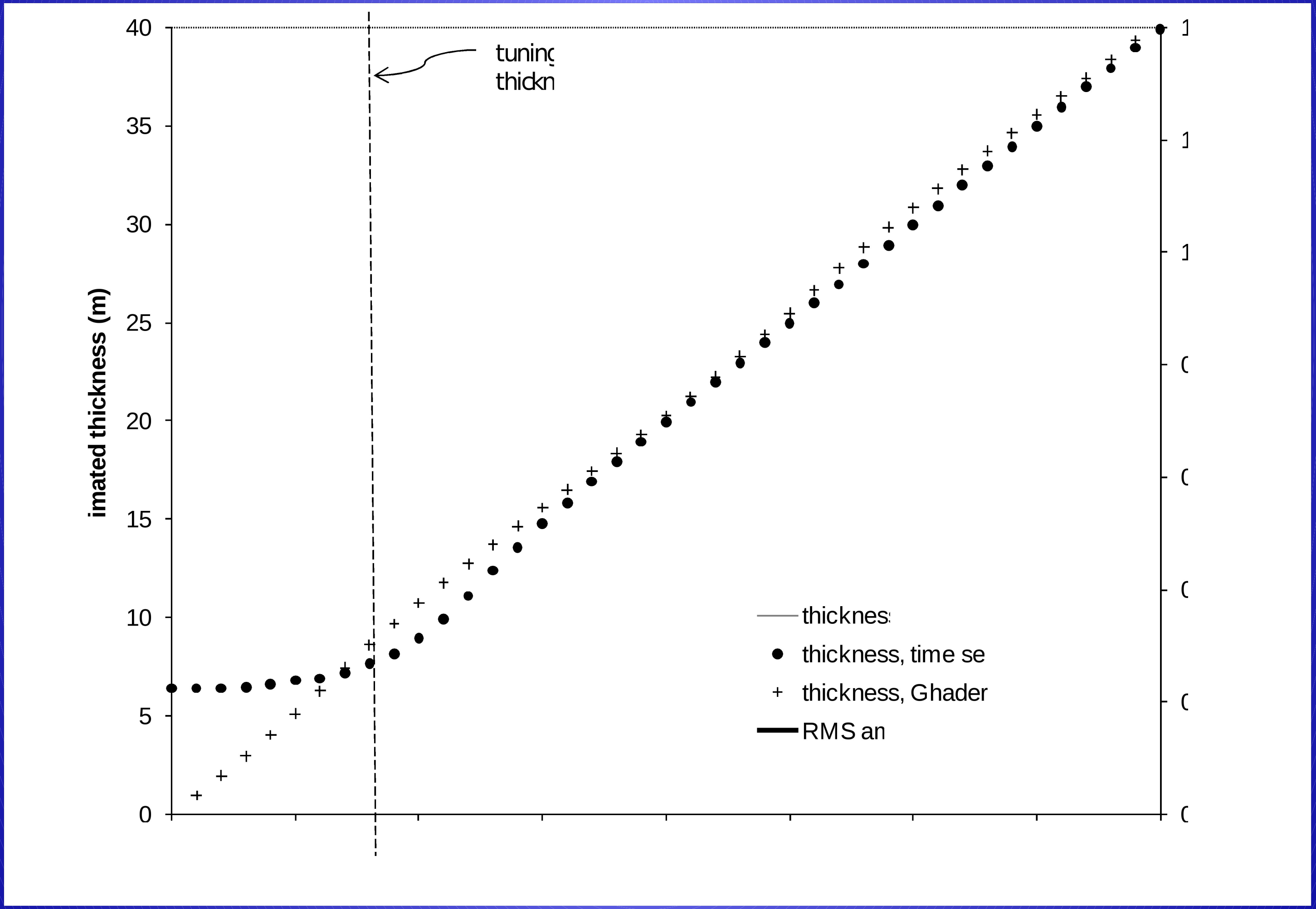


Seismic response



RMS amplitude response of the wedge

The comparison of the two methods in estimating ΔZ



Observations

- Direct picking on the wedge leads to
  - an underestimate for a limited range of thicknesses above the tuning thickness
  - For thicknesses below the tuning thickness, it tend to a minimum as the Wedge gets thinner, leading to a gross overestimate.
- Ghaderi & Landrø method:
  - The result is better by picking traveltime below the event.
  - Knowing velocity change, measurements of travel time below the 4D seismic anomaly, can predict the thickness below tuning.

ΔV not known

- The main challenge: ΔV is not always known
  - Lack of well log, etc.
- Ghaderi & Landrø (2009) propose the use of amplitude information to simultaneously estimate ΔV and ΔZ

Simultaneous estimation of ΔV and ΔZ

Ghaderi & Landrø, Geophysics (2009)

- 4D amplitude response of a thin layer :

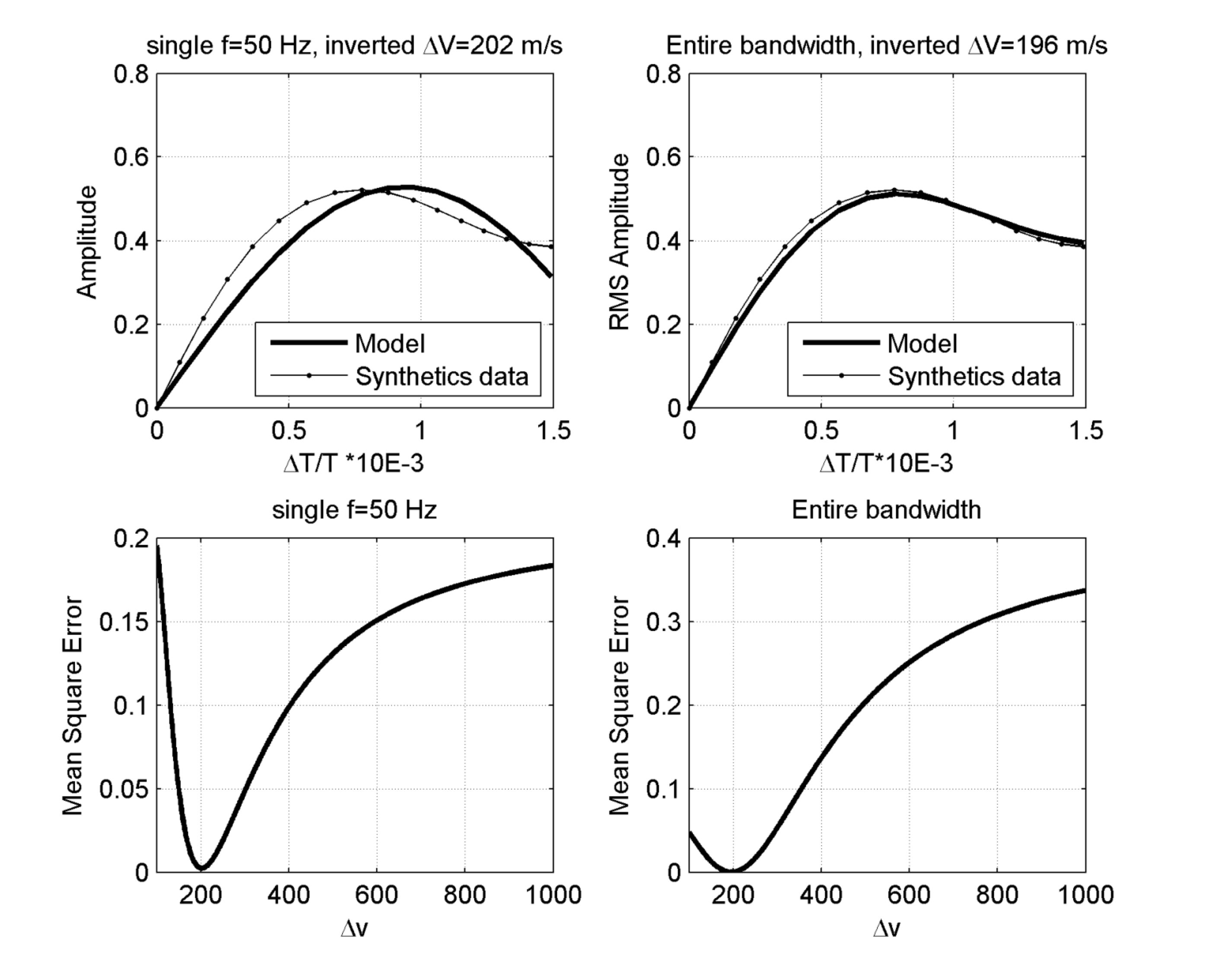
$$S_d(f_0) = -\frac{|P(f_0)|}{v_1 \cos^3\theta}\frac{\Delta T}{T} \times \text{sinc}\left(-\frac{\Delta T}{T}\frac{z_1 2\pi f_0}{\Delta v \cos\theta}\right)$$

- The corresponding RMS amplitude response

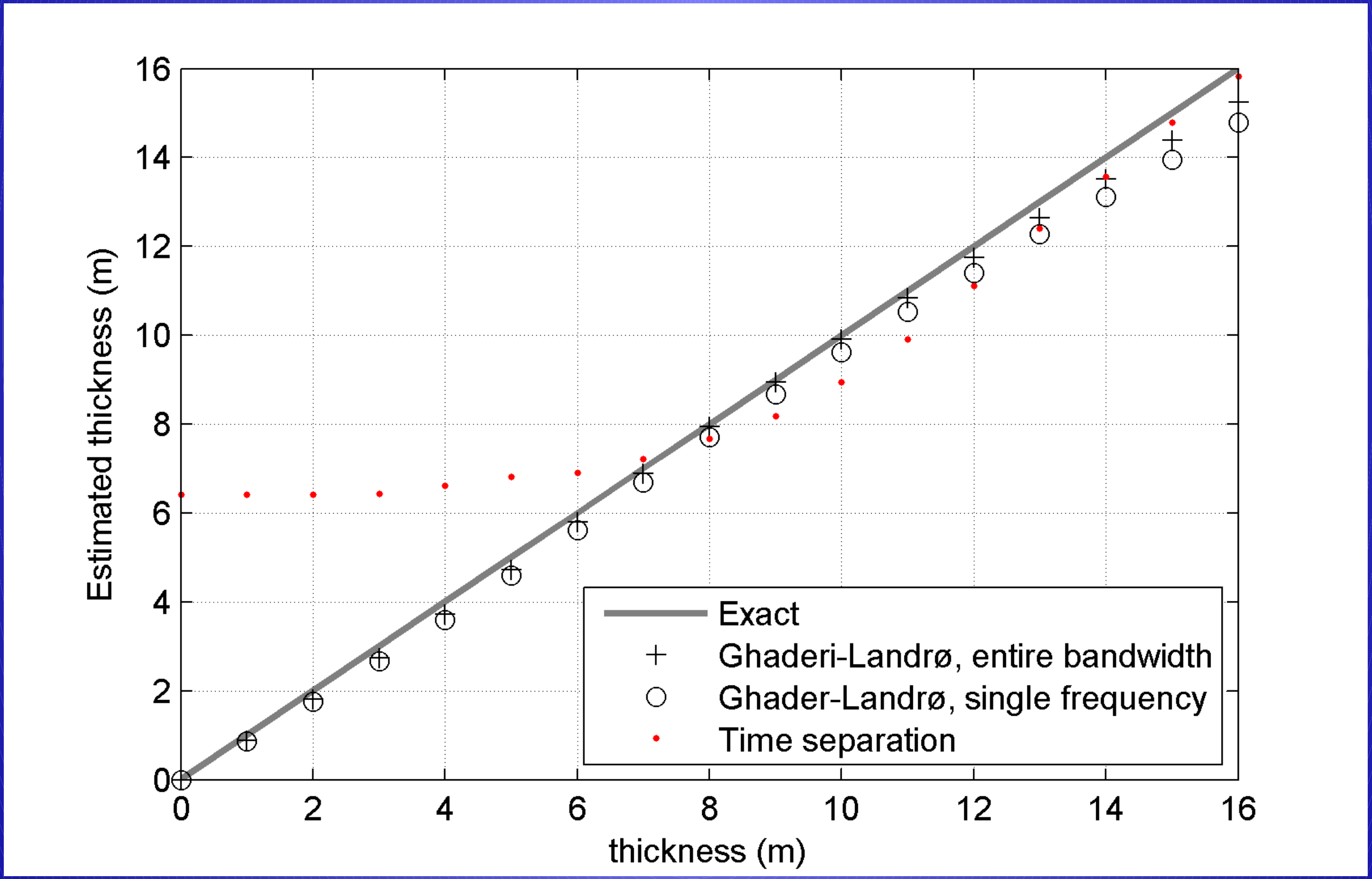
$$S^2_{d\_RMS} = \int_{f_l}^{f_h} S_d^2(\omega)\, d\omega$$

Measure S_d and ΔT → Invert for ΔV

Inverting for ΔV (exact : 200 m/s)



Estimated thicknesses from inversion

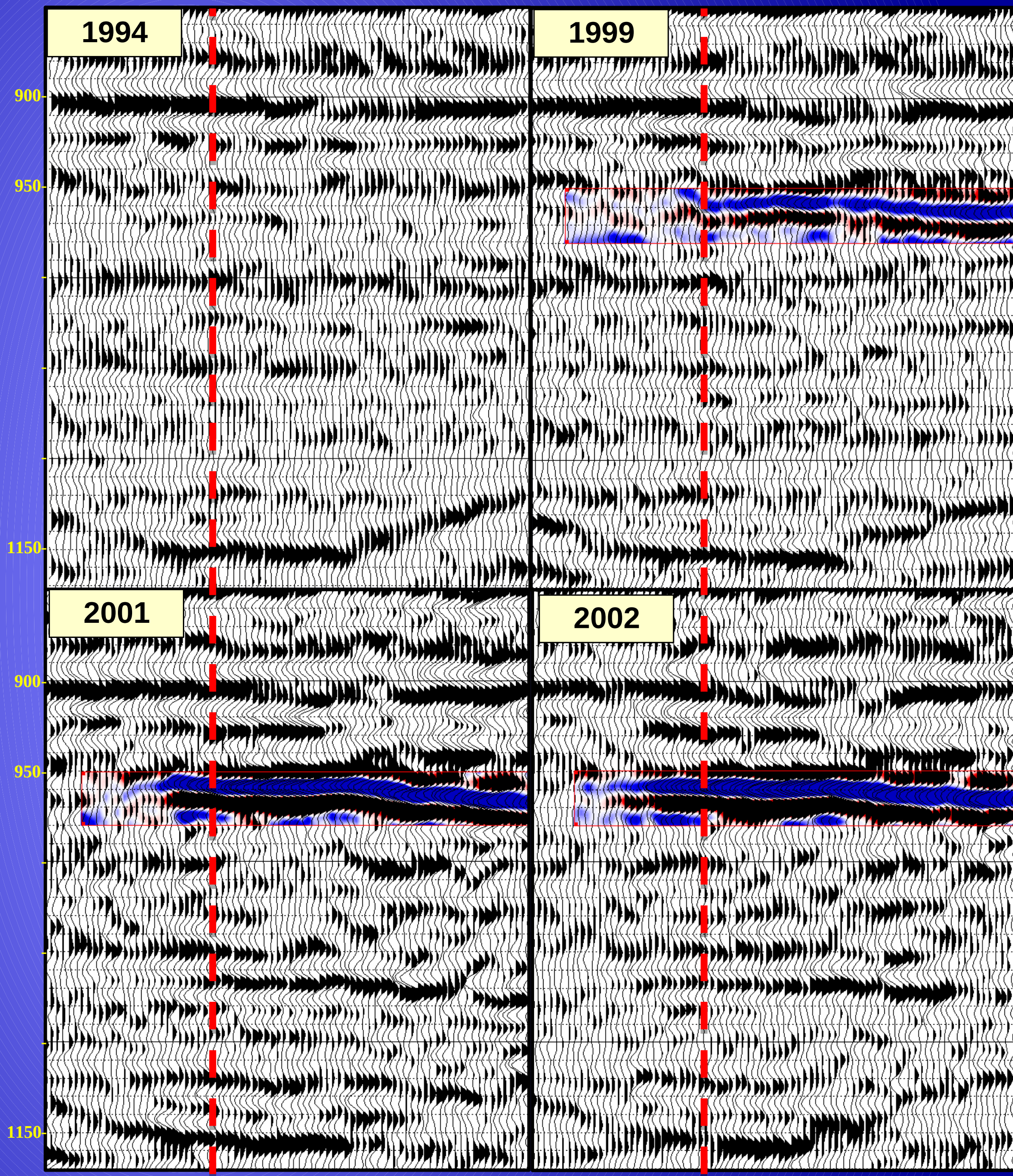


Back to real data

- Estimates of ΔV and ΔZ
  - According to Ghaderi&Landrø

Monitor year	Δv (m/s)	Δz (m)
1999	200	15 (4)
2001	400	15 (8)
2002	500	15 (10)

  - Values in parenthesis based on Gassmann and picked timeshifts



So, what is happening?

- This deviation may be due to the patchiness in saturation distribution

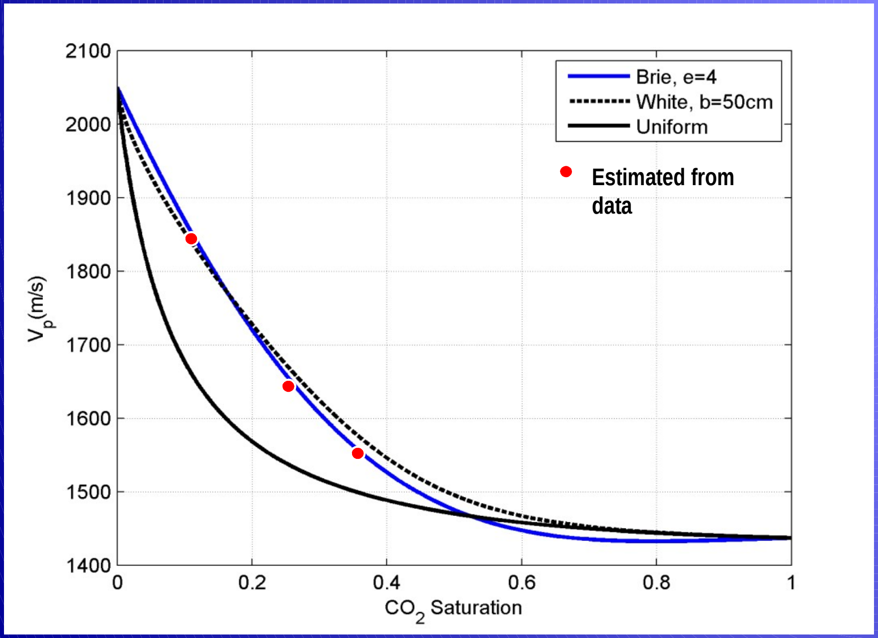
Definition: Patchy vs Uniform saturation

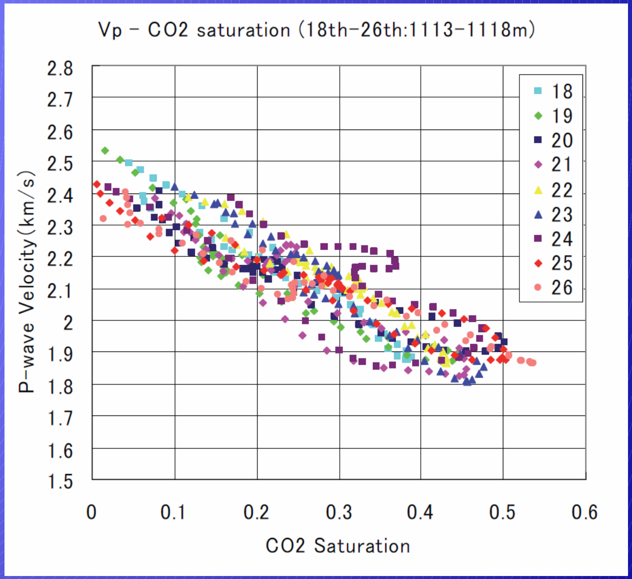
- Uniform saturation
  - Pore pressure can equilibrate over spatial scales less then the L_C during a seismic period
- Patchy saturation
  - Saturation patches larger than L_C where there is not enough time for wave-induced pore pressure gradient to equilibrate between pore fluid phases during the seismic period
- Characteristic diffusion length (seismic subresolution)

$$L_C = \sqrt{\frac{D}{f}}$$

Some rock physics . . .

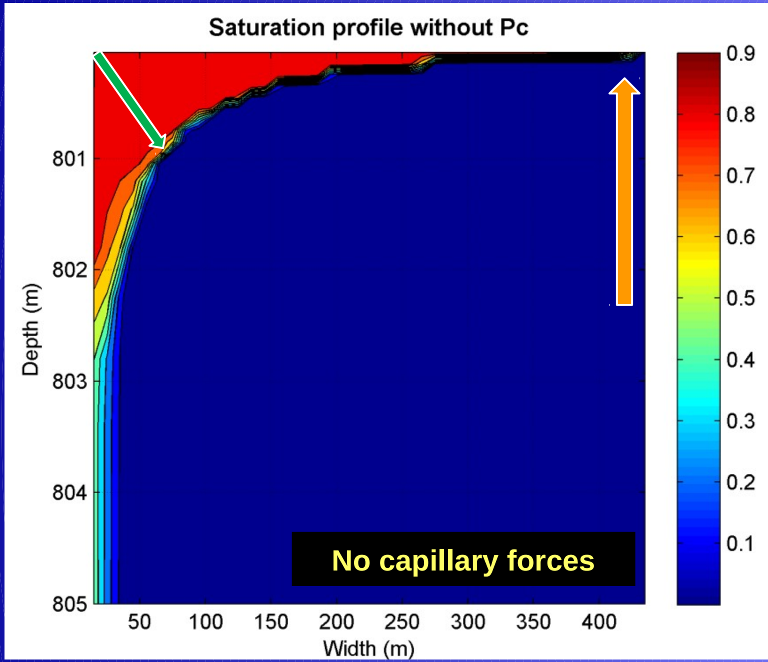
- By constraining the pairs, ΔZ and S_{CO2} with measured ΔV and ΔZ we can look at various rock physics models:
  - Gassmann-Wood
  - Empirical Brie's relation, calibrated with White's model

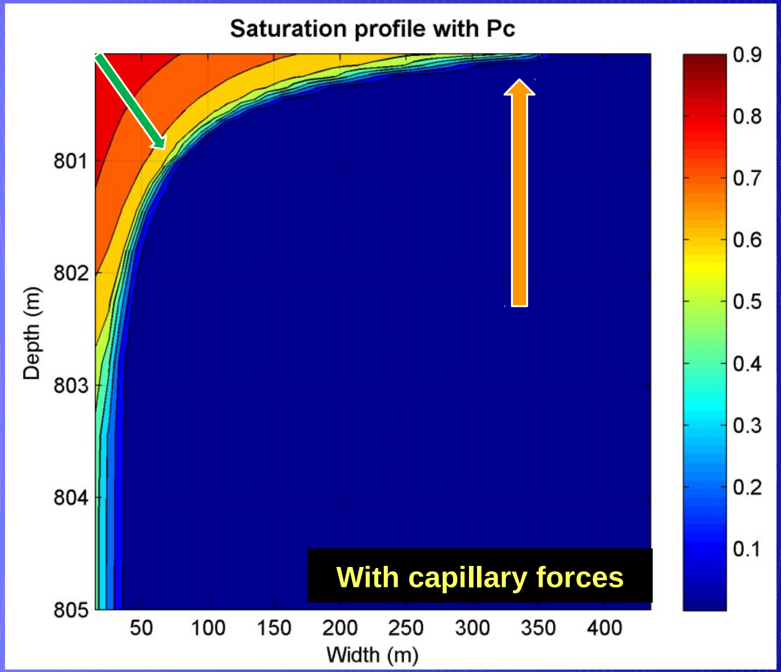




P-wave velocity and CO_2 saturation from Nagaoka field, Konishi et al, EAGE 2008

CO_2 distribution under thin shale layers

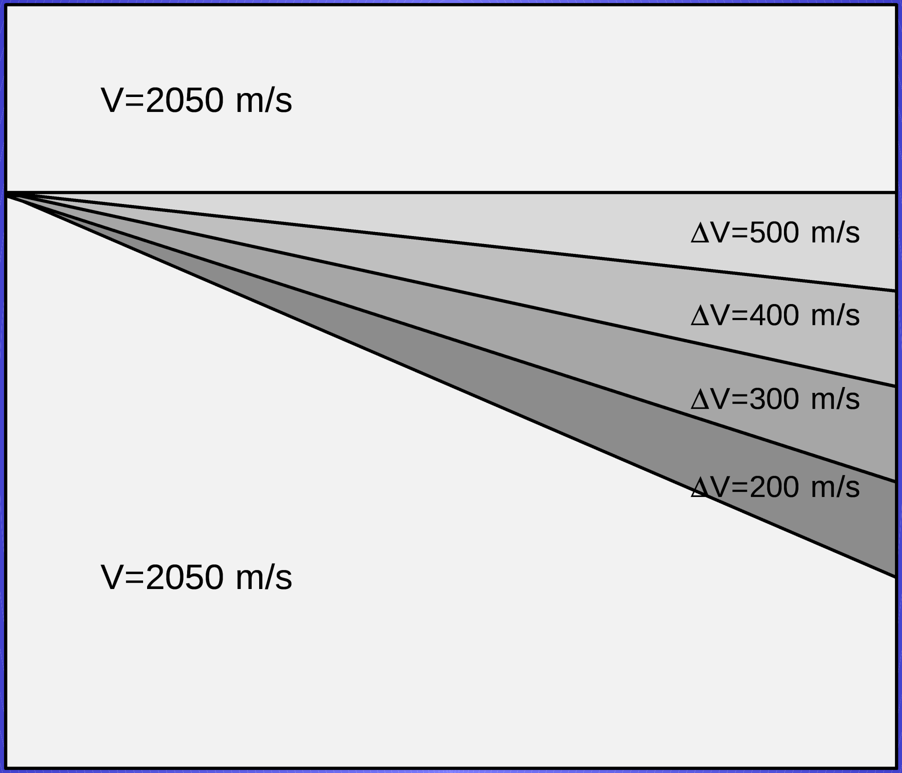




Influenced by capillary pressure having a decisive role on

- Saturation distribution under shale layers leading to zonations (transition zone)
- Smearing the CO_2 migration tip

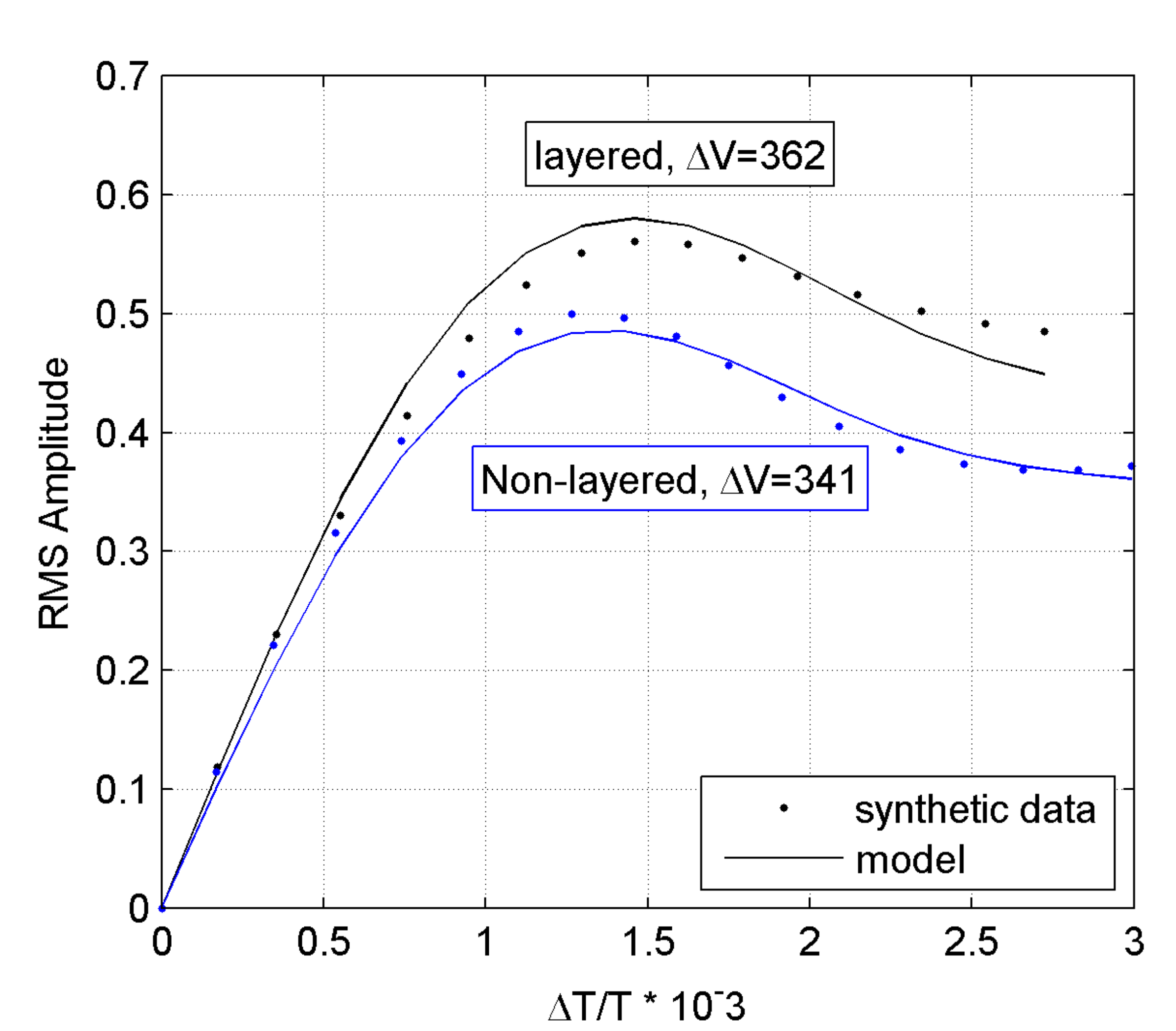
Modeling the transition zone



- 4 layer wedge model
- Progressively lower CO_2 saturations further down the model
- ΔV_{avg} = 350 m/s

Inverting for ΔV (average = 350 m/s)

Patchy saturation (4 layer model)

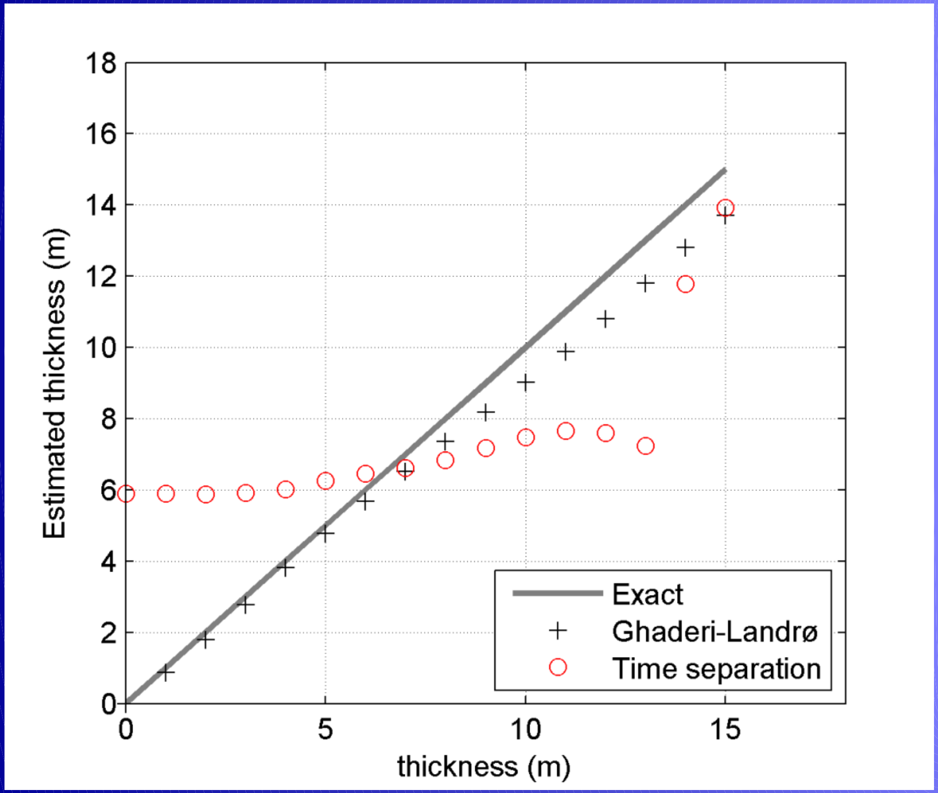


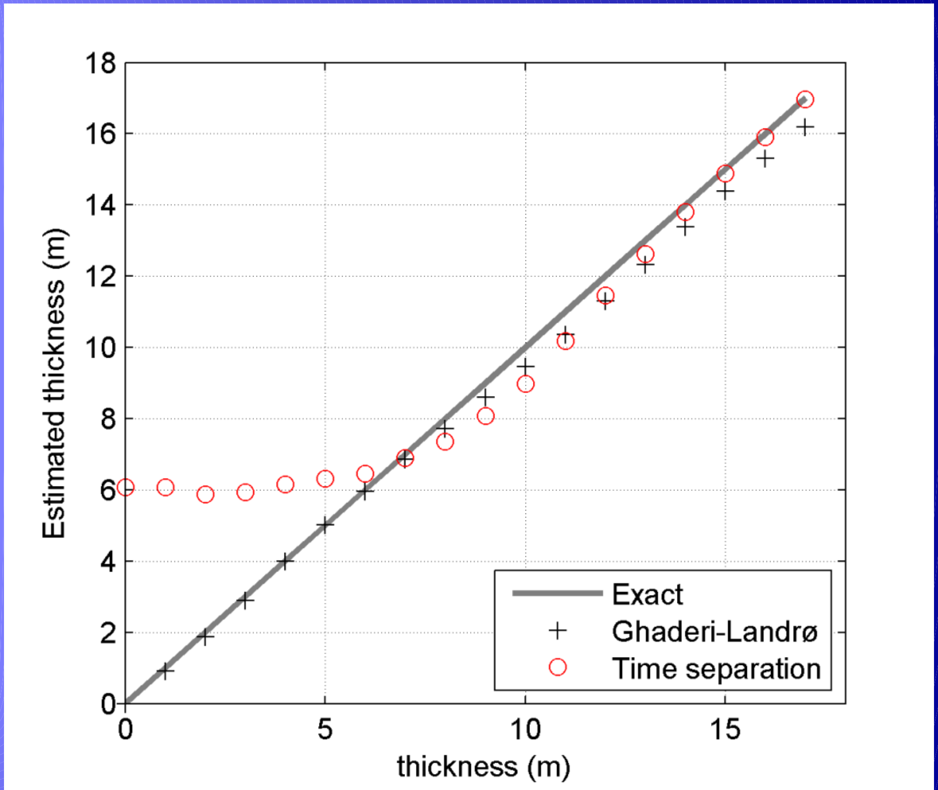
NOTE

Increase of RMS amplitude from Non-layered to layered case by 15%

Estimated thicknesses from inversion

Patchy saturation (4 layer model)



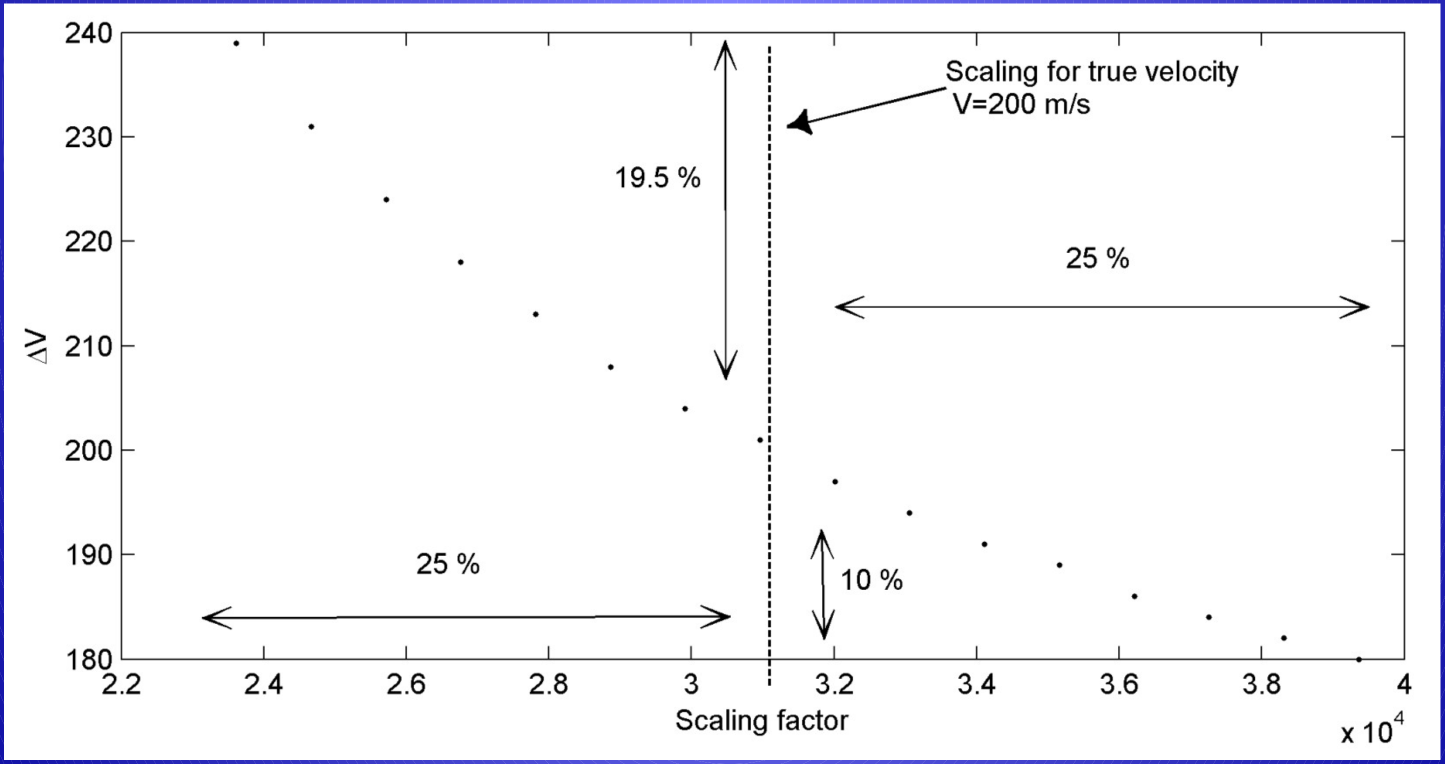


Layered

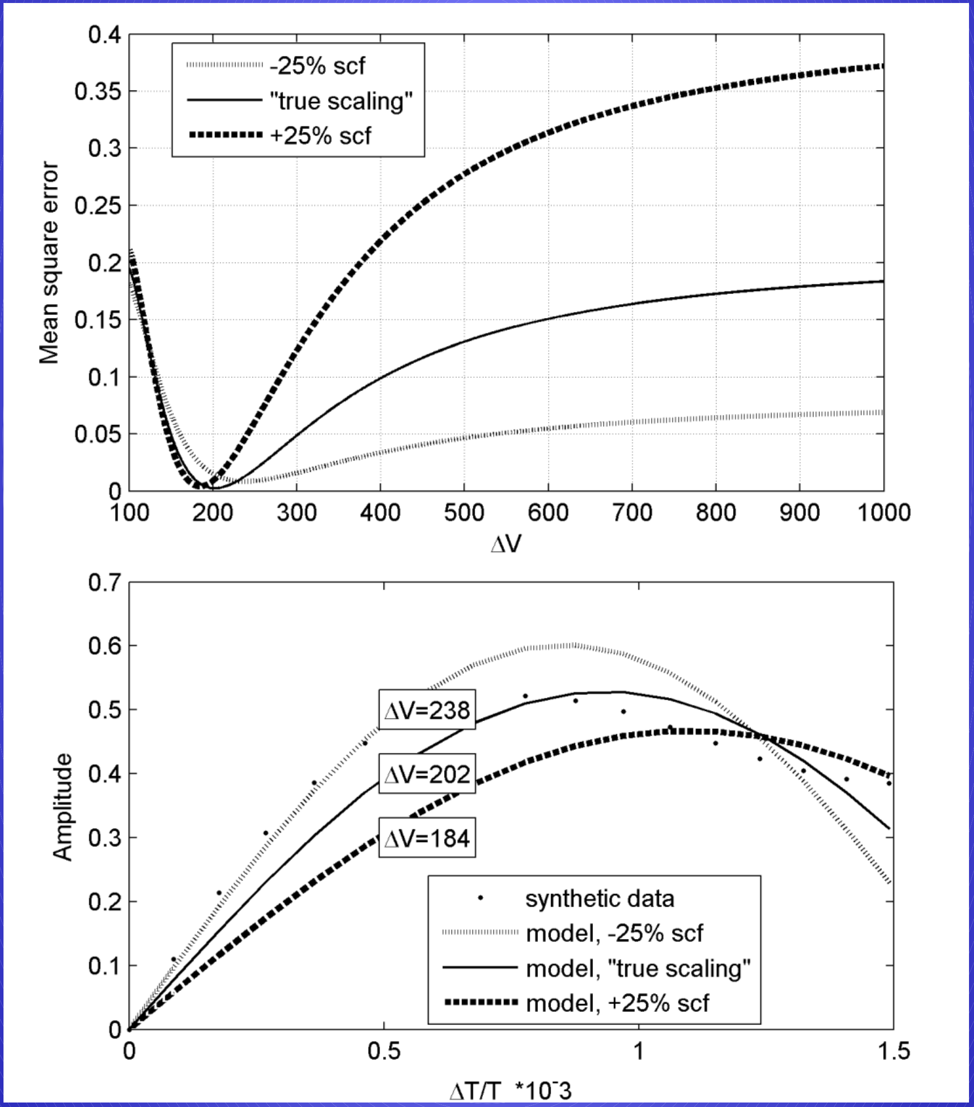
Non-Layered

Source amplitude

- The scaling factor to match the model with data
- Scaling affects the velocity estimation



Source amplitude determination



Conclusion

- An efficient method to estimate velocity and thickness change for thin CO_2 layers (uniform and patchy saturations)
- Further testing on real data is needed

Acknowledgement

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