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Time lapse pressure-saturation discrimination for CO_2 storage at the Snøhvit field

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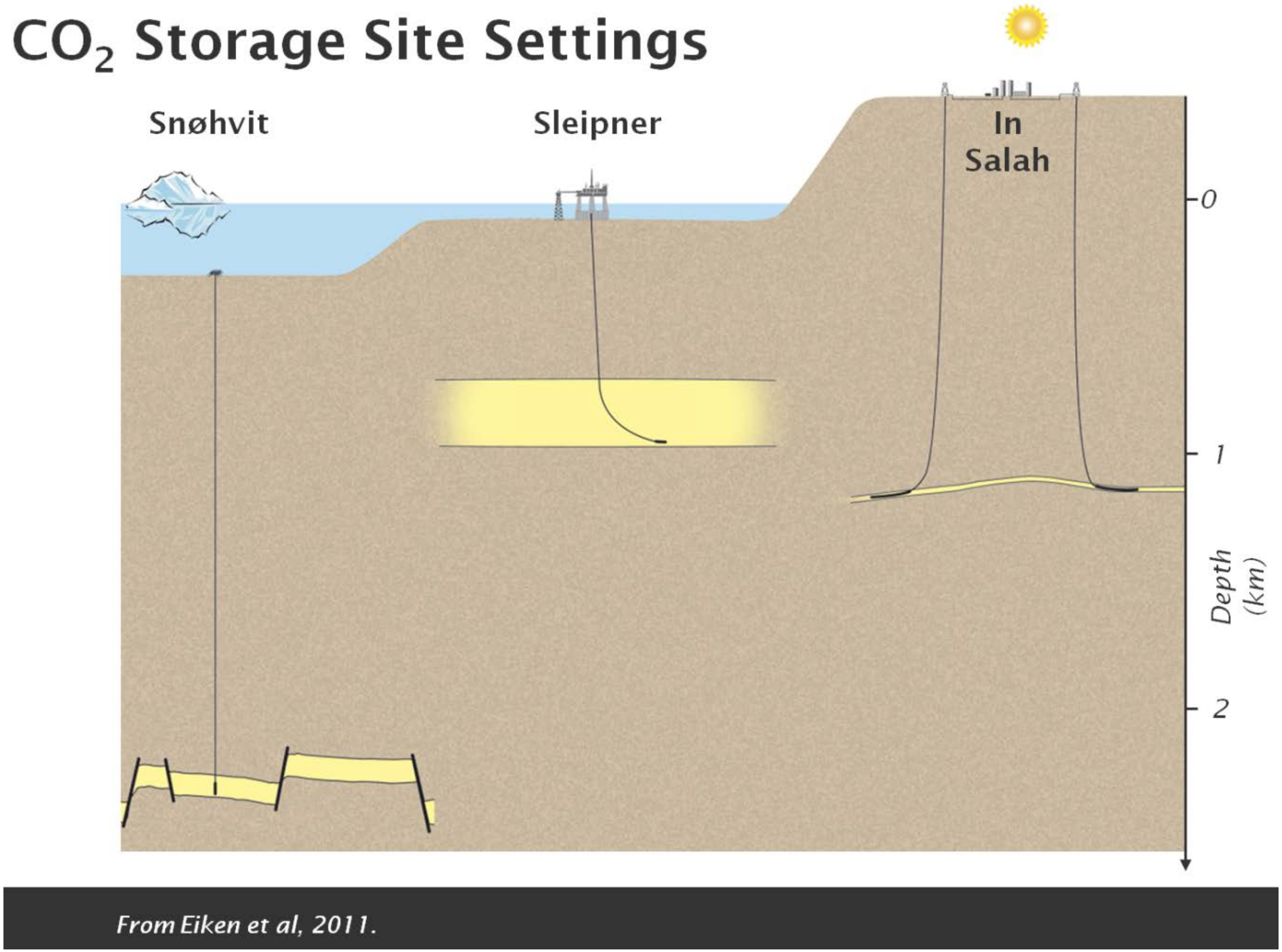
Introduction

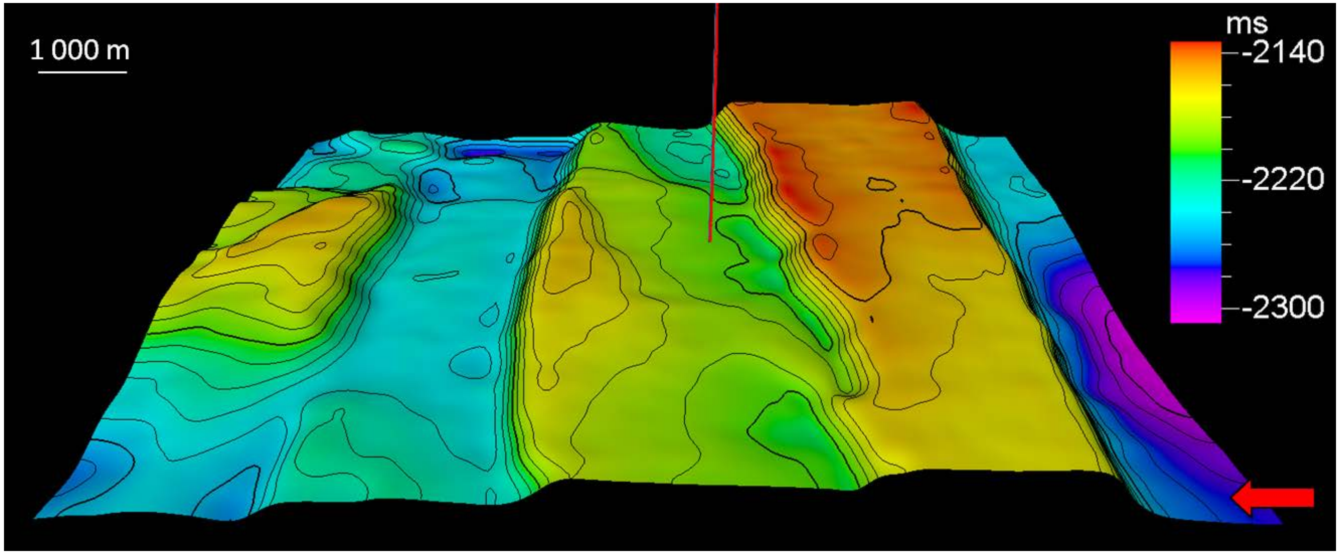
- The Snøhvit Field
- Methodology
- Calibration of reflectivity
- Rock physics versus seismic parameters
- Estimate of Mindlin exponent and saturation
- Results

CO_2 storage examples



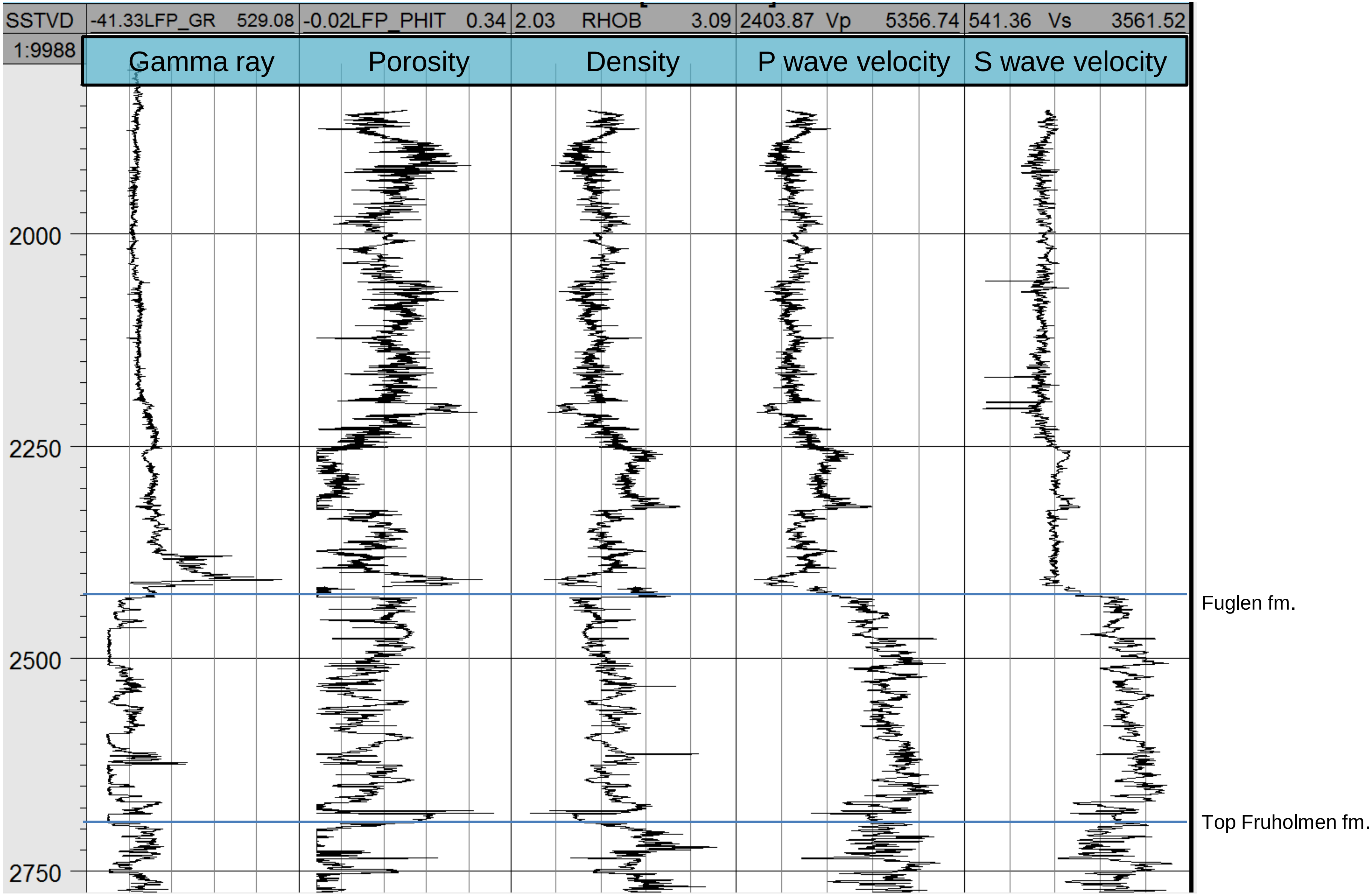
CO_2 injection on the Snøhvit Field

- Late Jurassic Tubåen formation
- Delta plain environment
- Faults East-West, injection zone ~ 2 500 m wide
- Compaction and cementation
- Base 2 670 m, ~ 110 meters thick
- Baseline 3D 2003, repeated 3D 2009
- Injection started April 2008

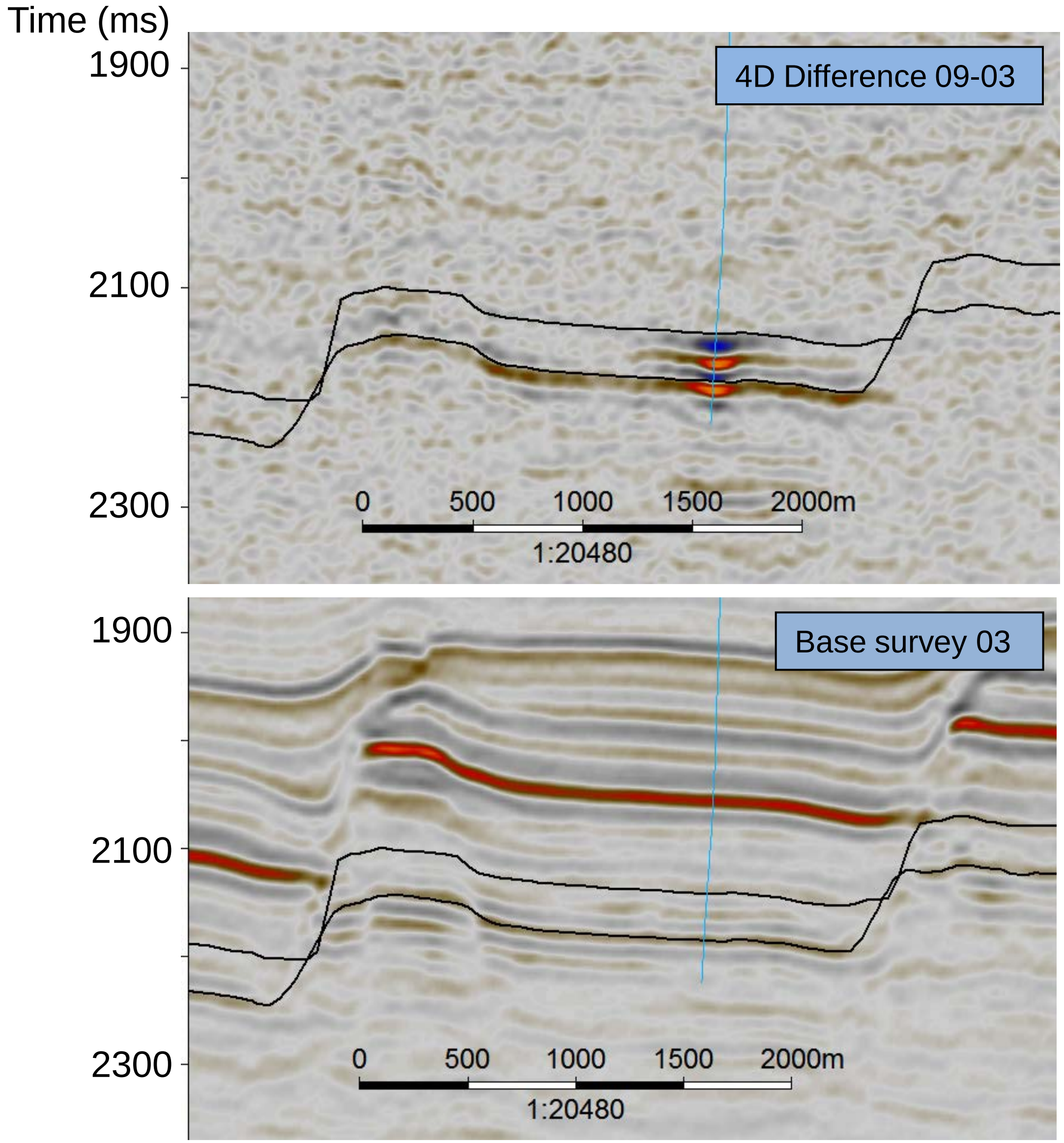


Topography of the reservoir in Tubåen formation. North direction is indicated by the arrow. The CO2-injection well is shown by the red solid line.

Well logs 7121/4F-2-H



CO_2 injection on the Snøhvit Field



Methodology

Landrø (2001):

$$\frac{\Delta\alpha}{\alpha} \approx k_\alpha \Delta S + l_\alpha \Delta P + m_\alpha \Delta P^2$$

Constants determined directly from pressure and saturation changes

$$\frac{\Delta\beta}{\beta} \approx k_\beta \Delta S + l_\beta \Delta P + m_\beta \Delta P^2$$

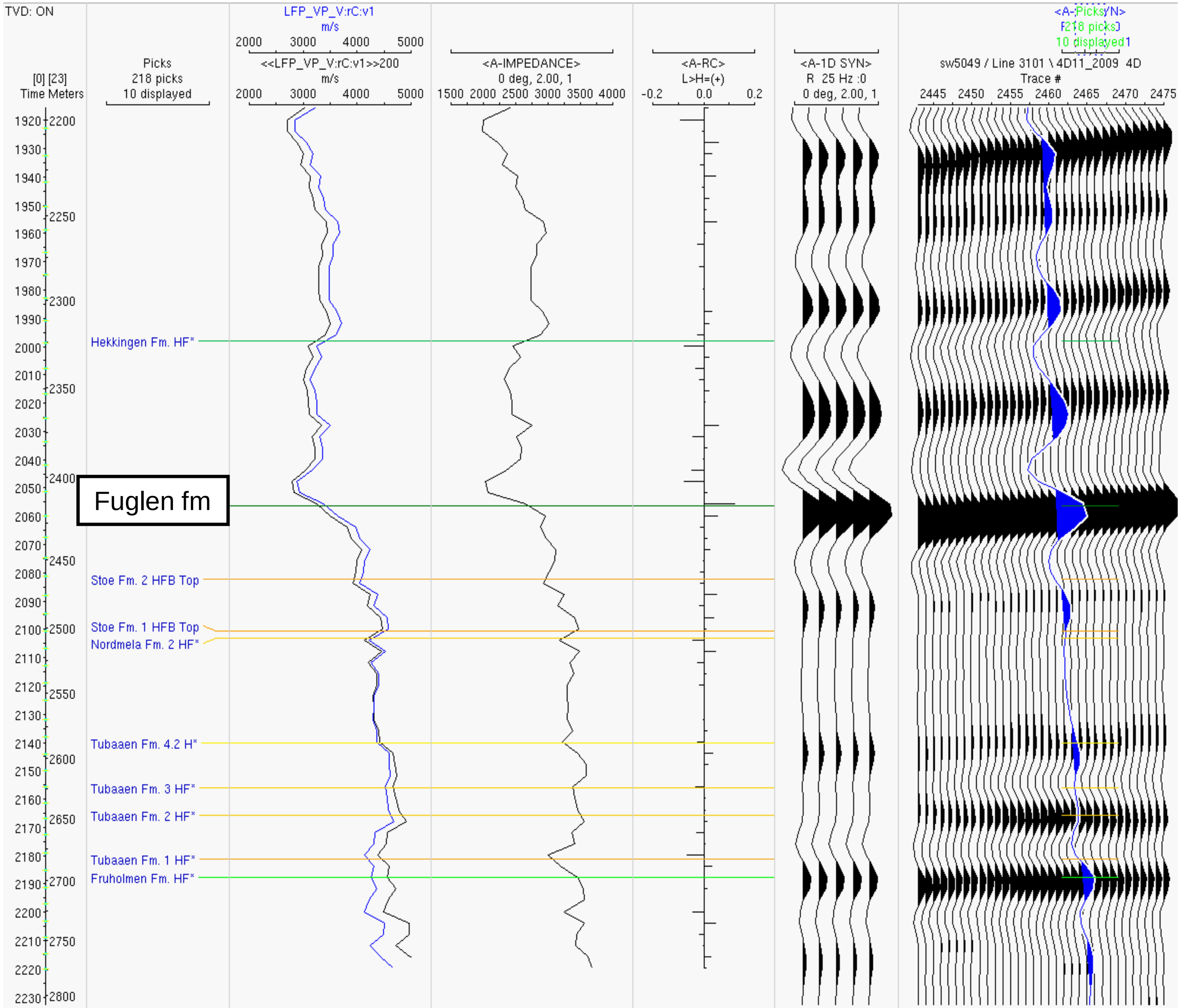
$$\frac{\Delta\rho}{\rho} \approx k_\rho \Delta S$$

$$\Delta R \approx \underbrace{\frac{1}{2}\left(k_\rho \Delta S + k_\alpha \Delta S + l_\alpha \Delta P + m_\alpha \Delta P^2\right)}_{\Delta R_0} + \underbrace{\left(\frac{1}{2}\left(k_\alpha \Delta S + l_\alpha \Delta P + m_\alpha \Delta P^2\right) - \frac{4\beta^2}{\alpha^2}\left(l_\beta \Delta P + m_\beta \Delta P^2\right)\right)}_{\Delta G} \sin^2\theta$$

$$\Delta T \approx -T\frac{\Delta\alpha}{\alpha} \approx -T\left(k_\alpha \Delta S + l_\alpha \Delta P + m_\alpha \Delta P^2\right)$$

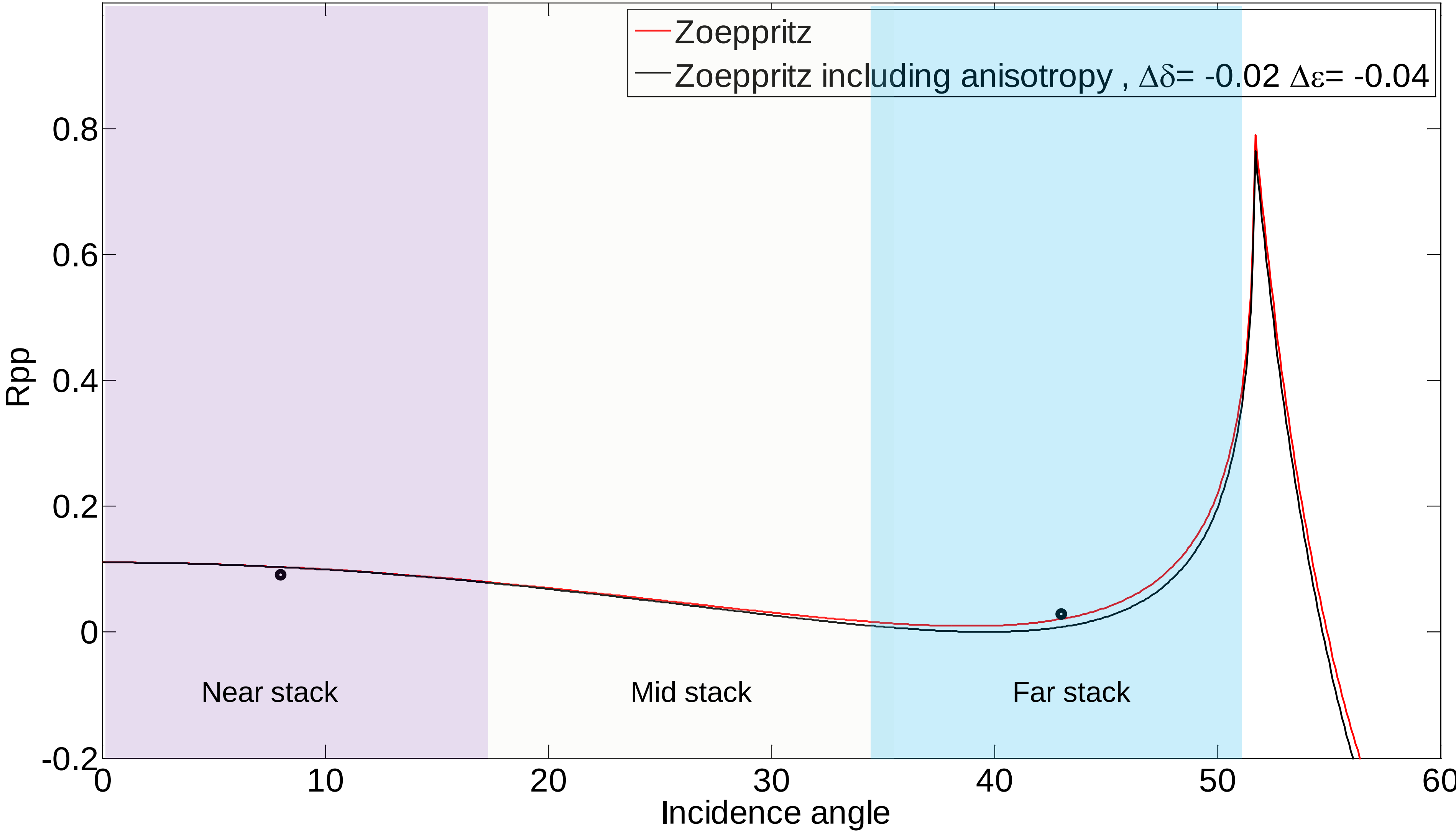
Time shift based on reflectivity changes – to be used for comparison with real timeshift

Well-tie

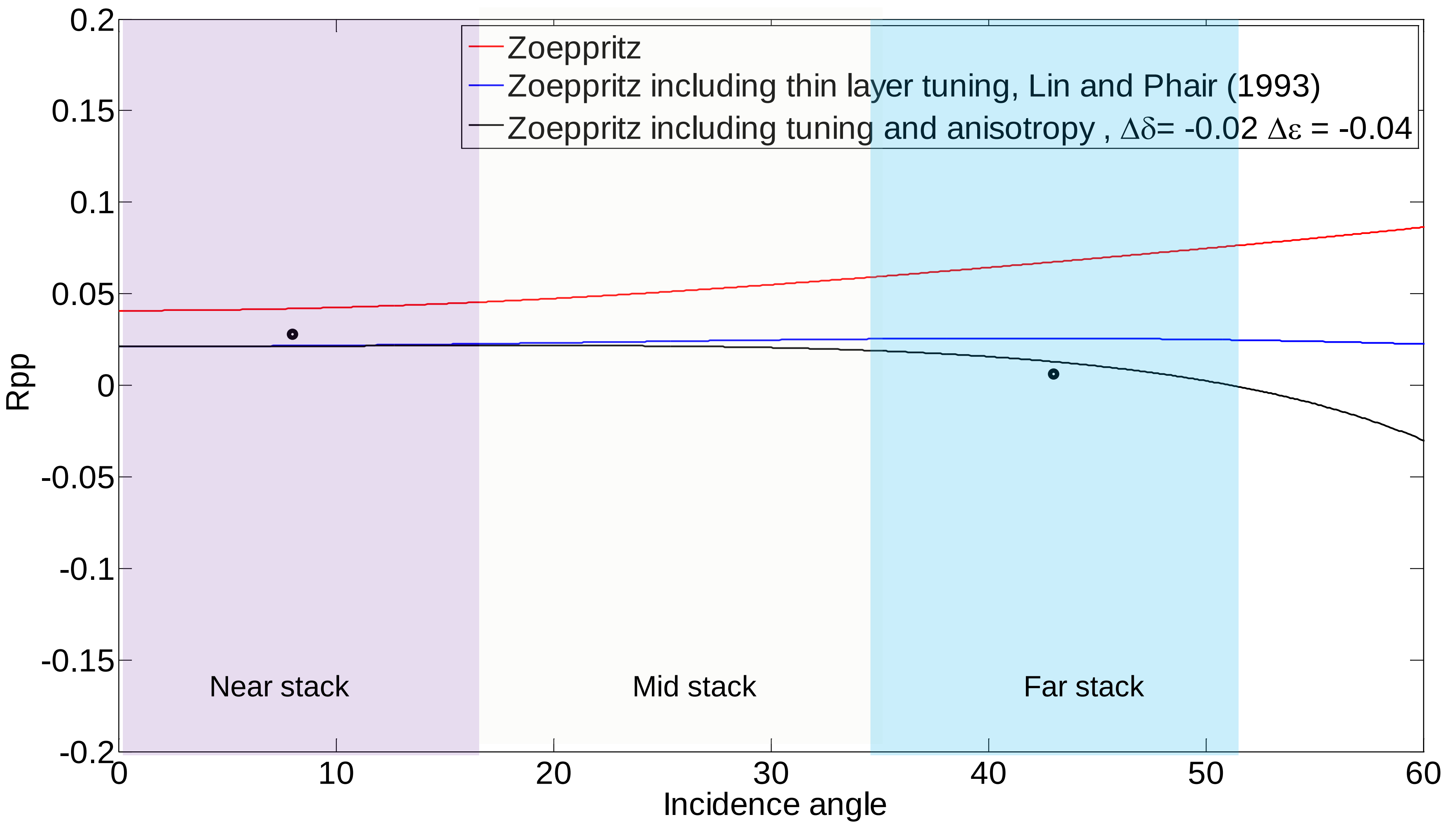


TVD: ON
LFP_VP_V:rC:v1
m/s
2000 3000 4000 5000
<A-PicksYN>
218 picks
10 displayed
[0] [23]
Time Meters
Picks
218 picks
10 displayed
<<LFP_VP_V:rC:v1>>200
m/s
2000 3000 4000 5000
<A-IMPEDANCE>
0 deg, 2.00, 1
1500 2000 2500 3000 3500 4000
<A-RC>
L>H=(+)
-0.2 0.0 0.2
<A-1D SYN>
R 25 Hz :0
0 deg, 2.00, 1
sw5049 / Line 3101 \ 4D11_2009 4D
Trace #
2445 2450 2455 2460 2465 2470 2475
Hekkingen Fm. HF*
Fuglen fm
Stoe Fm. 2 HFB Top
Stoe Fm. 1 HFB Top
Nordmela Fm. 2 HF*
Tubaaen Fm. 4.2 H*
Tubaaen Fm. 3 HF*
Tubaaen Fm. 2 HF*
Tubaaen Fm. 1 HF*
Fruholmen Fm. HF*

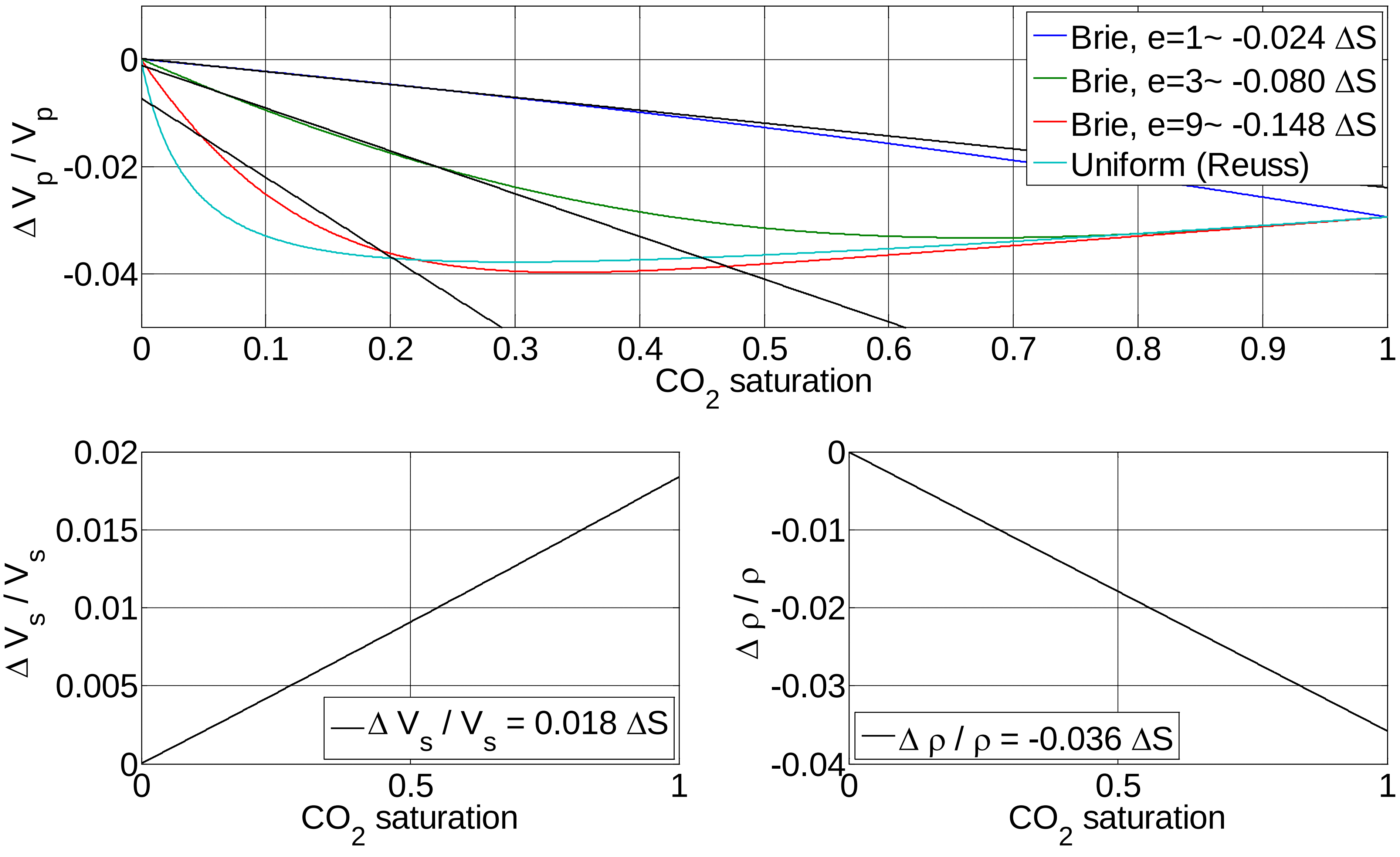
Calibrated reflectivity Fuglen fm.



Calibrated reflectivity Top Fruholmen fm.

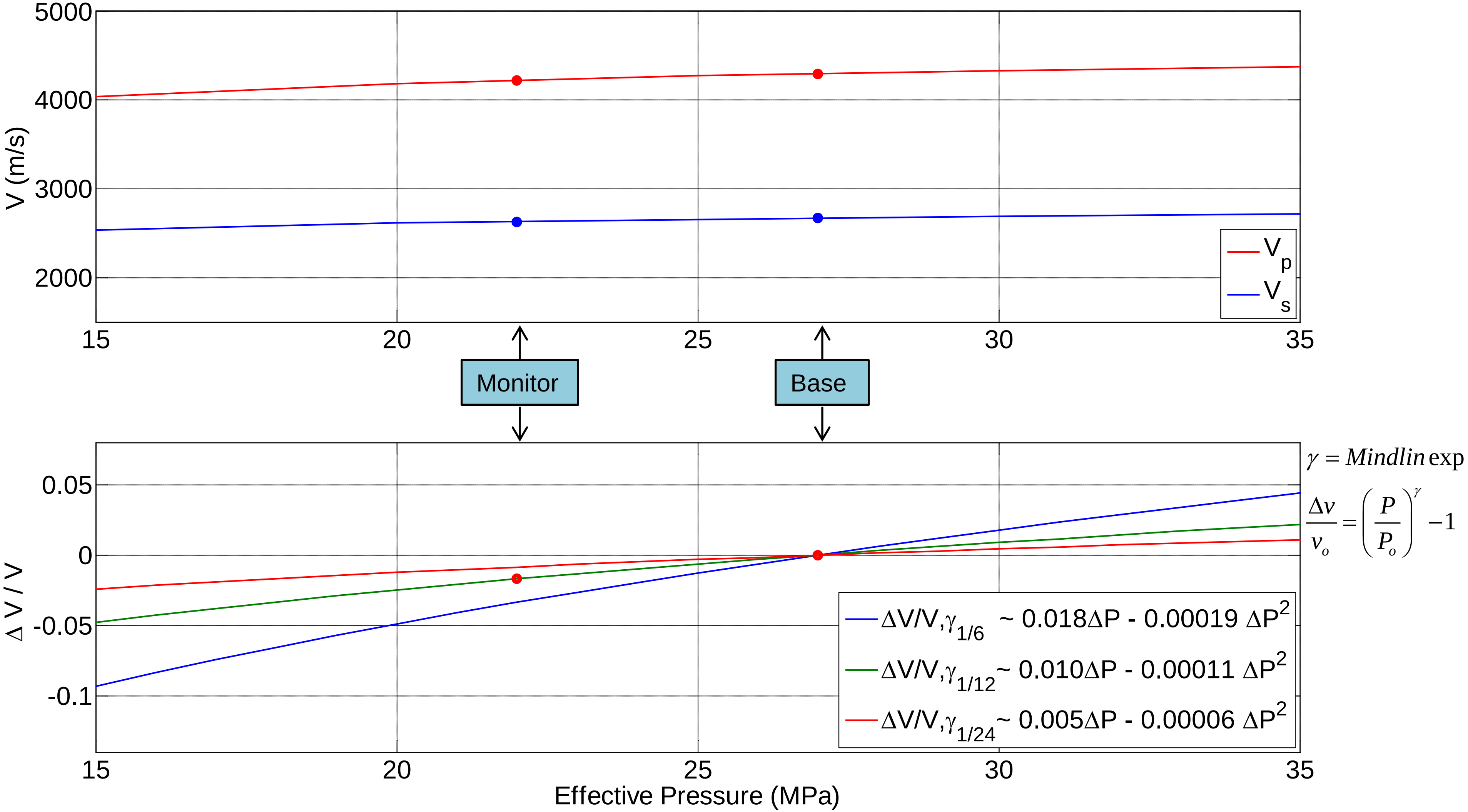


CO_2 saturation change



Pressure change

Average of three dry cores from the Tubåen formation



Pressure and saturation cubes

Based on near and far offset stacks

$$\Delta P_{Brie3,\gamma 1/12} = 71\Delta G - 49\Delta R_o$$

$$\Delta S_{Brie3,\gamma 1/12} = 6\Delta G + 13\Delta R_o$$

Consistency check: Use 4D timeshifts

$$\Delta T_{Brie3,\gamma 1/12} = -22\Delta G + 40\Delta R_o$$

ΔS denote change in oil saturation (CO_2 sat. 0-1)
ΔP denote change in net pressure (MPa)
ΔT denote change in time (ms)

Testing various rock physics parameters

Linearly dependency →

ΔS	Degree of patchiness	$Brie, e=1$	$Brie, e=3$	$Brie, e=9$
Variation in Mindlin exponent	$\gamma = 1/6$	$13\Delta G + 28\Delta R_o$	$6\Delta G + 13\Delta R_o$	$4\Delta G + 8\Delta R_o$
	$\gamma = 1/12$	$13\Delta G + 28\Delta R_o$	$6\Delta G + 13\Delta R_o$	$4\Delta G + 8\Delta R_o$
	$\gamma = 1/24$	$13\Delta G + 28\Delta R_o$	$6\Delta G + 13\Delta R_o$	$4\Delta G + 8\Delta R_o$

ΔP	Degree of patchiness	$Brie, e=1$	$Brie, e=3$	$Brie, e=9$
Variation in Mindlin exponent	$\gamma = 1/6$	$44\Delta G - 18\Delta R_o$	$40\Delta G - 27\Delta R_o$	$38\Delta G - 31\Delta R_o$
	$\gamma = 1/12$	$80\Delta G - 32\Delta R_o$	$71\Delta G - 49\Delta R_o$	$68\Delta G - 55\Delta R_o$
	$\gamma = 1/24$	$149\Delta G - 60\Delta R_o$	$134\Delta G - 92\Delta R_o$	$128\Delta G - 104\Delta R_o$

↓ Linearly dependency

=> Changing rock physics leads to scaling of the data, practically no relative changes

Estimate of Mindlin exponent and saturation

Using 3 measurements ($\Delta R_{o,}\Delta G,\Delta T$):

$$-2\Delta R_0 = k_\alpha \Delta S + k_\rho \Delta S + l_\alpha \Delta P$$

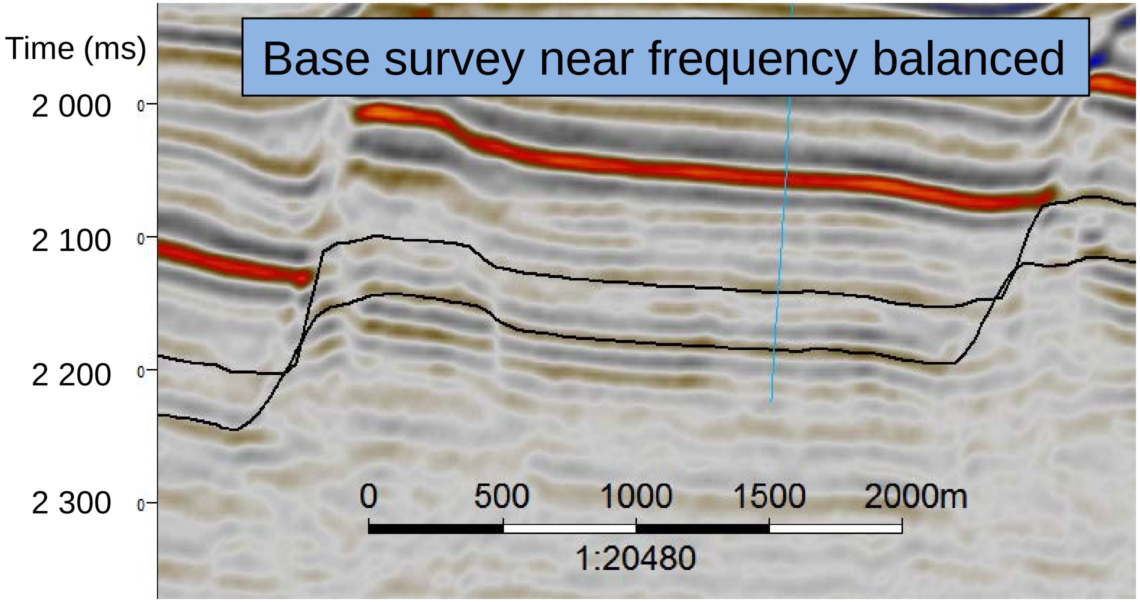
$$-2\Delta G = k_\alpha \Delta S + l_\alpha \Delta P - 8\frac{\beta^2}{\alpha^2} l_\alpha \Delta P$$

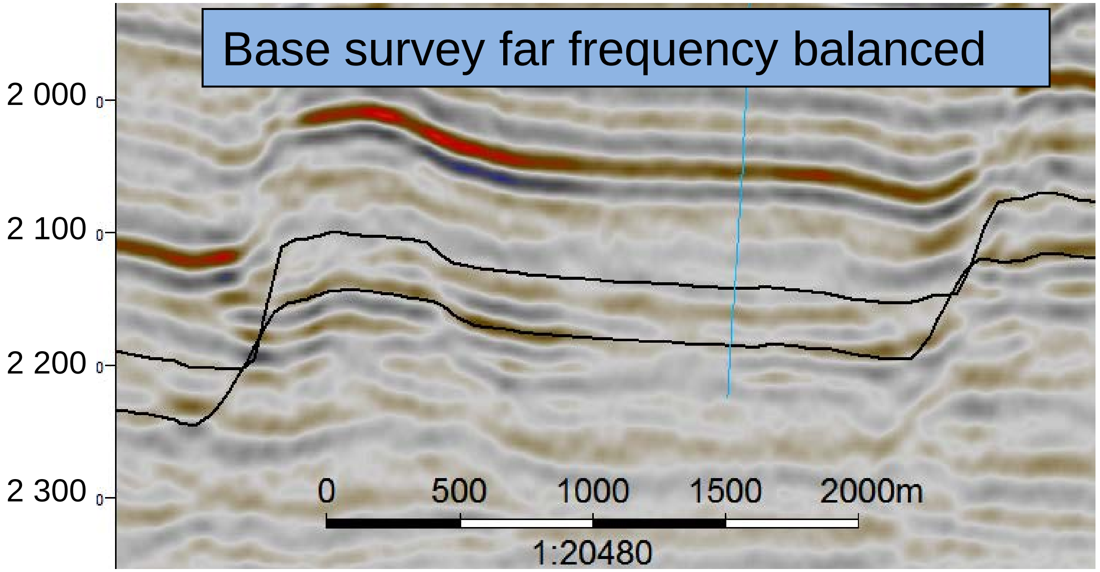
$$\frac{\Delta T}{T} = -k_\alpha \Delta S - l_\alpha \Delta P$$

$$l_{\alpha,well} = -\frac{\alpha^2}{8\beta^2 \Delta P}\left[\frac{\Delta T}{T} - 2\Delta G\right] = 0.012 MPa^{-1} \Rightarrow \gamma \approx \frac{1}{10}$$

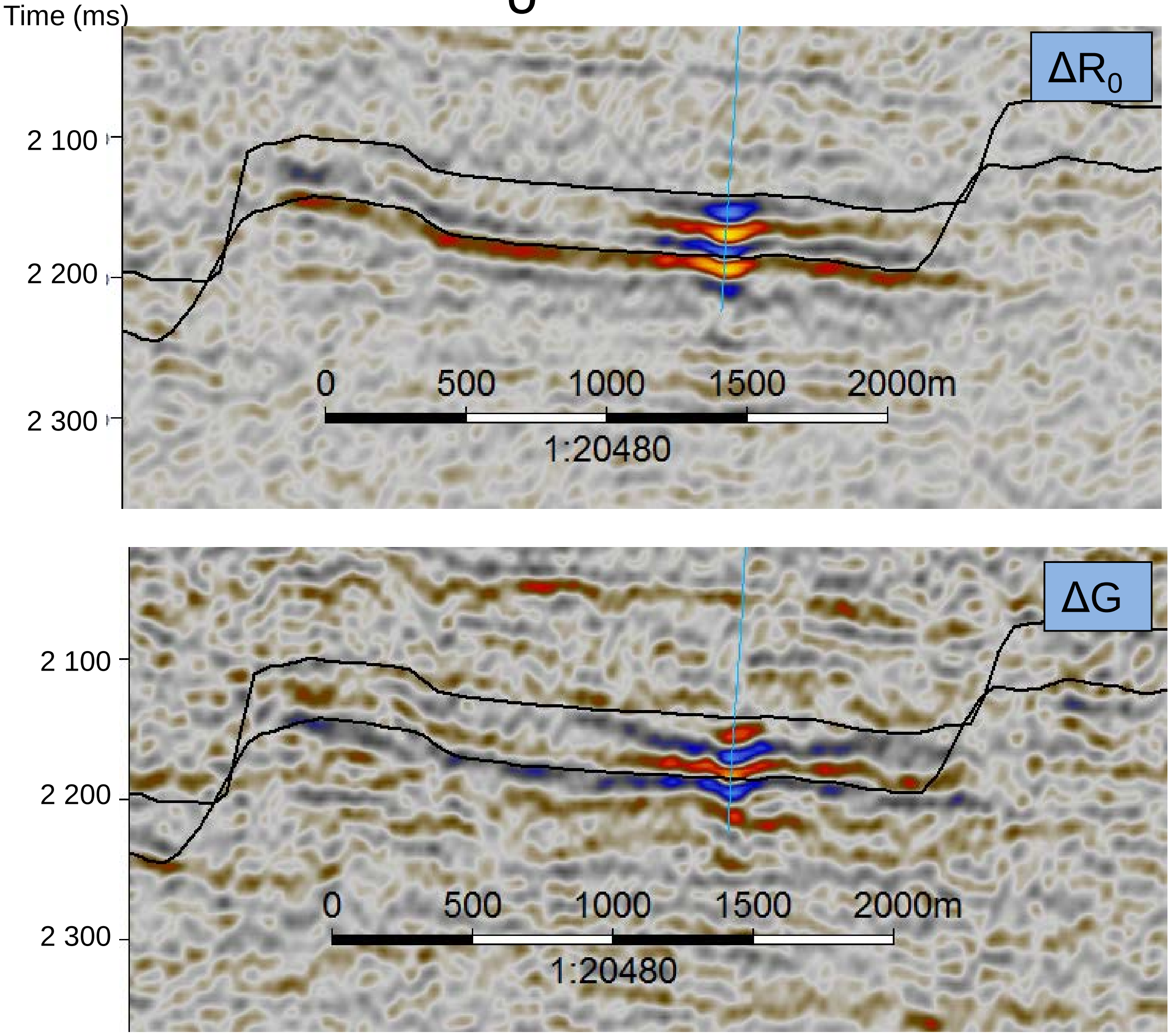
$$\Delta S_{well} = \frac{1}{k_\rho}\left[\frac{\Delta T}{T} - 2\Delta R_0\right] = 0.5$$

Near and far offset stacks

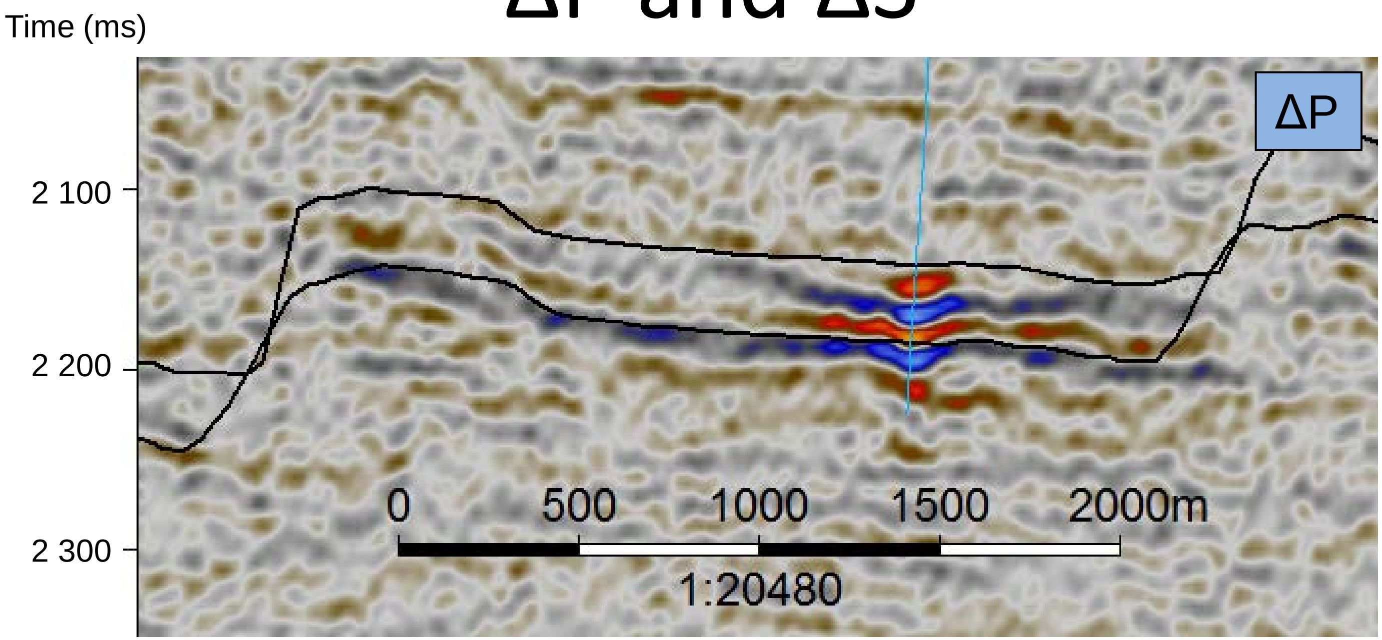




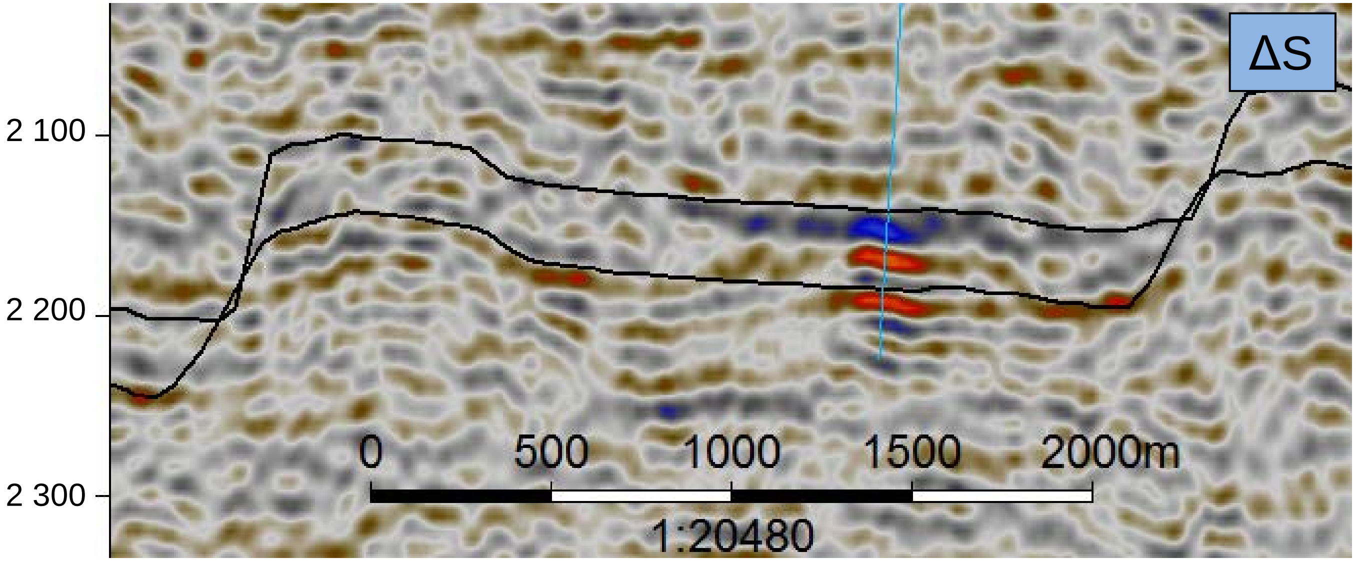
ΔR_o and ΔG



ΔP and ΔS



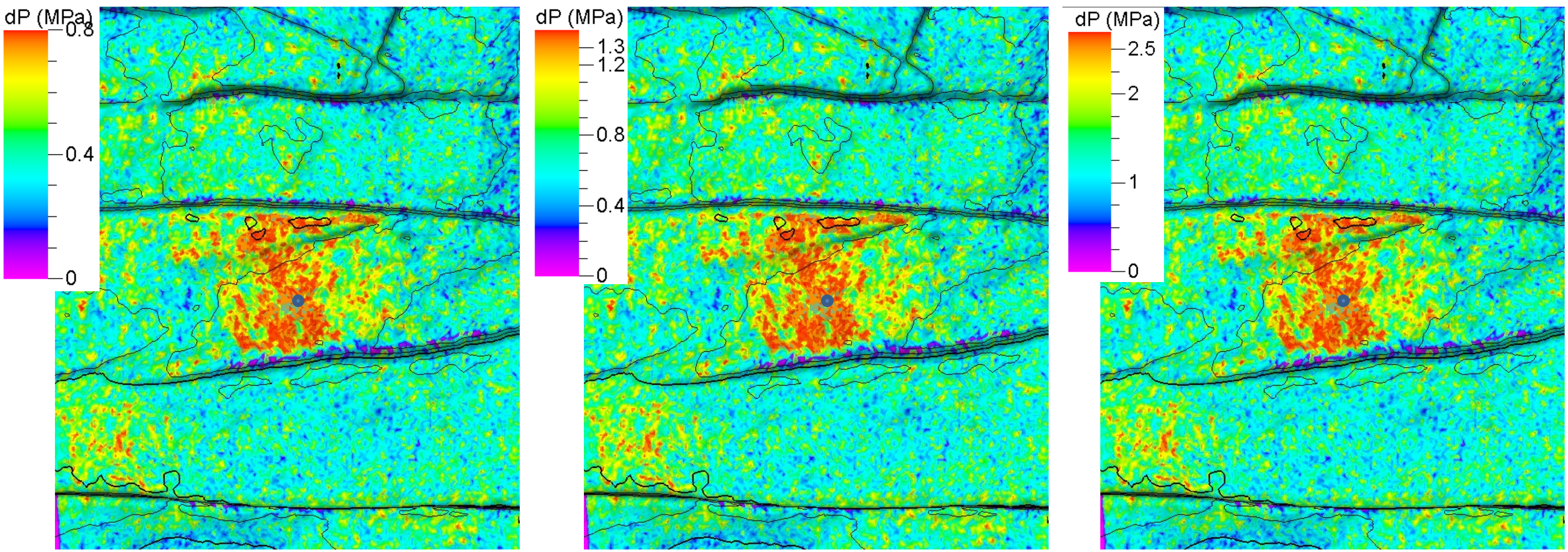
Brie e=3,
Mindlin
exponent =1/12



RMS amplitude ΔP reservoir zone

Mindlin exponent

γ= 1/6 γ= 1/12 γ= 1/24

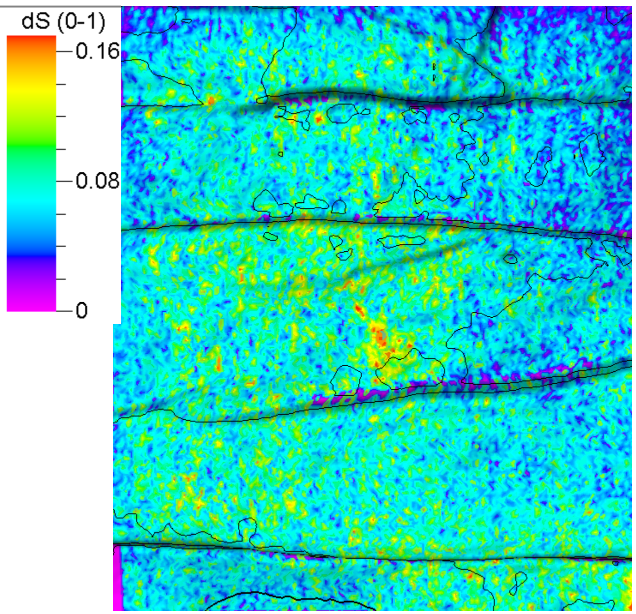


1 000 m

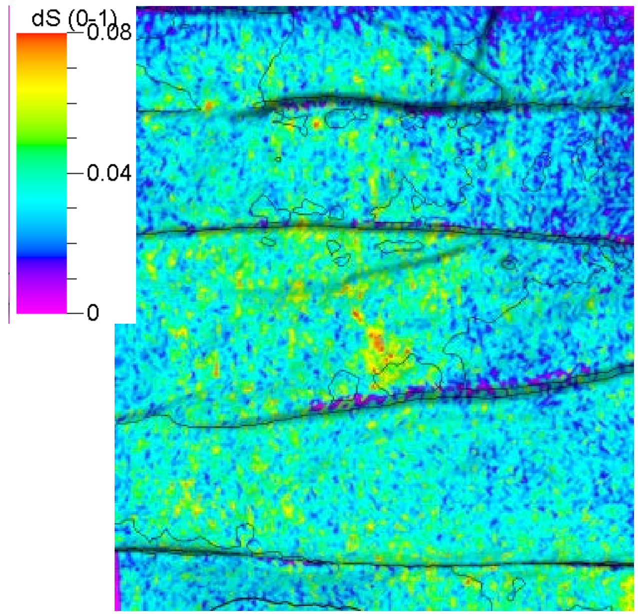
Brie e=3

RMS amplitude ΔS reservoir zone

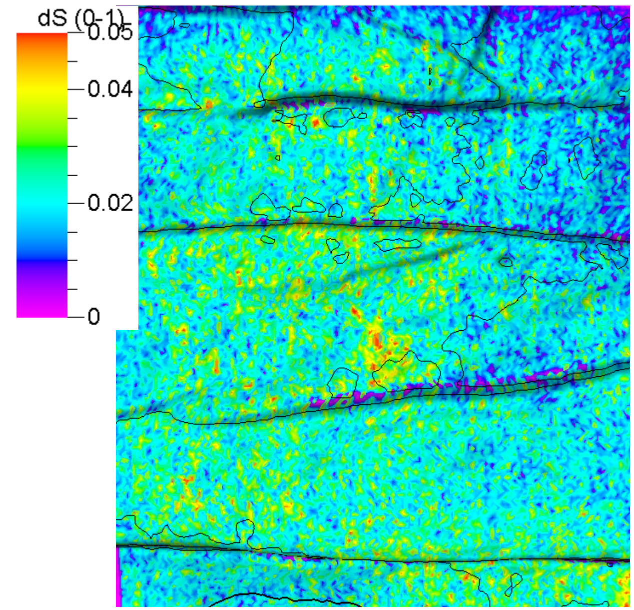
Brie e=1



Brie e=3



Brie e=9

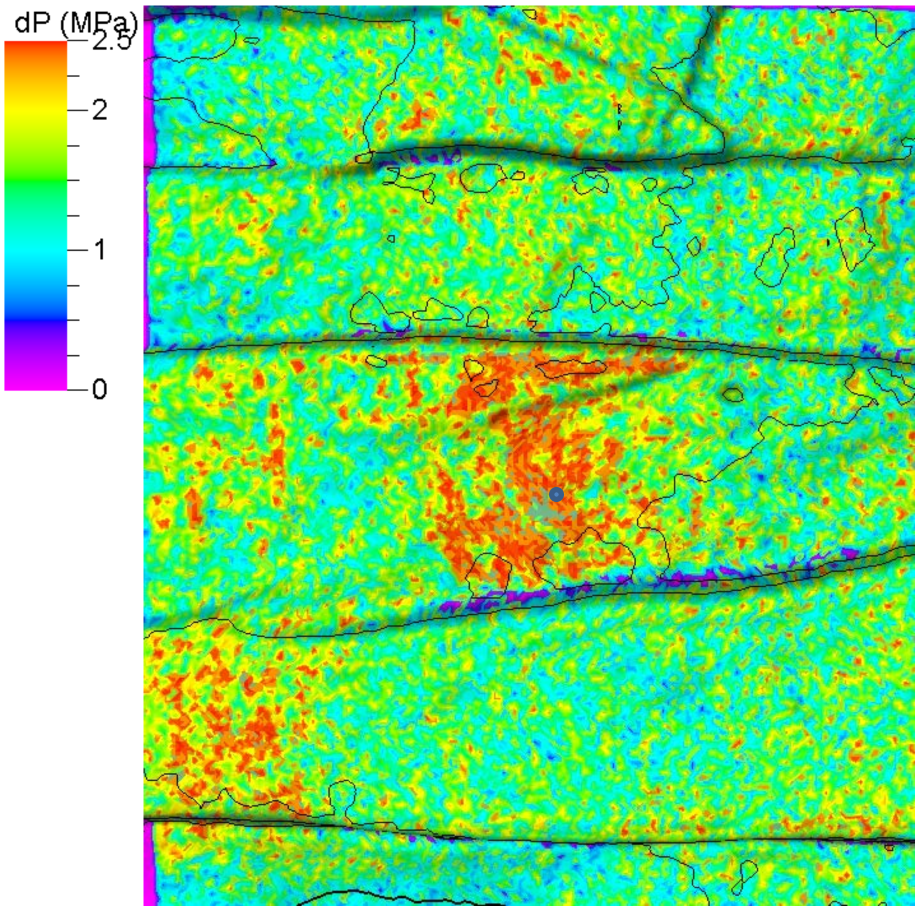


1 000 m

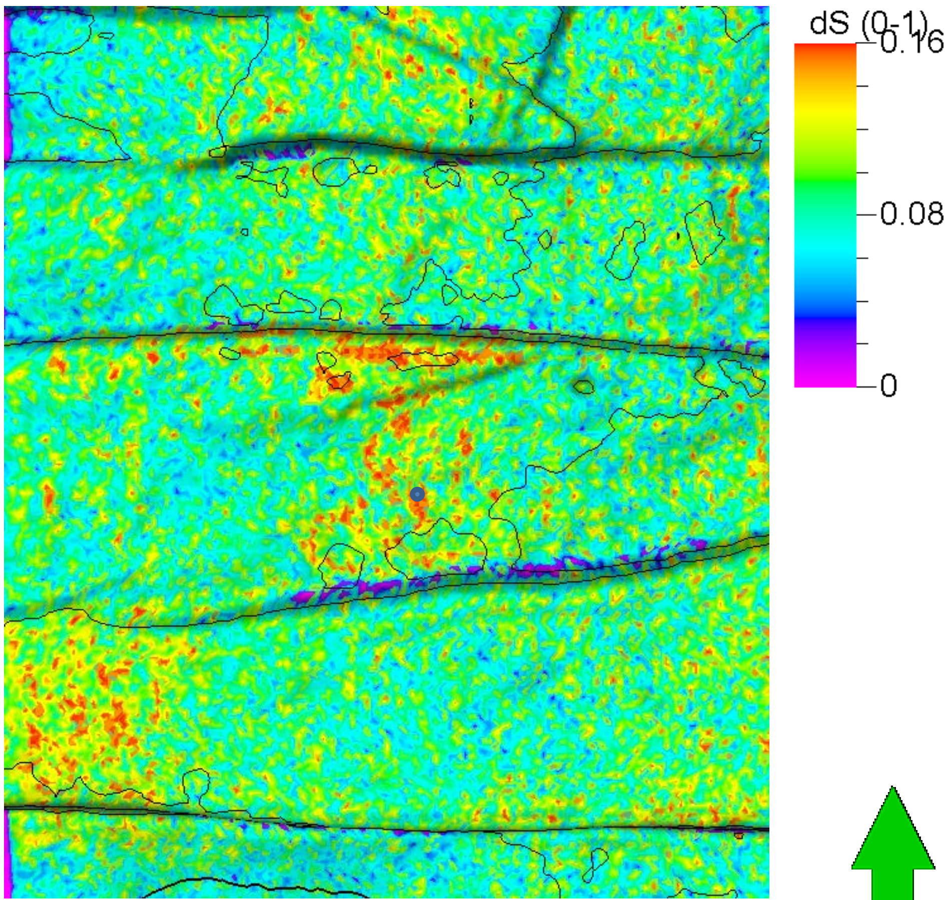
Mindlin exponent=1/12

RMS amplitude near-mid stacks

ΔP



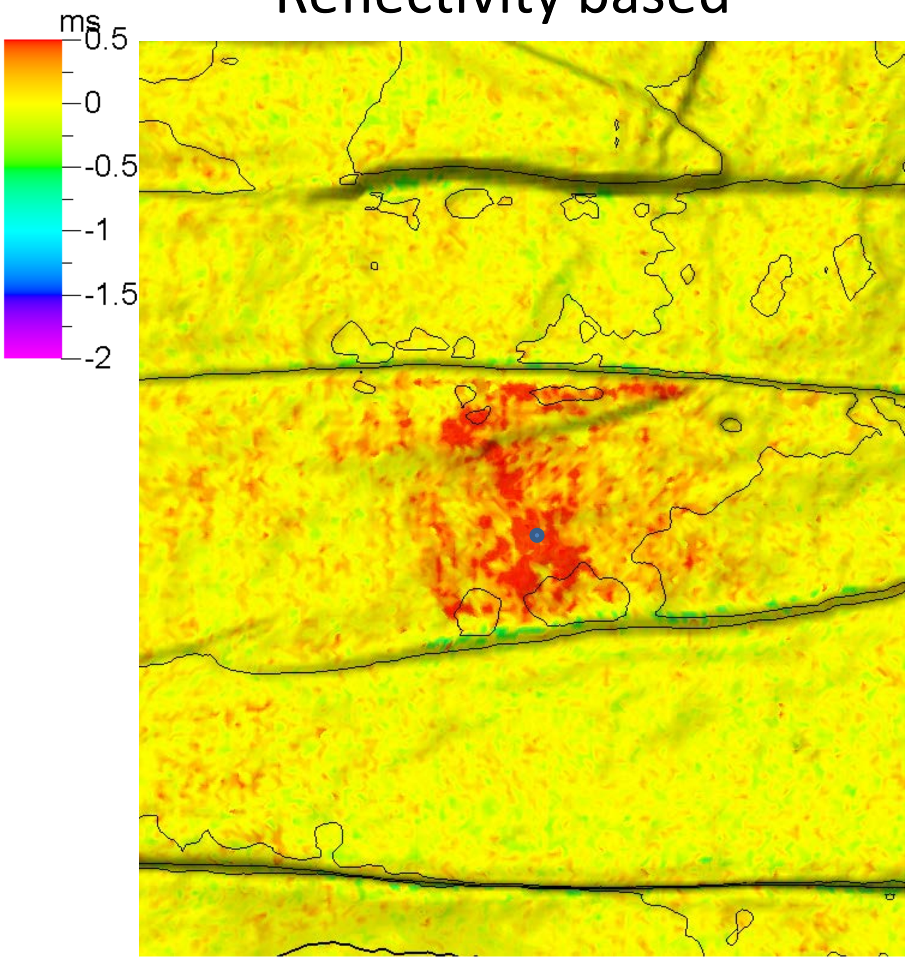
ΔS



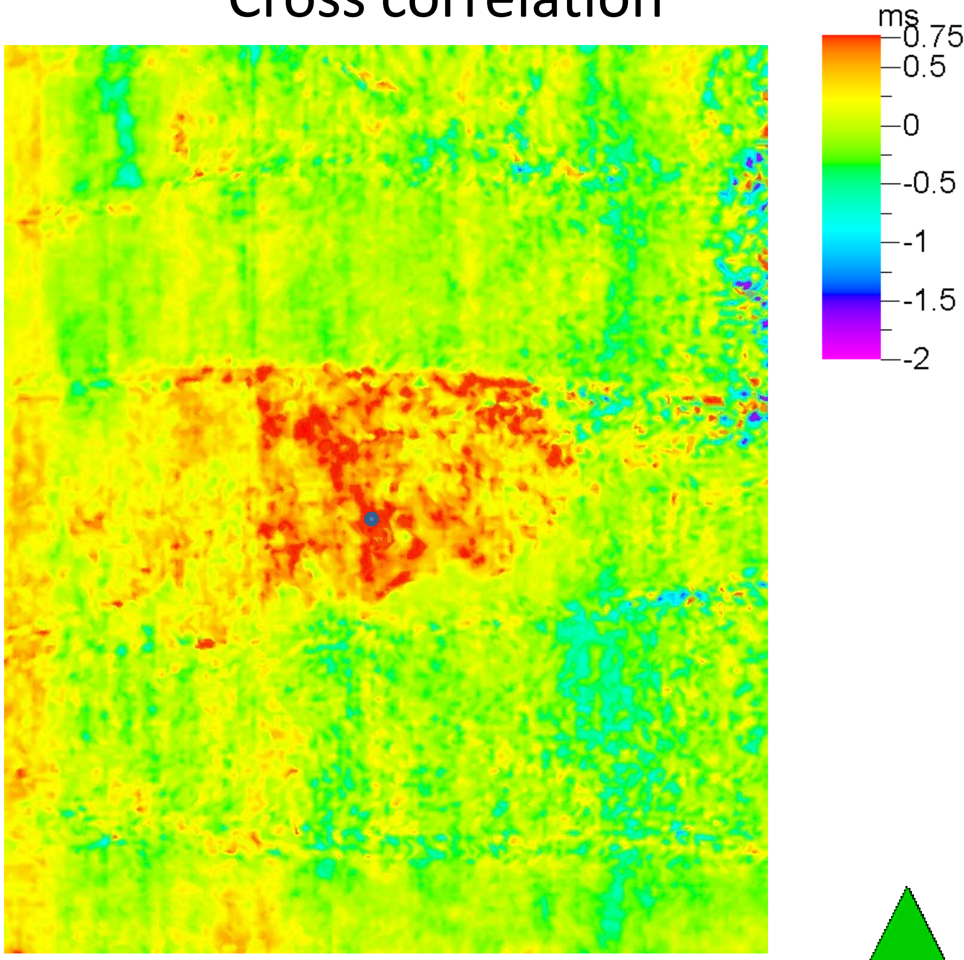
Brie e=3,
Mindlin exponent =1/12

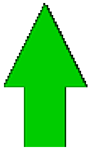
Timeshift

Reflectivity based



Cross correlation





Conclusions

- Pressure effect dominating 4D signature apart from close to well
- Fluid effect in near well area
- ΔP not influenced by degree of patchiness
- ΔS not influenced by variation in Mindlin exponent
- Good correlation between observed timeshift and estimated from pressure and saturation cubes
- Traveltime information used to determine Mindlin exponent and CO_2 saturation close to well

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