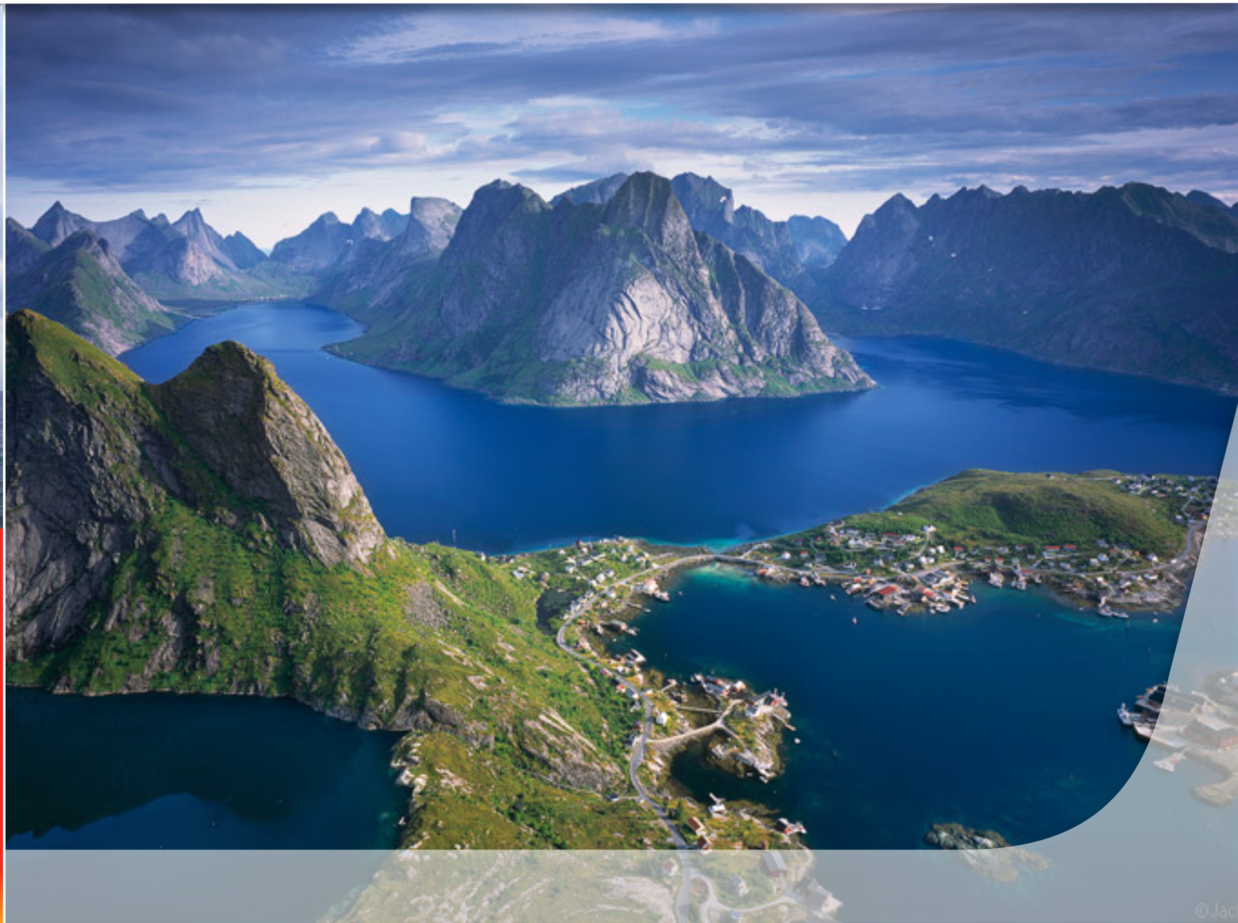
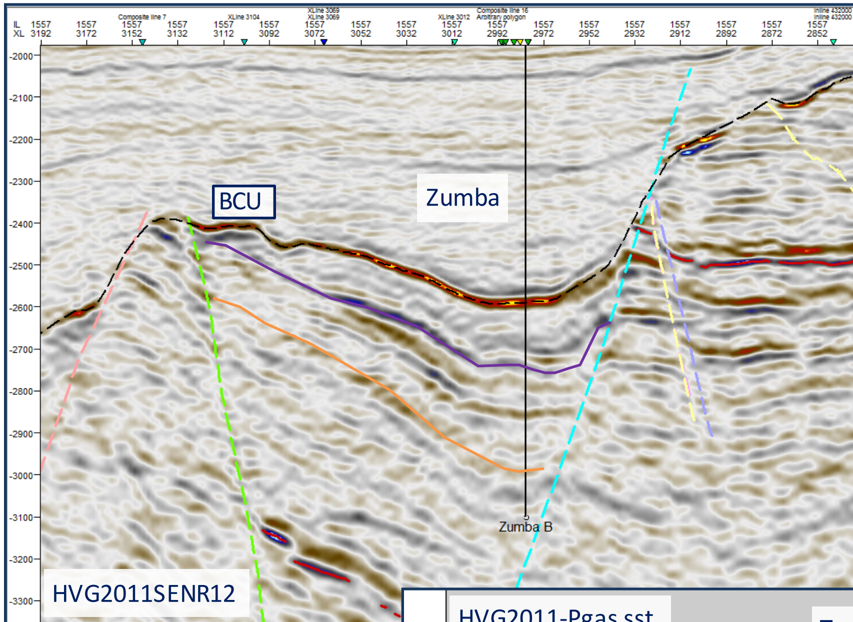
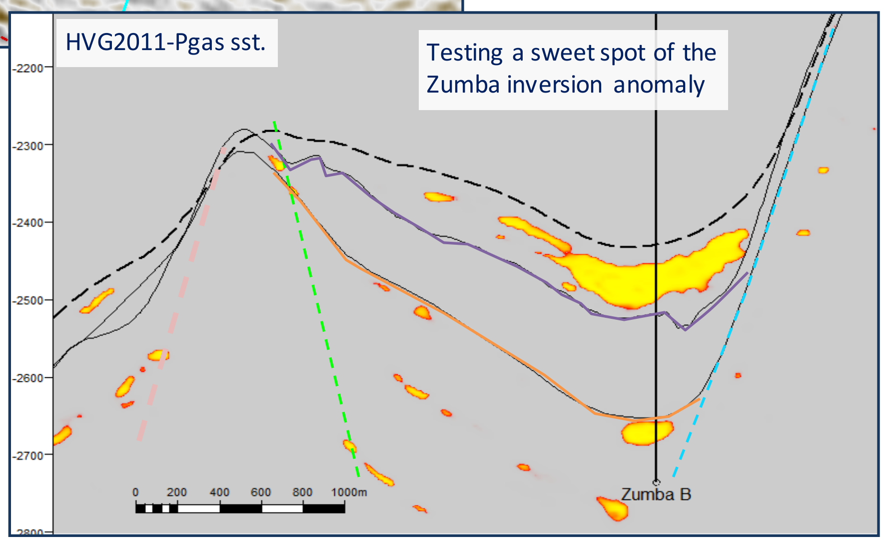
AVO inversion in exploration – Key learnings from a Norwegian Sea Prospect

Per Avseth, Tullow Oil Norge and NTNU (ROSE-Consortium, April 25-26, 2016)

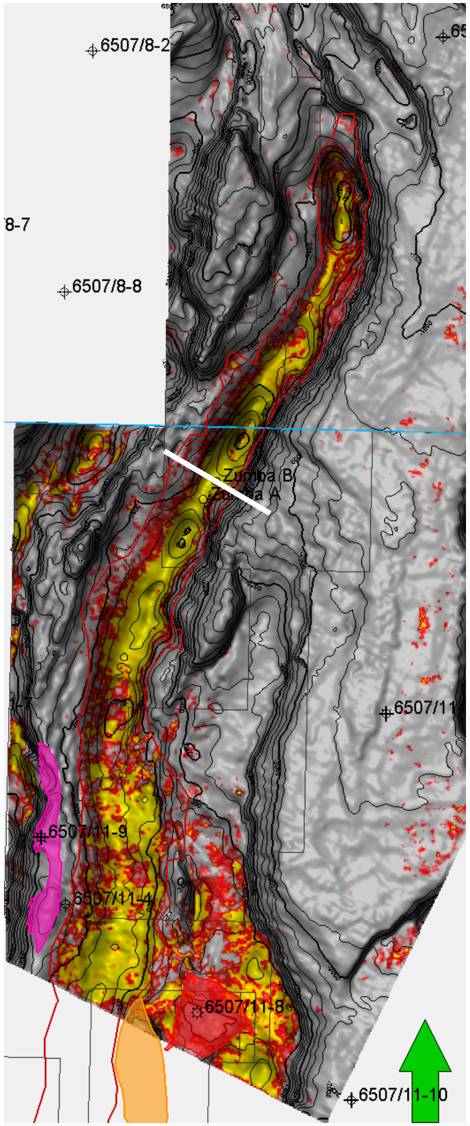


Zumba drill location and gas probability from AVO inversion



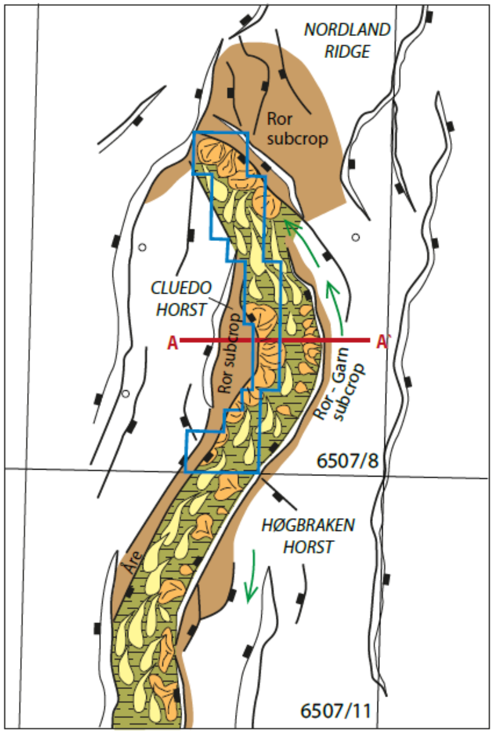


- BCU
- Intra Melke Unc
- Top Garn/Fangst
- Top Ror
- Intra Åre coal marker



A high-risk/high-reward play model that had to be drilled!

Rogn Fm. dep. model



P_source=1.0

P_mig=0.7

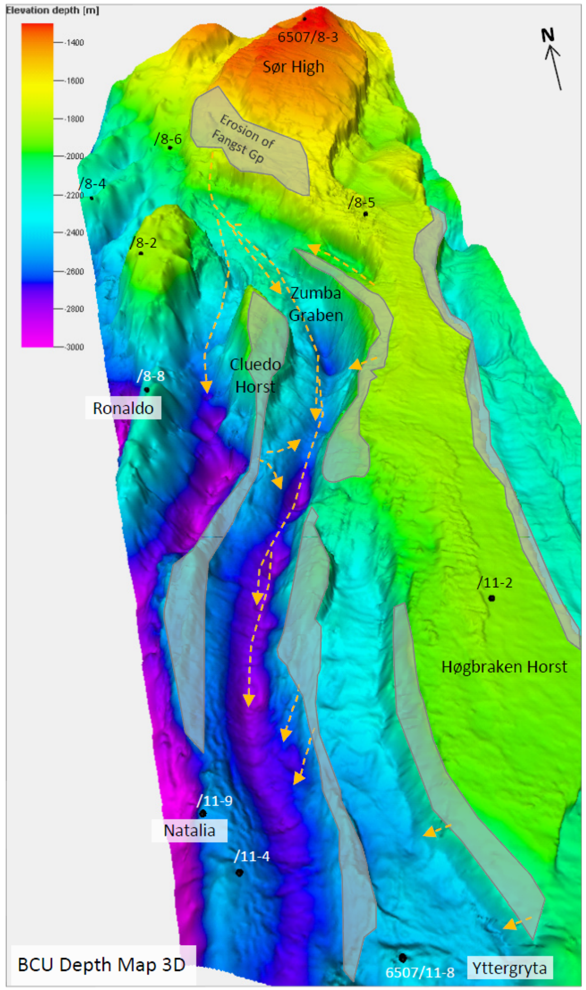
P_res=0.7

P_closure=0.9

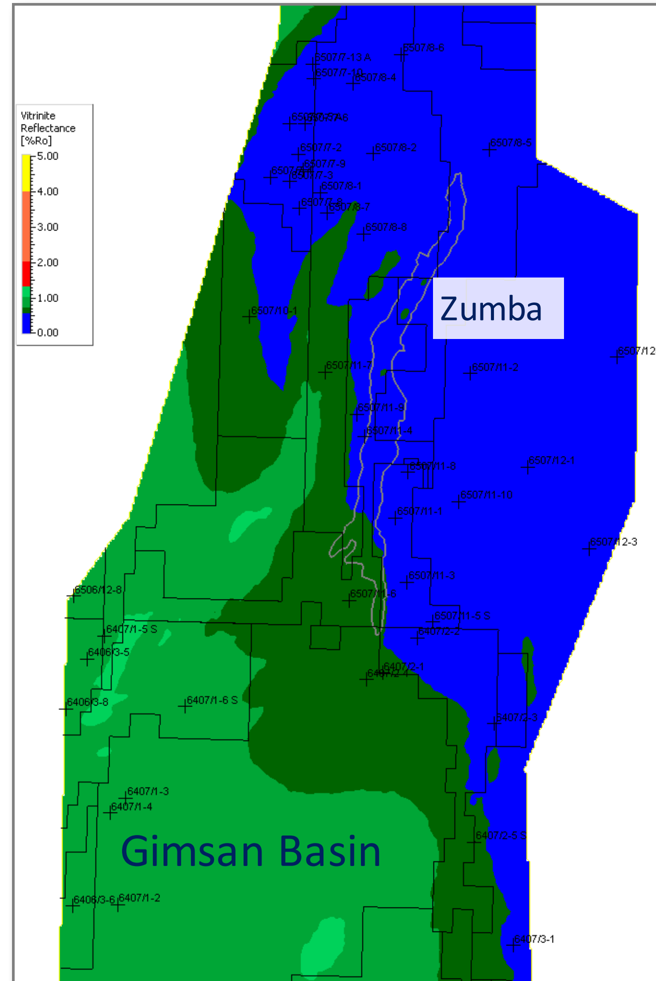
P_contain=0.6

P_discovery=0.265

Fangst Gp. erosion

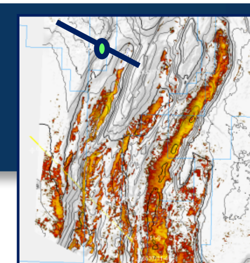


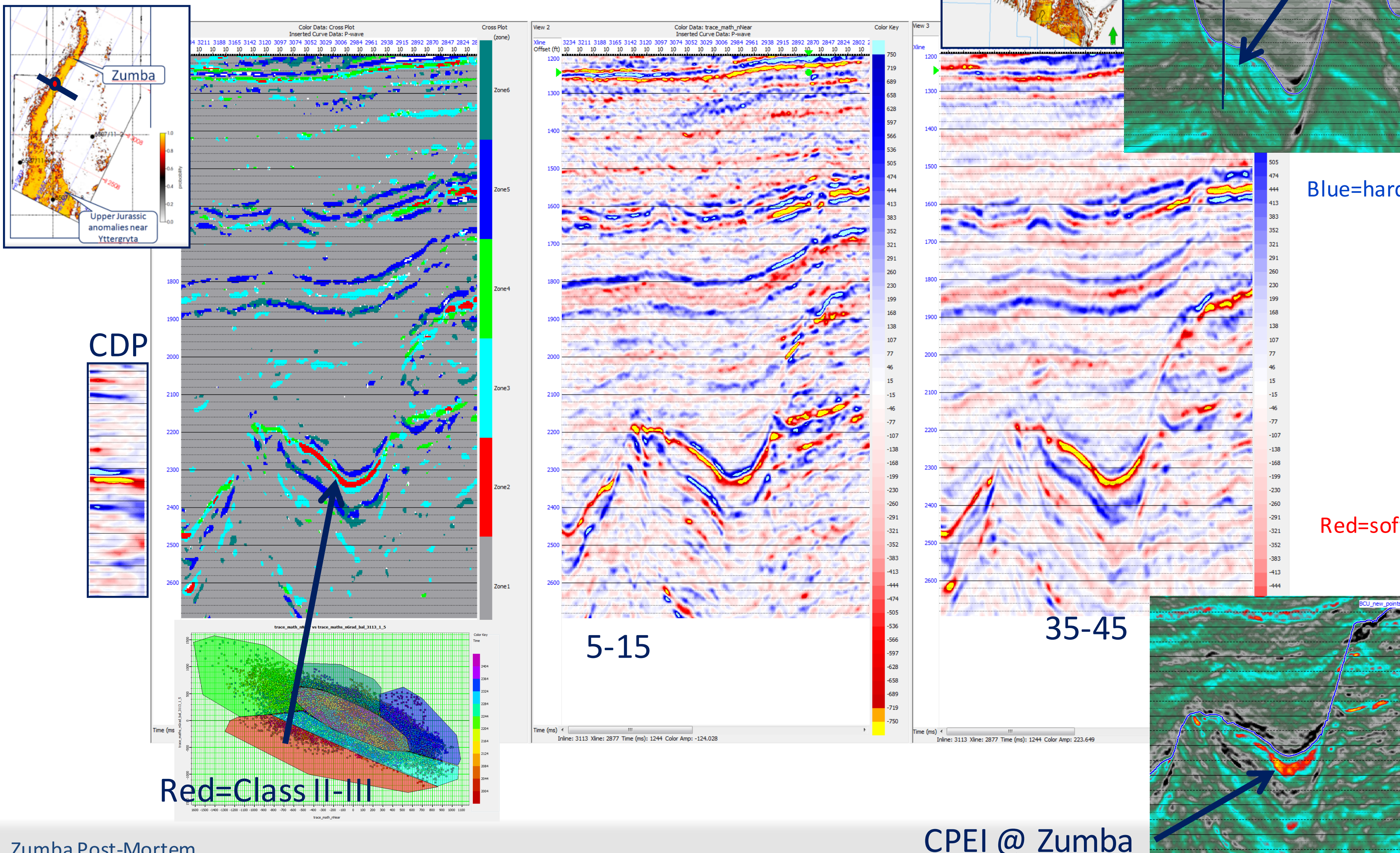
Spekk Fm maturation map



MMRA	P90	P50	mean	P10
mmboe PL591	20.9	73.2	101.3	226.9

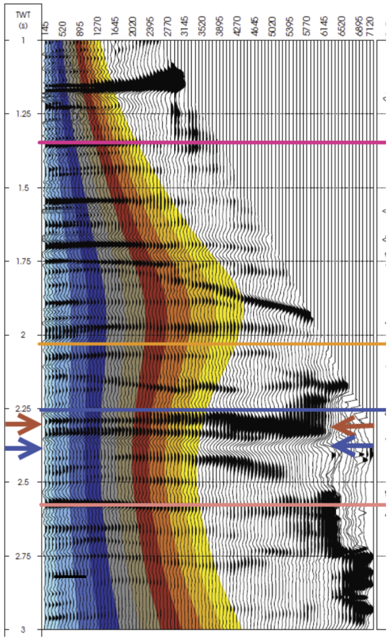
AVO anomaly @ Zumba (Broadband PSTM data)





AVO is controlled by contrasts in AI and Vp/Vs (assuming isotropic, elastic media)

Offset gather



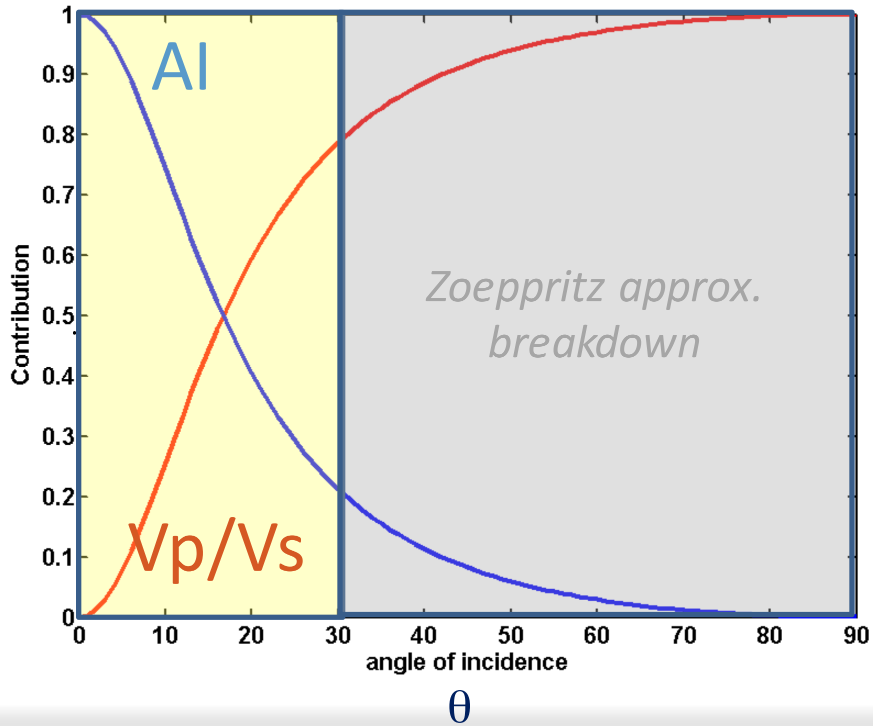
Verm and Hilterman approx:

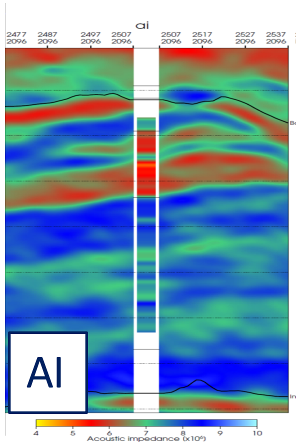
$$R(\theta)=NI\cos^2(\theta)+PR\sin^2(\theta)$$

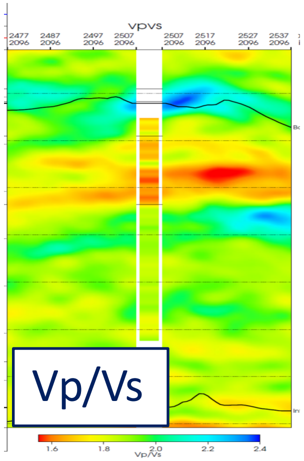
f(ΔAI / $\overline{AI}$)

f(Δ(Vp/Vs) / $\overline{(Vp/Vs)}$)

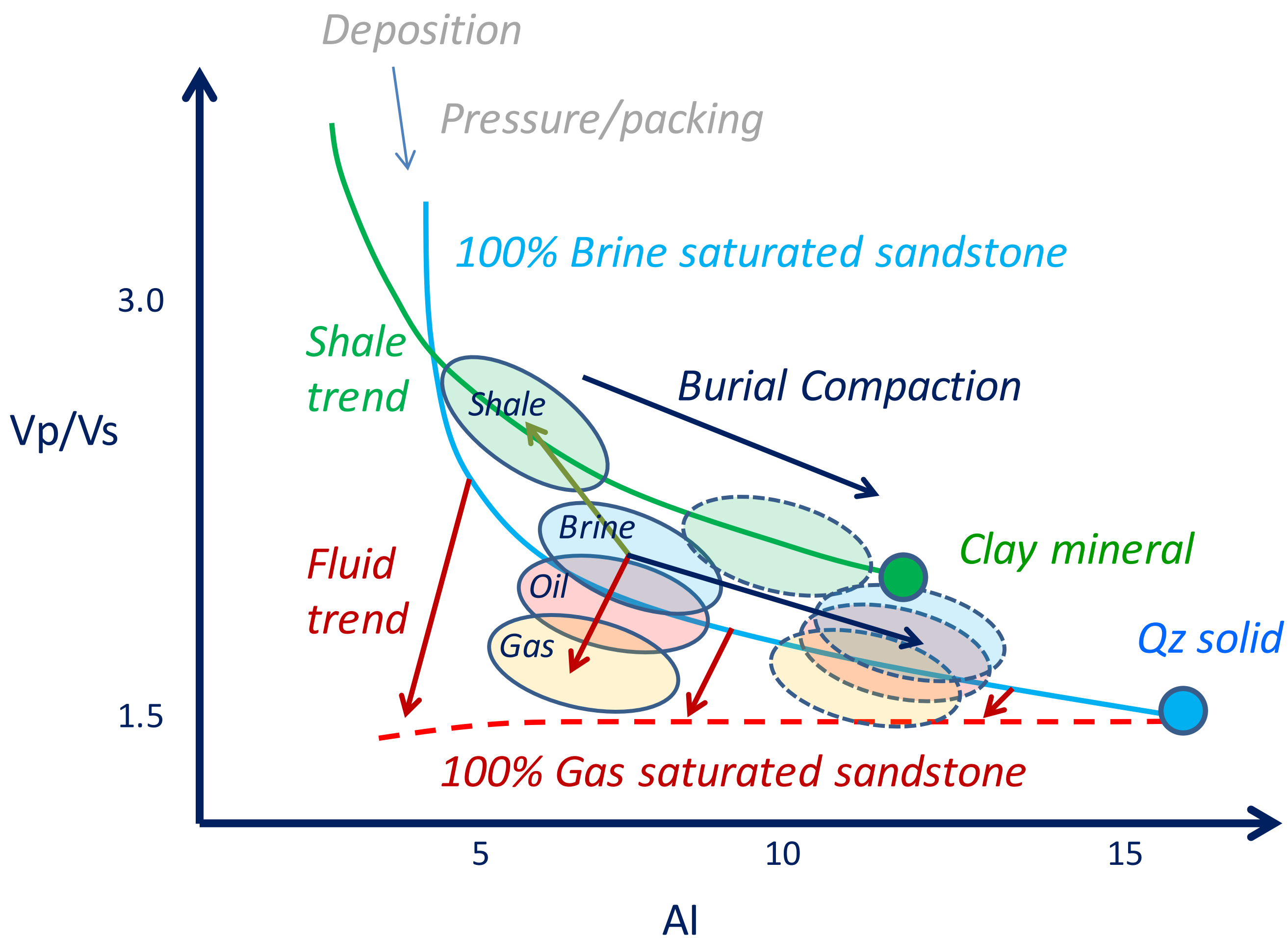
Valid



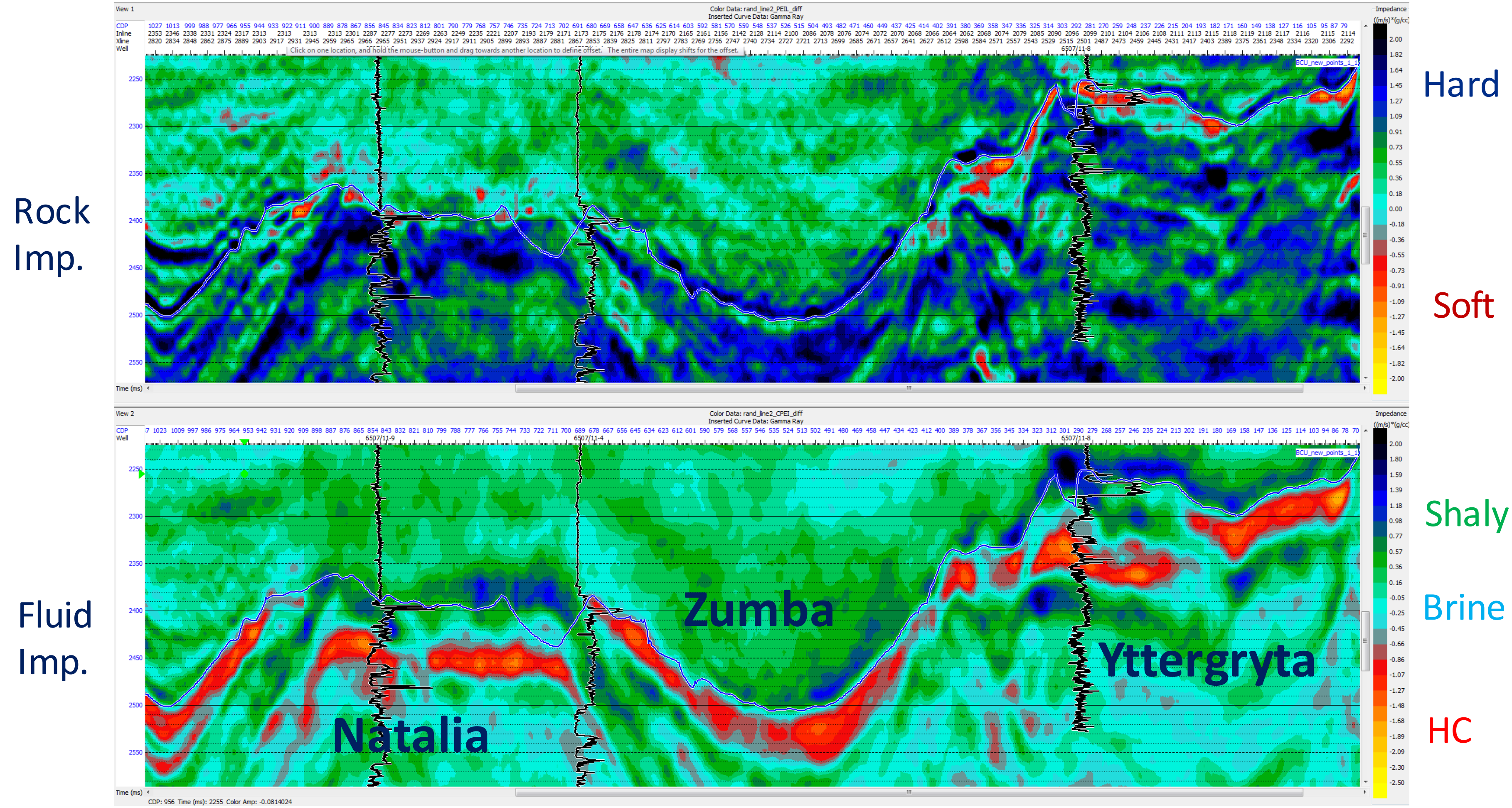




The anatomy of rock physics templates:
The effect of lithology, compaction and fluids.



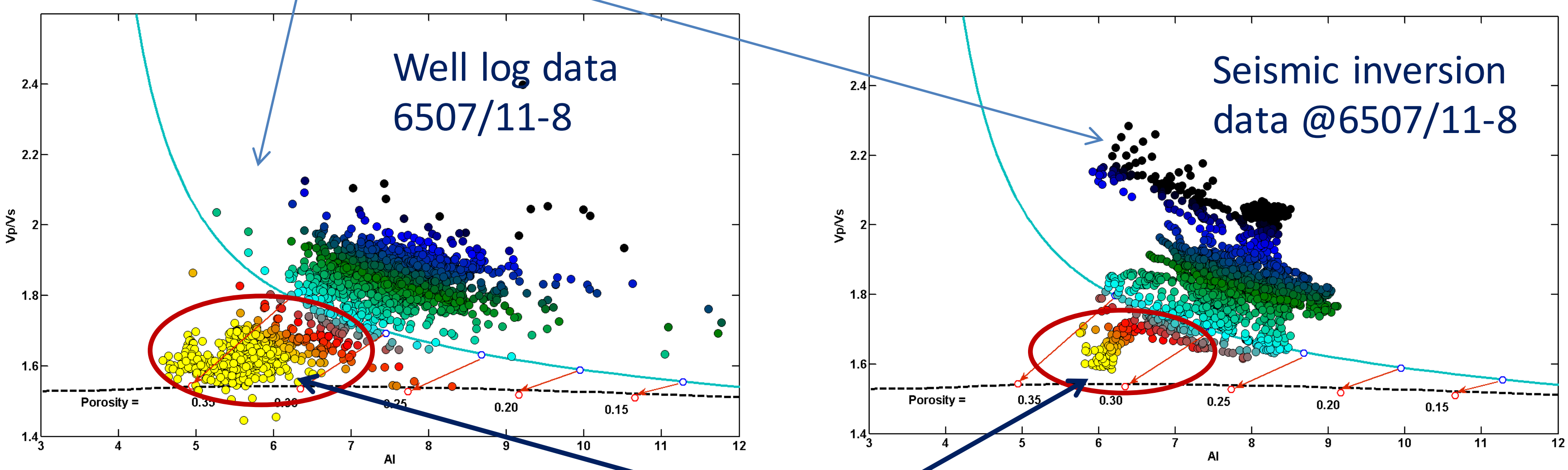
Random line across Yttergryta, Zumba and Natalia
Relative rock impedance (above) and fluid impedance (below)



Rock physics template analysis of well log and seismic inversion data @Yttergryta

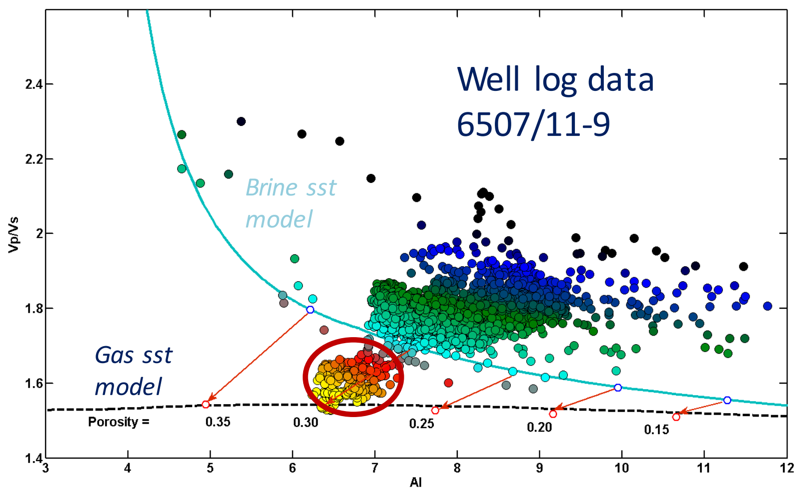
(Note that well log data starts right above Top Reservoir and therefore does not include overburden data, as in seismic inversion data)

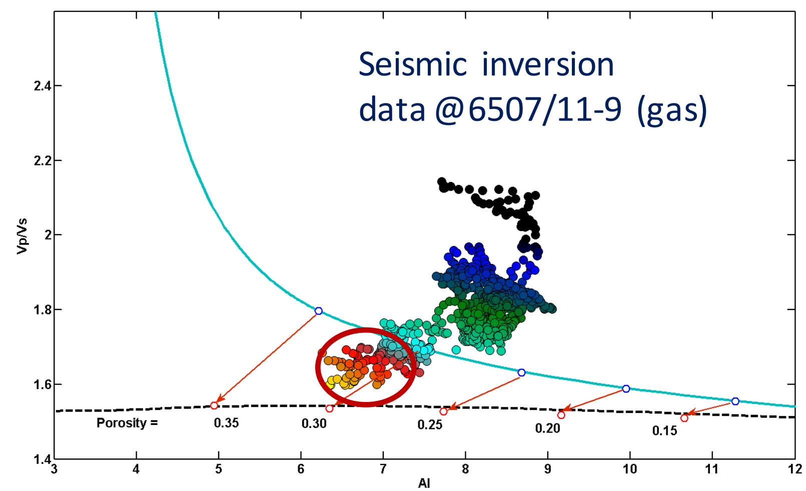
Colour = Fluid impedance



Gas filled Garn and Ile Fm; larger scatter in well log data due to well log resolution

Rock physics template analysis of well log and seismic inversion data @Natalia

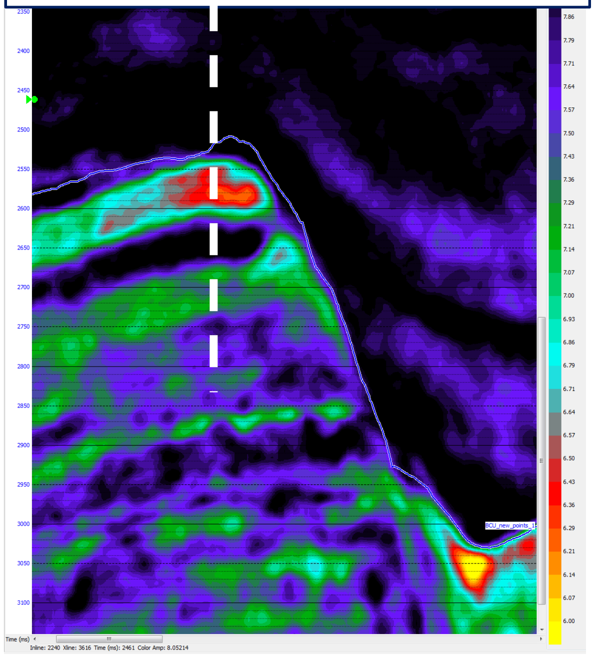


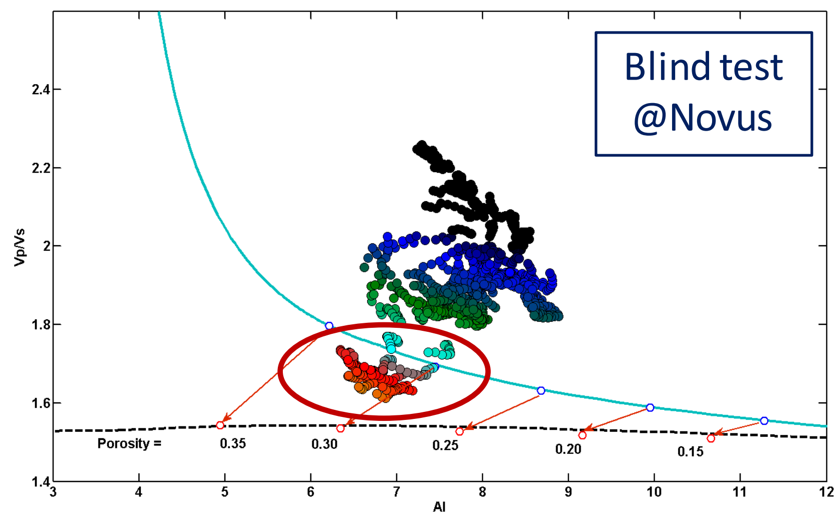


Colour = Fluid impedance

Blind test at Novus gas/oil discovery

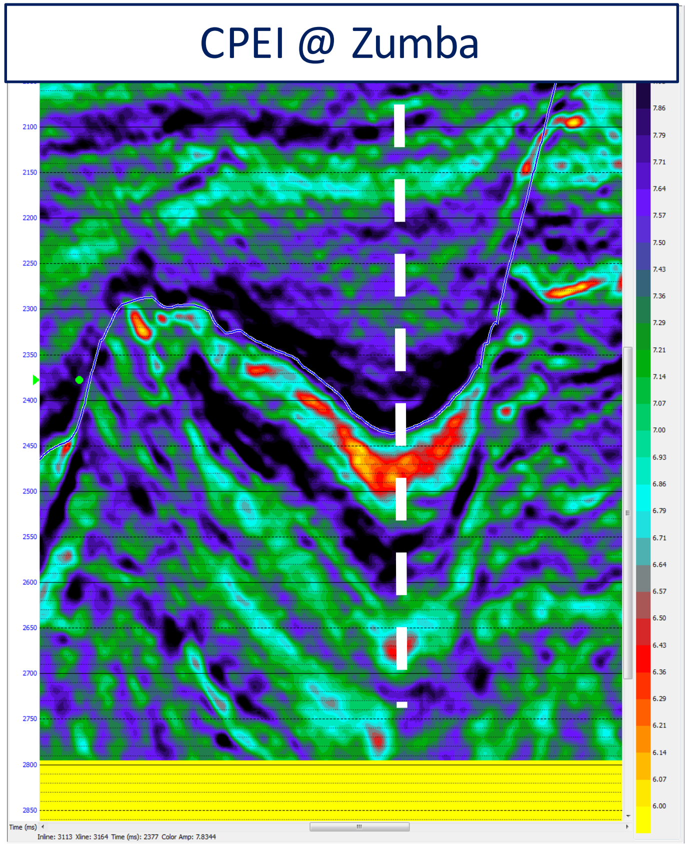
CPEI @ Novus 6507/10-2S

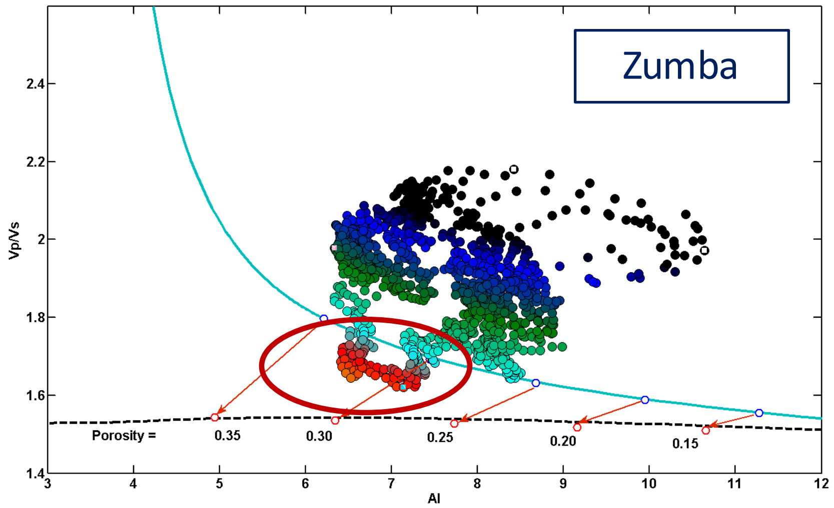




The Novus gas and oil discovery was drilled after inversion and served as a blind test.

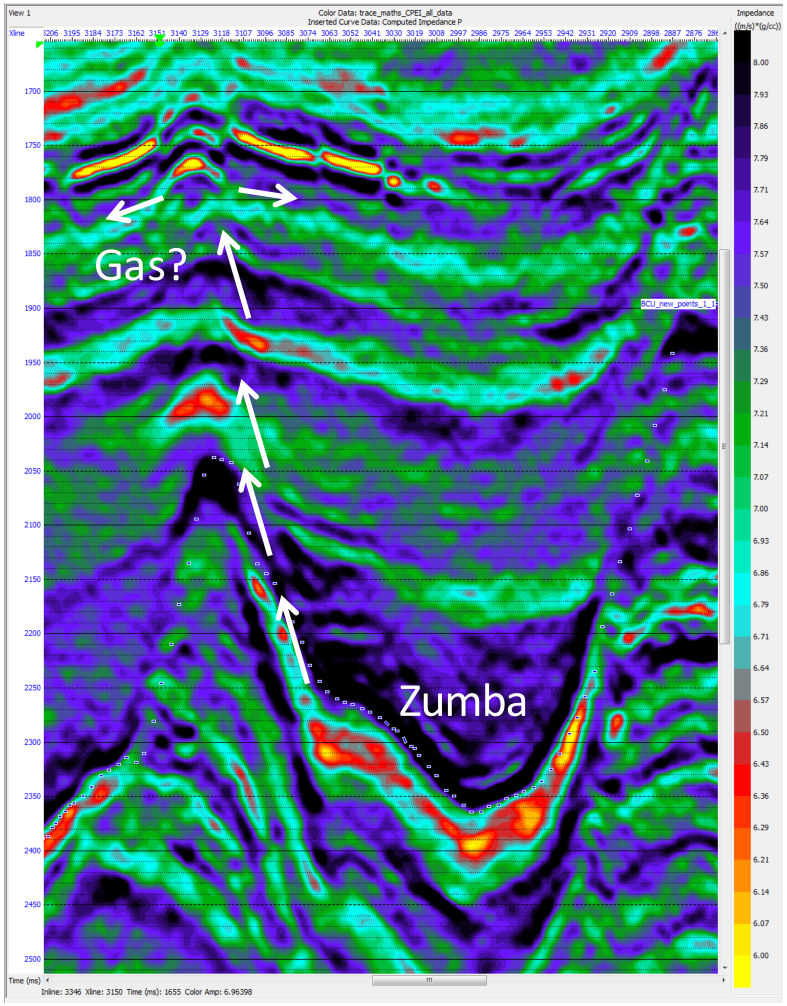
CPEI at Zumba drill location



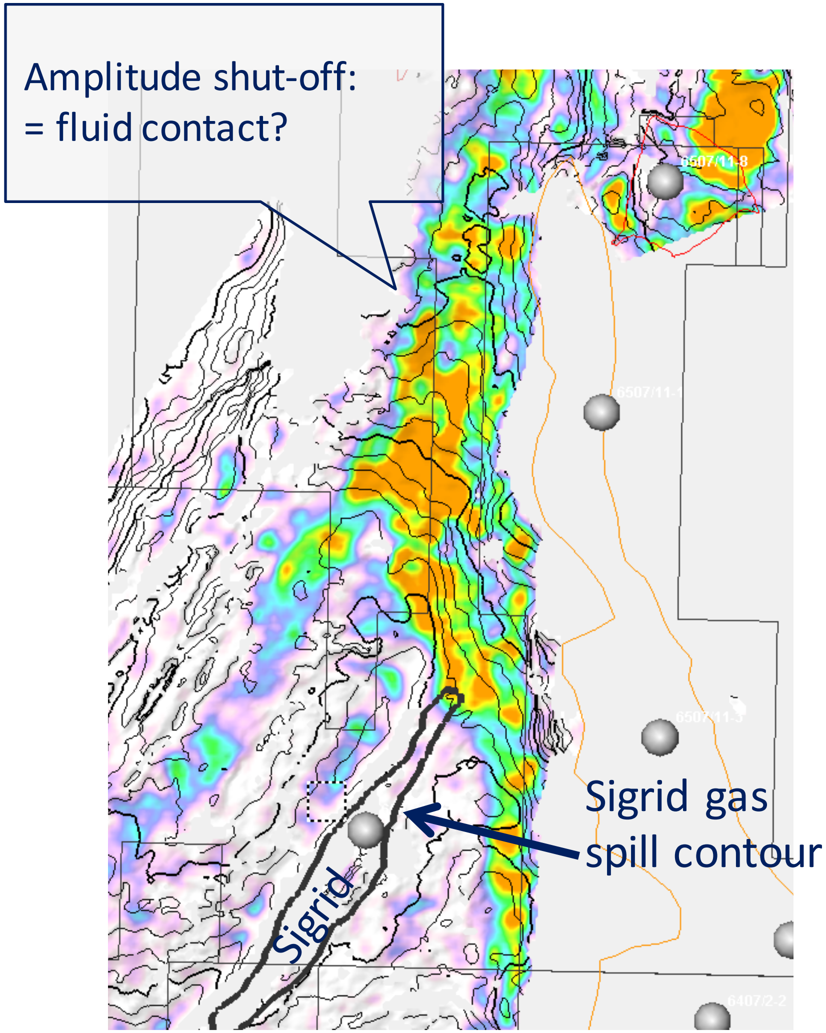


Zumba schows a clear RPT anomaly in the HC area of a template!

Geophysical attributes show leakage patterns and amplitude shut-off conforming with depth contour.



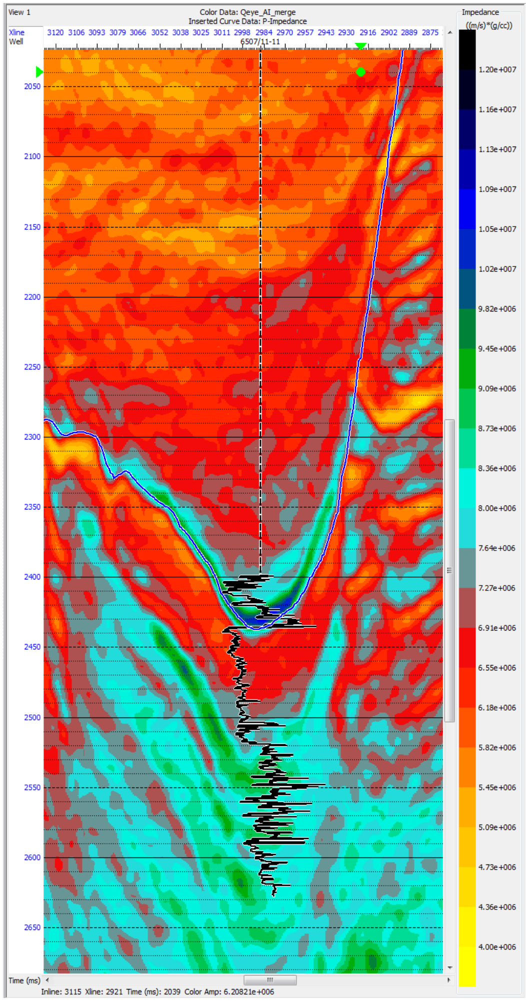
Fluid impedance attribute



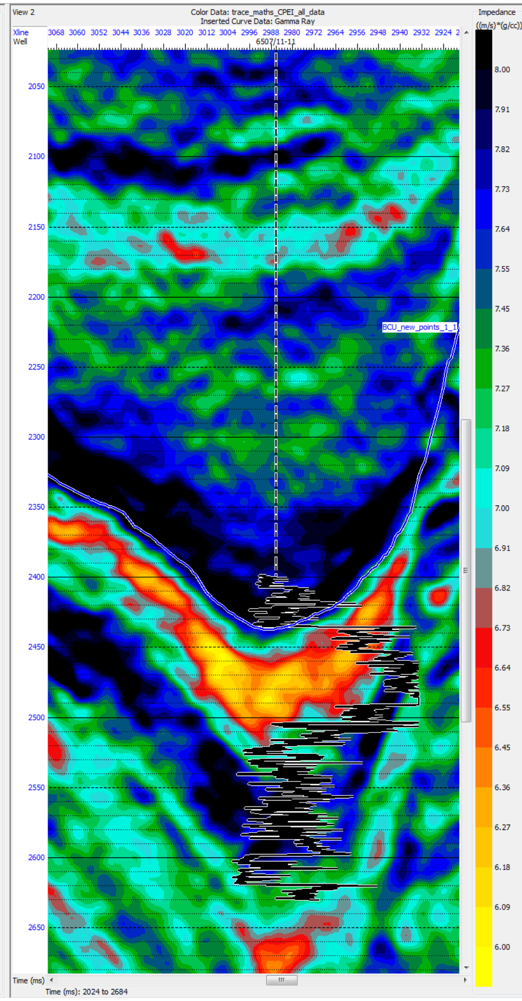
Key pre-drill uncertainties

- Data uncertainties: refractions, multiples, interference, focusing, processing artifacts
- Inversion uncertainties: pre-conditioning, low-f model, poor well control in graben, well log data availability/quality, wavelets, alignment, non-uniqueness
- Rock physics uncertainties: model choice, input parameters, rock physics ambiguities, anisotropy, attenuation, scale effects
- Geological uncertainties: residual gas, heterogeneous rocks, early maturation of Spekk

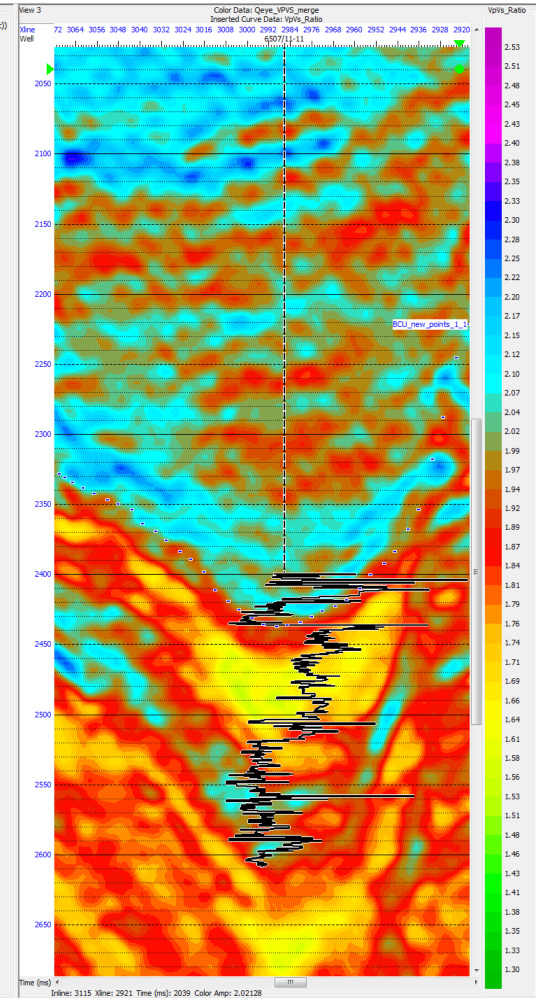
Pre-drill inversion versus post-drill observations



AI

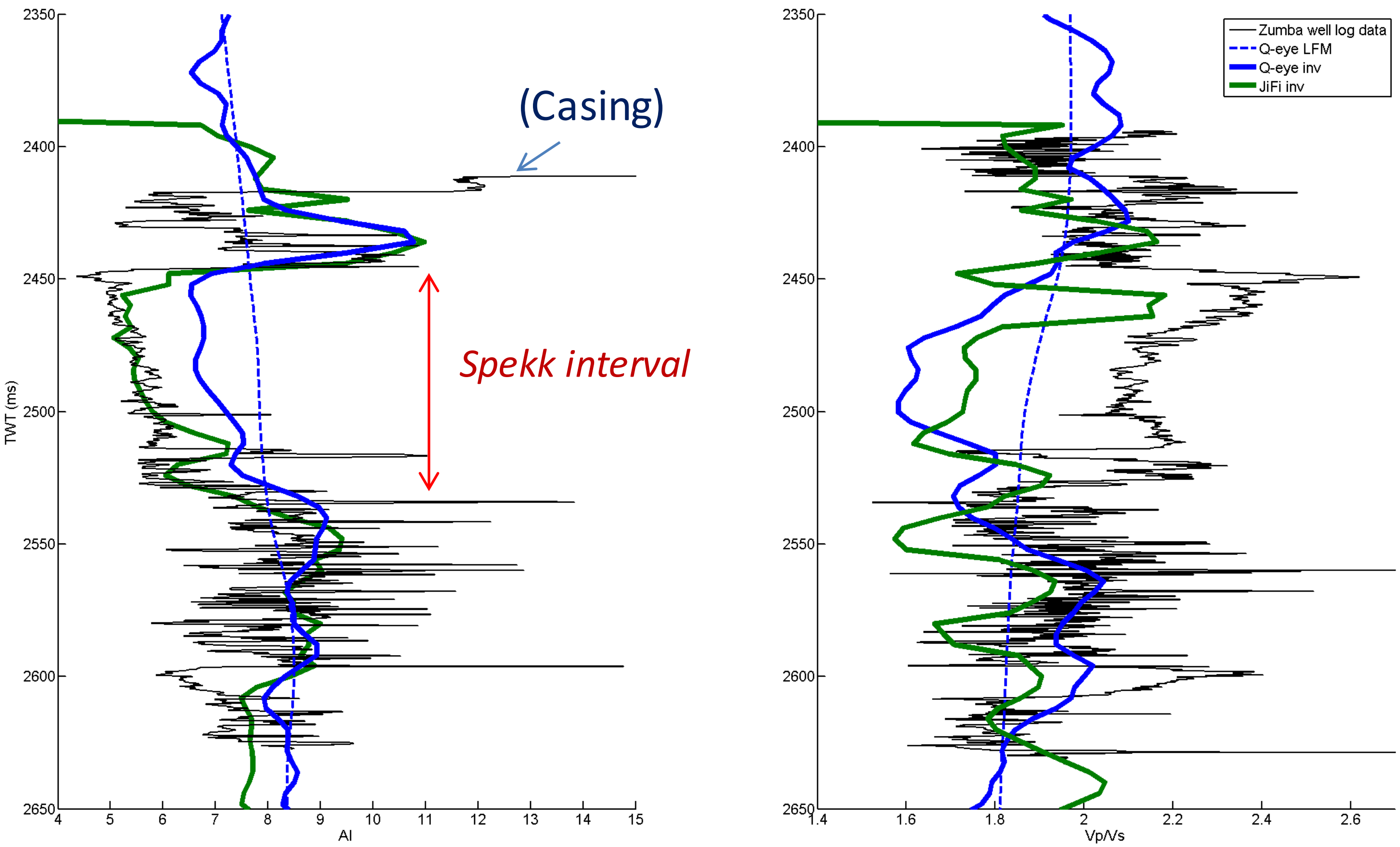


Fluid impedance

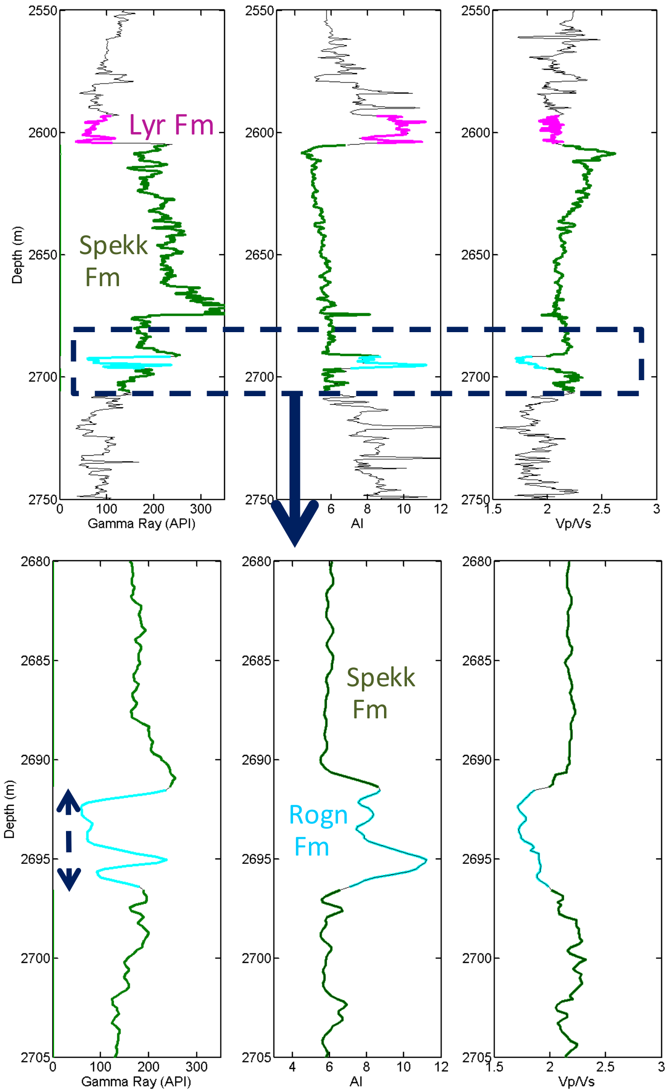


Vp/Vs

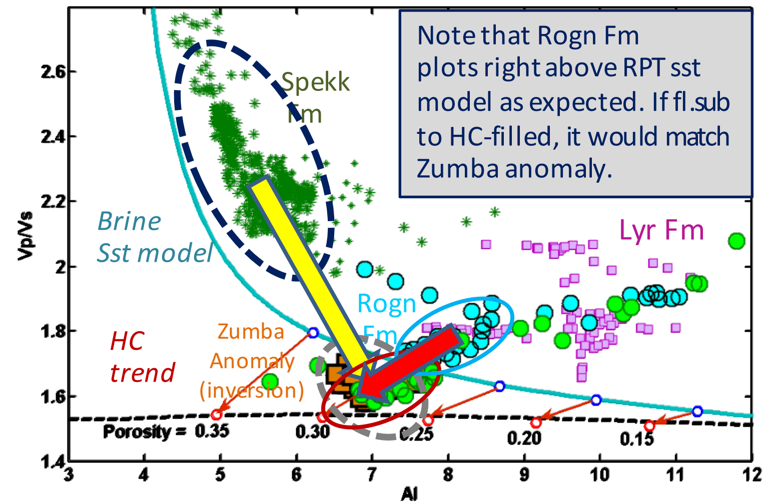
Comparing inversion results and well log data



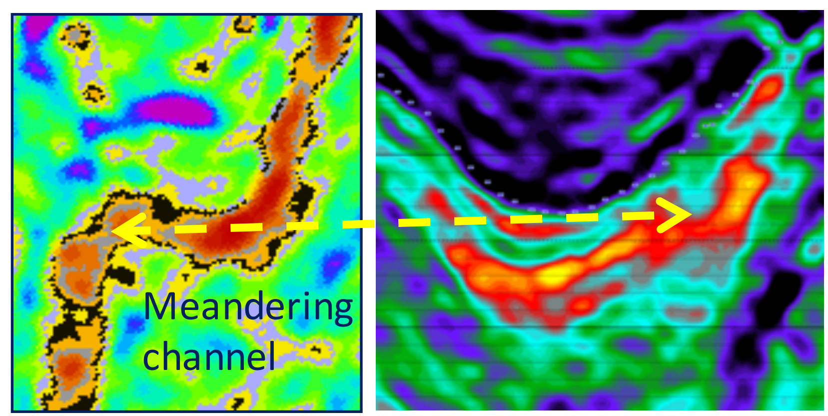
Thin Rogn sand encountered in Zumba well (4-5 m).
Agrees with observations in inversion attributes indicating sand erosion within Spekk interval.



Thin sandy interval within Spekk!



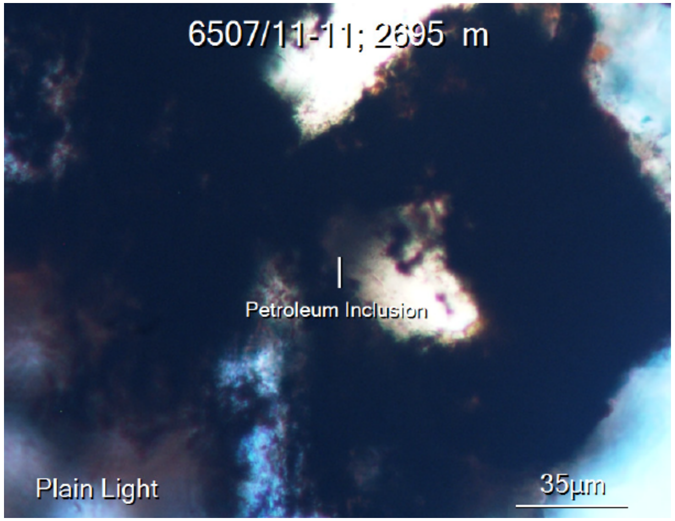
Inversion attributes in Zumba graben indicate sand erosion within Spekk interval, which agrees with observed Rogn Fm at well location

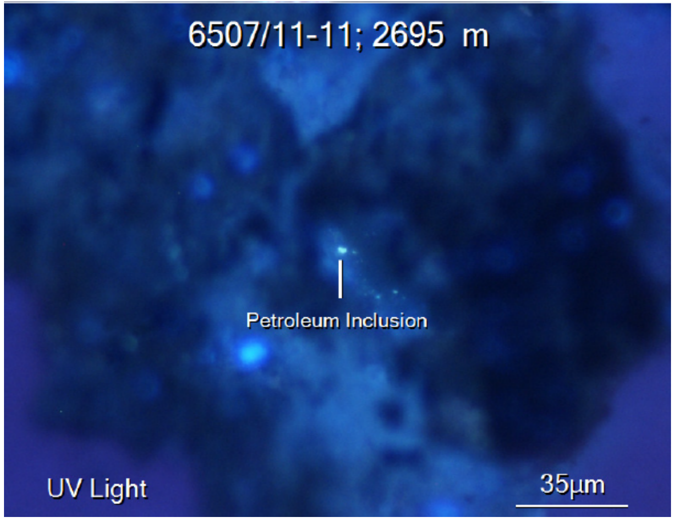


FIS studies: Oil shows in thin Rogn Fm sst

viii 2. *FIS CHEMICAL ZONATION*

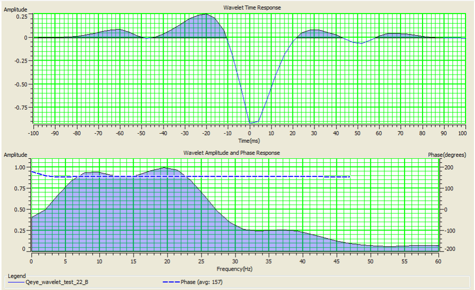
is documented at 2833 m. Seven thin sections were prepared. Samples from 2695 m and 2899 m contain rare, white-fluorescent, upper-moderate gravity liquid petroleum inclusions in sandstone. Trace yellow-fluorescing oil inclusions are observed at 2899 m. Again, liquid hydrocarbon migration appears to be recorded at these depths. Some liquid hydrocarbons could be sourced locally from appreciable mature oil-prone kerogen found in shale at 2731 m. No visible liquid petroleum inclusions were identified in other thin sections from 2611 m, 2656 m, 2731 m, 2815 m, and 2851 m. Shale at 2611 m, 2656 m, and 2695 m contains significant immature oil-prone kerogen and gas-prone kerogen. Trace to appreciable mature oil-prone kerogen and appreciable gas-prone kerogen is observed in shale in four deeper thin sections from 2731 m, 2815 m, 2851 m, and 2899 m. Trace live (fluorescent) petroleum stain is also noted at 2815 m.

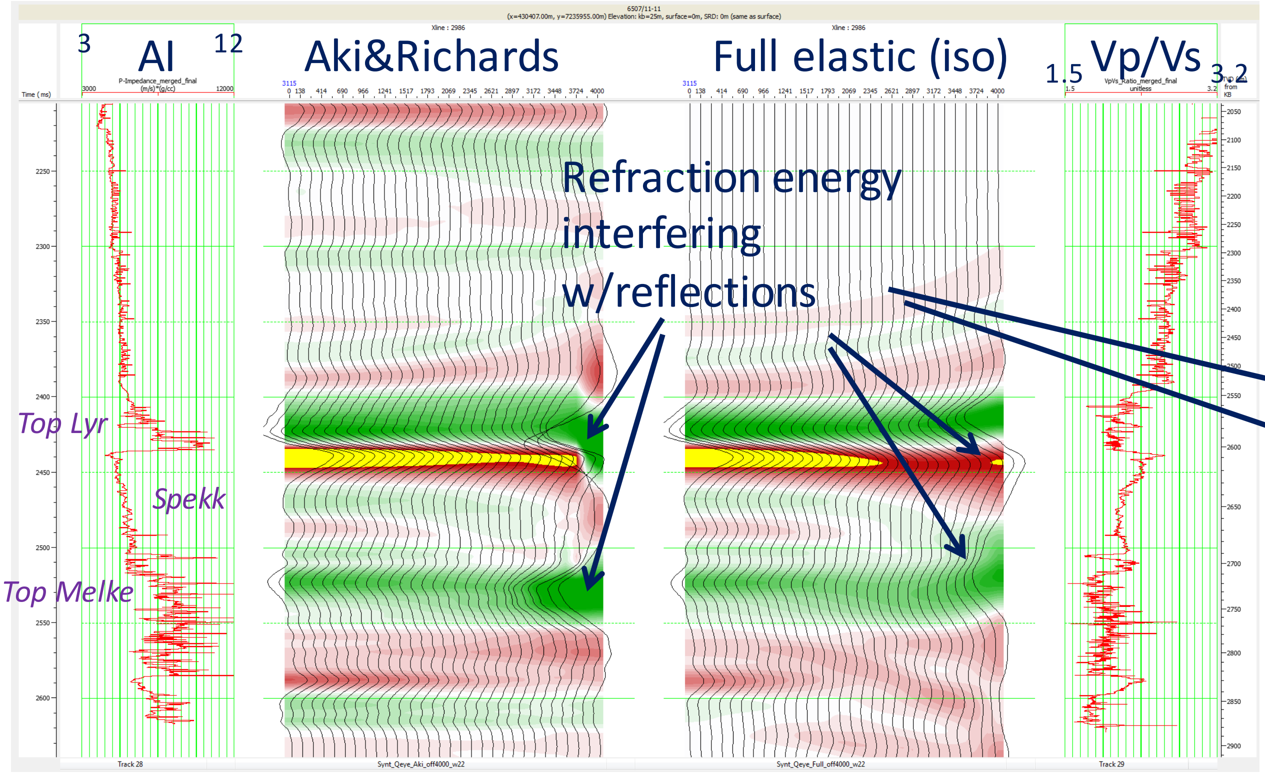


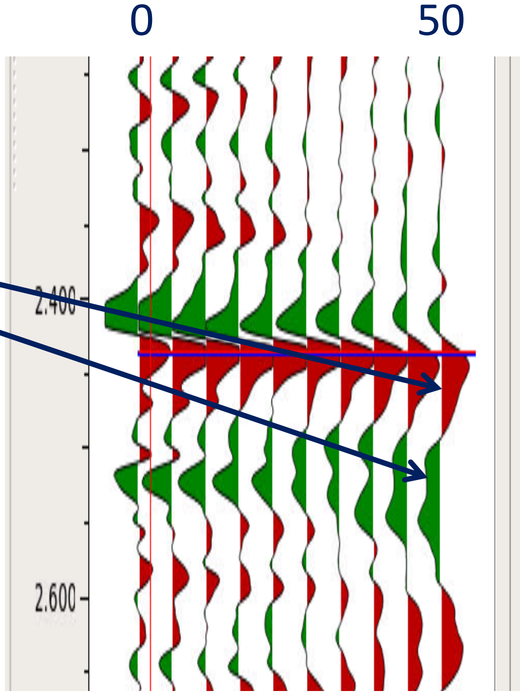


Synthetic AVO modeling versus Real CDP gather at Zumba location

Q-eye's wavelet at 20-25 degrees angle stack





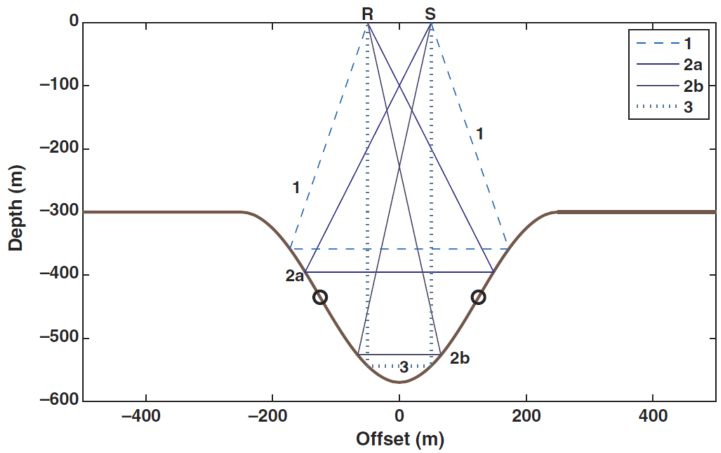


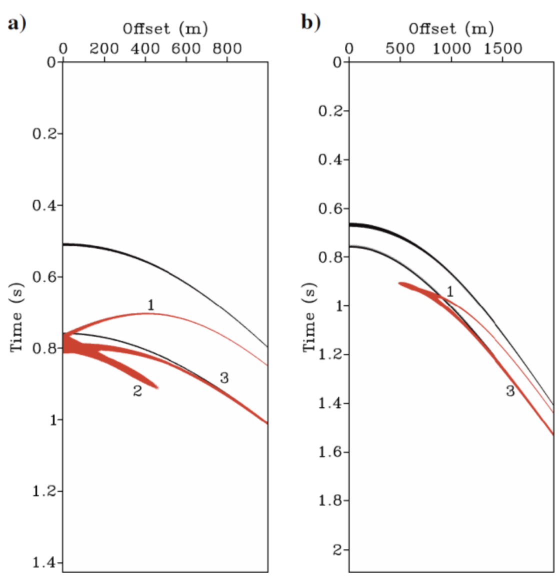
Top Lyr critical angle = asin(2600/3800)=43

Top Melke critical angle = asin(2500/3400)=47

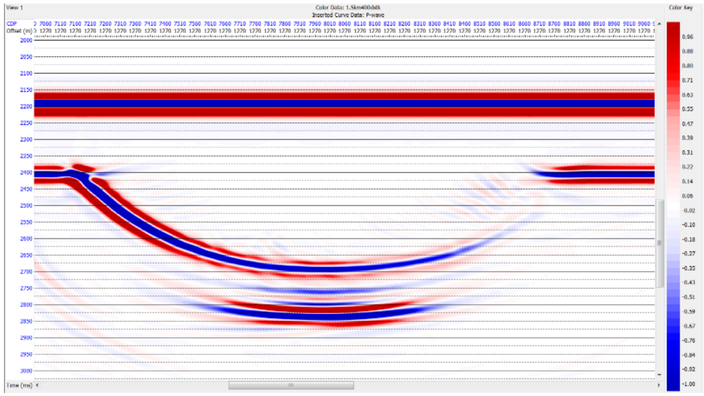
Prismatic waves can interfer with primaries, or create false anomalies by themselves

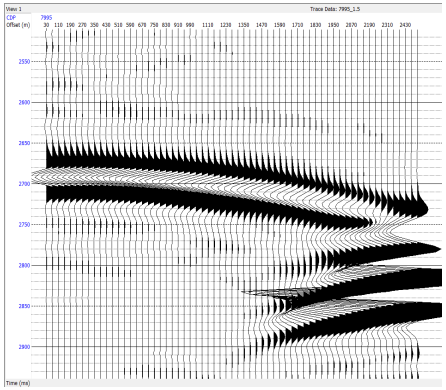
Deeks and Lumley, 2015

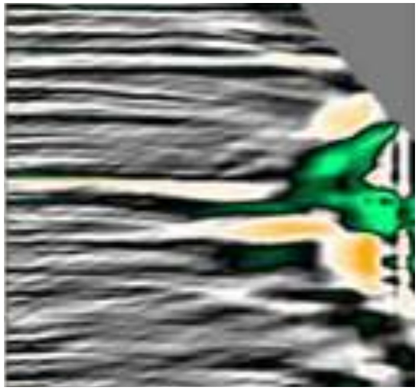


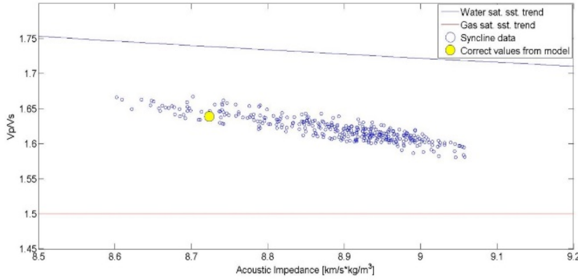


Heiebråten, 2014 (MS thesis, NTNU)



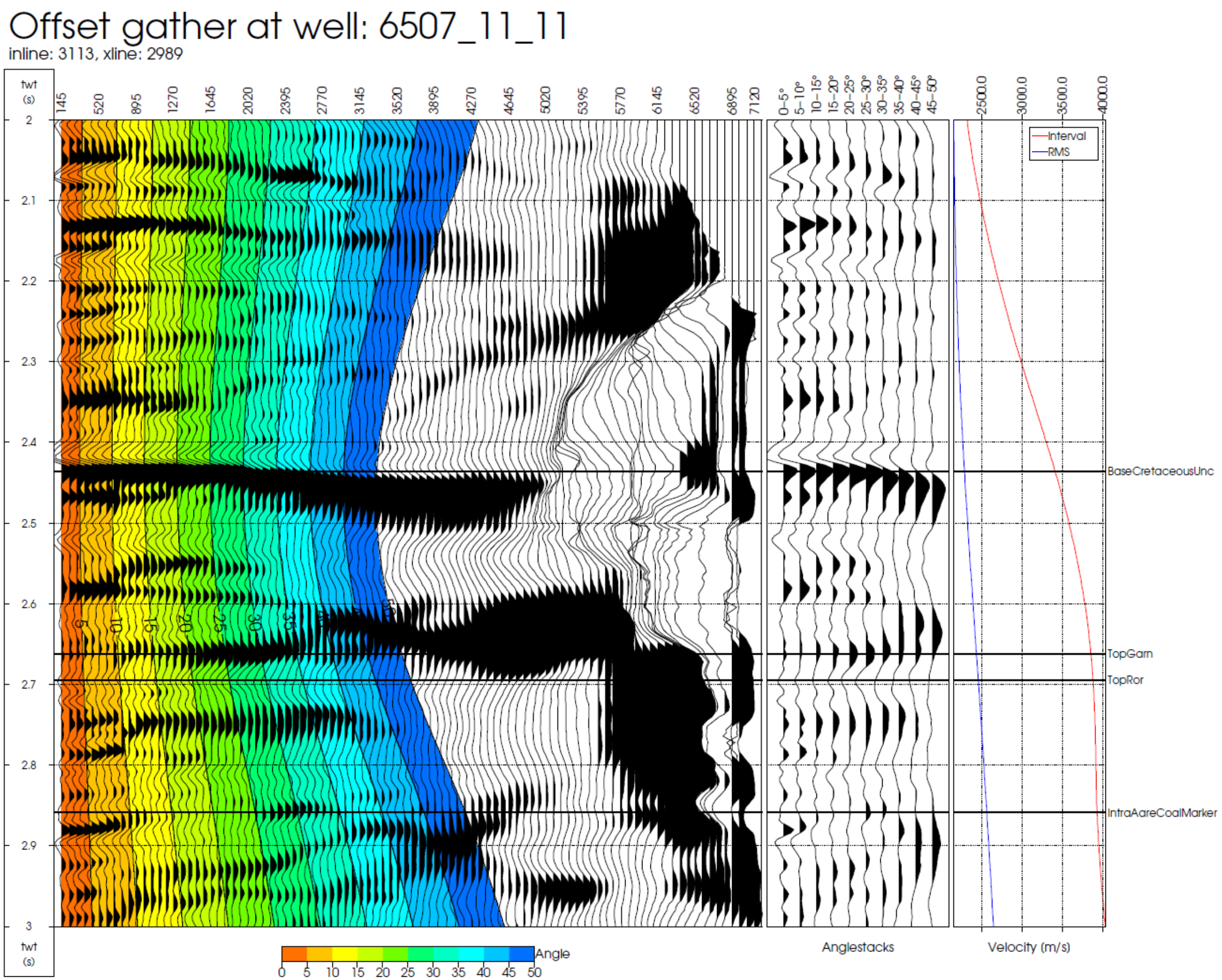




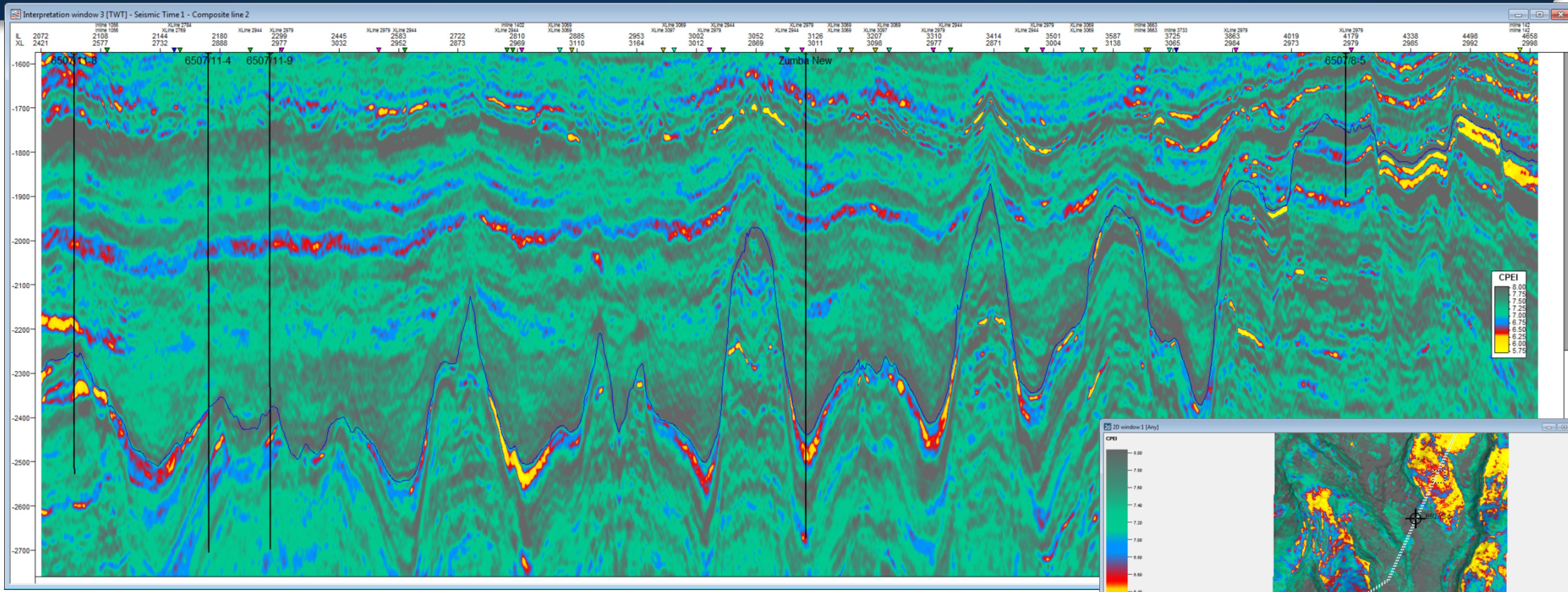


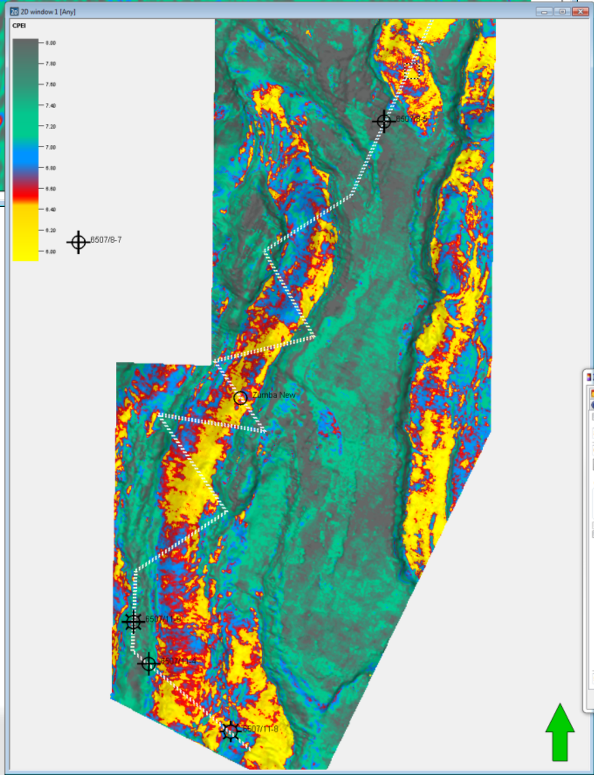
Angle range at Zumba location:
Apparently we remove most of refracted energy.

Black = soft

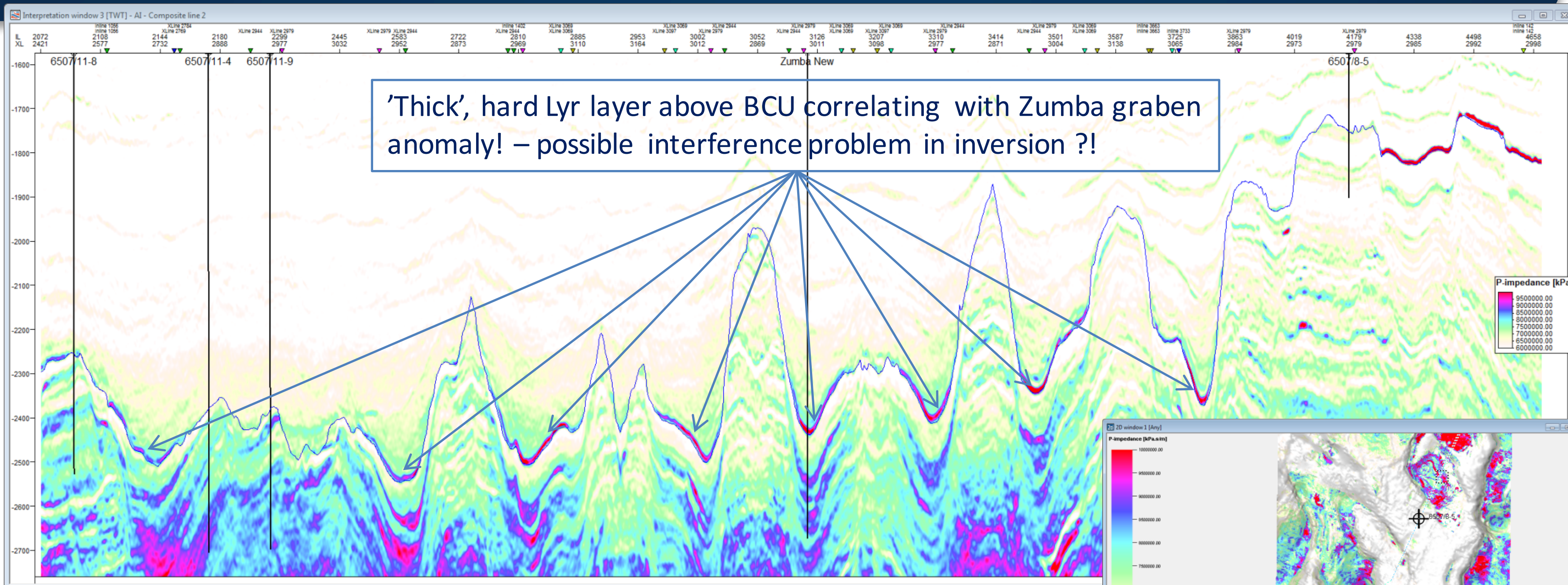


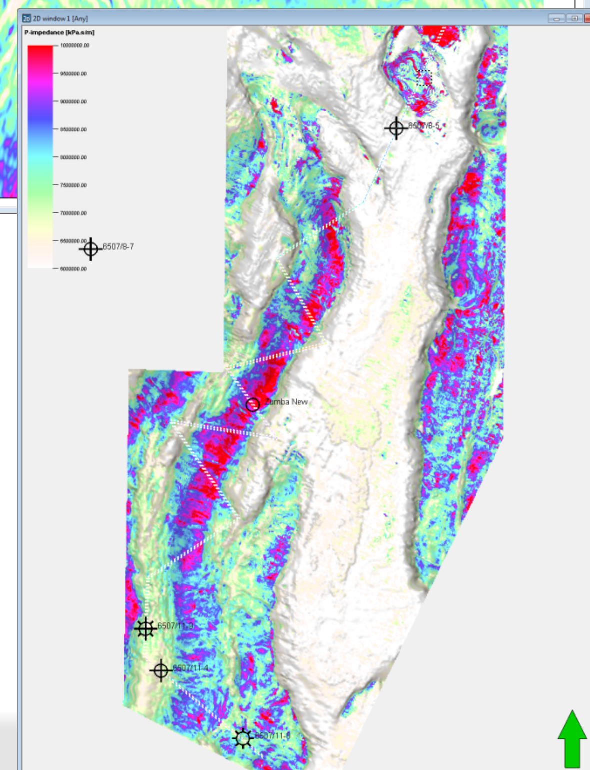
Fluid impedance along random line zig-zagging across graben





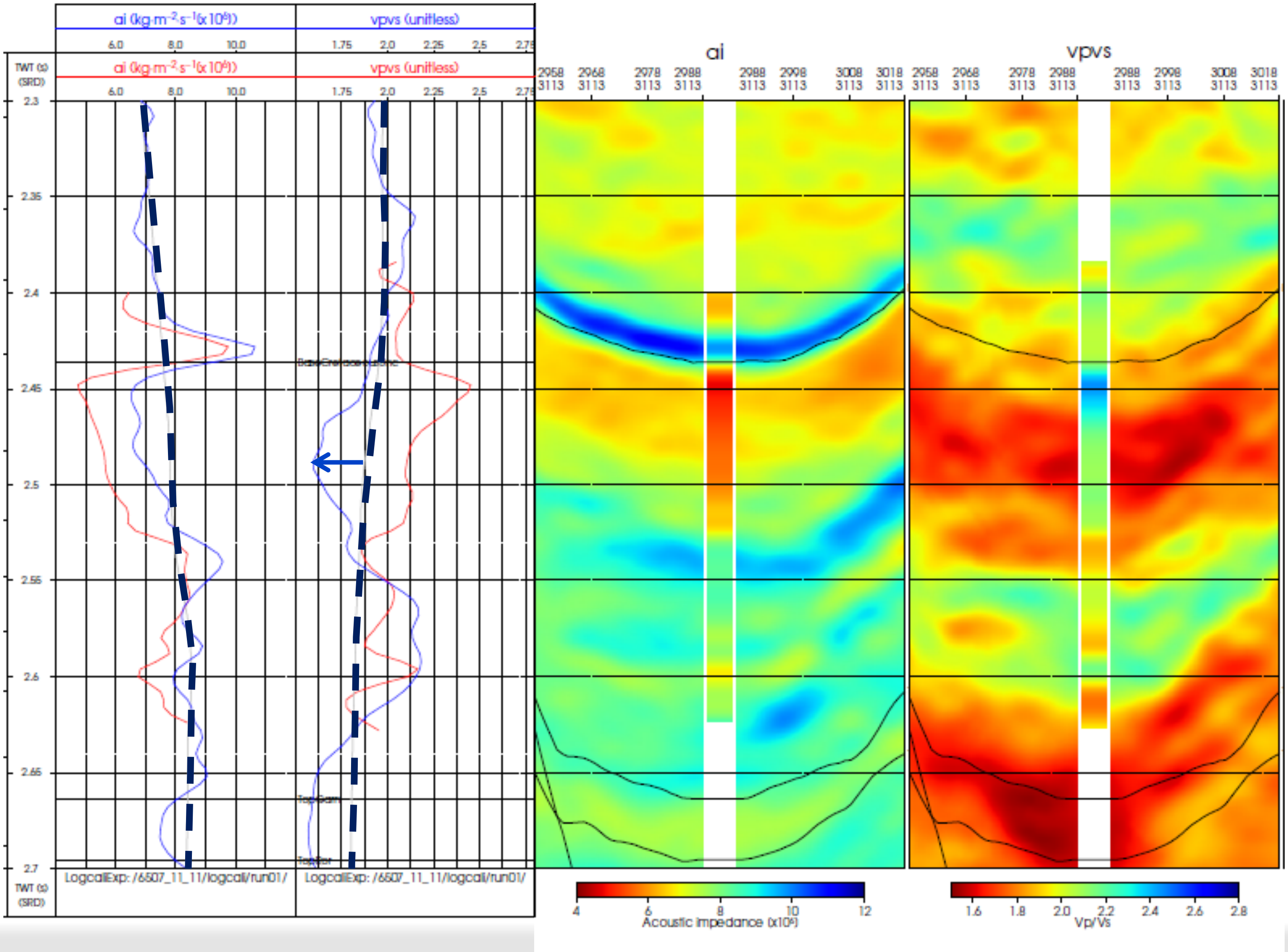
Same random line: Acoustic Impedance 2-14ms above BCU





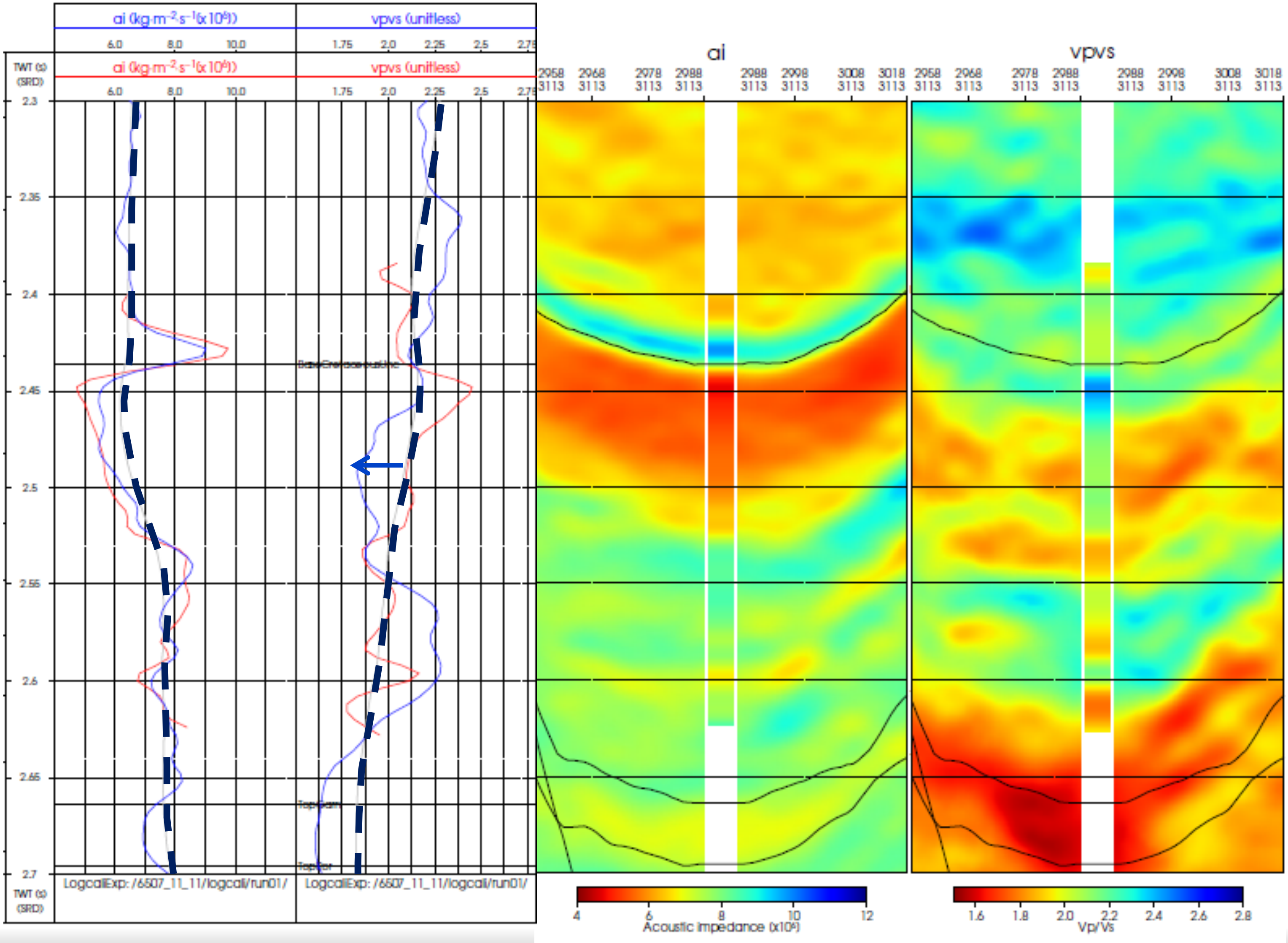
We see strong correlation between high AI in Lyr and CPEI anomalies in Spekk!

Pre-drill AVO inversion
Angles 5-50 degrees, LFM from interval velocities



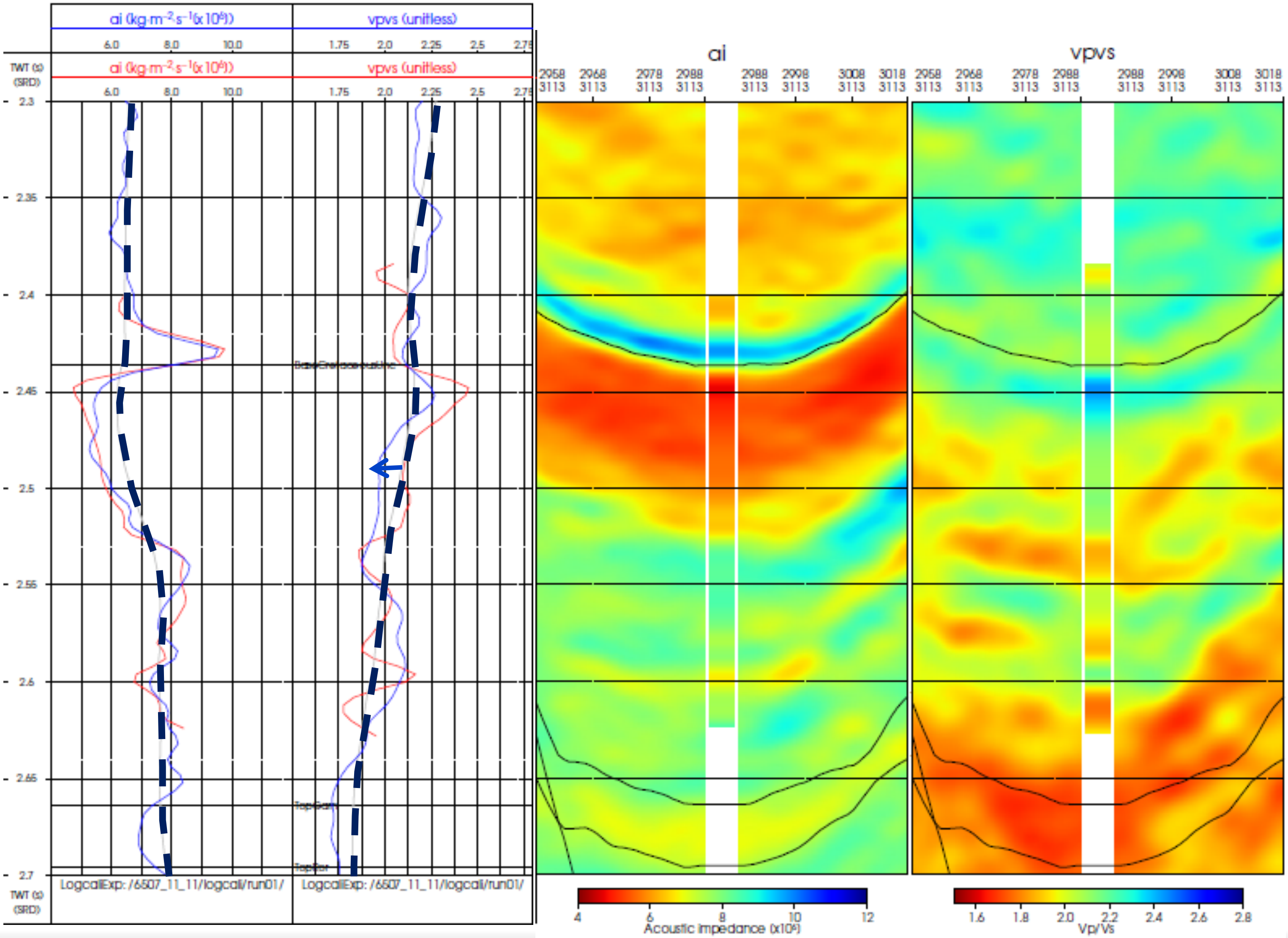
Post-drill AVO inversion (The effect of new LFM)

Angles: 5-50 degrees, updated LFM from new well log data, same wavelet



Post-drill AVO inversion (The effect of angle range)

Angles: 5-40 degrees, updated LFM from new well log data, same wavelet



Conclusions: What went wrong and key learnings for the future

- **Several reasons for the false AVO and wrong Vp/Vs predicted at Zumba:**

1) Interference/phase distortions and refracted energy from hard Lyr Fm.

2) Prism waves can have contributed to the AVO anomaly.

2) Error in low-f model caused by wrong input interval velocities in graben.

→ *False anomaly that plotted as HC-sst in a Rock Physics Template, and that showed plaucible geological morphology!*

- **Key geophysical learnings**:

1) Avoid angles above 40 degrees in simultaneous AVO inversion

2) Watch out for hard layers right above the target

3) Be aware of prism waves in syncline settings

3) Don't assume interval velocities are correct when building low-f model

4) We don't fully understand broad-band benefits (frequency) vs. pit-falls (phase) in AVO inversion.

5) The extrapolation problem (geology and geophysics issues). Be careful using inversion data away from well control, even if you have good seismic!

Thanks to my colleagues at Tullow Oil Norge for great teamwork, partners of licence PL591 (Lime, North, Pure) for valuable feedback, and to Q-eye Labs for AVO inversion data.