On some unsolved issues in shale rock physics

How do we model compaction, cementation and uplift of shales?

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Motivation: Why are shales important in QI?

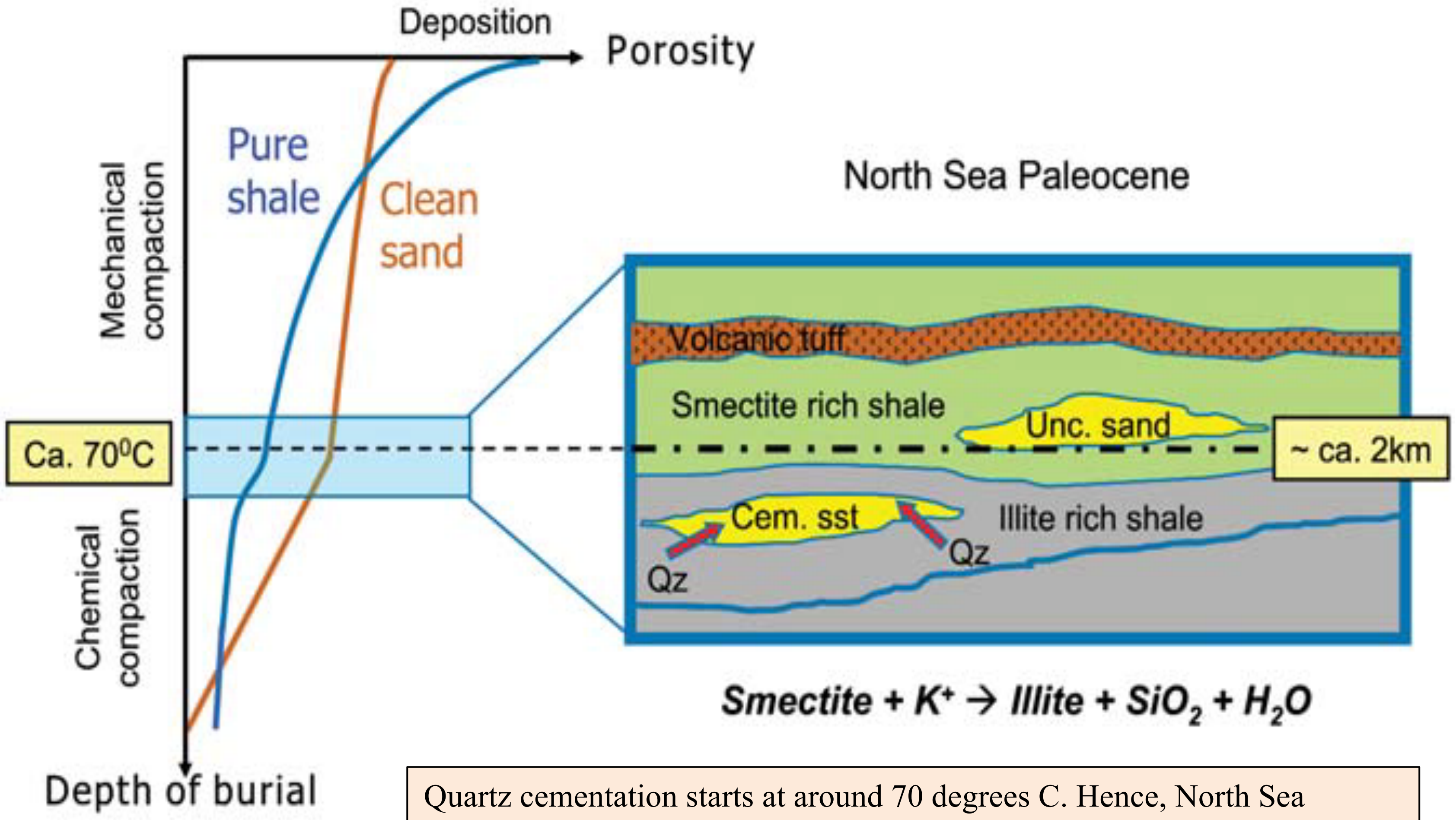
Terracotta Army, Xian, China (200 bC).

- Shales comprise most of the overburden rocks.
- Normal compaction trends of shales can be used to estimate uplift.
- Shales define the background trend in AVO data
- Shales, as cap-rocks, impacts the AVO reflectivities of top and base of reservoirs.
- Organic-rich shales are the most common source rocks.
- Intra-reservoir shales contribute to reservoir heterogeneity, baffles and barriers for fluid flow.

Key issue: How to extrapolate shale properties away from wells?

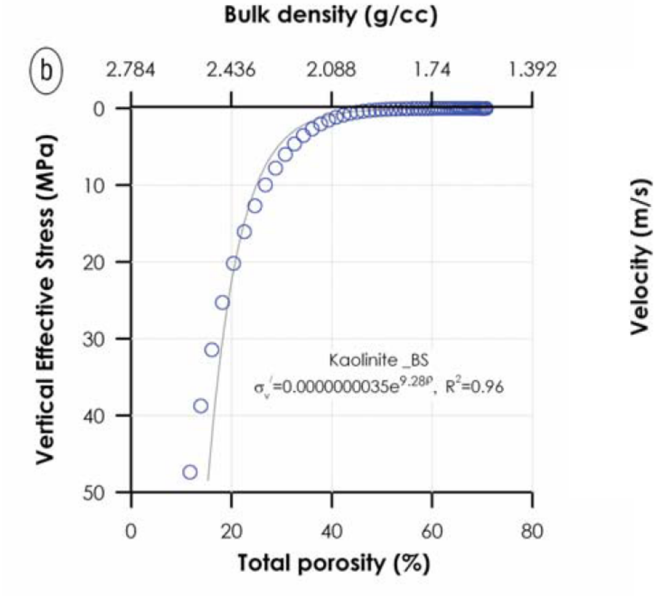
- How do we extrapolate elastic properties of shales away from wells?
- How do we best model rock physics properties of shales during burial and uplift? (Porosity and velocity versus depth).
- How do we take into account stress sensitivity in shales?
- How do we best model chemical compaction and cementation in shales?
- How do we discriminate depositional trends and diagenetic trends in shales?

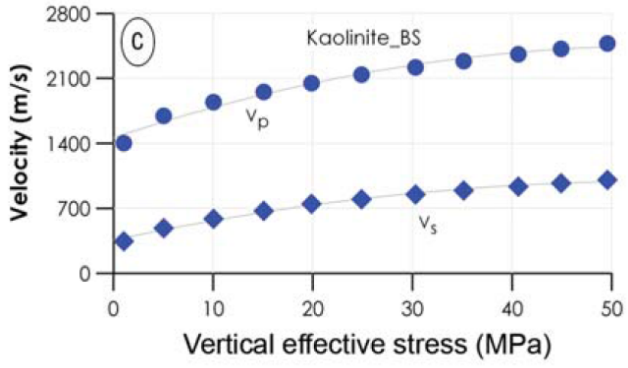
Sand and shale compaction trends in the North Sea

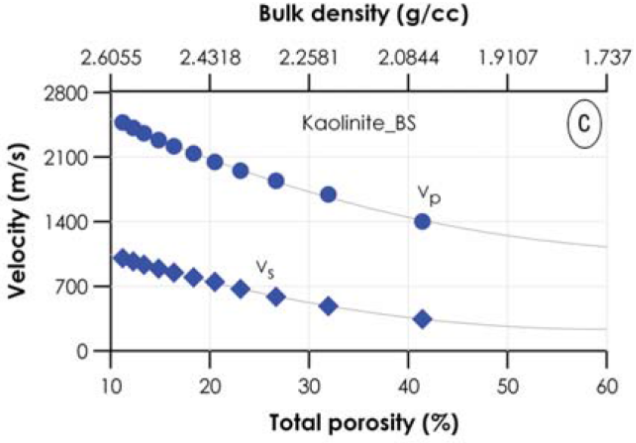


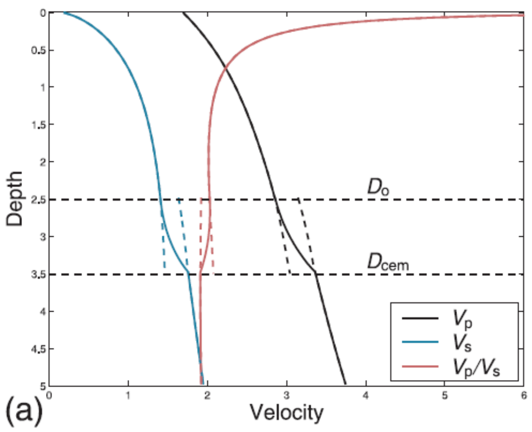
Quartz cementation starts at around 70 degrees C. Hence, North Sea Paleocene sands can both be unconsolidated and cemented. Shales transform from smectite-rich to illite-rich at around the same temperature.

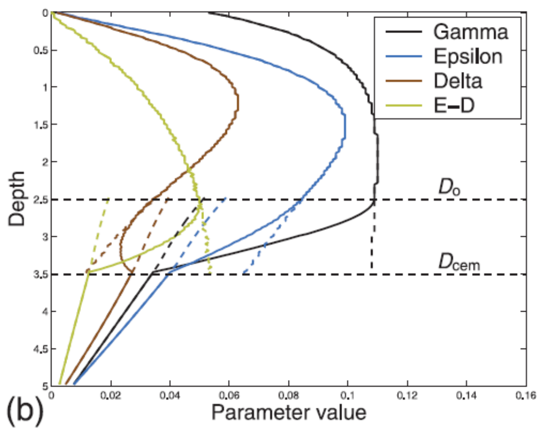
Mechanical versus chemical compaction of shales. Experimental observations (Mondol et al. 2008) and rock-physics modeling (Dræge et al., 2006).

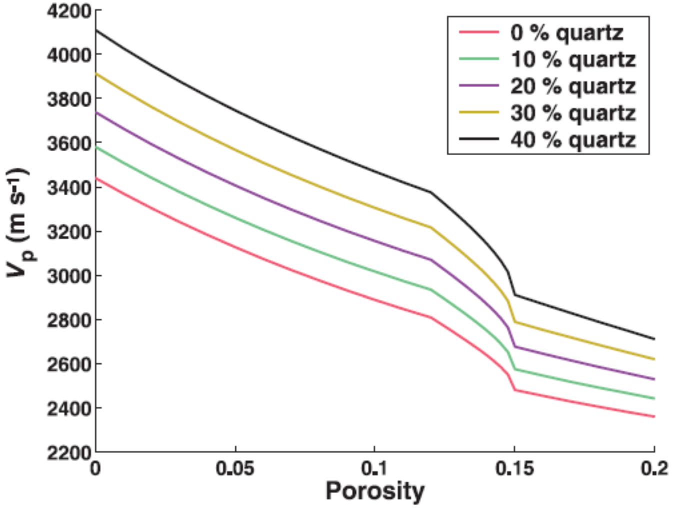




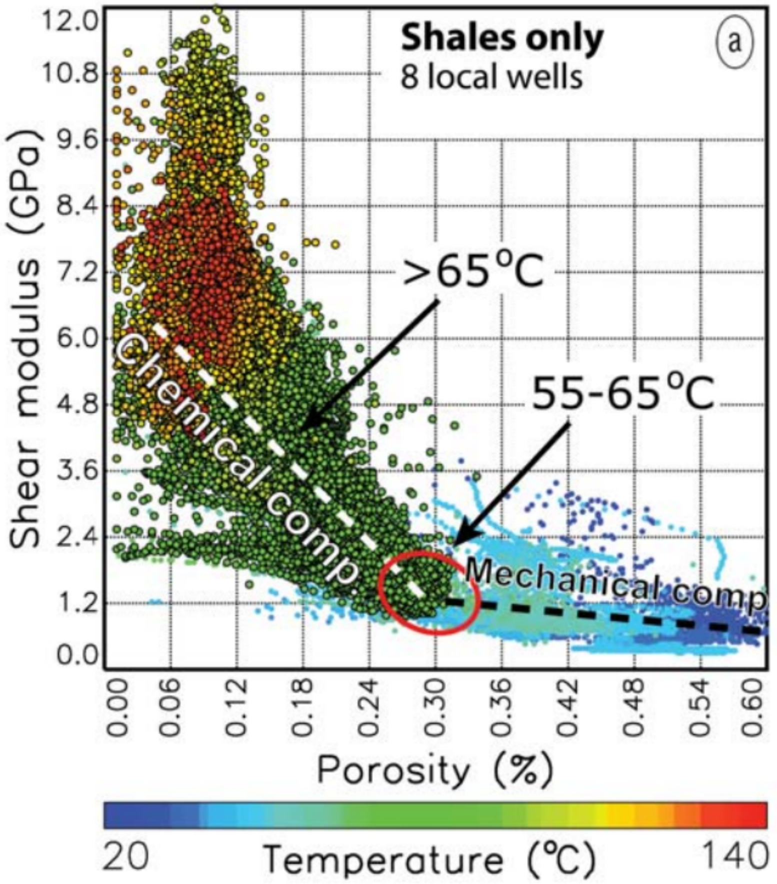




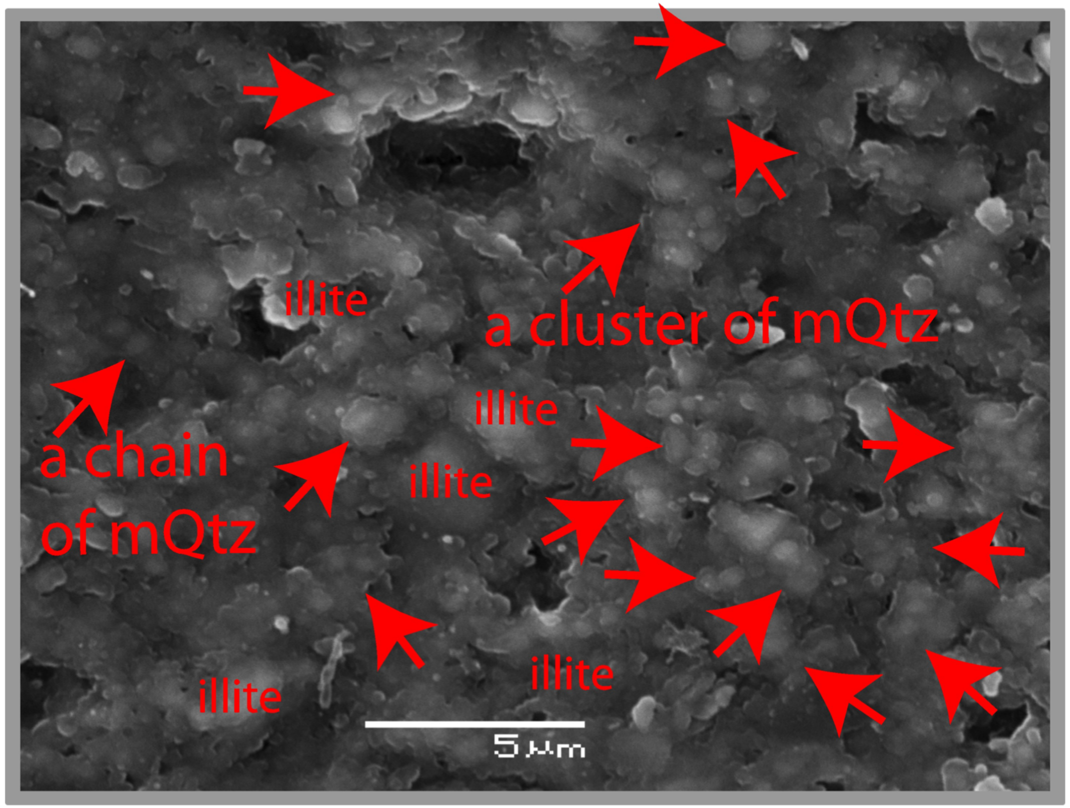




Documentation of chemical compaction and quartz cementation in shales.

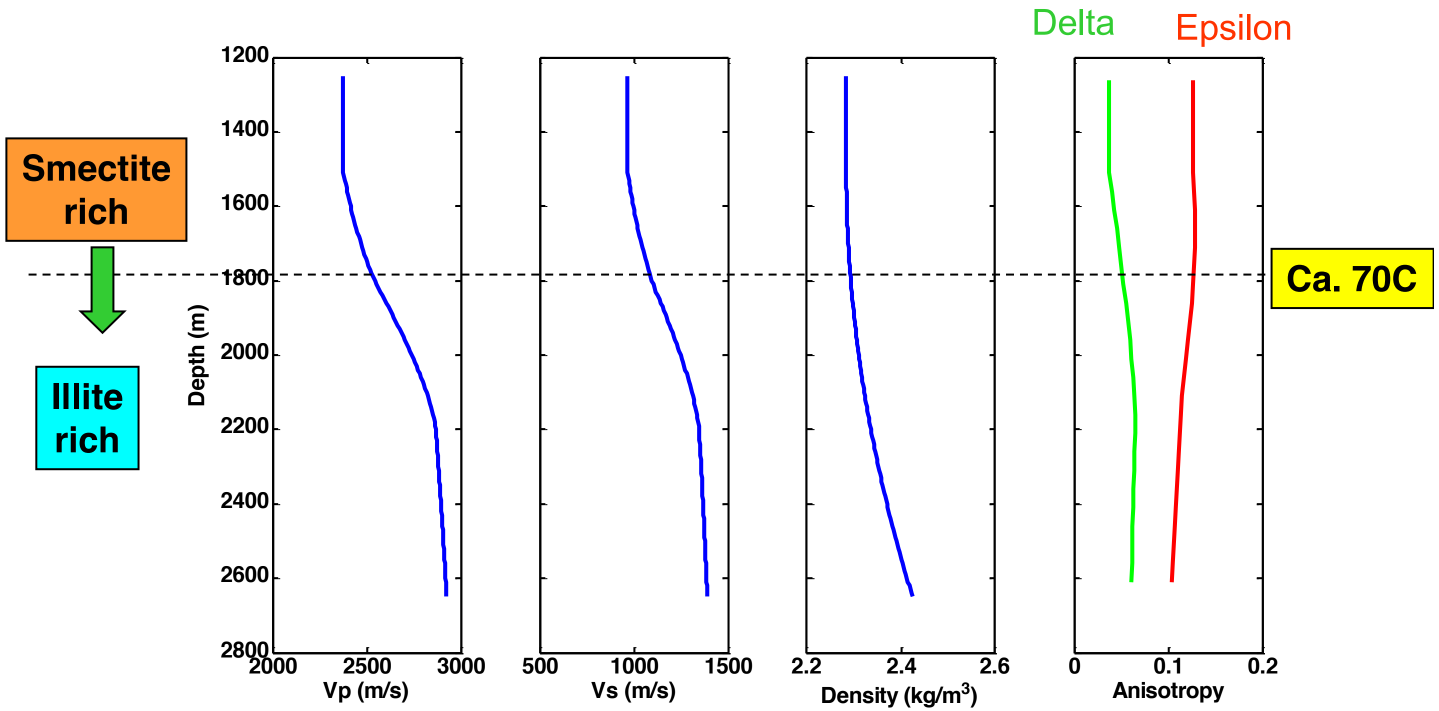


Storvoll and Brevik, 2008



Thyberg et al., 2009

Depth trend modeling of shales (Avseth et al., 2008)



Smectite + K → Illite + Si + H_2O

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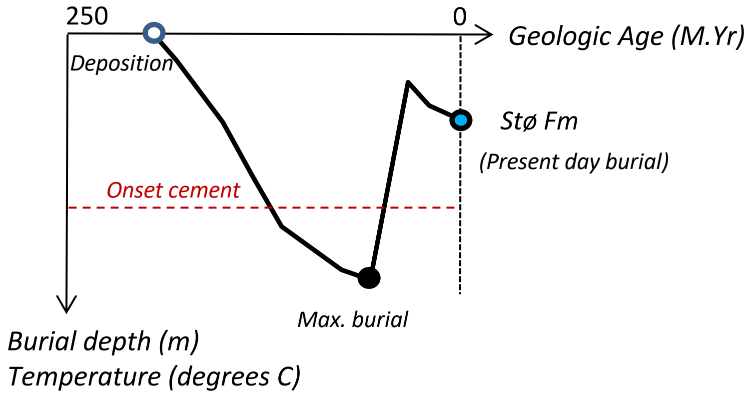
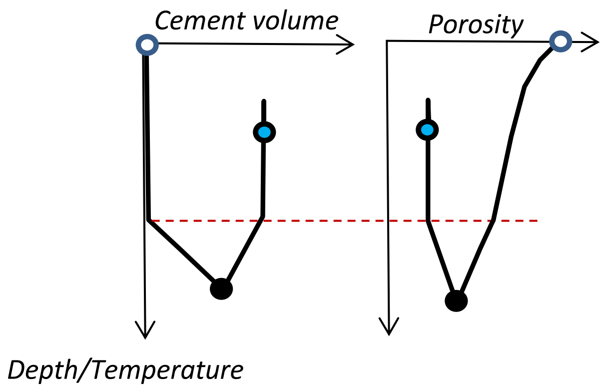
Rock physics and AVO modeling constrained by burial history

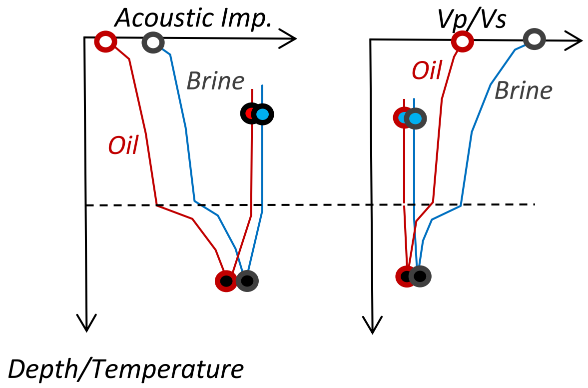
1. Burial history



2. Diagenetic modeling (Walderhaug)

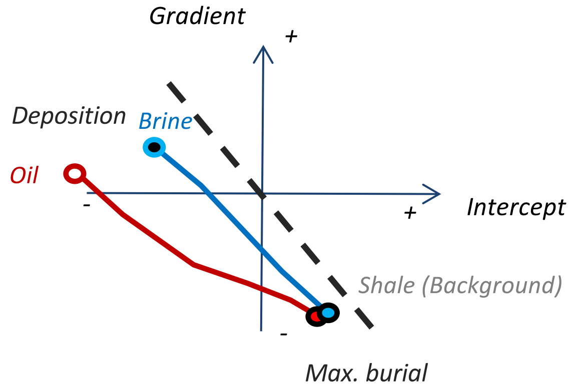


3. Rock physics modeling (Dvorkin-Nur)



+ shale compaction and RP

4. AVO modeling (Zoeppritz)



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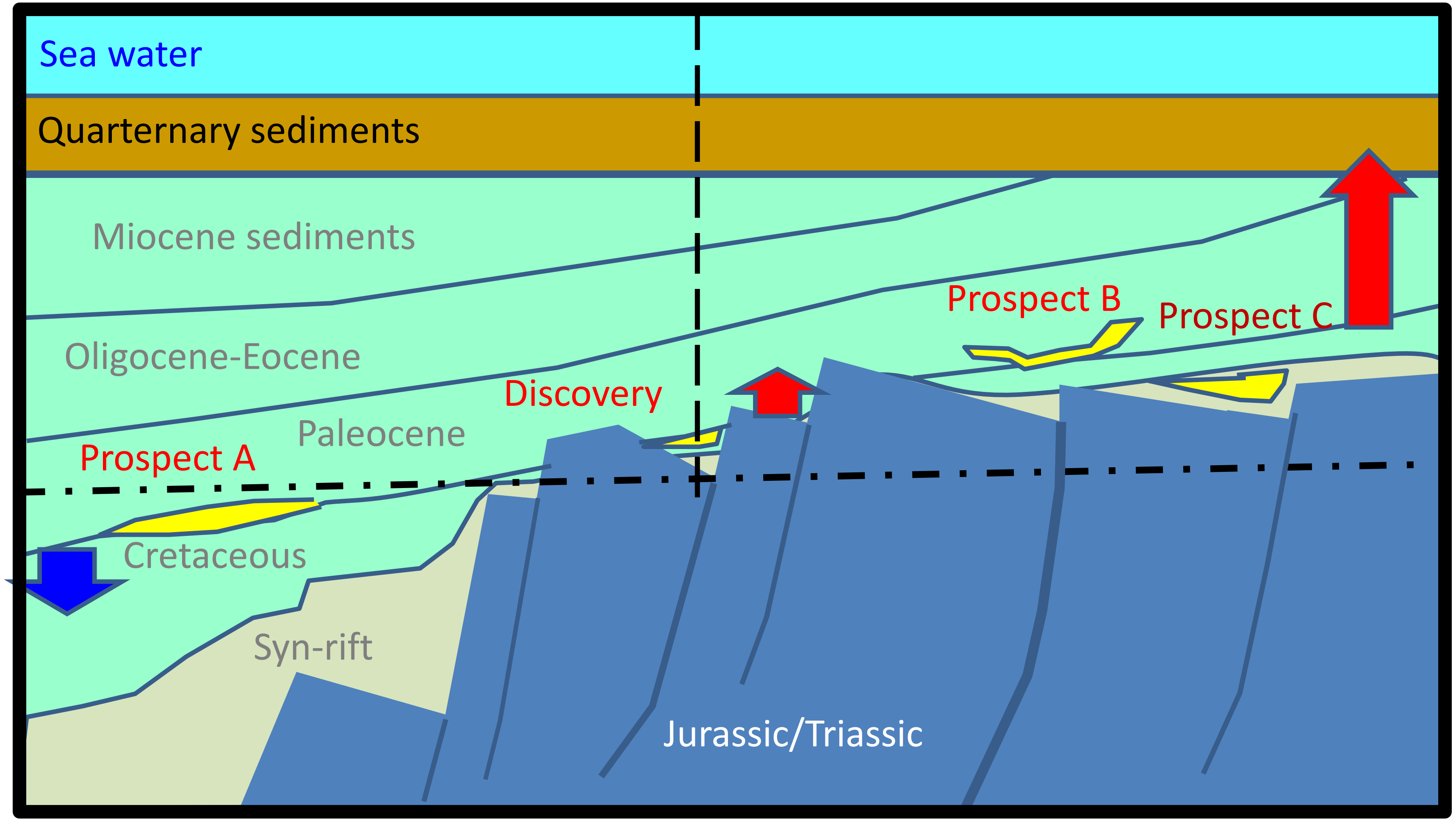
A «typical» present day geo-section offshore Norway



Cenozoic uplift
Increasing landward

70 C

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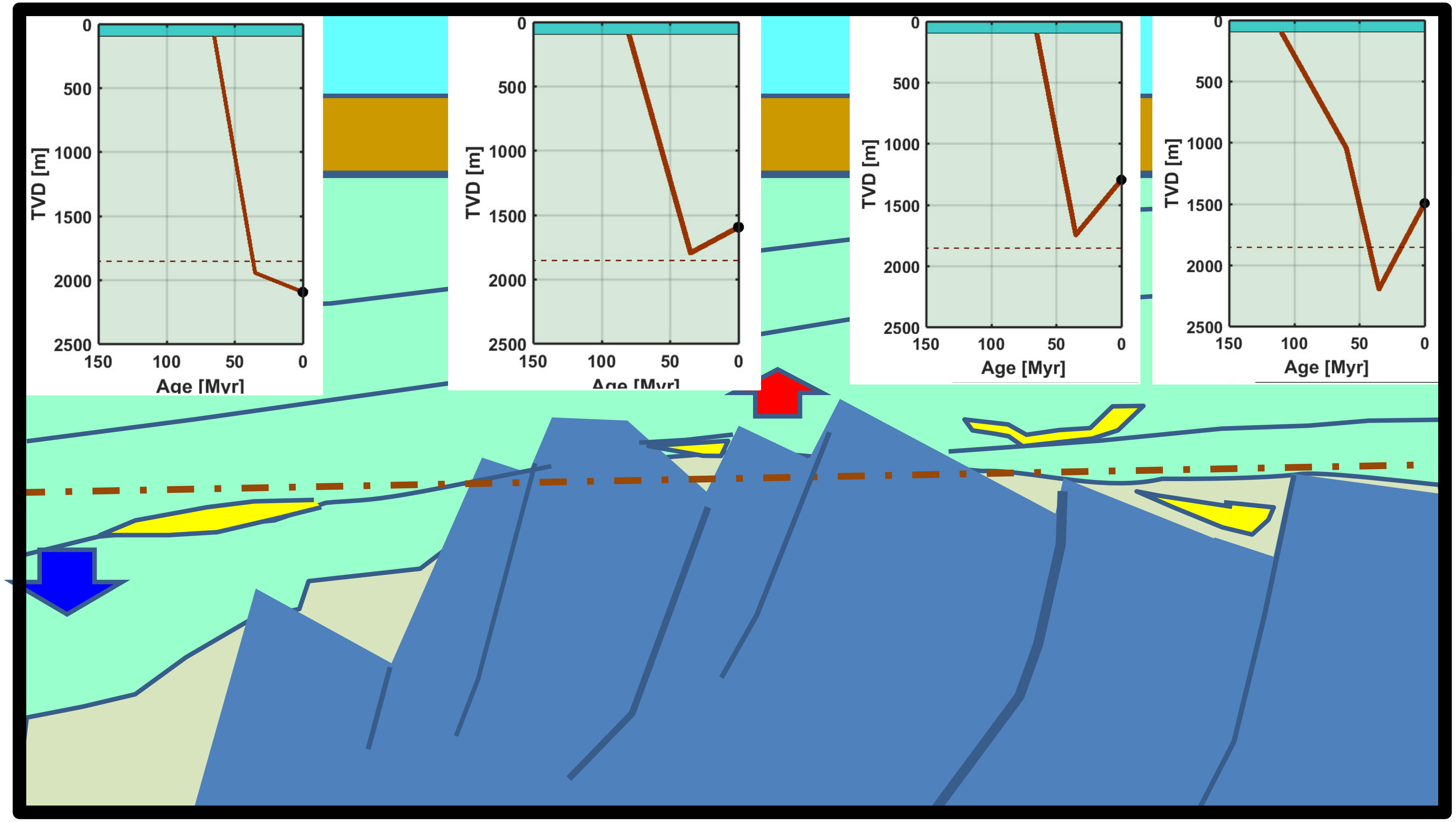
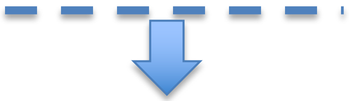
«Restoring» geo-section to maximum burial. Have prospects been into the frying pan?

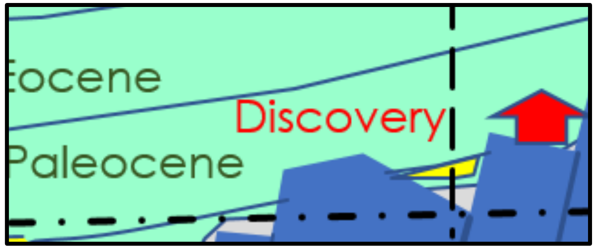


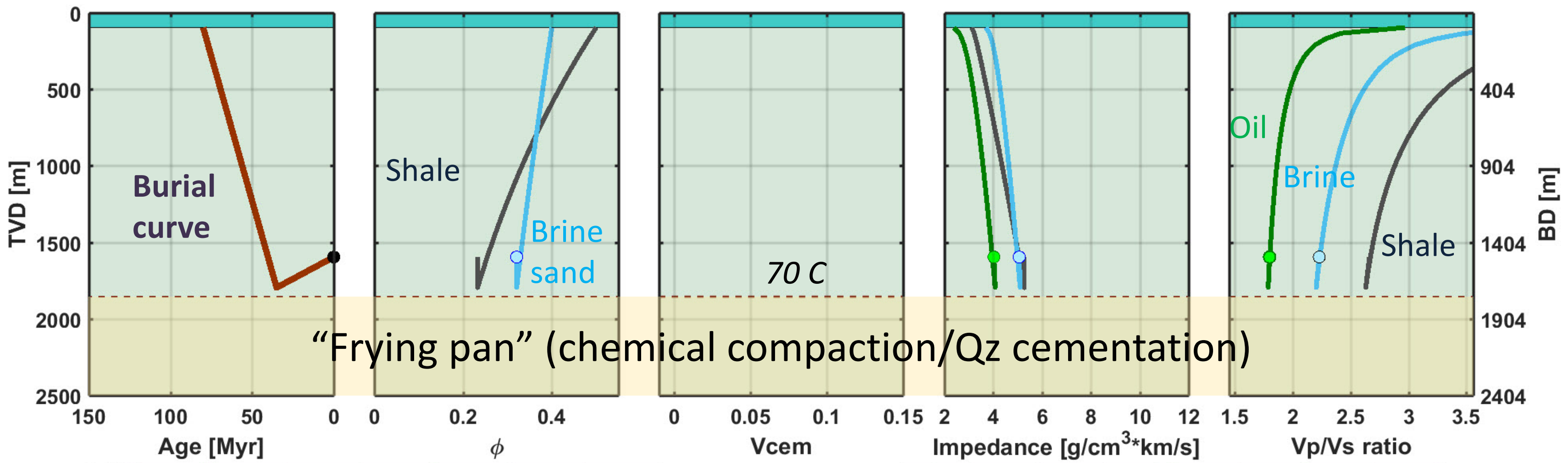


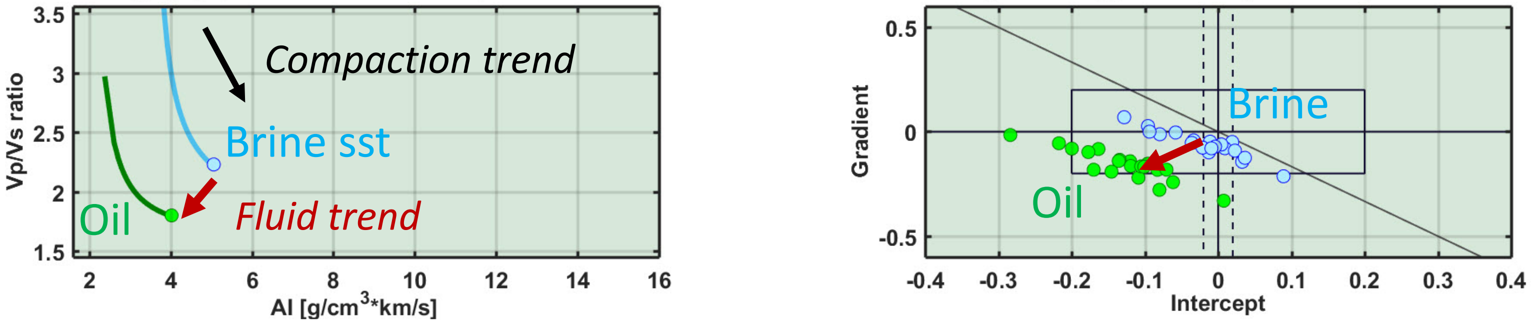
The "Frying Pan"
(T>70 C required for Qz-cem.)

Burial constrained AVO modeling at "Discovery" well.

(Campanian sands w/oil give AVO class III)

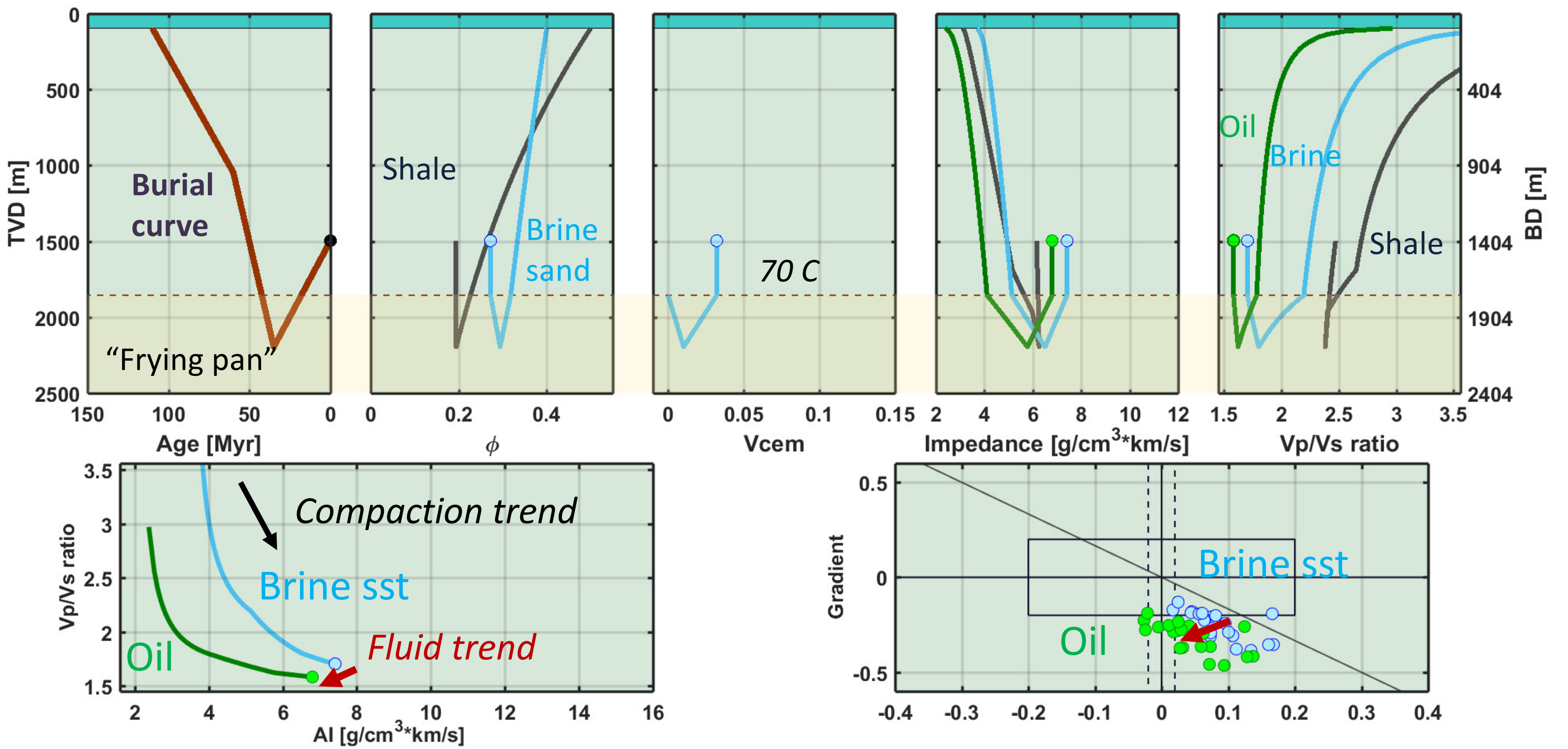




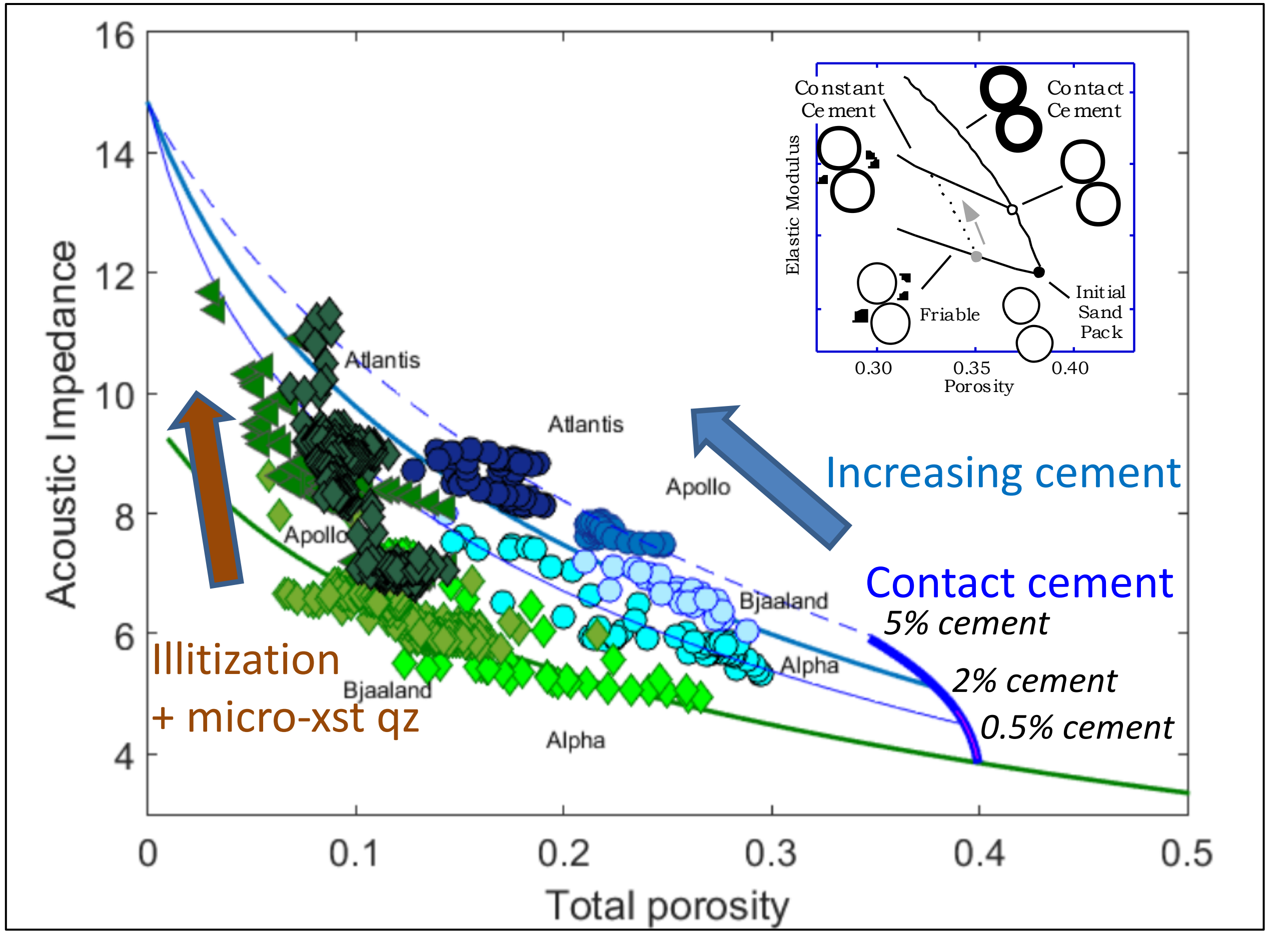


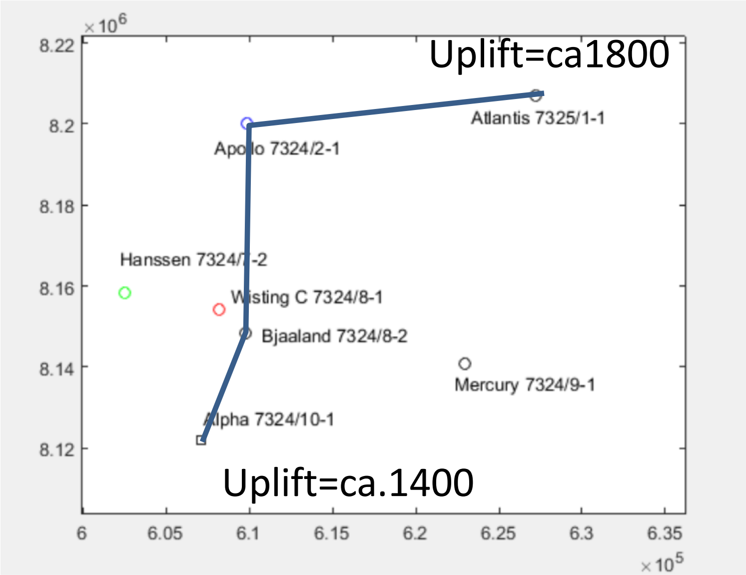
Burial constrained AVO modeling at prospect C (Aptian sst)

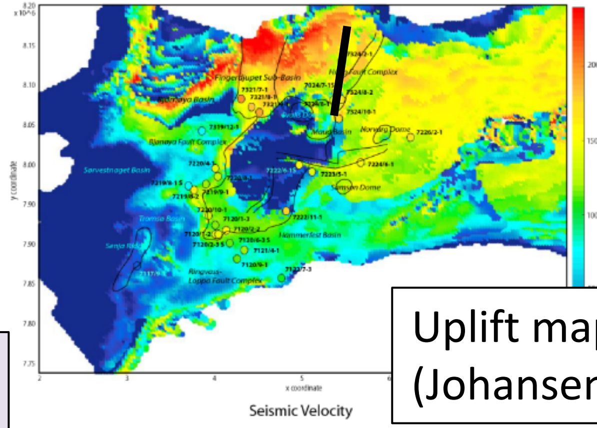
Oil-filled sst = AVO class IIp



Barents Sea Example: Acoustic impedance (water-saturated) vs. porosity along south-north well log profile



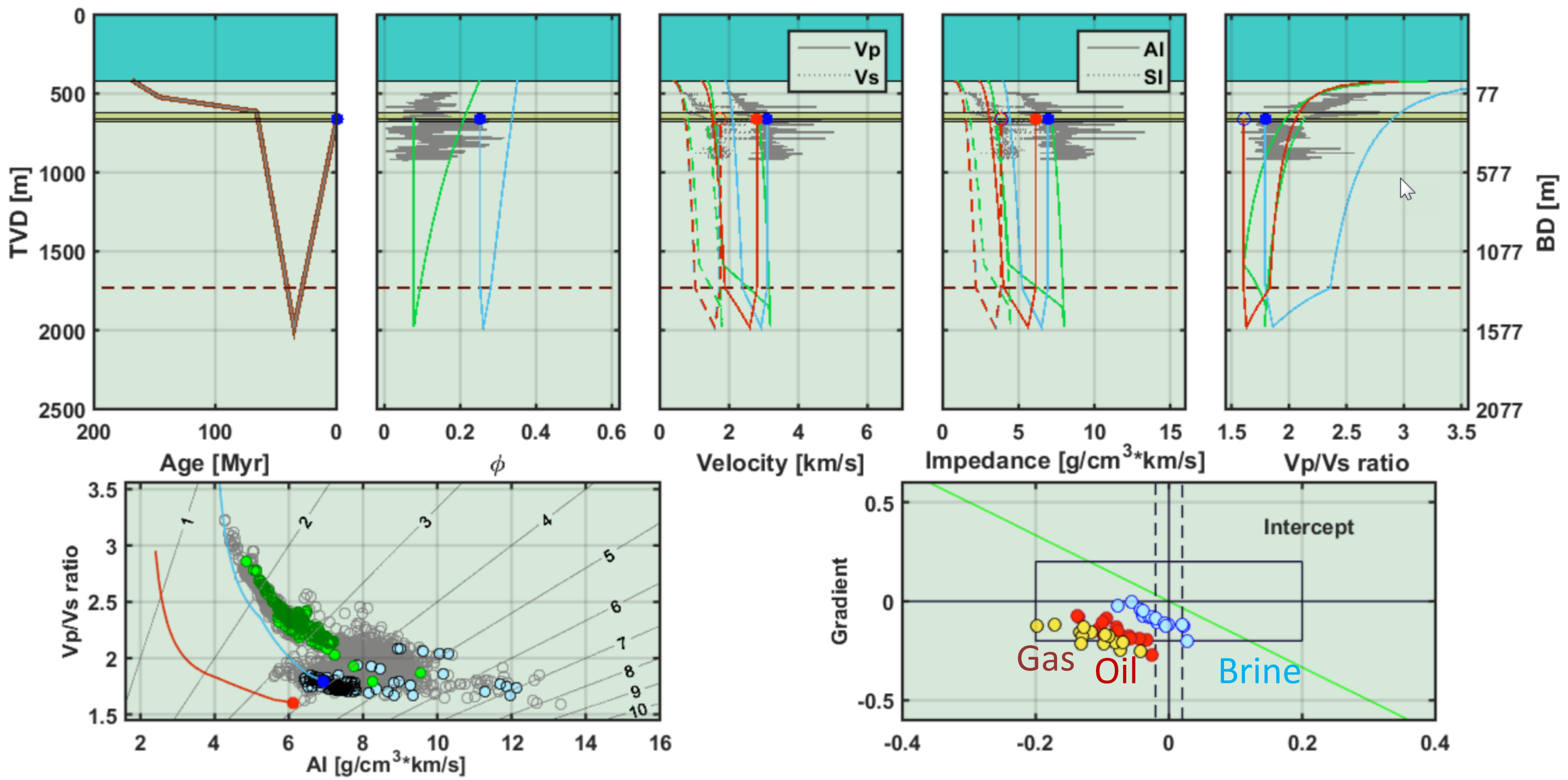




Uplift map (Johansen, 2017)

Sandstones of Stø Fm are getting increasingly stiffer northwards, likely related to increasing maximum burial. Fuglen shales show a significant trend change in northern wells (Atlantis and Apollo), likely related to illitization and micro-crystalline cementation of shales (see Thyberg et al., 2009; Storvoll and Brevik, 2008).

Expected AVO signatures at Top Stø: Class III AVO for both oil and gas.



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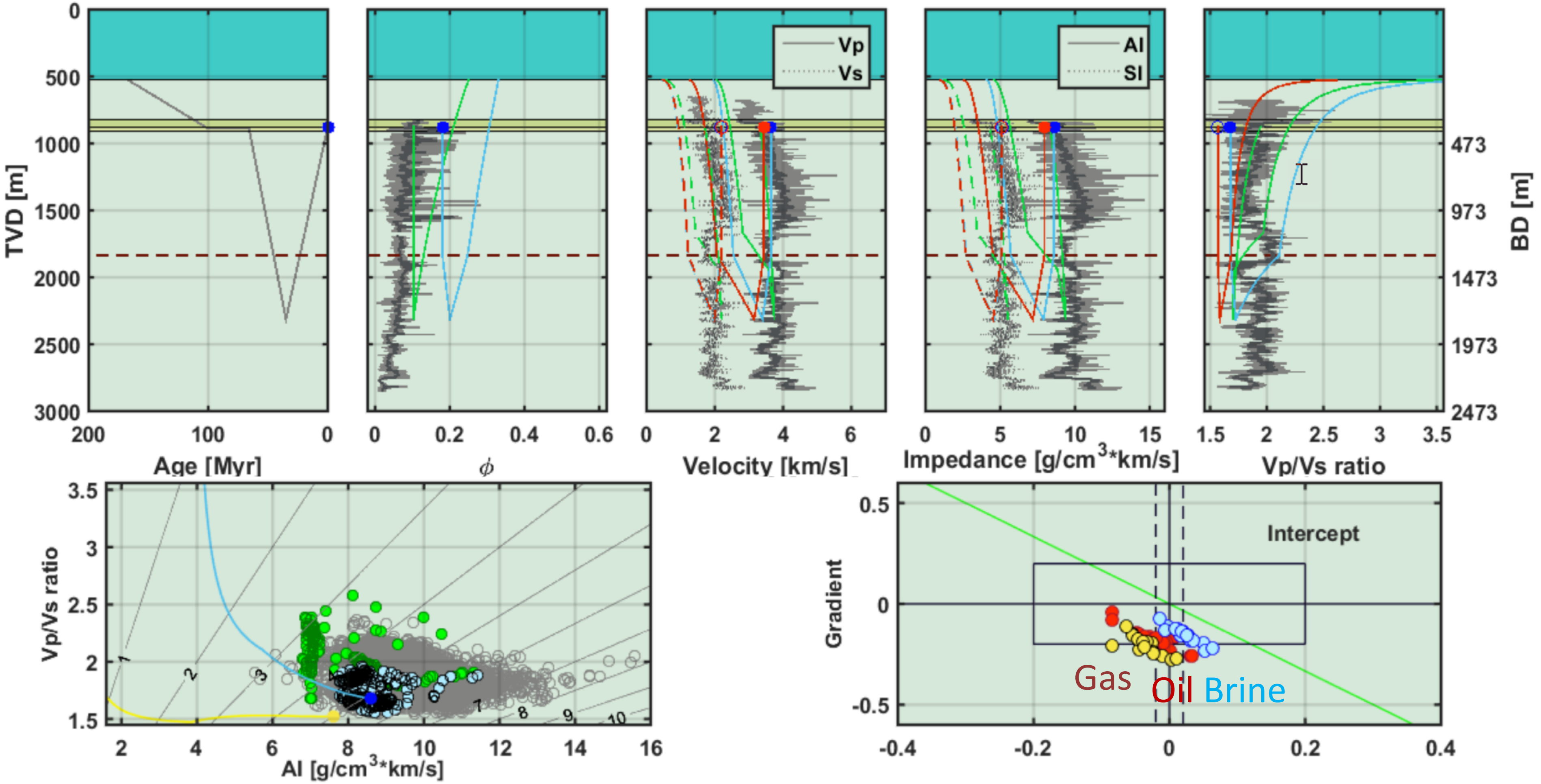
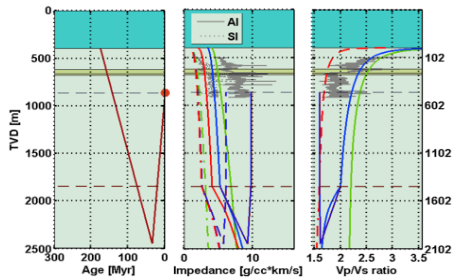
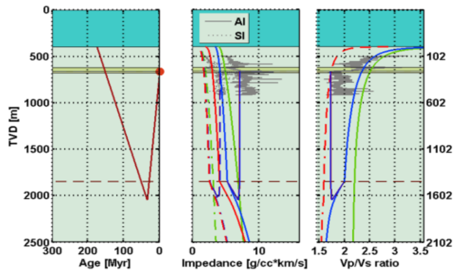
Zoomed in further:
Expected AVO class IIp-II for oil and gas.

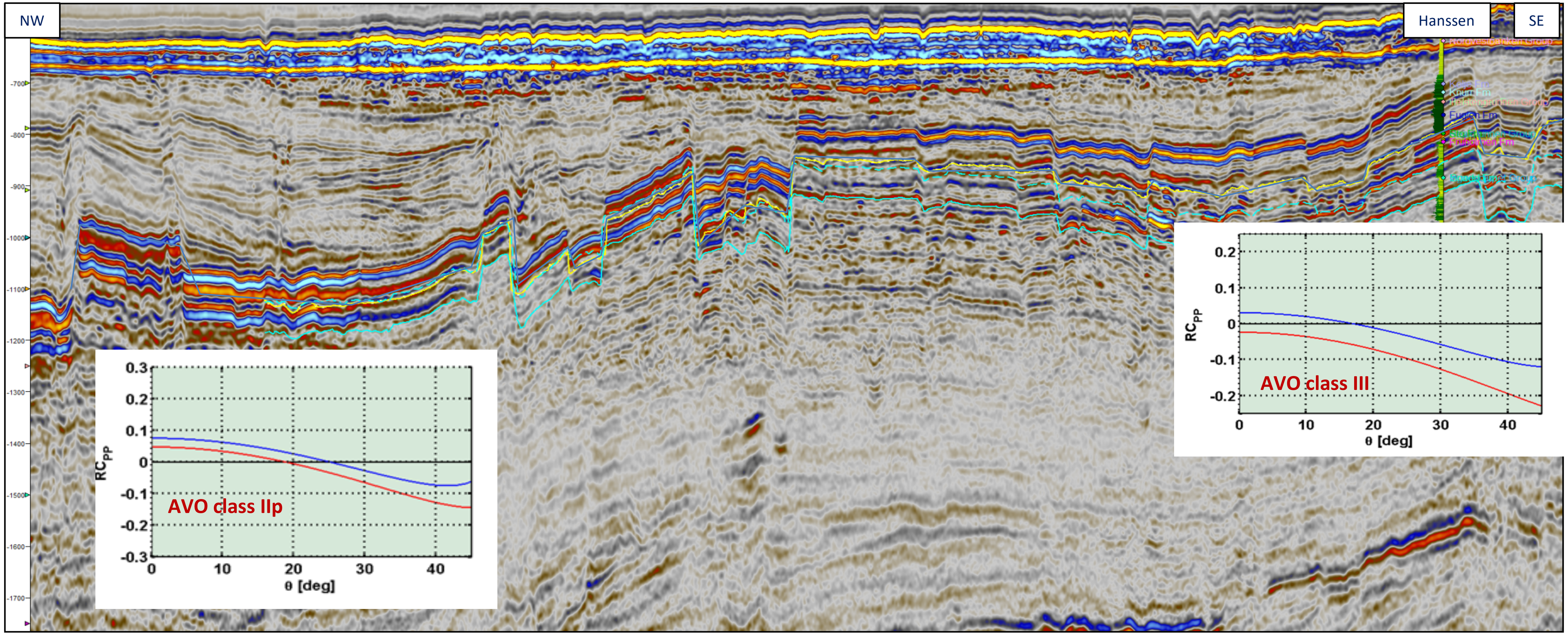


Hoop Area – Burial history affect seismic signatures (due to changes in both shales and sst)





Data courtesy of TGS



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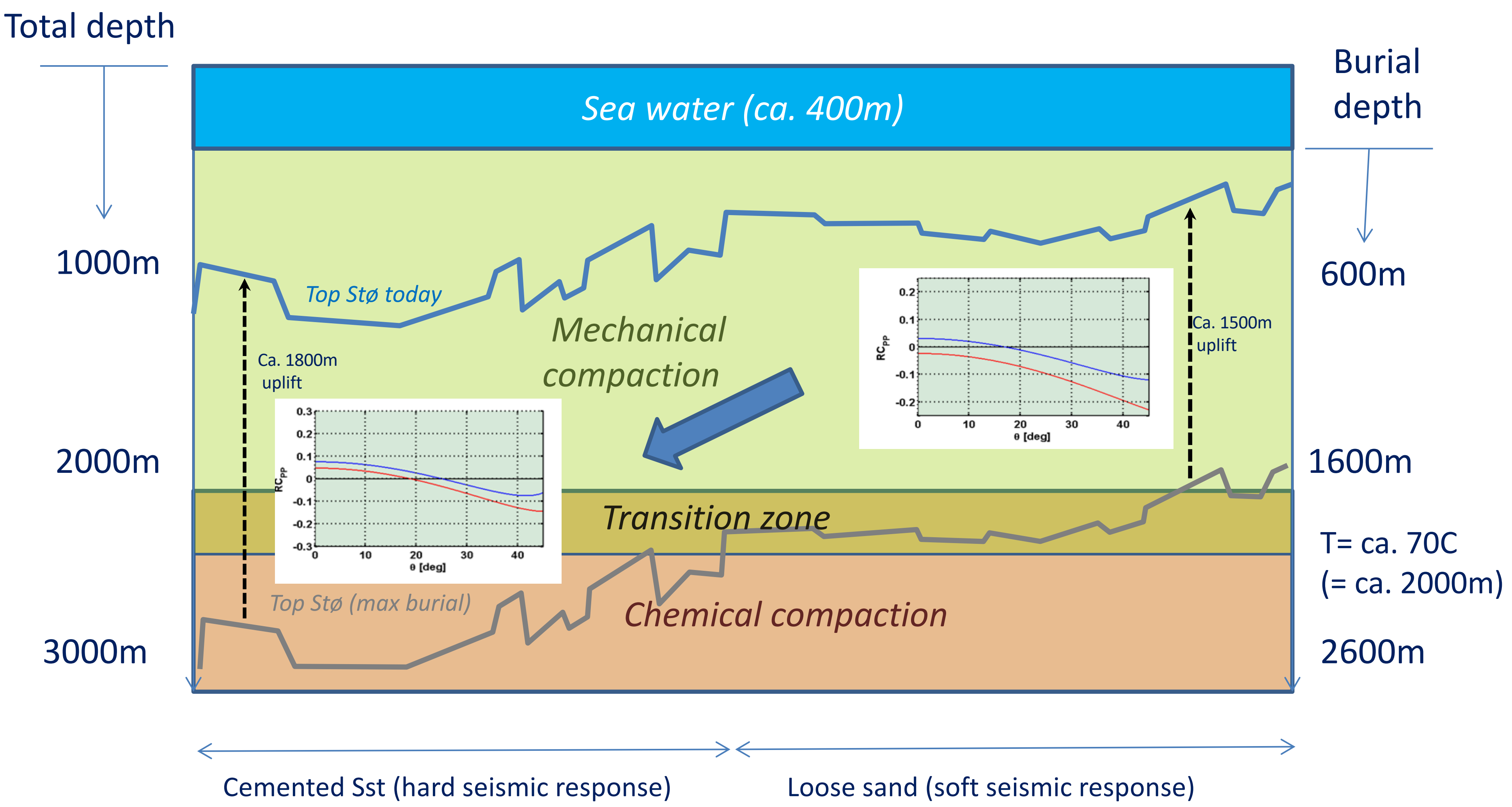
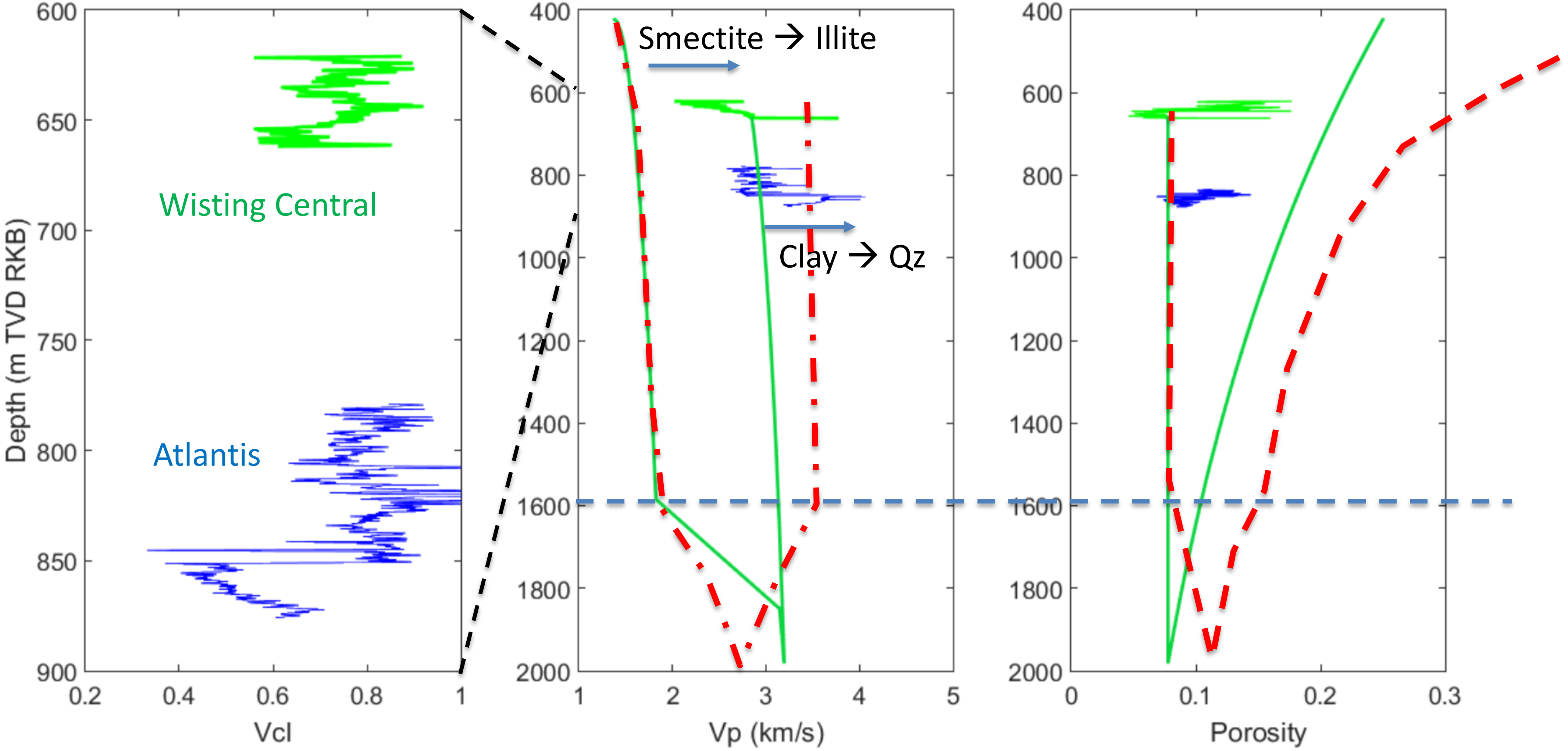
Schematic illustration of burial history, rock consolidation and AVO signatures

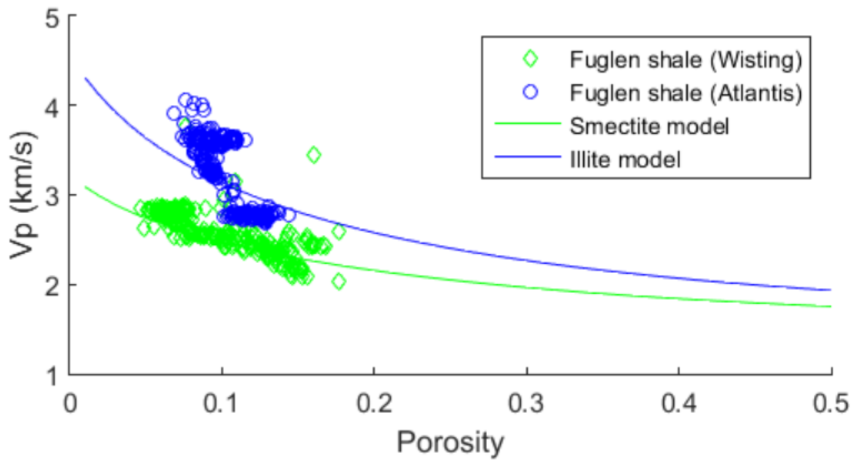


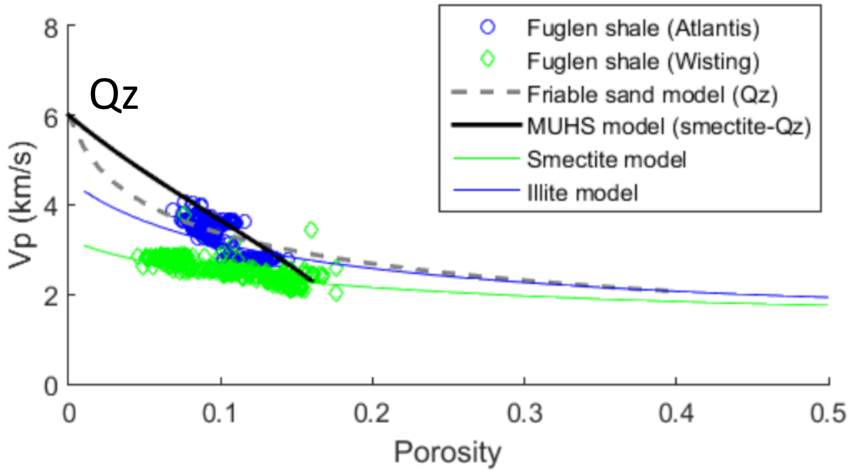
Shale depth t
Fuglen F

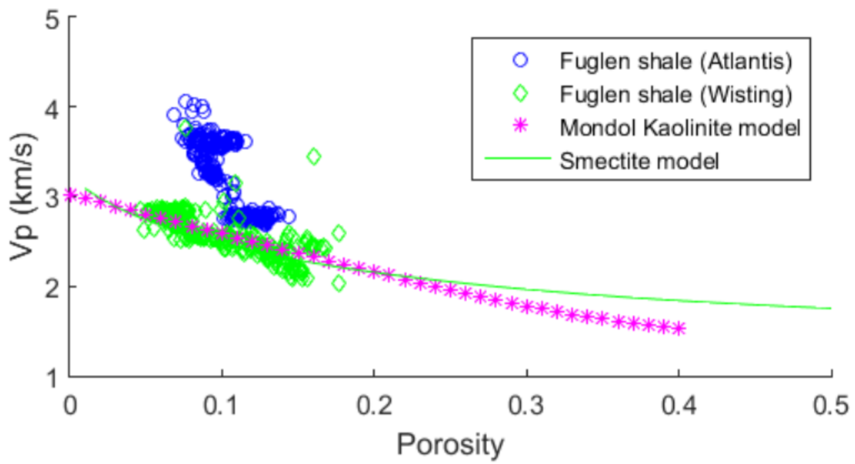
$$V_{q2} = \varphi_0 - (\varphi_0 - V_{q1})exp\frac{-MaA_0}{\rho\varphi_0 bc \times ln10}[10^{bT_2} - 10^{bT_1}]$$

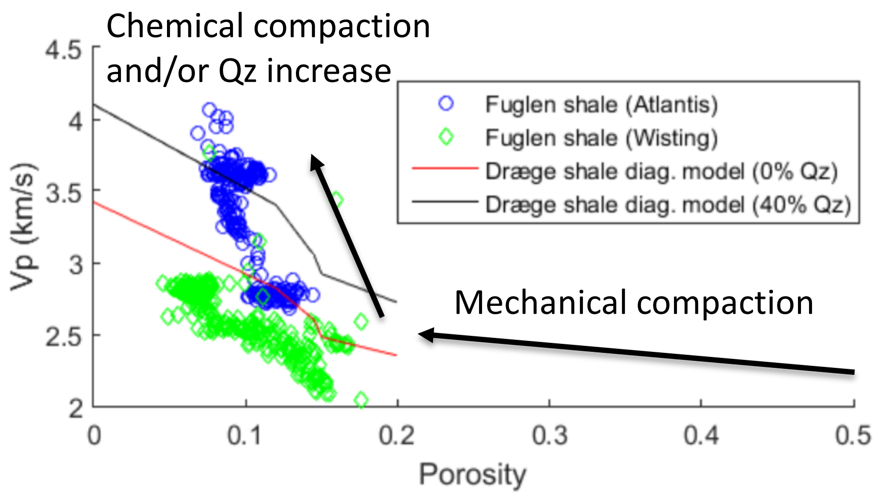


Rock physics modeling of Wisting and Atlantis caprock shale (Fuglen Fm)

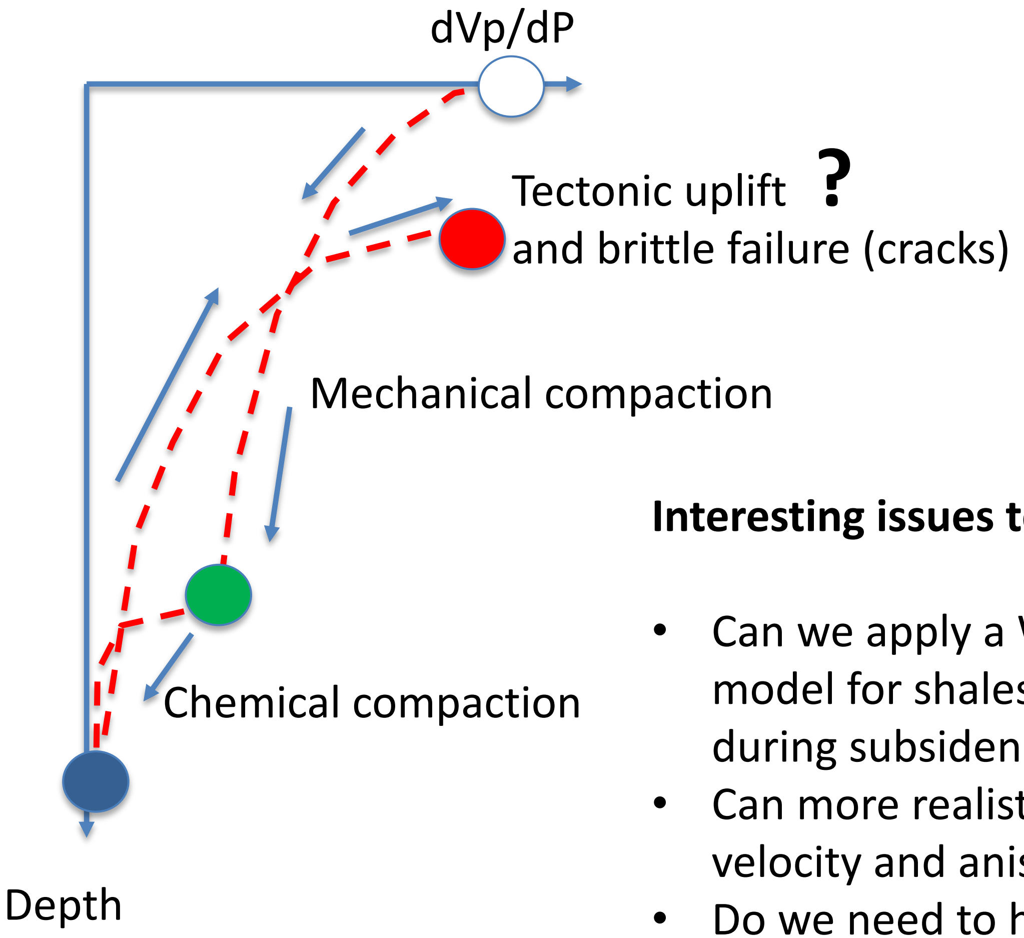








The road ahead – Improved understanding of shale RP properties during burial and uplift



Interesting issues to consider:

- Can we apply a Walderhaug-type cement model for shales? (Cementation both during subsidence and uplift if T>Tc)
- Can more realistic shale trends give better velocity and anisotropy predictions?
- Do we need to honour stress anisotropy during uplift?
- Implications for seal integrity?