Mechanisms for Top Seal Leakage - Evidence from Shear Wave Splitting

Michael Kendall[1] and Quentin Fisher[2]

1 - Department of Earth Sciences, University of Bristol, Wills Memorial Building, Queen's Road, Bristol, BS8 1RJ, UK. gljmk@bristol.ac.uk

2 - Centre for Integrated Petroleum Engineering and Geoscience, School of Earth and Environment , University of Leeds, q.fisher@see.leeds.ac.uk

CiPEG

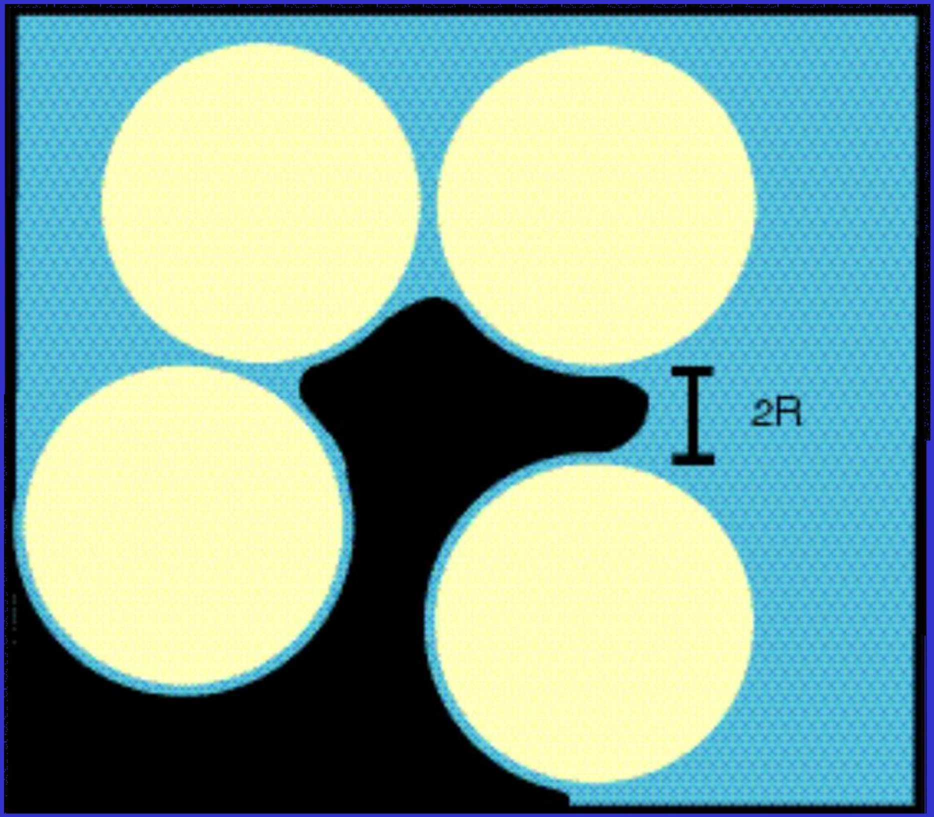
University of BRISTOL

UNIVERSITY OF LEEDS

Outline

- Top Seal Leakage Mechanisms
  - Capillary vs fracture leakage
- Shear wave splitting
- Valhall microseismicity
  - Temporal variations
  - Frequency dependence
- Drive and top seal leakage in HTHP reservoirs
- Conclusions

Capillary seals



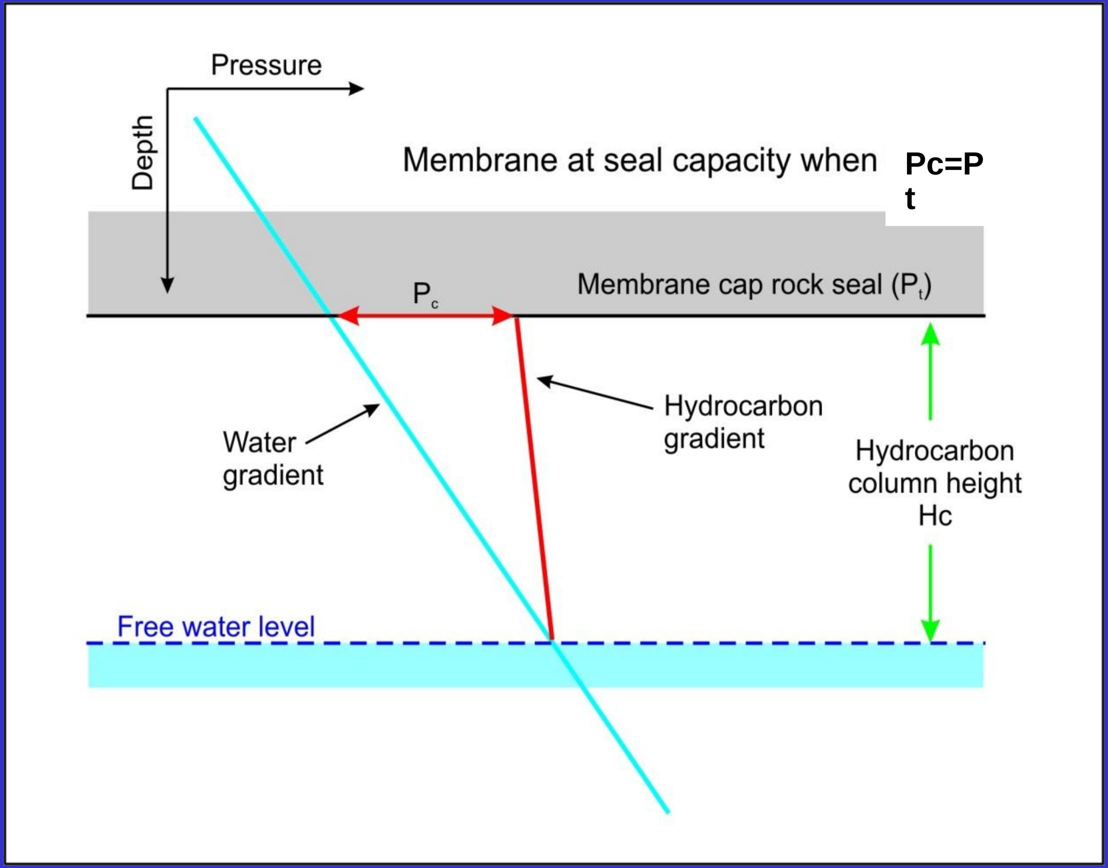
$$P_c = \frac{2\sigma \cos\theta}{R}$$

Where:

- P_{th} = *threshold pressure (psi)*
- σ = *interfacial tension (Dynes/cm)*
- θ= *contact angle*
- R = *pore throat radius (microns)*

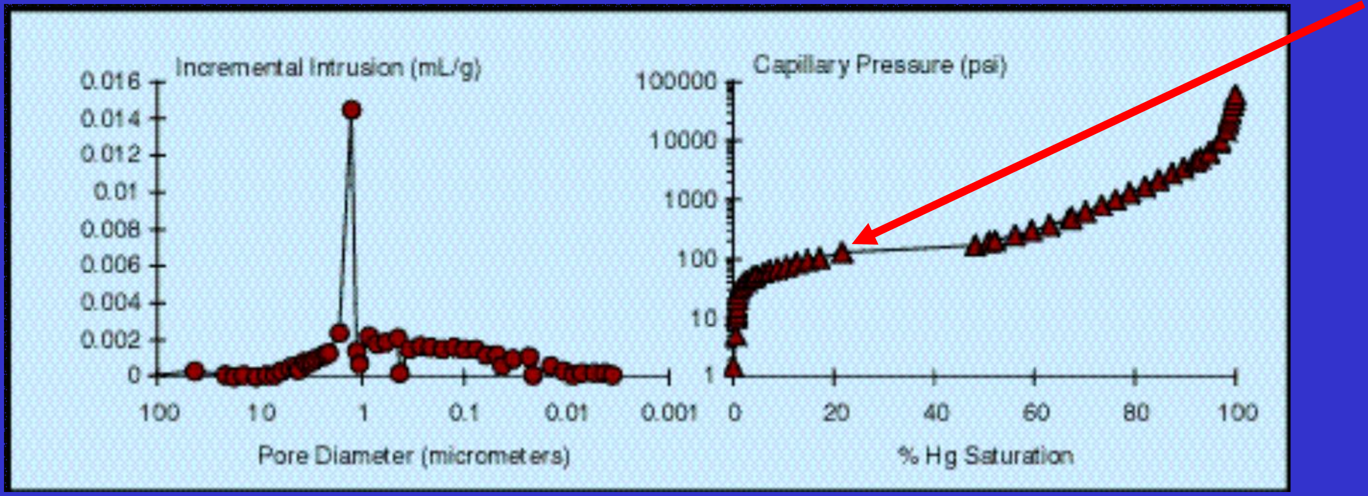
Top seals have small pore-throat sizes and therefore can act as capillary seals

Buoyancy Force (P_b) (Capillary Pressure, P_c)



- Buoyancy Force or Capillary pressure (P_c) increases with height above free water level.
- Maximum column height supported is sealing capacity

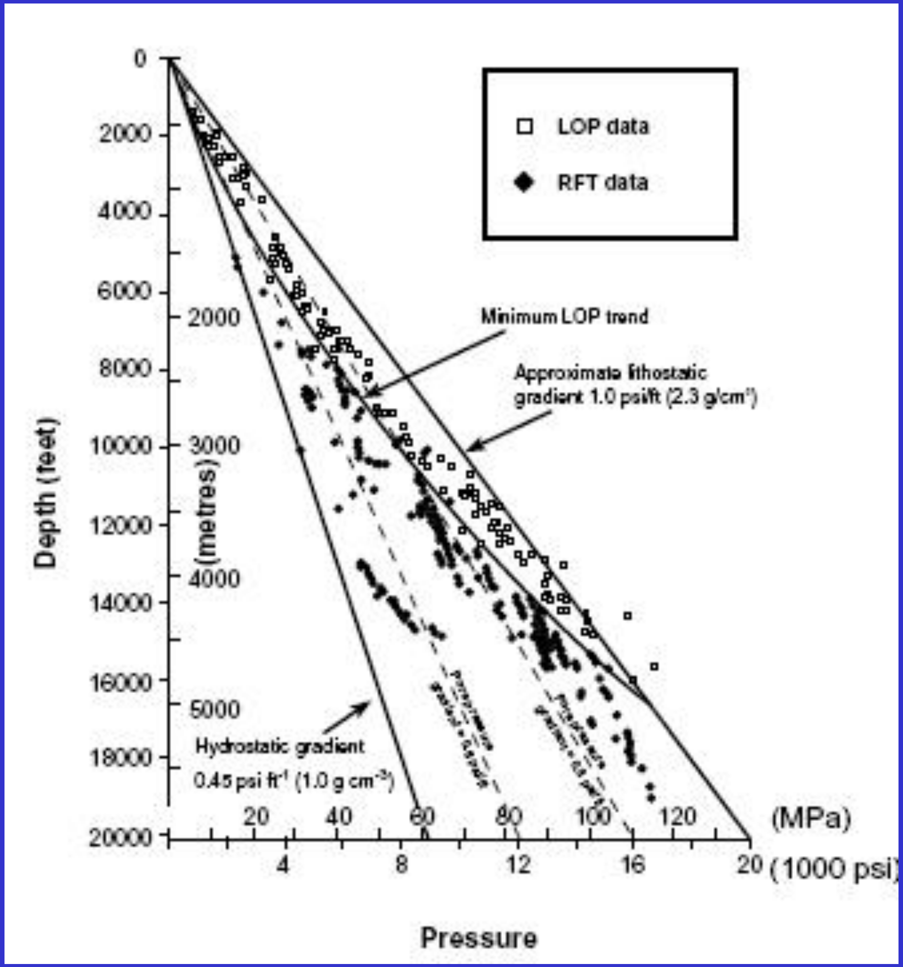
Hg-injection analysis



- Hydrocarbon column heights often calculated from Hg-injection data assuming a water-wet top seal
- Shale samples frequently have threshold pressures that can support very high column heights (>> km's)

Leakage along hydrofractures

- Pore pressure needs to overcome minimum horizontal stress while leakage occurs



From Nordgård Bolås and Hermunrud, 2003

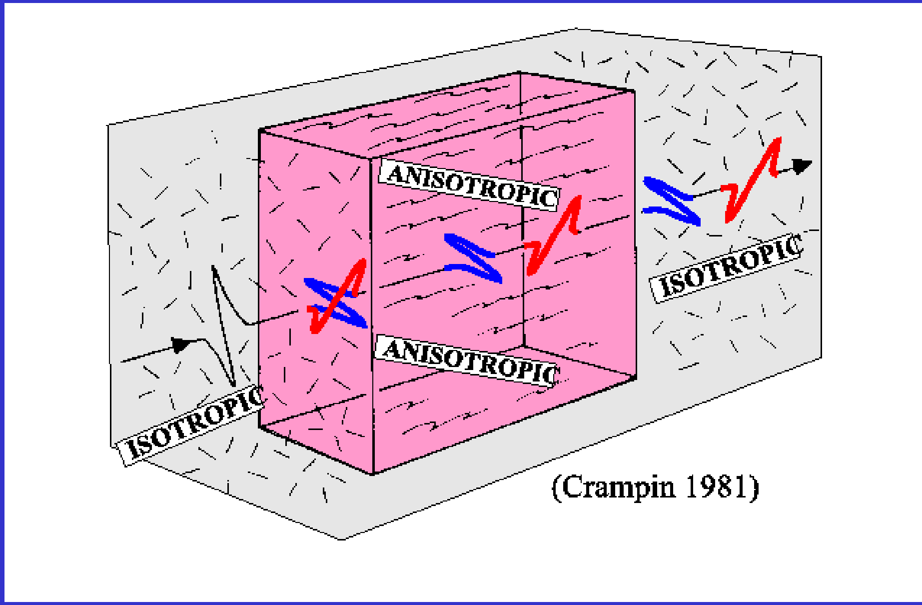
Problems with existing methodologies

- Large regional databases may be needed to predict distribution of pore pressure and hence hydrofracture formation
- Large regional databases of the capillary pressure characteristics of top seals are needed to predict capillary leakage
- Often capillary pressure measurements suggest top seals shouldn't leak
- Hydrocarbons often found in cuttings throughout top seal,
  - Seems slightly inconsistent with localised flow through large fractures
  - Seems slightly inconsistent with an invasion percolation leakage as would be expected via capillary leakage
- **Are there other leakage mechanisms?**
- **Are there better methodologies to identify leaked reservoirs?**

Shear wave splitting

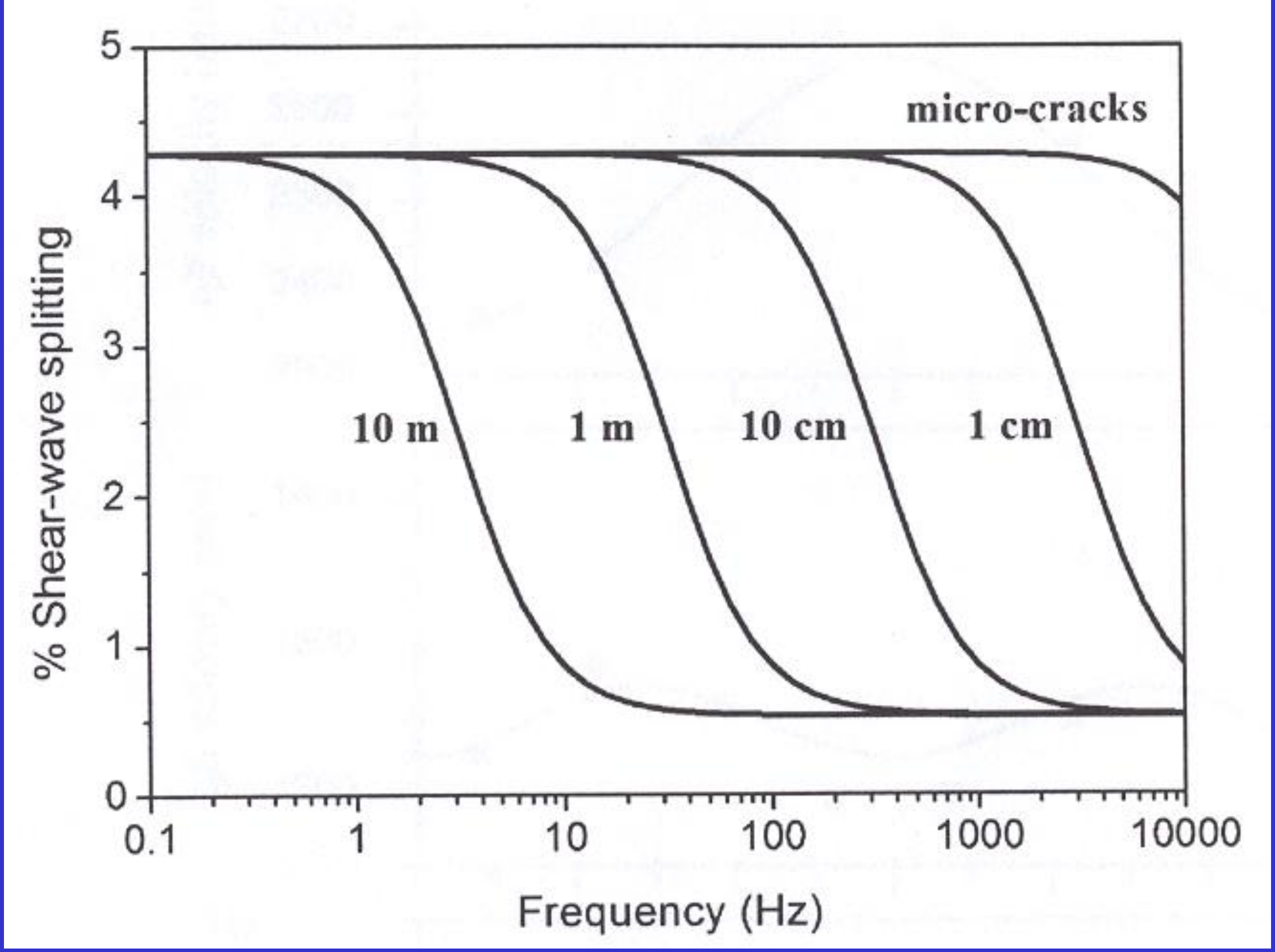
Seismic anisotropy & shear wave splitting

- Seismic anisotropy is the directional dependence in seismic velocities
  - Indicator of order in a medium
  - Indicator of style of flow, stress regime or fracturing



Shear-wave splitting

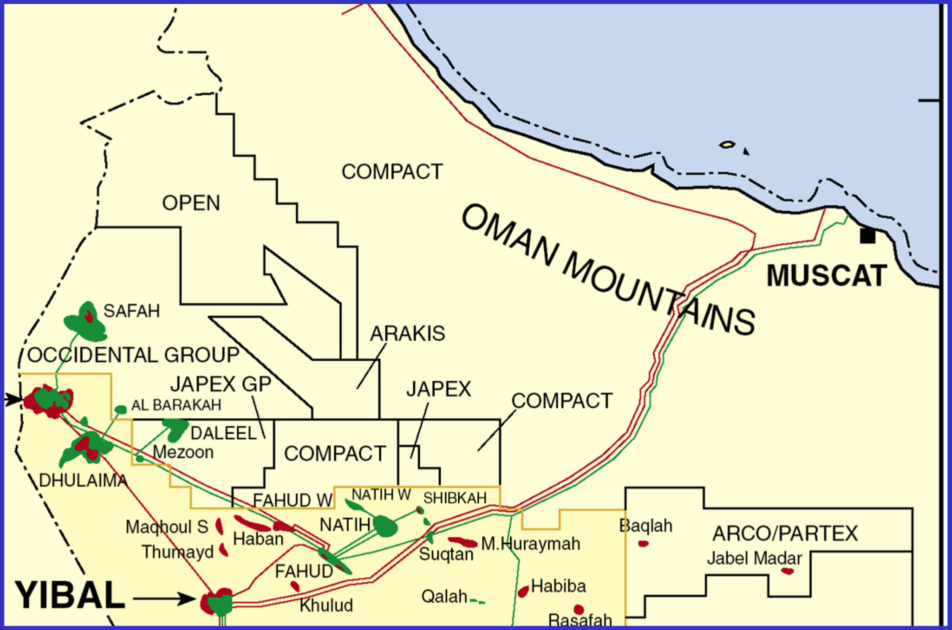
Fracture size estimation using frequency-dependent shear-wave splitting

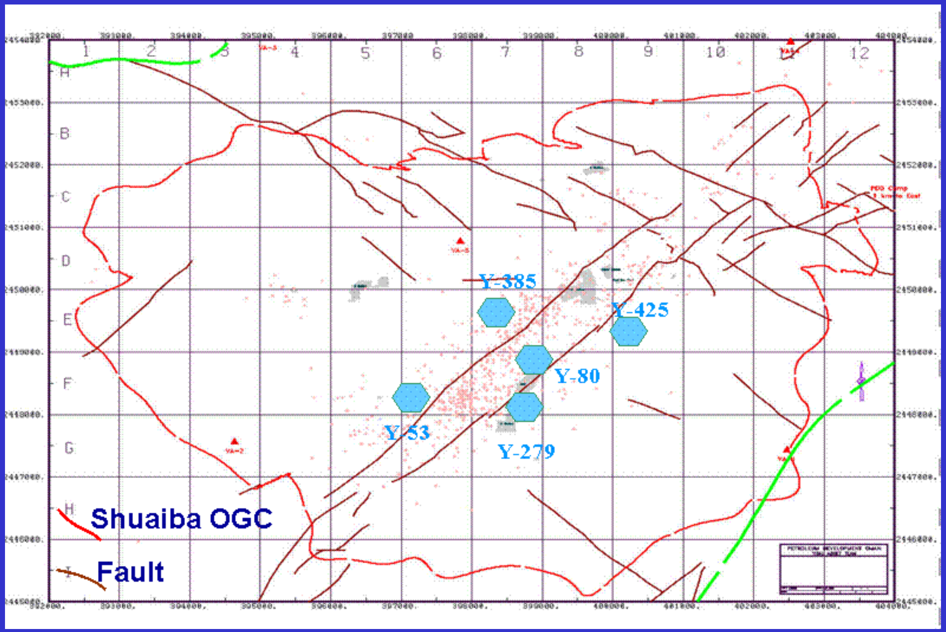


After Maultzsch et al. (2003); EAP work

Yibal field, Oman

- 1+ year experiment
- ~40 3C receivers
- Vertical arrays in 5 boreholes
- 22 days of data, 600 located events



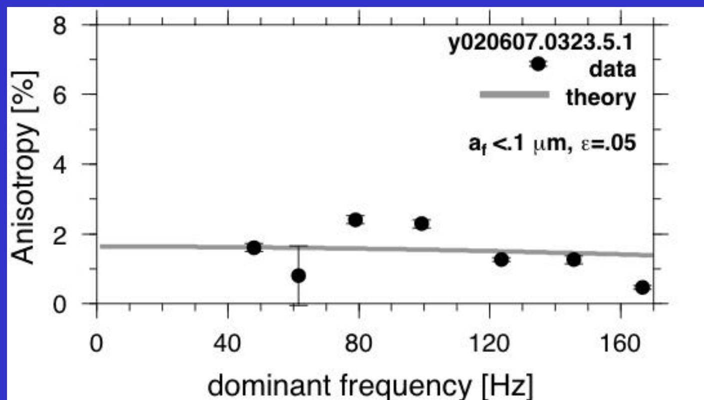


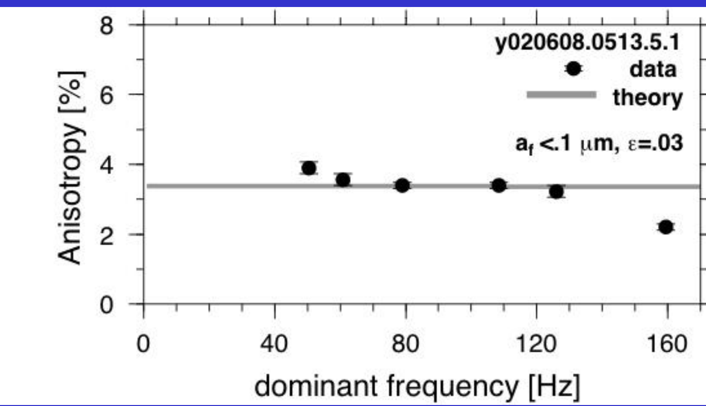
University of BRISTOL

UNIVERSITY OF LEEDS

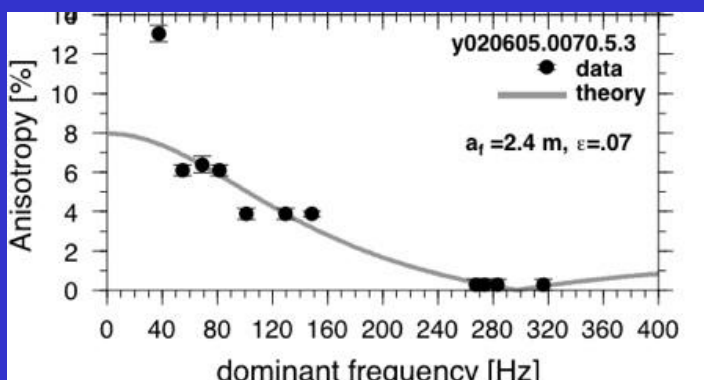
Frequency dependence of shear wave splitting

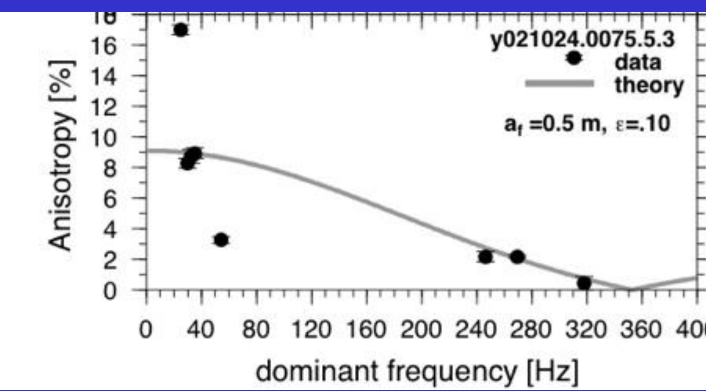
- Caprock: No frequency dependence - suggests length scales smaller than 1μm - rock is acting as a seal.





- Reservoir: Frequency dependence suggests fractures of ~1m scale, in agreement with outcrop and core analysis.





See: Al-Anboori, Kendall and Chapman, 2006

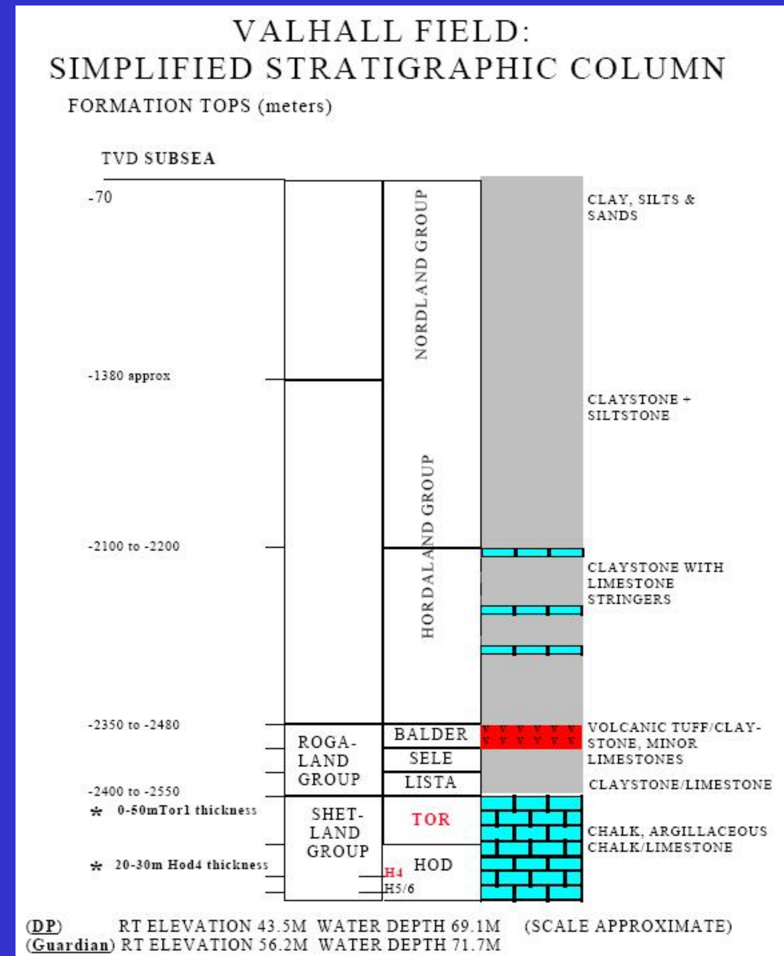
CiPEG

University of BRISTOL

UNIVERSITY OF LEEDS

Valhall Field - Background

(from Barkved, 2003)



(from Kristiansen, 2003)

CiPEG

University of BRISTOL

UNIVERSITY OF LEEDS

Valhall Field - Background

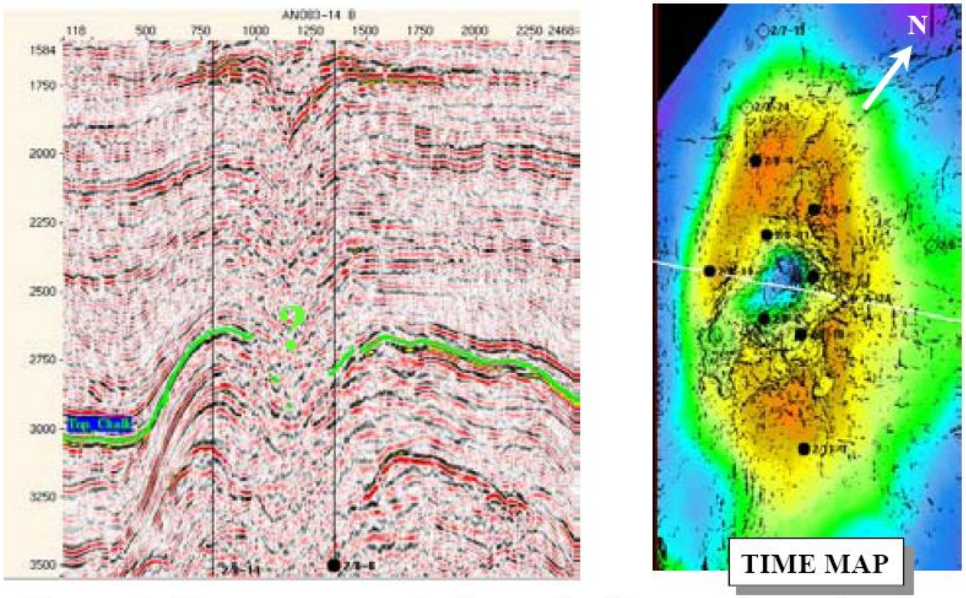
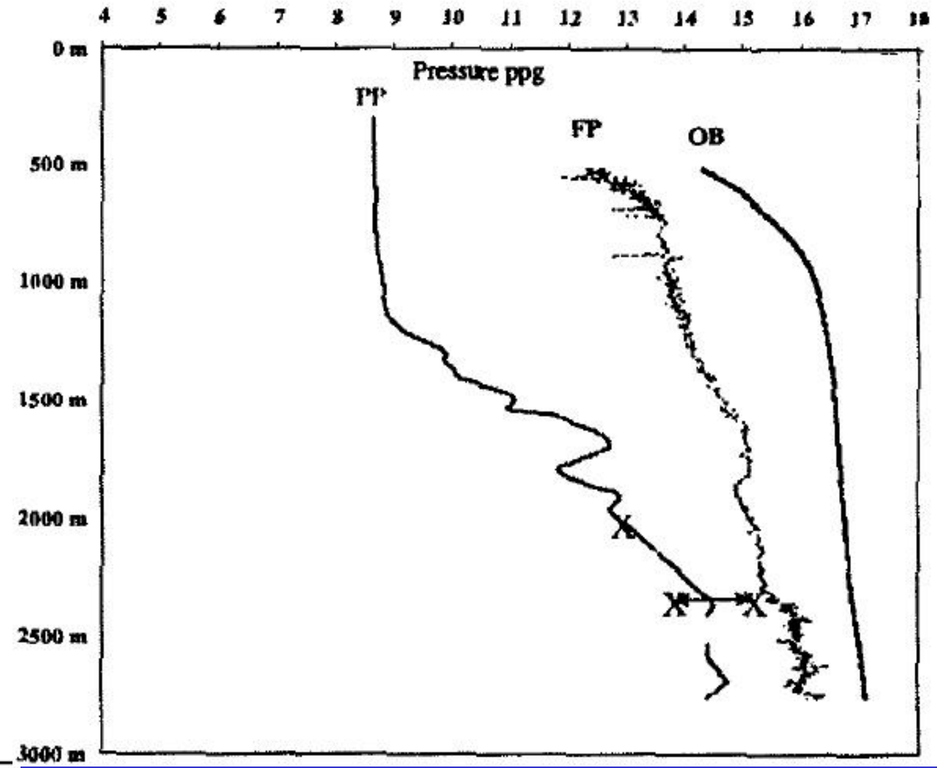


Figure 6: The presence of a low velocity gas-charged Miocene diatomaceous interval creates a "gas cloud" effect that distorts the seismic time data.



(from Barkved, 2003)

(from Kristiansen, 1998)

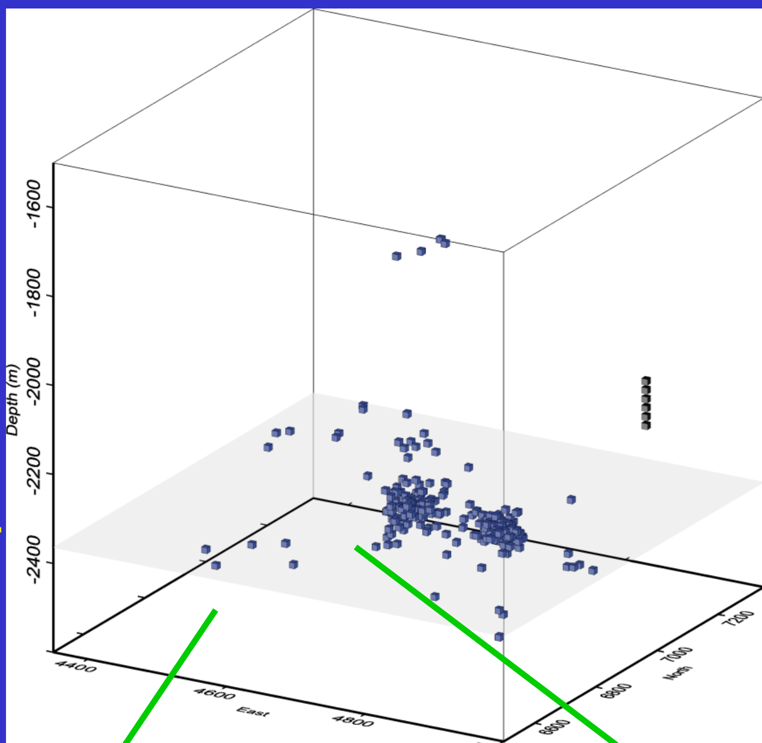
CiPEG

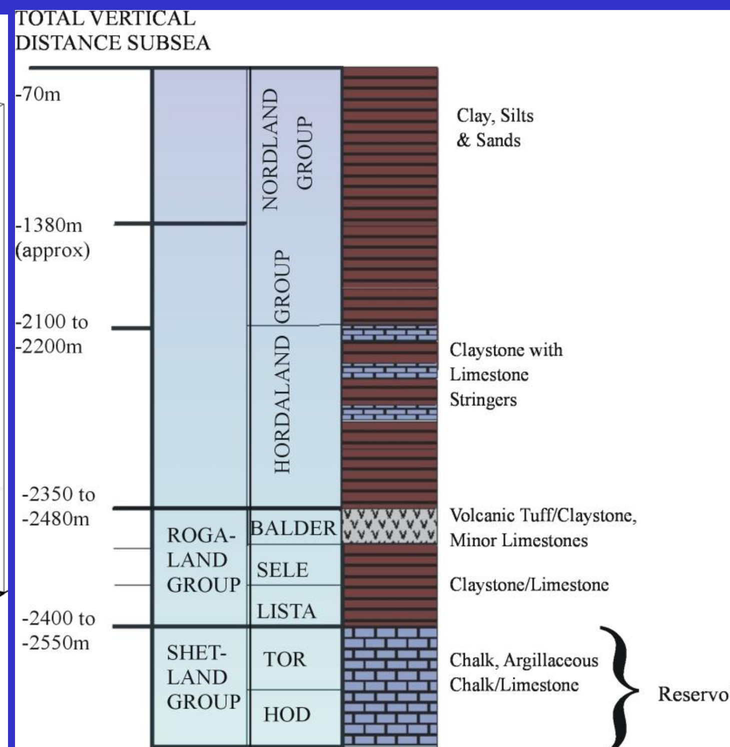
University of BRISTOL

UNIVERSITY OF LEEDS

Valhall microseismic experiment

- 2 month experiment, 6 receivers, 3 component, Vertical array, 20 m spacing, 324 Located events
- Initial analysis suggested distributed in two diffuse clusters





Top Balder

Reservoir

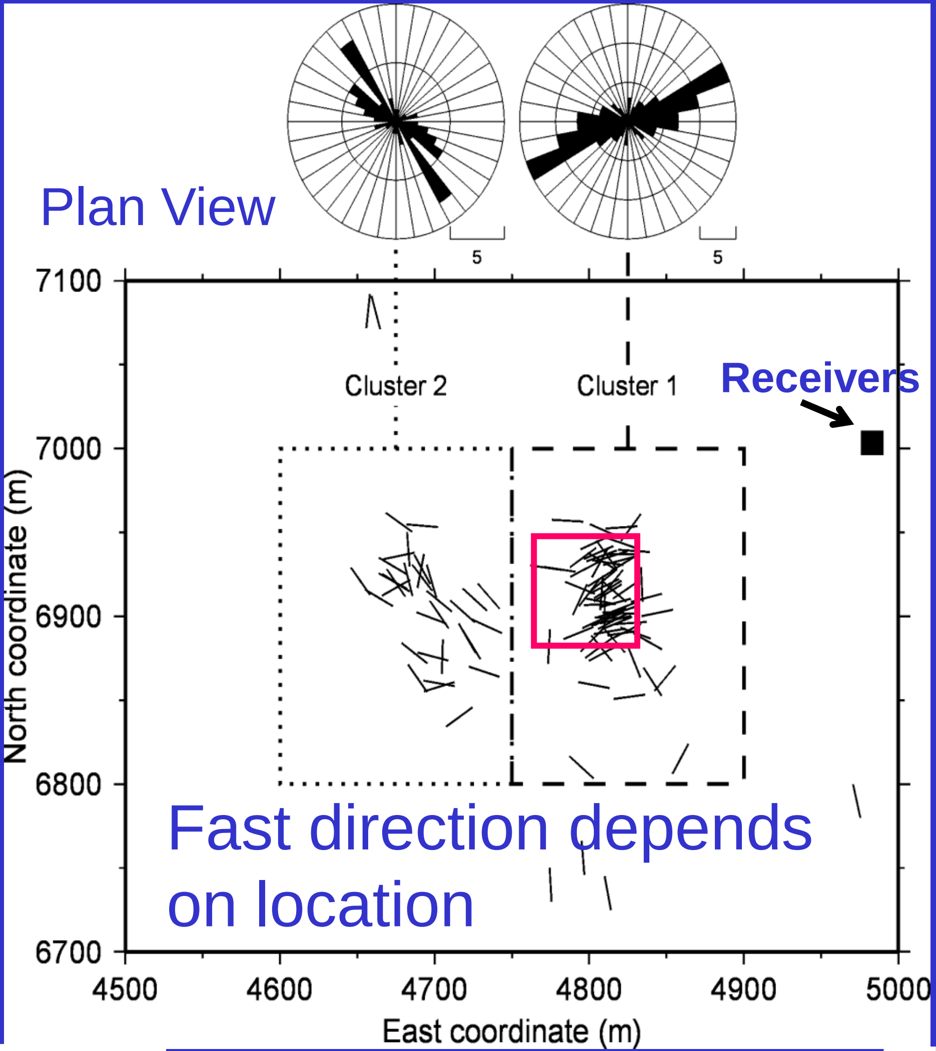
Cap rock

CiPEG

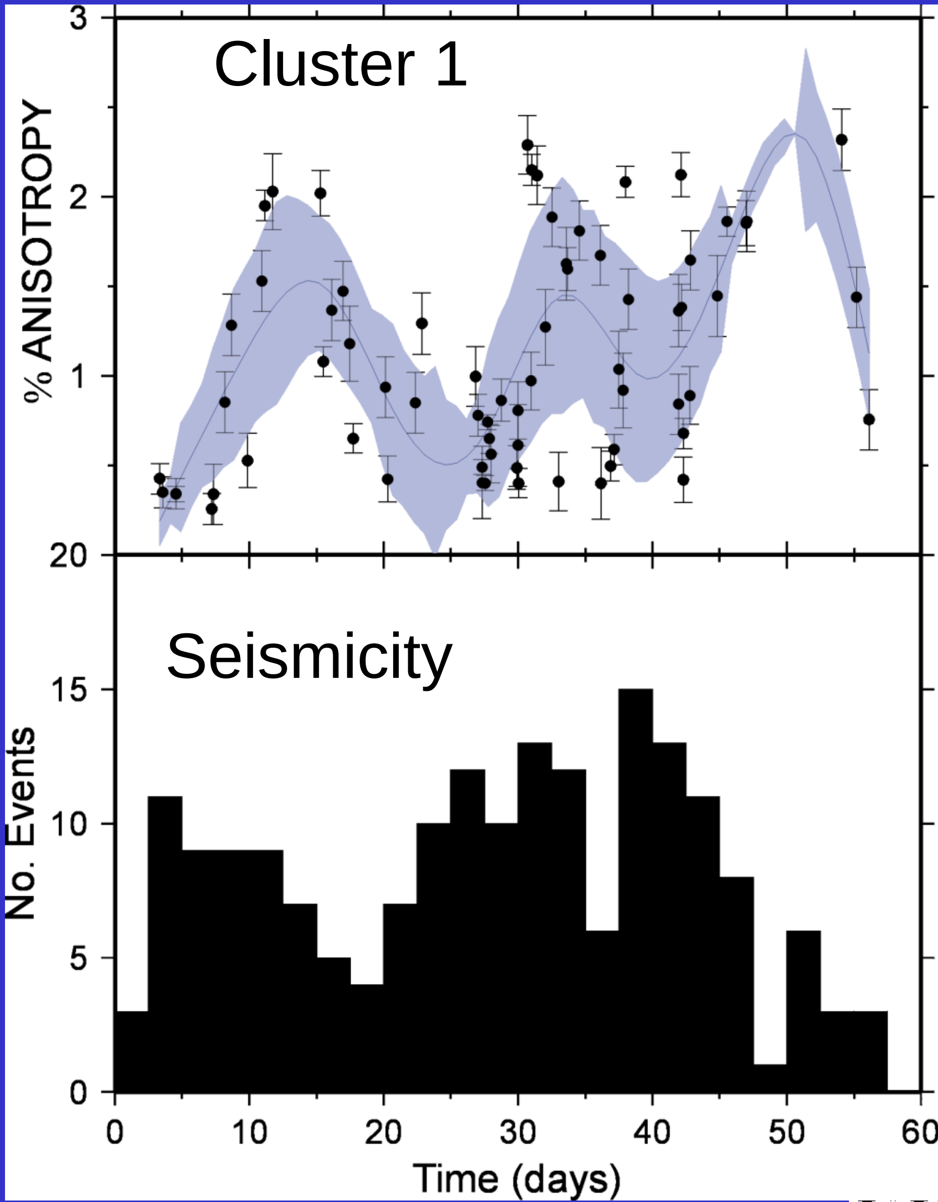
University of BRISTOL

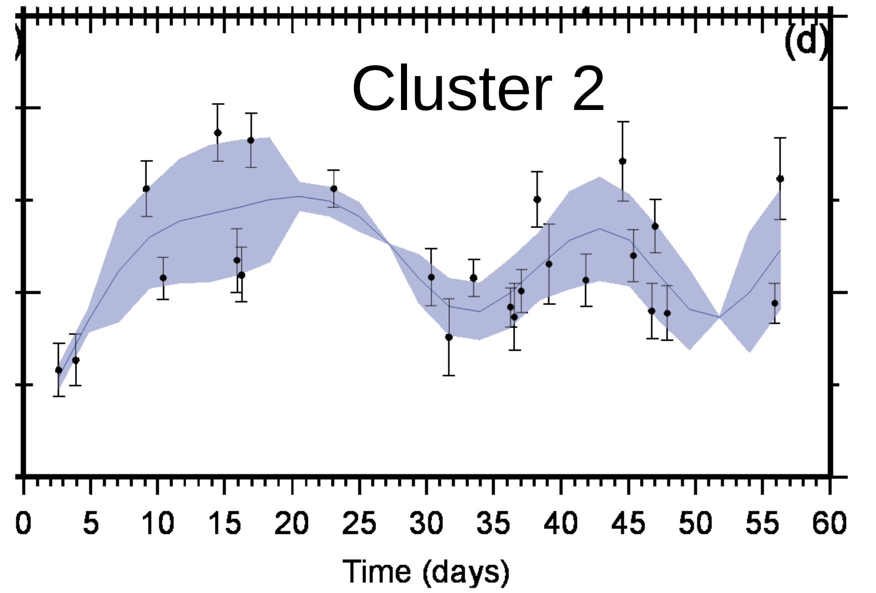
UNIVERSITY OF LEEDS

Splitting results - location and fast direction



Temporal variations in anisotropy





In-synch variations between clusters.

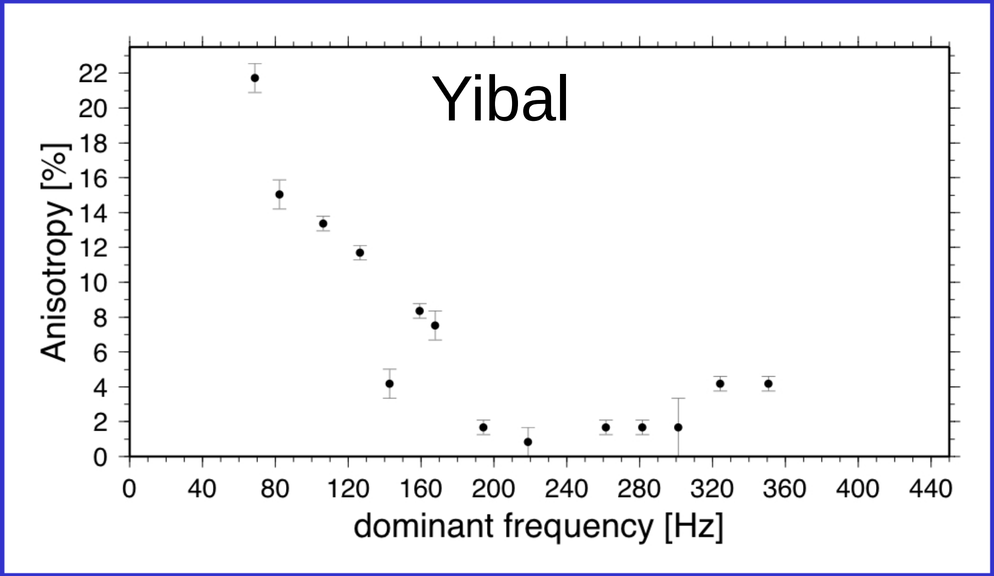
- cannot be explained with a single set of fractures.

Frequency dependence of S-wave splitting

Yibal Reservoir:

• Results for carbonate reservoir.

• Clear freq-dependent anisotropy

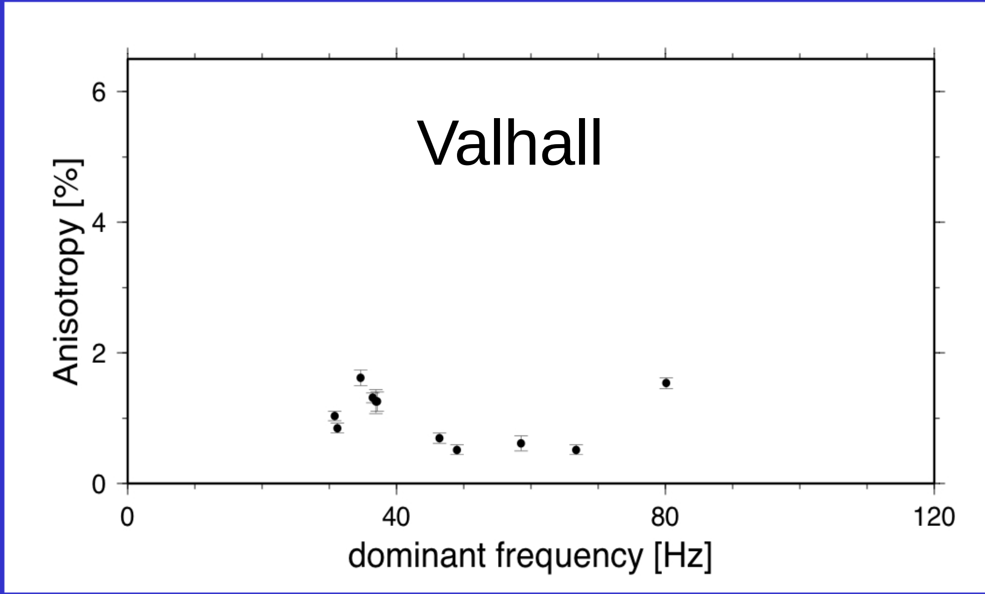


Valhall Caprock:

• Results for overburden

• Low amount of anisotropy

• No obvious freq-dependent anisotropy



CiPEG

University of BRISTOL

UNIVERSITY OF LEEDS

Potential implications of shear wave splitting results

- Gas cloud above Valhall and oil within cuttings provides evidence of hydrocarbon leakage from structure
- Temporal variation of shear wave splitting and lack of frequency dependence in overburden of Valhall suggests presence of microcracks
- Overpressures immediately above the reservoir approach fracture gradient
- Is it possible that overpressures are causing dilation of pore space in overburden (i.e. microfracture formation) that reduces the capillary entry pressure of the caprock?
- **In other words, could leakage be occurring by an hybrid leakage mechanism somewhere between large-scale fracture formation and pure capillary leakage?**

Permeability vs confining pressure

- Experimental data shows dramatic increase in single-phase permeability as P_p reaches confining pressure
- In nature this is equivalent to P_p approaching S_{hmin}

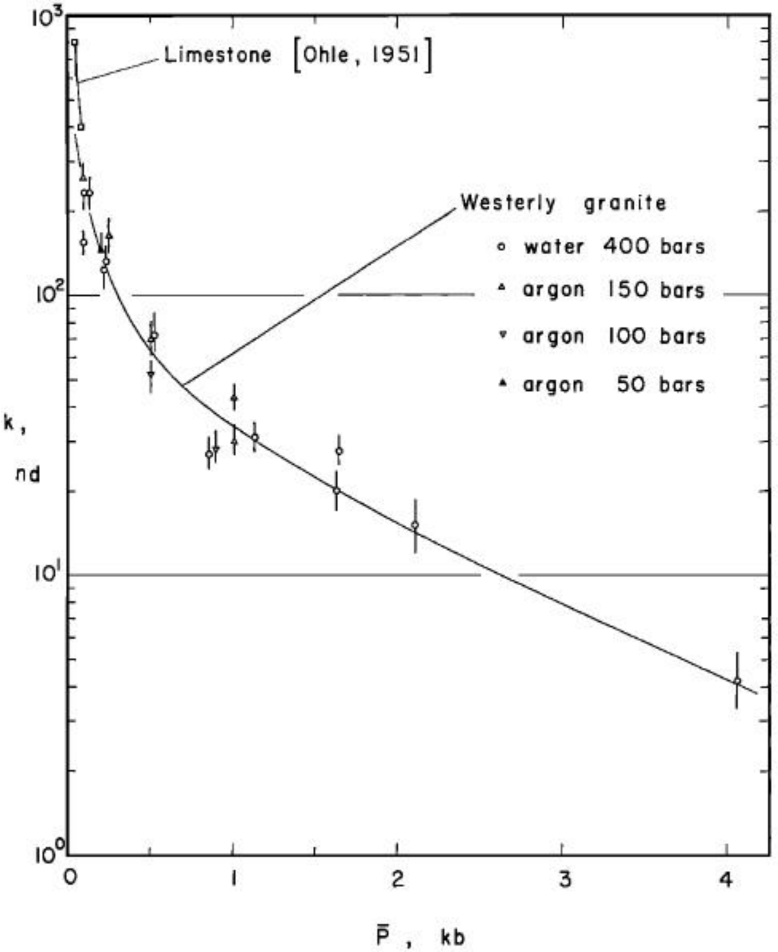


Fig. 5. Permeability k as a function of effective confining pressure $\overline{P}$. Length of short bars indicates probable error for each measurement.

From Brace et al., 1968

CiPEG

University of Bristol

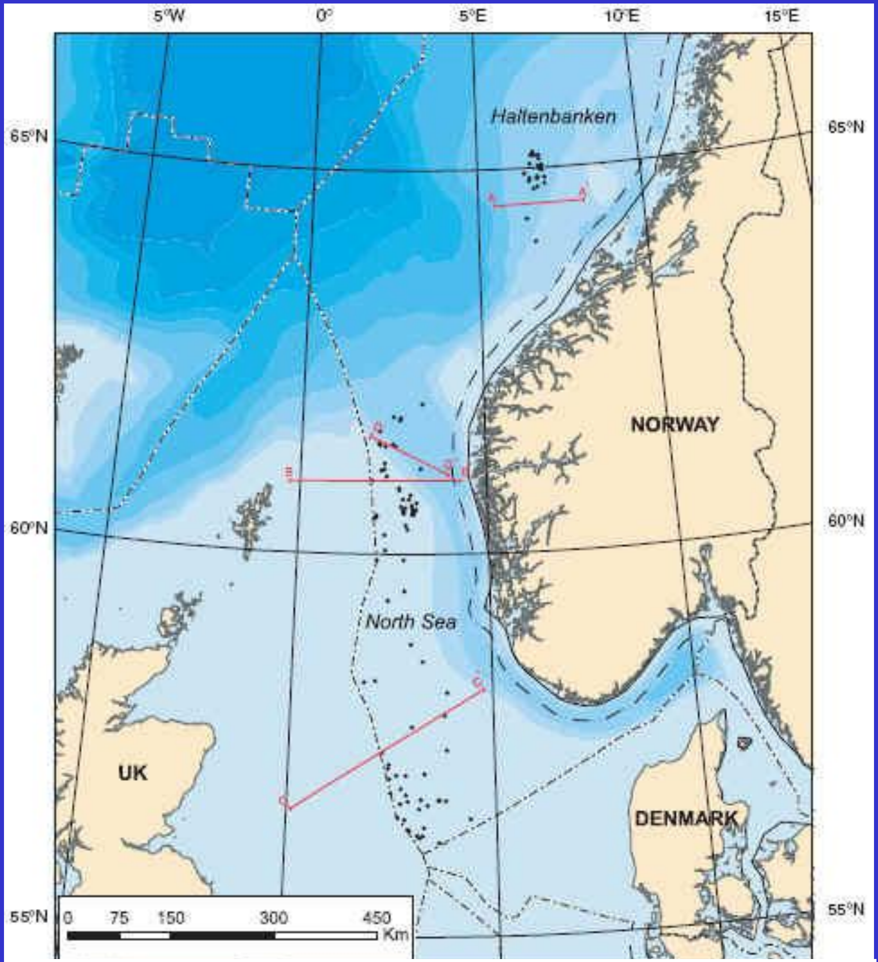
University of Leeds

Petroleum leakage from reservoirs

- Two end-member mechanisms for leakage described as points of reference
  - Leakage along faults and fractures at hydrostatic pore pressures
    - Leakage requires brittle rheology
    - Important in deep/hot reservoirs and those that have experience massive up-lift
  - Leakage through fractures in ductile caprock
    - Requires P_p to exceed S_{hmin}
    - <u>Requires large amount of pressure support to keep fractures open during leakage</u>

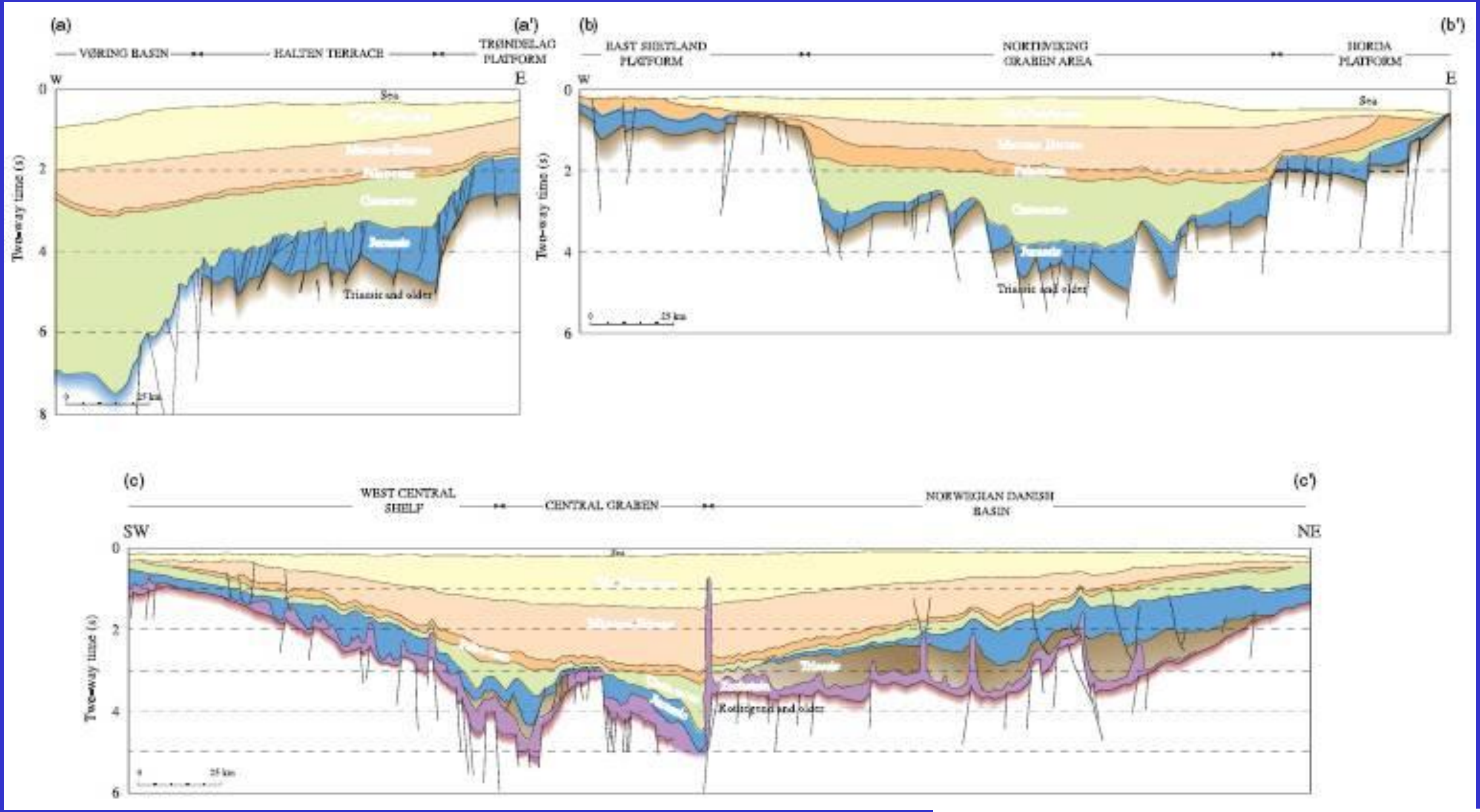
Leakage distribution in North Sea/Haltenbanken

- High incidence of leakage to west of Haltenbanken
- Moderate incidence of leakage towards south of Central Graben
- Low incidence of leakage in northern North Sea



(from Tiege et al., 2007)

Leakage distribution in North Sea/Haltenbanken



(from Teige et al., 2007)

Conclusions

- Passive seismic monitoring has revealed that shear wave splitting occurs in the overburden of Valhall
- The lack of frequency dependence may indicate the presence of distributed microcracks/dilated grain boundaries within the overburden
- The Valhall caprock contains a gas cloud and oil within cuttings providing evidence of leakage
- Integration of observations may indicate an hybrid mechanism for leakage of caprocks that is somewhere between the formation of large-scale hydrofractures and pure capillary leakage

Conclusions

- Considerable drive is required to keep fractures open in ductile caprocks for extensive hydrocarbon leakage to occur
  - Drive should therefore be considered when risking top seal leakage
- Jurassic sediments in western Haltenbanken have ample drive and have experienced considerable leakage
- Leakage is not as common in northern North Sea where there is less drive for leakage
- Leakage in HTHP reservoirs in Central Graben is intermediate