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In-situ stress field characterization to support the energy transition

British Geological Survey

Talk Outline

- UK Net zero targets
- Introduction to the SHARP project
- In-situ stress field
- Collection of new stress field observations
- Current understanding of the stress field near SHARP case study
- Results and conclusions

UK Net Zero Targets

UK Net Zero Commitments

- In 2019 UK government committed to reduce greenhouse emissions by
  - 68% by 2030, based on 1990 levels (1)
  - 100% by 2050, based on 1990 levels (1)
- This was reviewed in 2022 with the UK having reduced emissions by nearly 50% based on 1990 levels (2)
- Achieving this target requires the removal of CO2 through CCS alongside low carbon technologies such as geothermal (2)

Removals of Carbon Dioxide

- “Net zero must involve capturing emissions from processes which still use fossil fuels and storing this carbon” (2)
- “At present, approximately 0.1% of carbon dioxide generated from geological sources is restored to the geosphere
- Achieving geological net zero means, very simply, increasing this re-stored fraction to 100%” (2)
- By 2050 UK residual emissions are expected to be 40 to 100 $MtCO_2$ p/a (2)

NSTA Carbon Storage Licensing Round

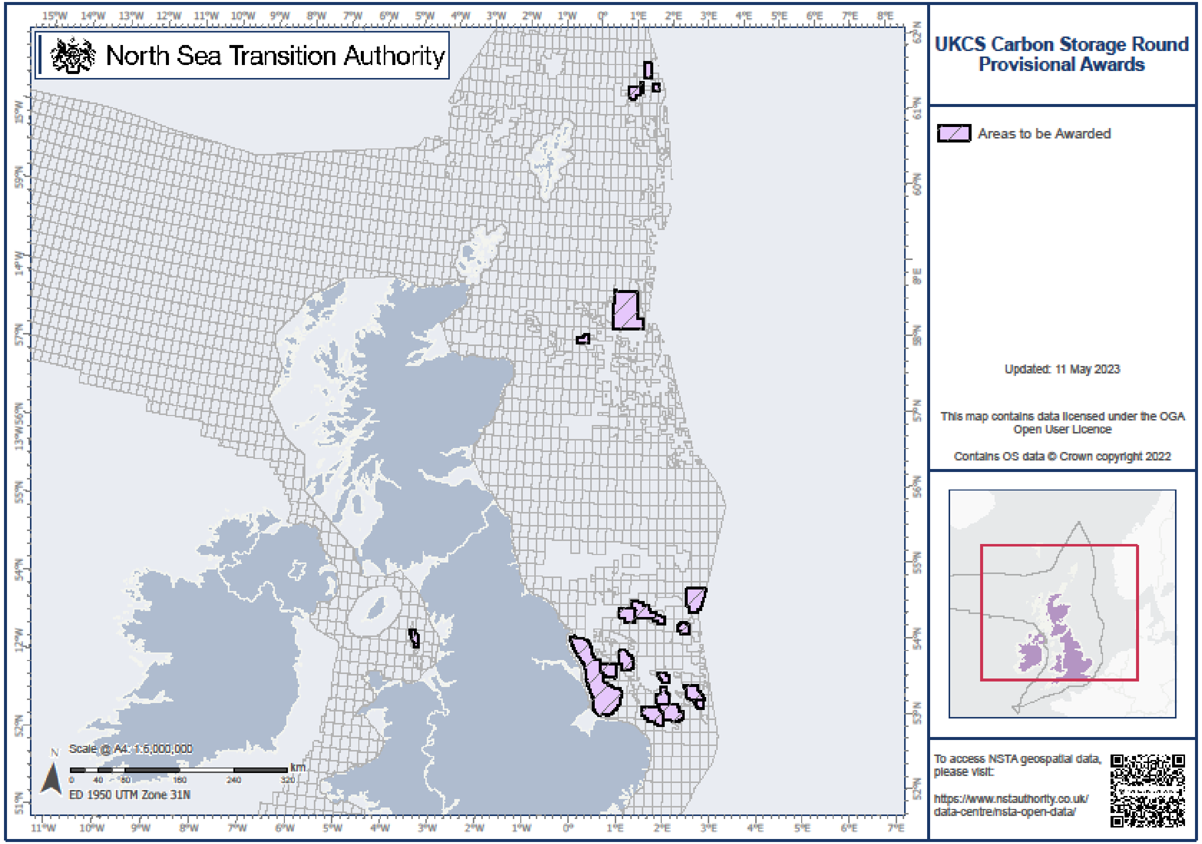


Image from: NSTA (2023)

- First UK carbon storage licensing round
- On the 18th May 2023 provisional storage licenses were offered for offshore sites

Role of BGS in the energy transition

- Public facing body providing information to government, industry and academia

- BGS contributes towards Net Zero by allowing our stakeholders to optimise the role, scale and location of multiple geological decarbonisation technologies in the UK. (3)

- “BGS will facilitate the implementation of subsurface, zero-carbon technologies by delivering data, analysis and knowledge.” (3)

SHARP Storage:

Stress history and reservoir pressure for improved quantification of CO_2 storage containment risks

SHARP Storage

- Collaboration between 16 research institutions and companies under the Accelerating CCS Technologies (ACT3) Programme

- The project aims to understand and reduce the uncertainties related to subsurface CO_2 storage containment risk by characterising the in-situ stress and its evolution

- Six case studies from chosen from sites in the North Sea and India (4)

SHARP Storage

Accelerating CCS Technologies

SHARP Stress Field Characterisation

- Aims to understand and mitigate risks from seismicity and fault reactivation.

- Split into three work packages:
  - Integrated North Sea seismic catalogue
  - Update existing catalogue of borehole stress observations
  - Investigate the use of shear wave splitting to characterise the stress field

In-situ stress field

Tectonic stress field

- At depth, the tectonic stress field can be resolved into three principal components:
  - Vertical stress
  - Minimum Horizontal Stress
  - Maximum Horizontal stress

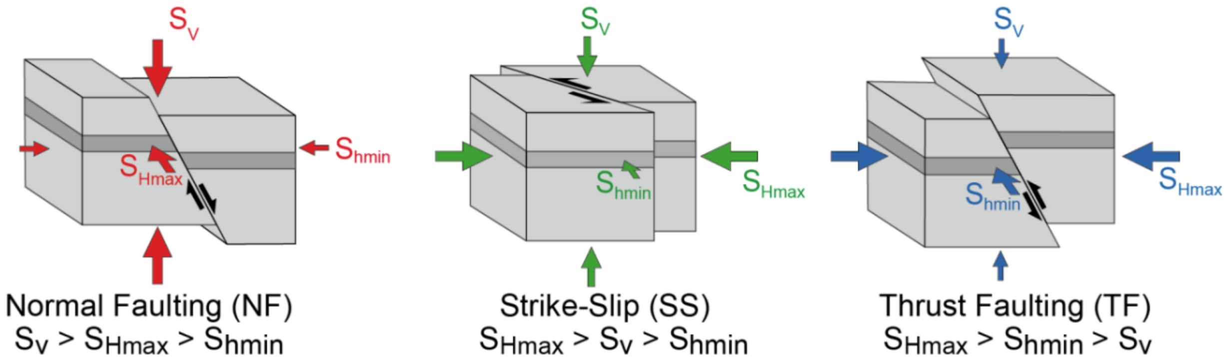


Image from: Heidbach *et al*. (2016a)

Tectonic stress field - Continued

- Full characterisation of the stress field also requires an understanding of
  - Orientation of the horizontal stresses
  - Pore pressure

- An understanding of the stress field is required for the:
  - Planning drilling operation
  - Fault Stability Analysis

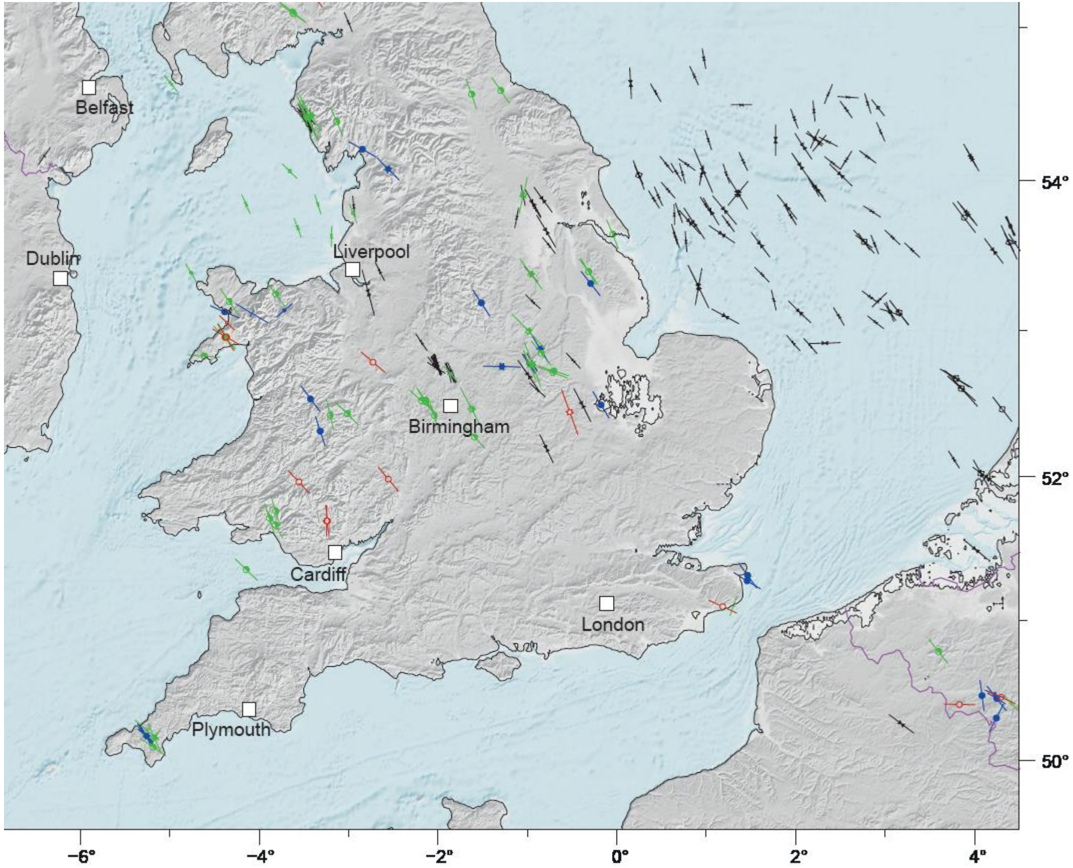


Image from: Kingdon *et al*. (2022)

World Stress Map Project

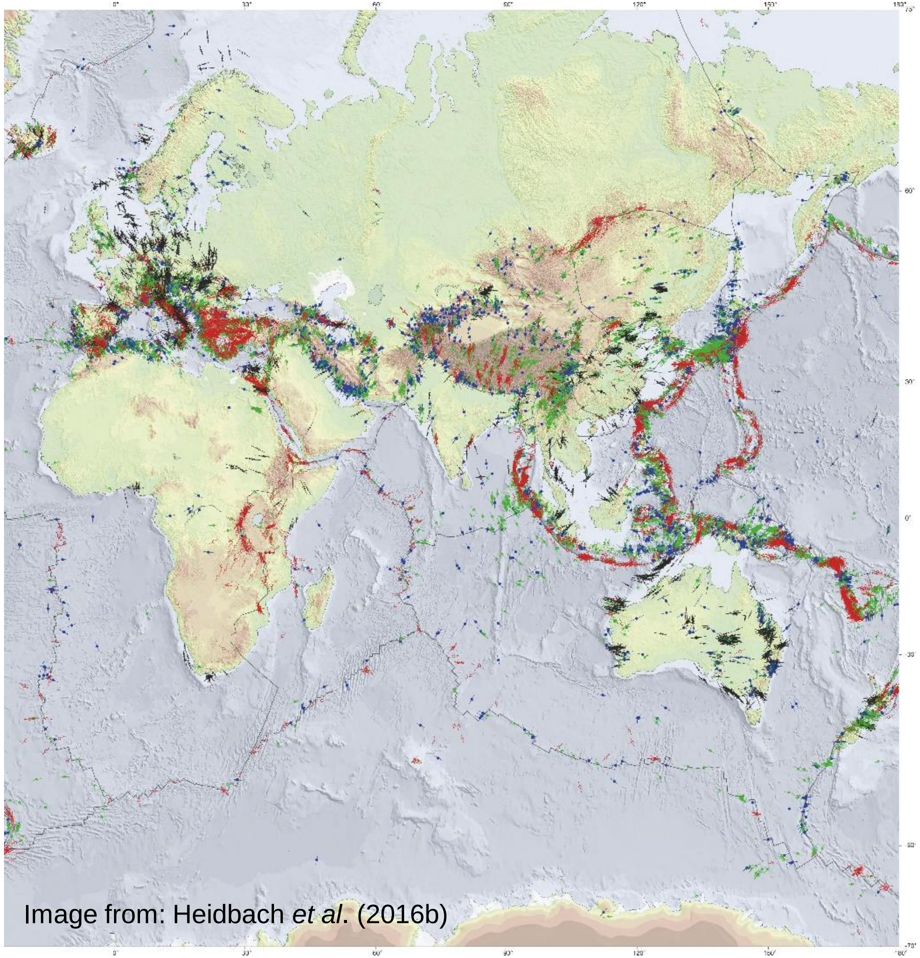


Image from: Heidbach *et al*. (2016b)

- Global compilation of data on the current stress field (5)
- Commenced in 1986
- Now has over 42500 records of the crustal stress field
- 473 records for the UK, updated 2022 (6)
- Observations from 0 – 40 km depth
- Open source resource available online: https://www.world-stress-map.org/

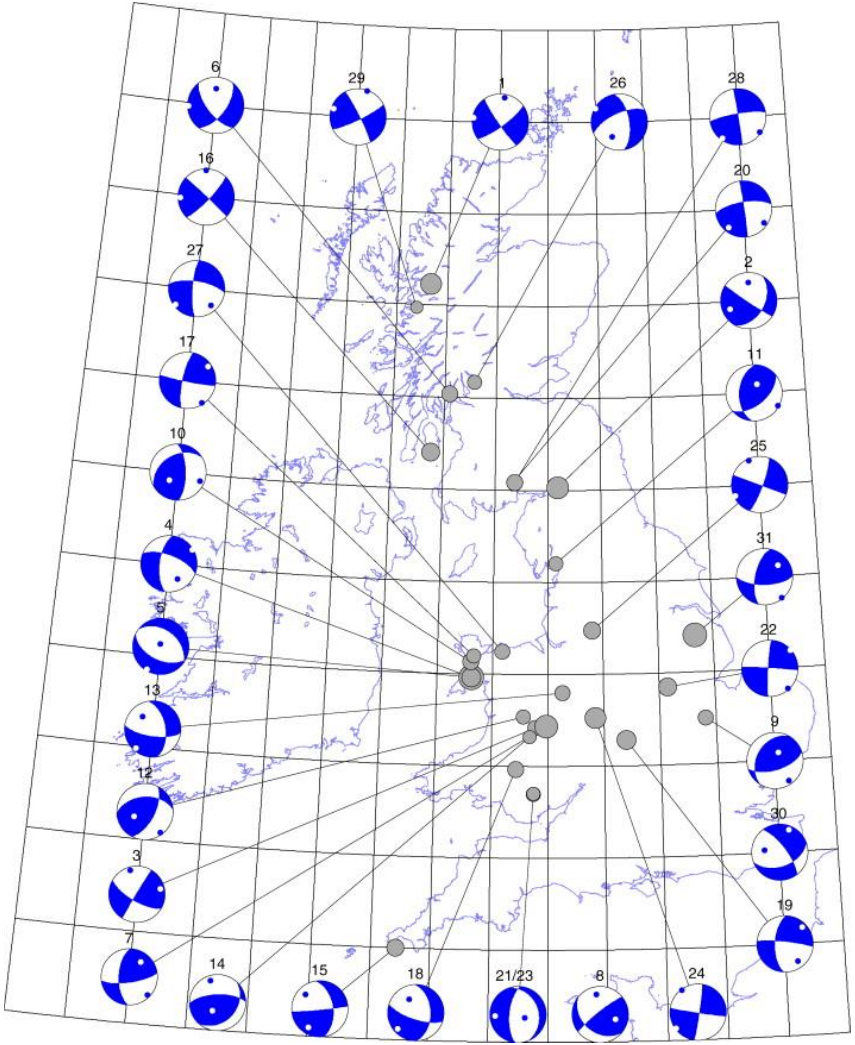


Image from:
Baptie. (2010)

Stress field observations

- Stress field observations can be collected from earthquake monitoring or subsurface activity such as mining or drilling
- Earthquake focal plane mechanisms can yield information on:
  - Stress field orientation
  - Ratio of the magnitudes of the principal stresses
  - Faulting regime
- Borehole stress field observations can provide information on:
  - Pore pressure
  - Stress magnitudes
  - Stress field orientation

Collection of new stress field data

North Sea – Regional data provision

- The North Sea area covers the territory of five different Countries
- Each has their own organisation to make data available.
- Each organisation has a different policy with regards to data access and usage constraints
- For seismic data there may be multiple catalogues per country

Image from: Kingdon *et al*. (2023)

Earthquake Focal Mechanism Data

- Earthquake Focal Plane Mechanism data based on analysis of Earthquakes

- Not all earthquakes have calculated focal mechanisms due to detection rates and spacing of monitoring sections

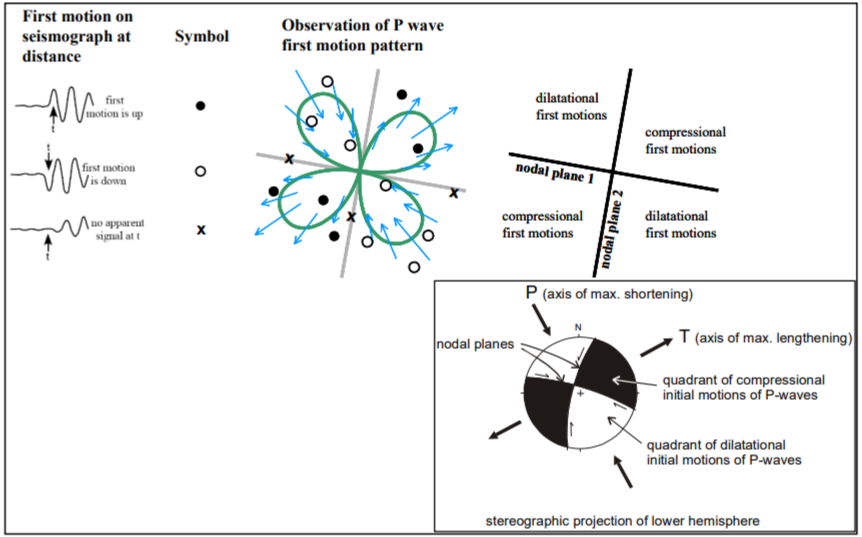


Image from: Heidbach *et al*. (2016a)

- Analysis can be undertaken in multiple ways including:
  - First Motion of P waves
  - Moment Tensor Inversion

- These solutions are dependent on the quality

- Individual solutions can be ambiguous so are often combined in a formal stress inversion (FMF)

Borehole stress observations

- Above 4 km most stress field observations come from boreholes

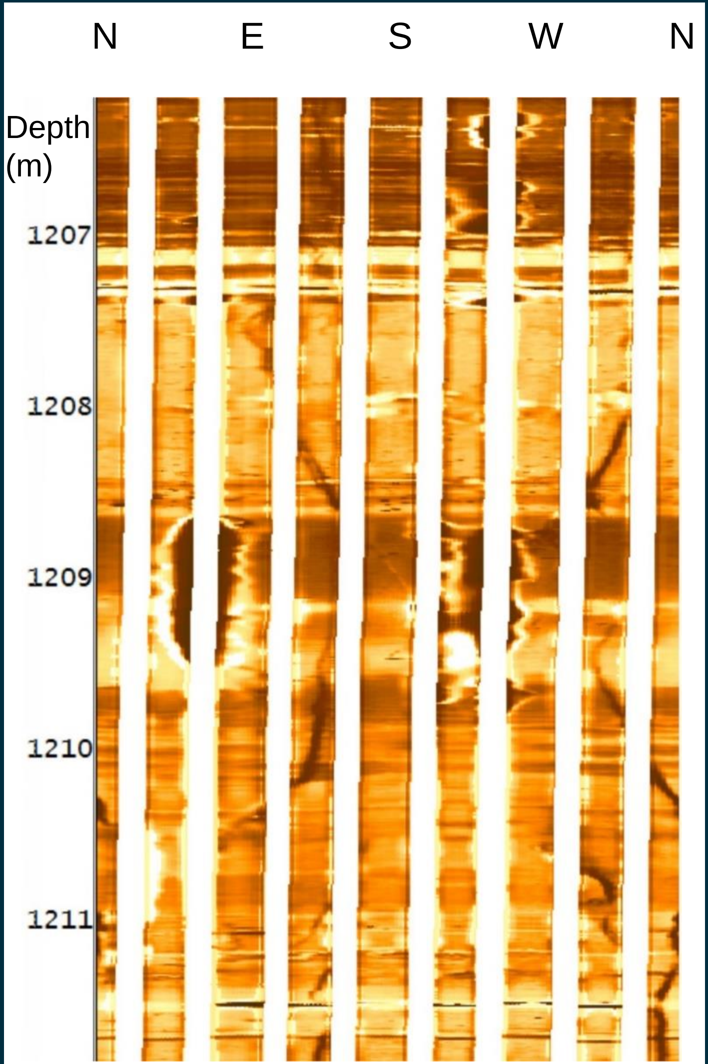
- Under the right conditions data from boreholes can be used to determine

Regional or site specific

– Orientations of horizontal stresses
– Magnitude of vertical stress
– Pore pressure
– Magnitude of least principal stress (minimum horizontal stress, Shmin in normal and strike – slip faulting environments

Site specific

– Can also be used to constrain maximum horizontal stress magnitude (SHMax)



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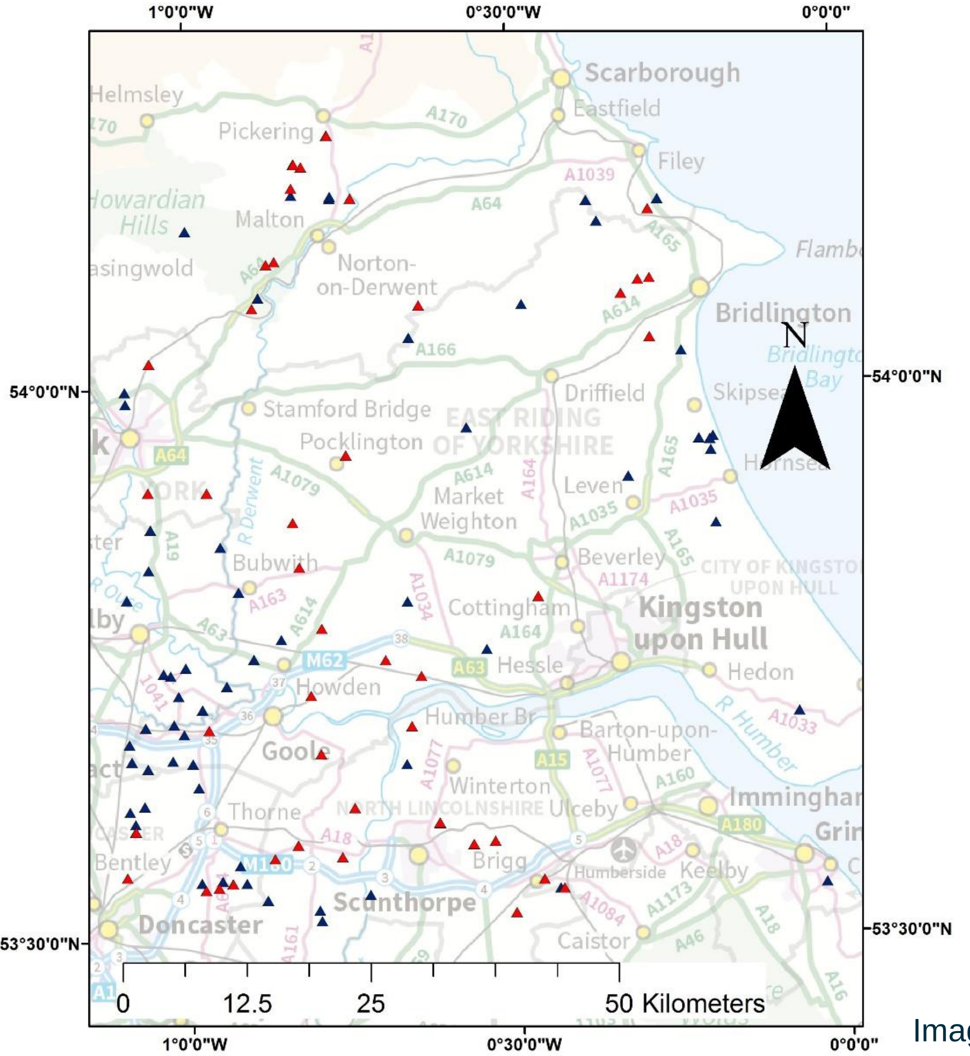


Collection of new data

- Simplest method is to mine useable information from existing wells
- For the UK, this data is largely from wells licensed by the North Sea Transition Authority
- UK analysis has found approximately 20 – 45% of wells were suitable for stress field characterisation (7)

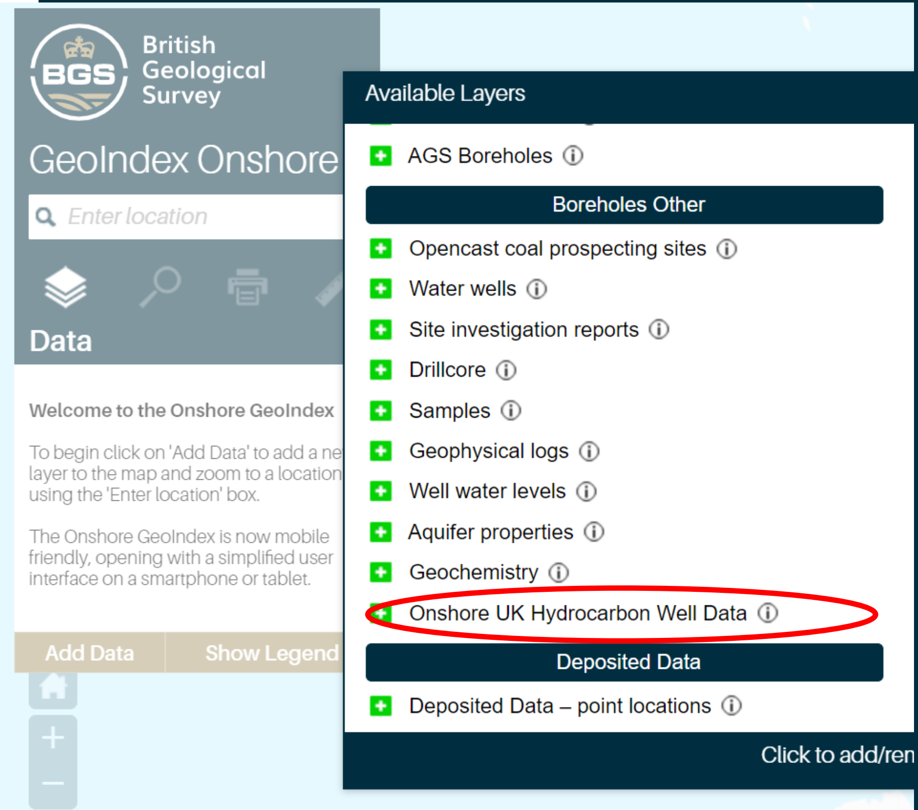
Image from Fellgett *et al*. (2017)

Access to NSTA well data

- Within the last 12 months data for onshore boreholes licensed by NSTA is now released

- This information is served on behalf of the NSTA via the BGS GeoIndex: https://www.bgs.ac.uk/map-viewers/geoindex-onshore/

- Offshore data can be access via the National Data Repository: https://ndr.nstauthority.co.uk/

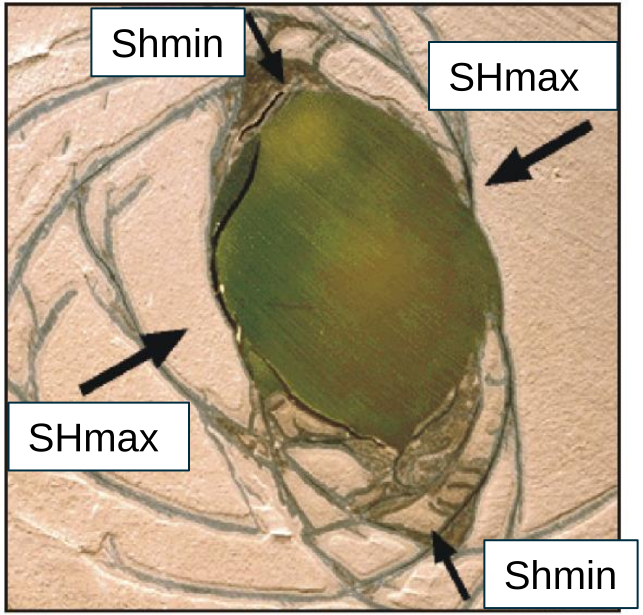


https://www.bgs.ac.uk/map-viewers/geoindex-onshore/

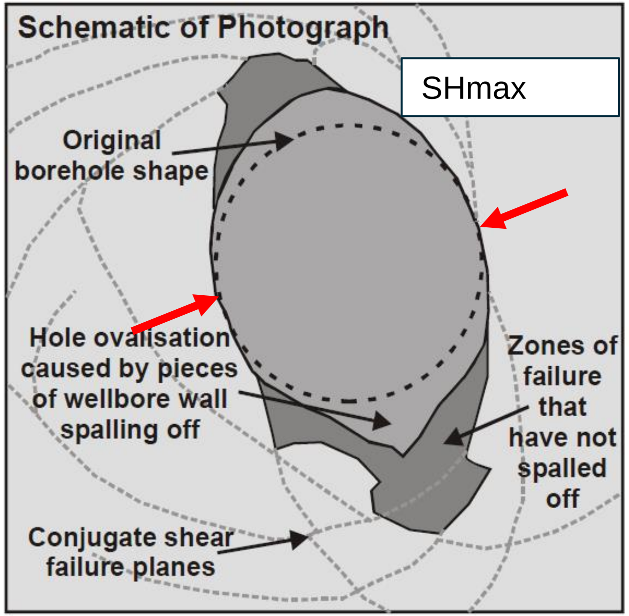
Stress Field Orientation

Stress Orientations in Boreholes: Breakouts

- Breakouts are stress induced enlargements of the borehole wall which can be identified from wireline log data, specifically Four-Arm / Dual Caliper tools and Borehole Imaging tools
- In vertical wells breakouts form perpendicular to the direction of SHmax.



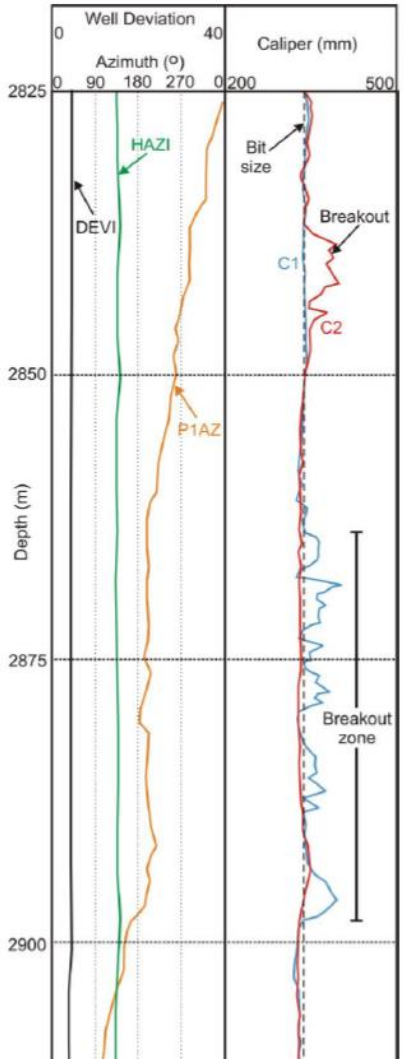
Left: Photograph of laboratory simulated borehole breakout



Right: Diagram identifying the main features

Image from: Heidbach *et al*. (2016a)

Breakouts from Caliper Data



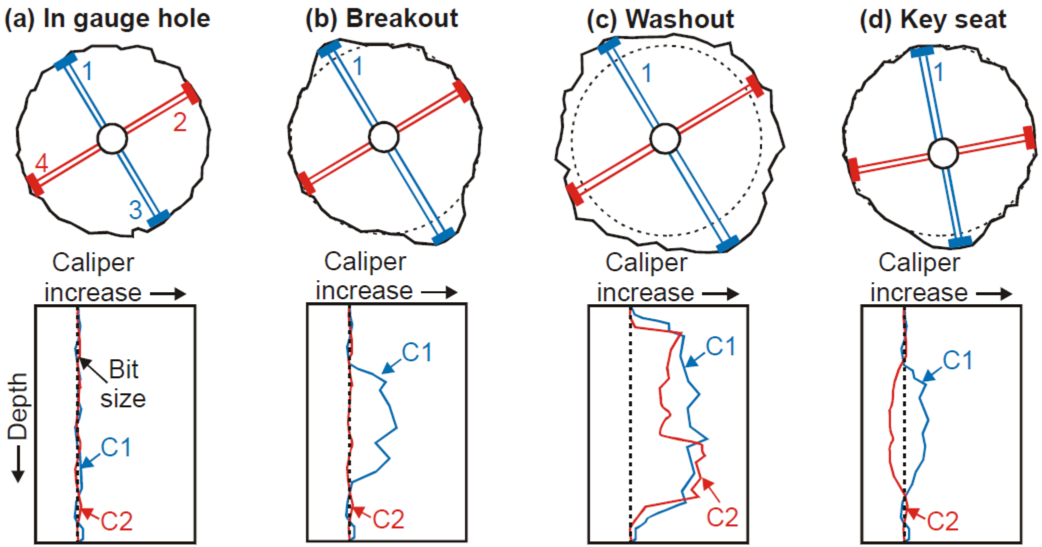


Fig. 4.4-1: Common types of enlarged borehole and their caliper log response. Figure is modified after Plumb and Hickman (1985).

Four-arm caliper log example.

Caliper log plot displaying borehole breakouts. Caliper one (C1) locks into breakout zone from 2895-2860 m (P1AZ ≈ 200°), the tool then rotates 90° and Caliper two (C2) locks into another breakout from 2845-2835 m (P1AZ ≈ 290°). Both breakout zones are oriented approximately 020° and suggest a S_{Hmax} direction of 110°. The borehole is deviated 4° (DEVI) towards 140° (HAZI).

Images from: Heidbach *et al*. (2016a)

Criteria for interpreting features from WSM

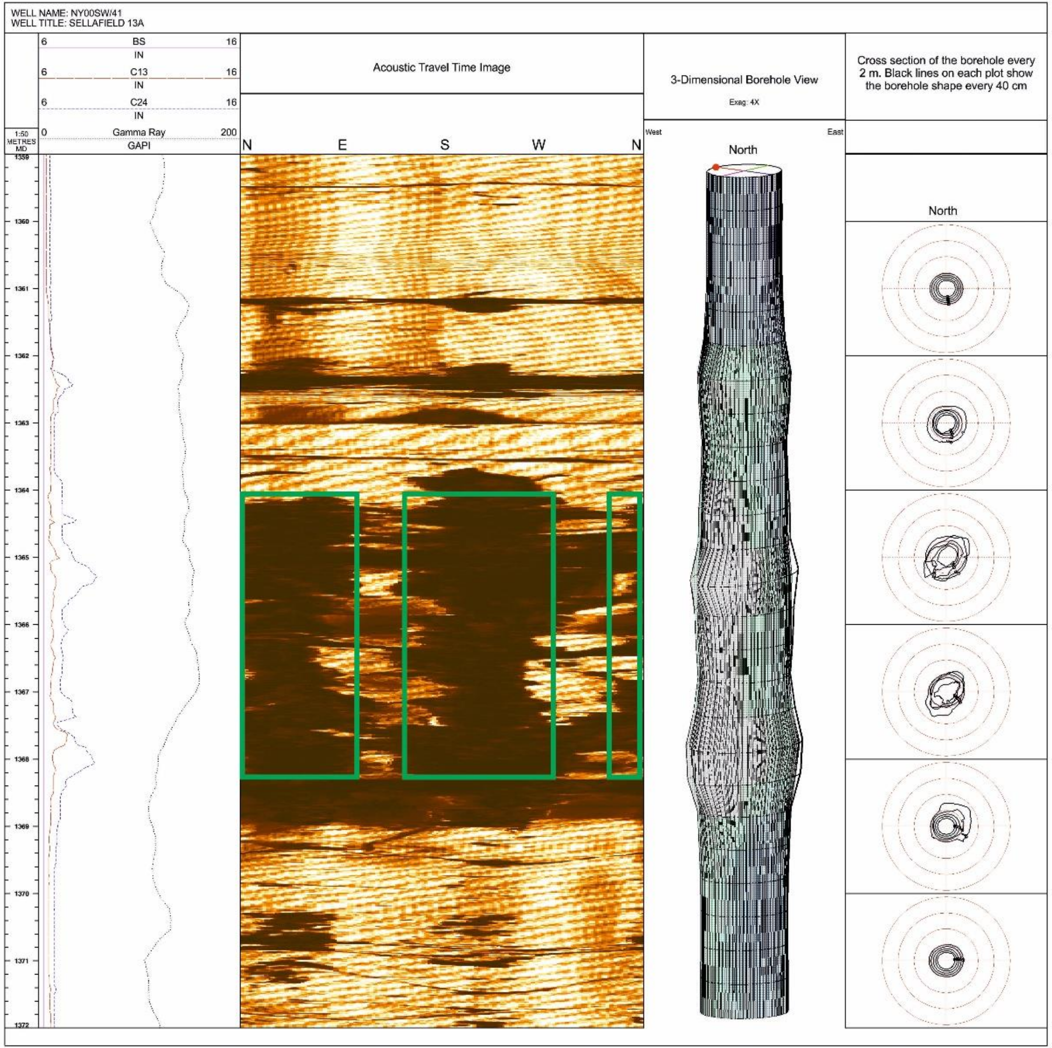
Tab. 4.4-1: Detection criteria borehole breakouts from four-arm caliper data.

1. Tool rotation must cease in the zone of enlargement.
2. There must be clear tool rotation into and out of the enlargement zone.
3. The smaller caliper reading is close to bit size. Top and bottom of the breakout should be well marked.
4. Caliper difference has to exceed bit size by 10 %.
5. The enlargement orientation should not coincide with the high side of the borehole in wells deviated by more than 5°.
6. The length of the enlargement zone must be greater than 1 m.

From: Heidbach *et al*. (2016)

Image logging of breakouts

- Image logs provide much higher vertical resolution than calipers
- 2.5 mm vs. 5-15 cm
- Allows for smaller breakouts to be identified



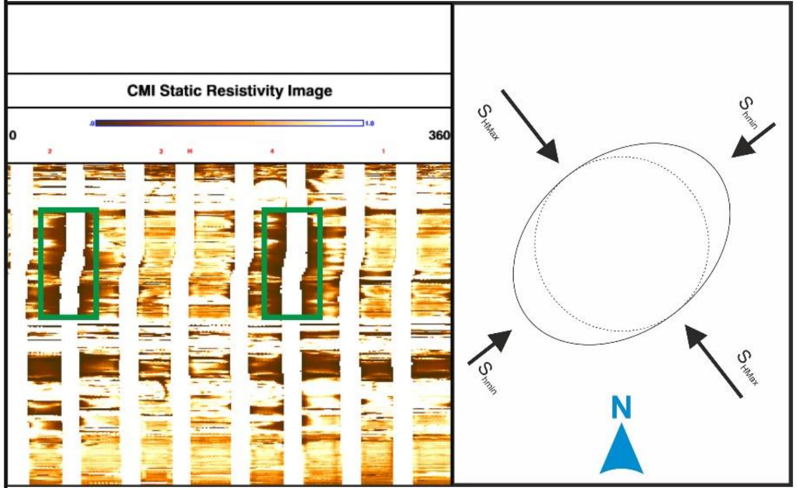


Image from Fellgett *et al*. (2017)

Drilling Induced Tensile Fractures

- These are small scale tensile fractures created in the drilling process
- Also created during well testing (FIT)
- Often near vertical thin features
- Orientation is parallel to SHMax
- Some authors suggest they indicate high differential stress (Zoback, 2010)
- These features should appear at 90 degrees to breakout orientation

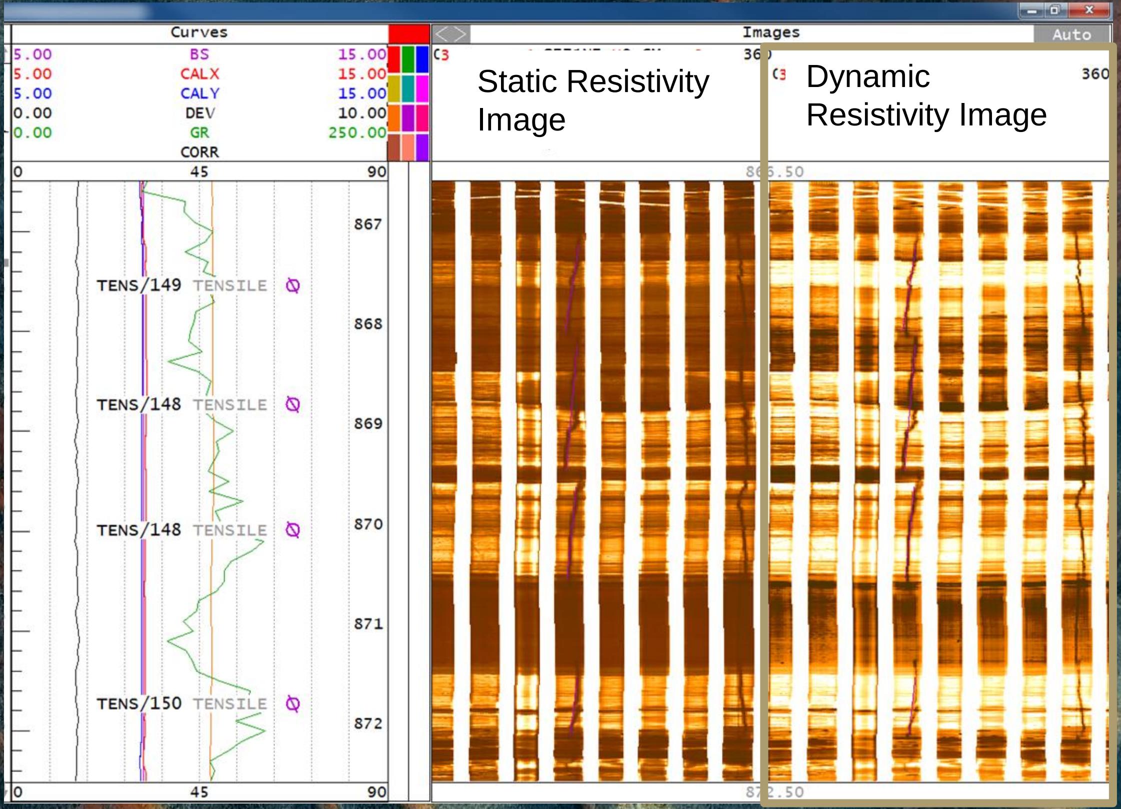


Image from Fellgett *et al*. (2020)

S_{hmin}, S_V, Pore pressure

Minimum Horizontal Stress (S_{hmin})

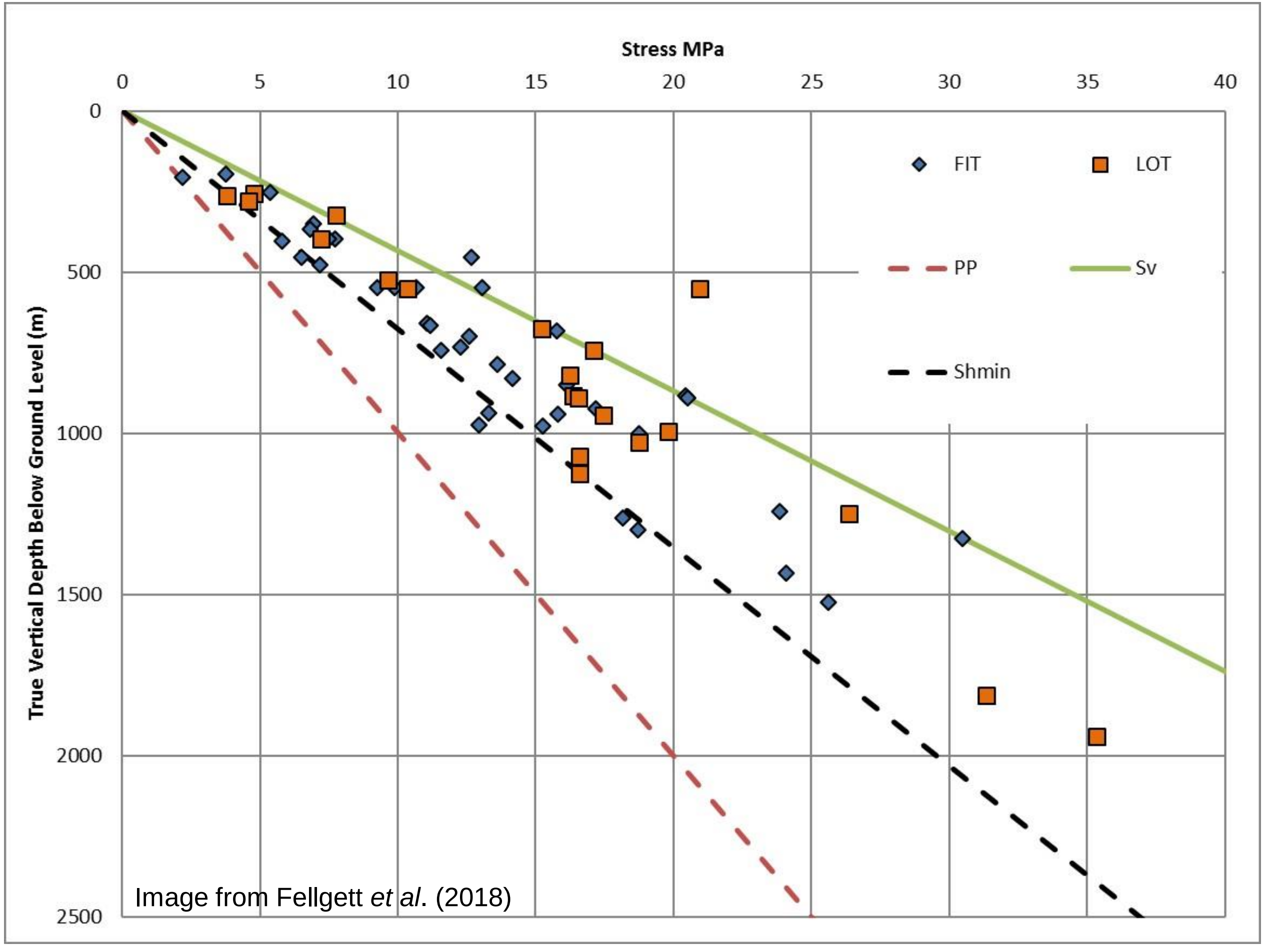
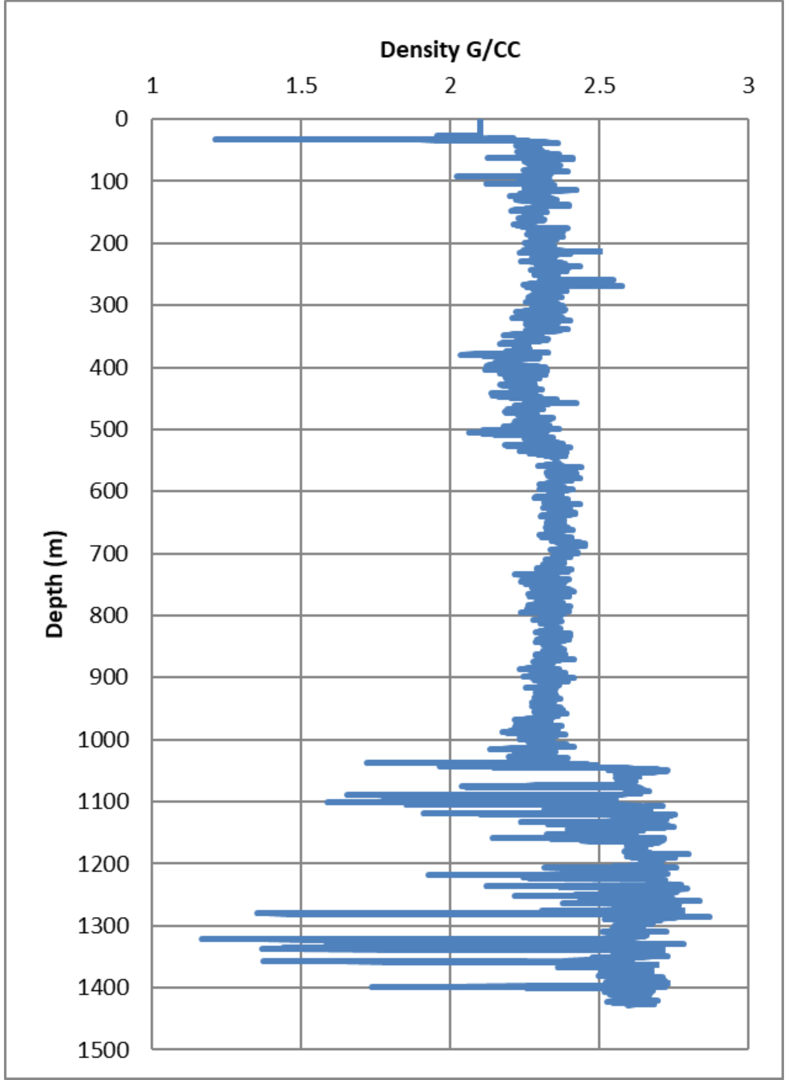


Image from Fellgett *et al*. (2018)

- Regionally the lower bound of S_{hmin} can be calculated (8), this can be taken into fault reactivation models
- Information taken from XLOT, LOT and FIT data
- Almost no XLOT data onshore in the UK, and where LOT data is collected it is usually recorded as a single figure

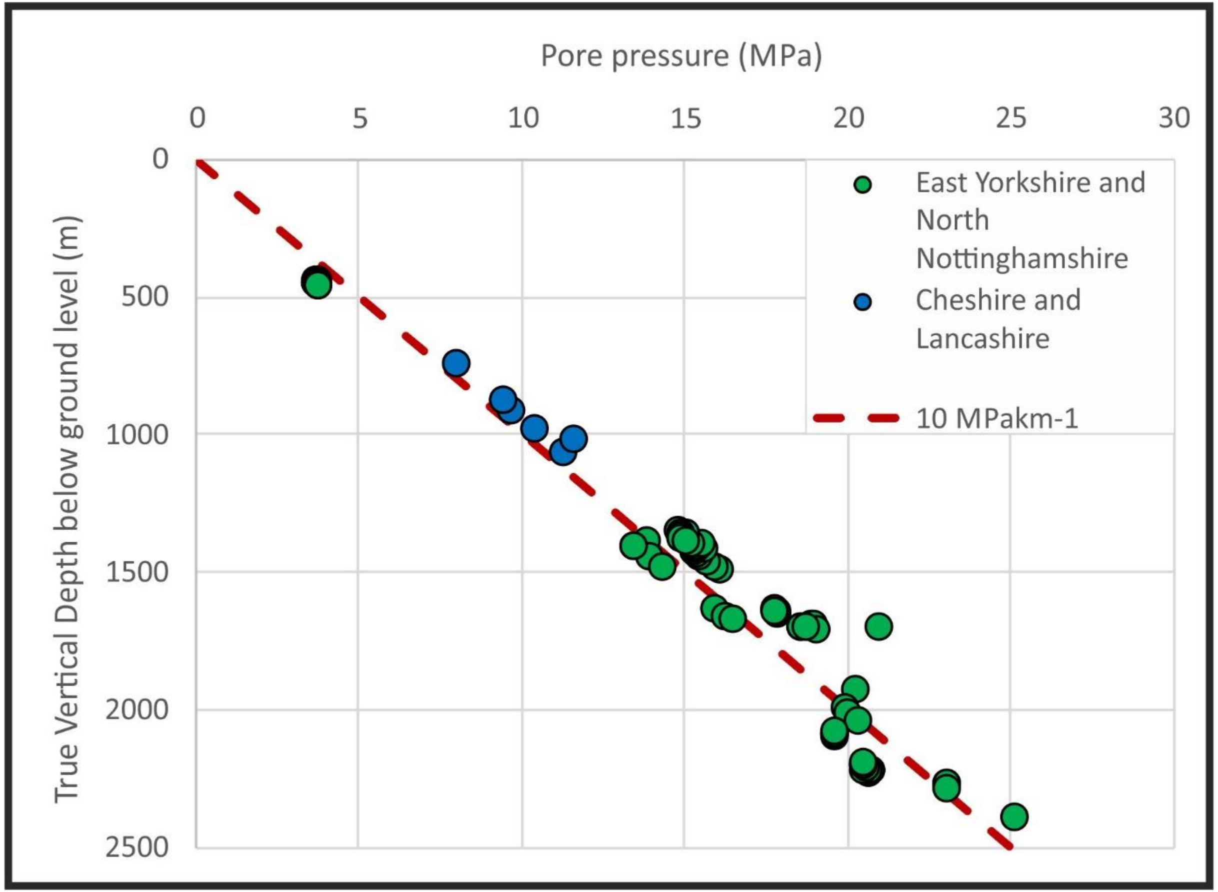


Vertical Stress

- Calculated from wireline density logs (9)
- Often requires substitute densities for shallow uneconomic units
- Vertical stresses can be impacted by overpressure and significant density contrasts such as evaporites
- Analysis of the UK suggests vertical stress likely to fall between 23 $MPakm^{-1}$ and 26 $MPakm^{-1}$ (7)

Pore pressure

- rft and mdt type tools provide information on pore pressure
- Drill stem tests can also be used
- Biased dataset as these tools won’t collect data in impermeable units



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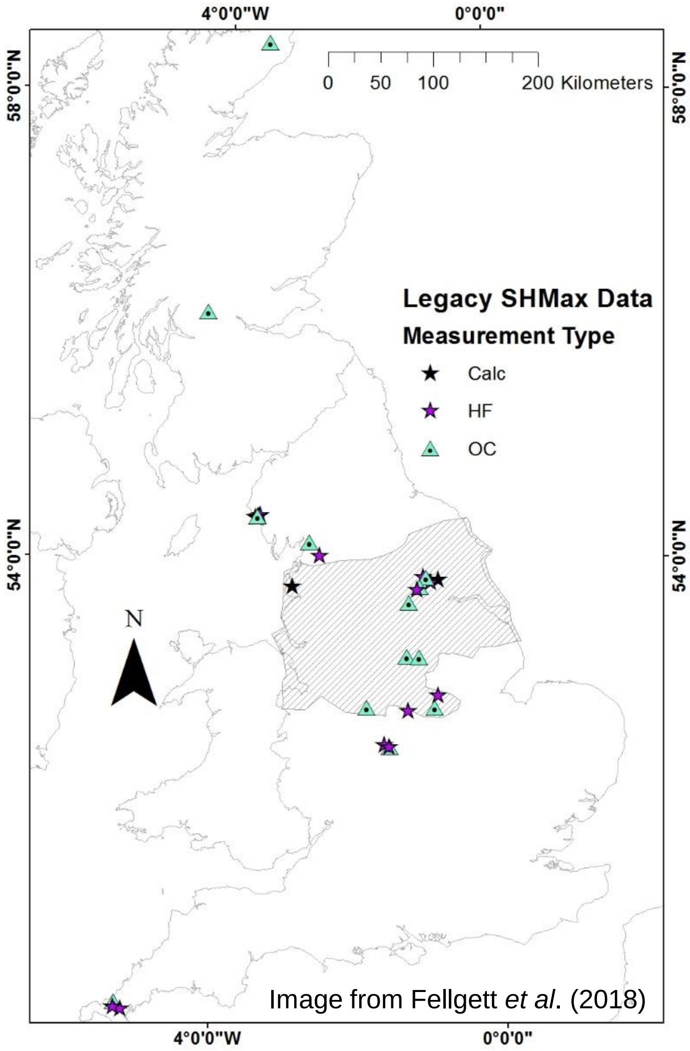
S_{HMax}



Maximum horizontal stress (S_{HMax})

- Difficult to determine reliably due to the number of parameters that need to be considered
- This means estimates can only be site specific
- A variety of techniques can be used but each has significant uncertainties associated e.g.
  - Stress polygons (10) potentially overestimates S_{HMax} by 20% (11)
  - Hydraulic fracturing which can have error bars of ± 15 Mpa (12)

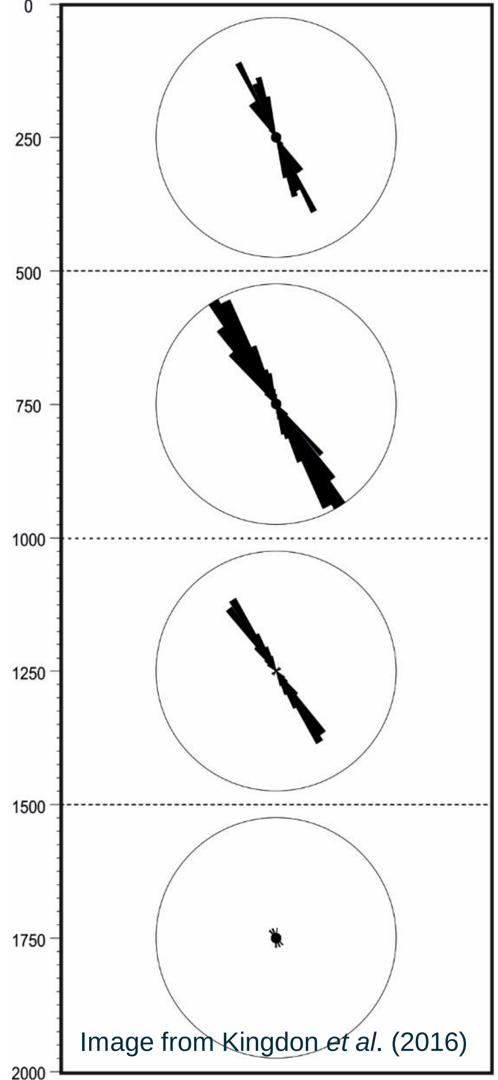
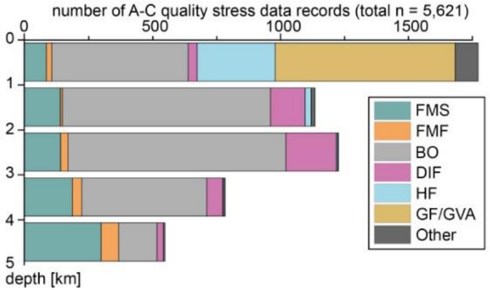


Image from Kingdon *et al*. (2016)

Uncertainties in stress field characterisation

- In the top 5 km of the earth's crust most stress field observations come from borehole sources
- These are often isolated measurements which must be combined to build a regional understanding
- This can have the impact of masking local variations
- High quality data remains scarce



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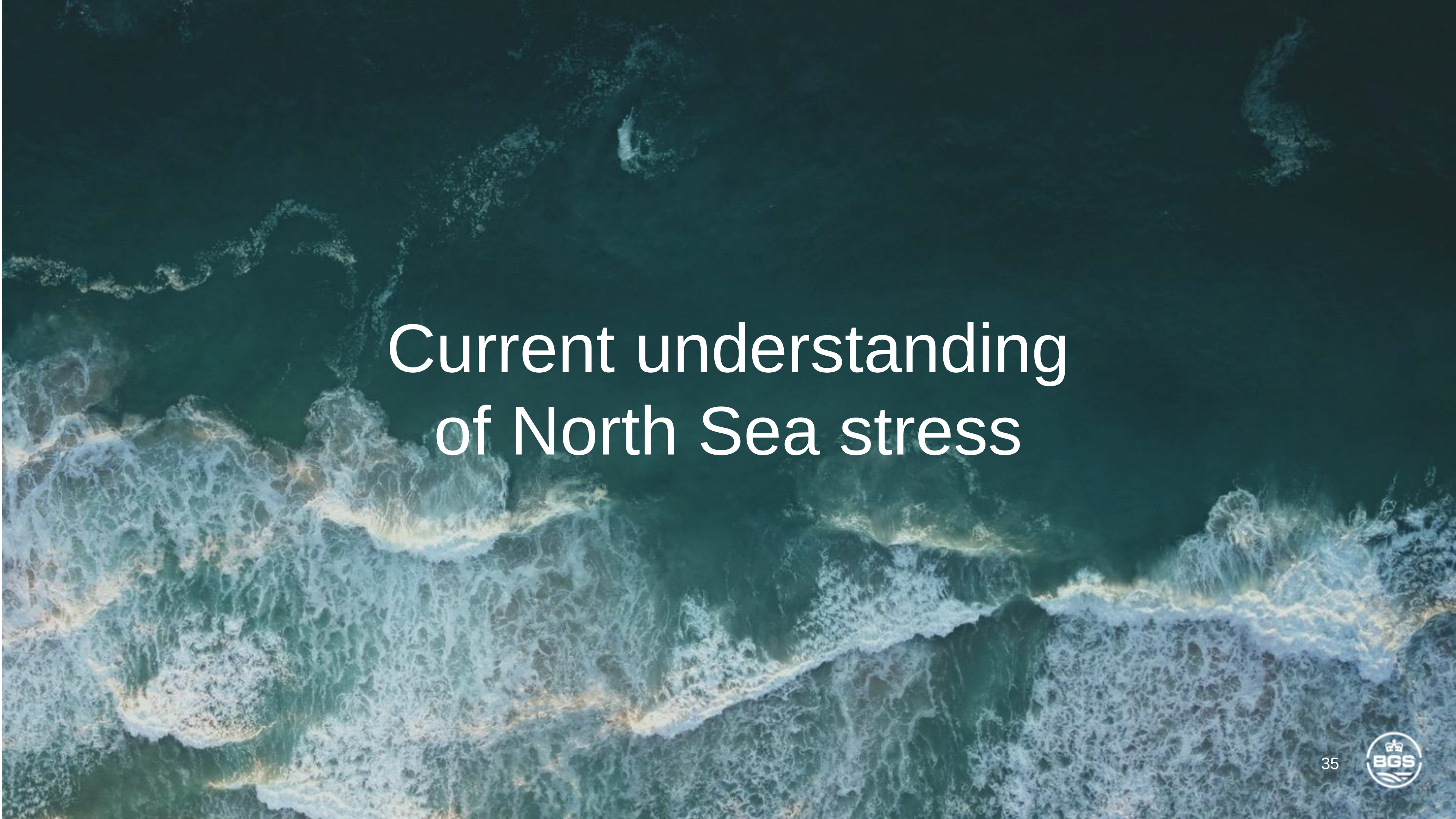
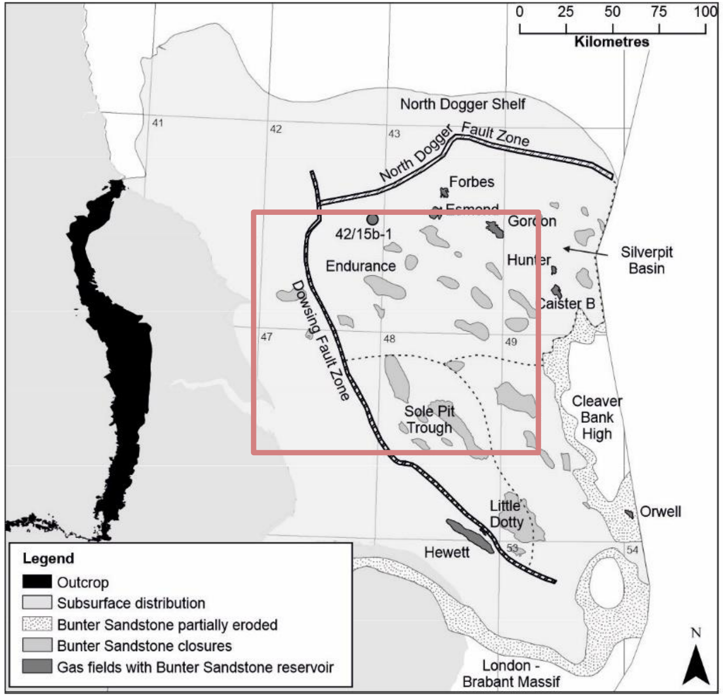


Current understanding of North Sea stress

Endurance Field

- One of the SHARP case study sites
- Reservoir target is the Triassic Bunter Sandstone Formation
- Estimated storage capacity of circa 450 MT (13)
- Saline aquifer formation
- Trap formed by large elongate anticlinal structure
- Several other structural closures of interest for CO_2 storage
- Some gas accumulations present in some structures



Regional mapping of stress orientations

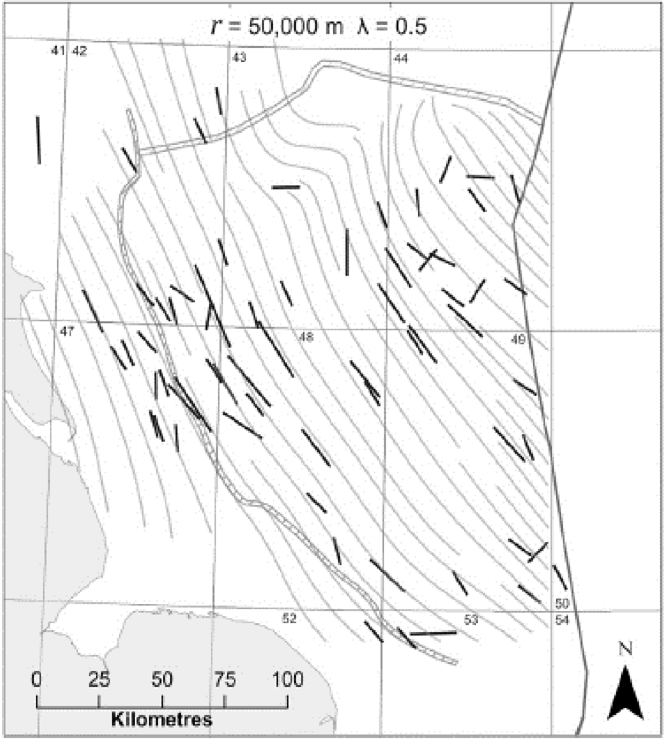
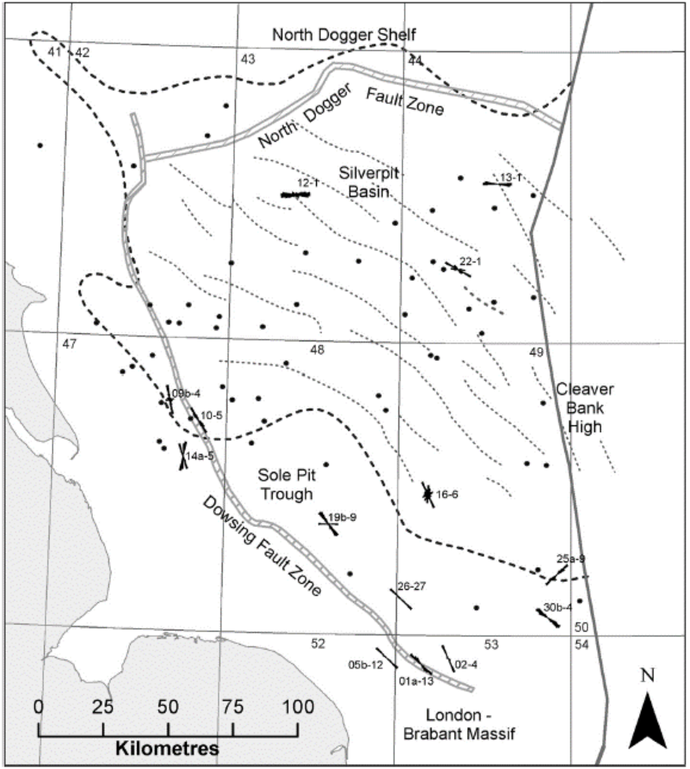


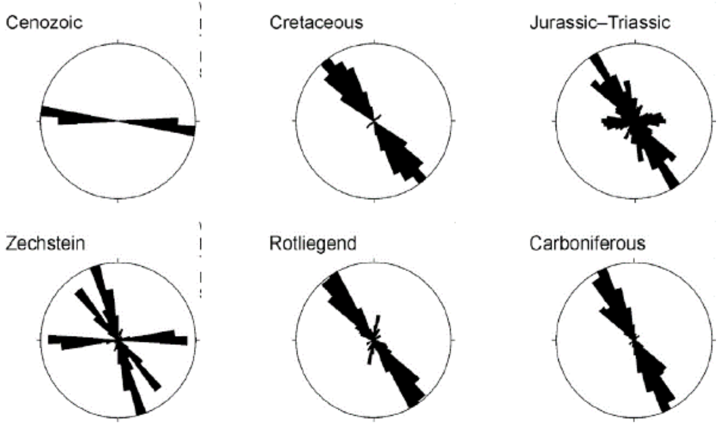
Image from Williams *et al*. (2015)

- Area reviewed by BGS in 2015 (14)
- Stress field orientation from breakouts in 66 wells
  - Assessed four-arm caliper logs from 266 wells
  - Image logs analysed for 6 wells
- Average orientation of SHmax is 148º ± 31º
- Some local variation
- No image logs above Zechstein

Detachment of stress field?



- Some evidence, but lack of adequate data limits confidence
- Recent drilling efforts have not identified evidence for differential horizontal stress in post-Zechstein cover
- DITFs presents below salt suggesting strike-slip



Images from Williams *et al*. (2015)

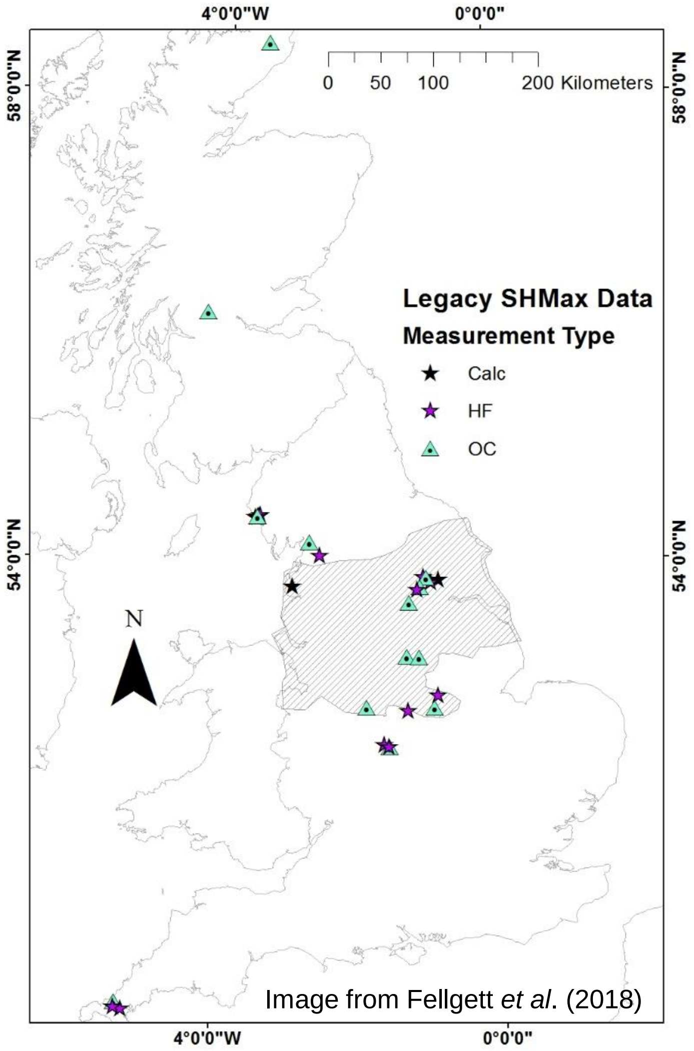


Image from Fellgett *et al*. (2018)

Remaining uncertainties in stress field determination

North Sea

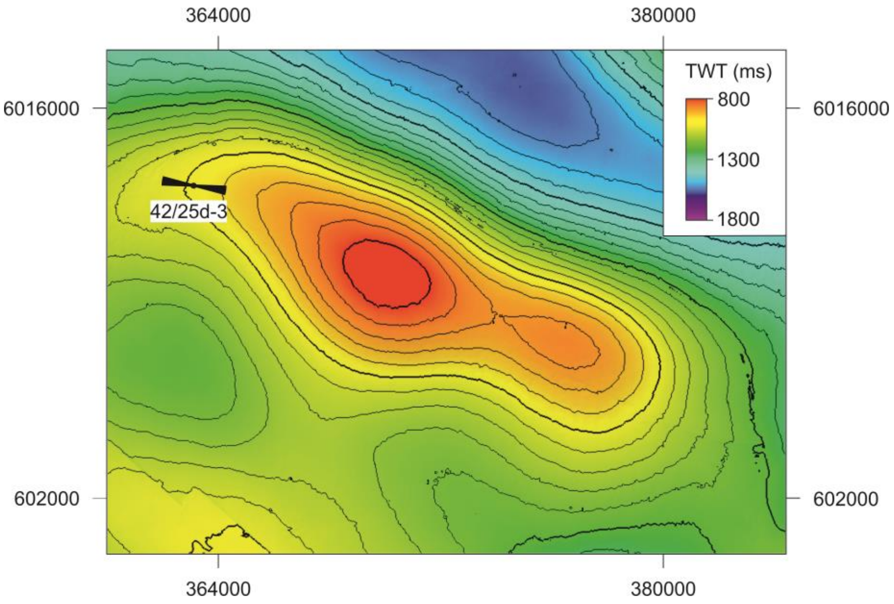
- The data suggest detachment of the stress field above the Zechstein evaporites, however there is significant uncertainty about this
- Very little data in the strata above the Zechstein
- The best stress magnitude data exist for Endurance
  - How applicable are the Endurance stress gradients to the rest of the formation?

Additional questions

- Can new techniques e.g. shear wave splitting improve stress orientation determination?
- Can new analysis provide a better link between borehole and seismic based stress field observations?

Project Results

Project Results



- Work has been completed to compile an updated seismic catalogue for the North Sea (15)
- Thousands of wells have been screened for data suitable for stress orientation determination
- New observations available for 90 wells in the vicinity of some of the case study sites
- Plans to integrate new techniques with existing catalogues to improve stress determination.

Conclusions

- Stress field characterisation is a critical aspect for a significant number of net zero projects from CCS to deep geothermal
- Characterisation of the stress field is heavily impacted by the availability of data
- This has knock on effects for the planning of subsurface operations at both shallow and deep scales
- Research funding allows investigation of new techniques and synthesis of data to support industry

THANK YOU

Any questions?

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