Defining in-situ stress magnitude and the responses of geology to stress anisotropy in heterogeneous lithologies for the United Kingdom

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Abstract Text:

Exploitation of shale gas in the USA has led to interest in similar UK deposits. After tremors at the Preese Hall well in 2011, the process of hydraulic fracturing has become contentious. In-situ stress orientation controls the direction that fractures propagate from a well.

World Stress Map (WSM) data coverage for the UK has historically been sparse. Improvements to the stress orientations for the UK are vital for reducing risk levels of induced seismicity. In some offshore basins, maximum horizontal stress (S_{HMax}) is sub-parallel to major inverted Permo-Triassic faults, episodically reactivated during the Cenozoic, indicating a degree of structural control.

Understanding for UK stress magnitude has been poor. Data for Northern England has been augmented with new estimates of vertical stress (S_v), minimum horizontal stress (S_{hmin}) and pore pressure, focussed on potentially prospective basins east and west of the Pennines. Calculated values combined with legacy hydraulic fracturing and overcoring data show vertical stress gradients vary from 23 to 26 MPa/Km^{-1}. Cheshire and Scotland show higher S_{hmin} values by 2 MPa/Km^{-1} compared to Yorkshire and South East England. S_{HMax} values exceeds the S_v which in turn exceeds S_{hmin} indicating a predominantly strike slip environment. Pore pressure appears to be uniformly hydrostatic across the studied regions. There is some evidence above 1200 m depth of reverse faulting in igneous rocks in Cornwall, Leicestershire and Cumbria.

Analysis of borehole imaging for the lithologically heterogeneous Carboniferous Coal Measures, highlights variability failure modes over confined vertical intervals. Breakouts are disproportionately located in “seatearths”, palaeosols located stratigraphically beneath coal seams. Drilling induced tensile fractures are located within close proximity in overbank silt/clay facies and relatively massive channel sands that typically over and underlie coal deposits. Strength tests show that breakouts occur in the “seatearth” facies because of high frequency pedogenic slickensides. Failure mode in response to stress, whilst consistent in orientation, are highly complex. Responses of individual facies are highly dependent upon the detailed lithology and diagenetic alteration of these materials.

Plain-Language Summary:

Newly calculated in-situ stress magnitude data has improved the UK database of this important data, vital for understanding how rocks may behave under hydraulic fracturing or "fracking." As this process is controversial in the UK, all new data adds to our understanding of the potential risks of this process. The mode of deformation that rocks experience are highly dependent upon their detailed geology. New data from the highly variable UK Coal Measures Group highlights the degree of lithological control on these processes.

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British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

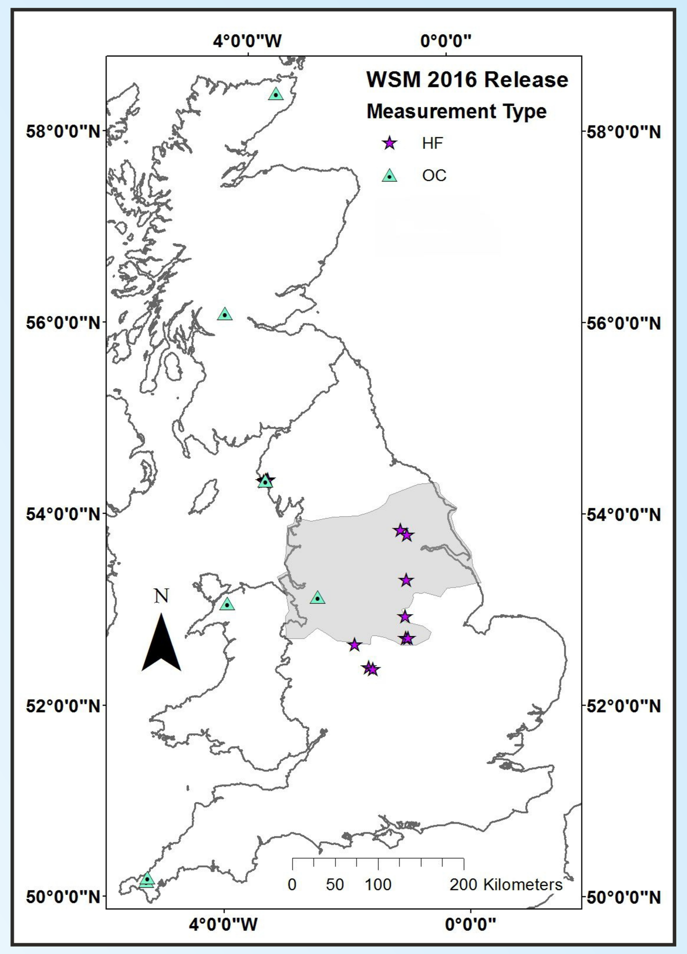
Andrew Kingdon, Mark Fellgett, Lorraine Field, Marcus Dobbs, Audrey Ougier-Simon and John Williams

UK in-situ stress field

Large scale development of shale gas in the USA has led to interest in similar UK sediments. Following tremors associated with "hydraulic fracturing" in the Preese Hall 1 well in 2011, an expert review panel examined issues around shale gas extraction (Mair et al. 2012) and concluded that more needed to be to done to characterise stresses and faults in UK shales.

Well constrained UK information on in-situ stress was extremely limited. The World Stress Map database (Heidbach et al. 2016), the only international and open source of stress data lacked UK data. Kingdon et al. (2016) significantly extended the available database of stress orientation information. However, stress magnitude data was limited to a few sites and was particularly sparse in those UK regions currently being investigated for unconventional hydrocarbon resources (Fig.1A).

Utilising legacy data from peer-review publications, borehole records and well testing (Fig. 1B) UK stress magnitude data have been examined, with a particular focus on areas with resource potential. These new results have shown that pore pressure (P_P) is hydrostatic and vertical stress gradients vary between 23- 26 MPakm^{-1} (Fig. 2).



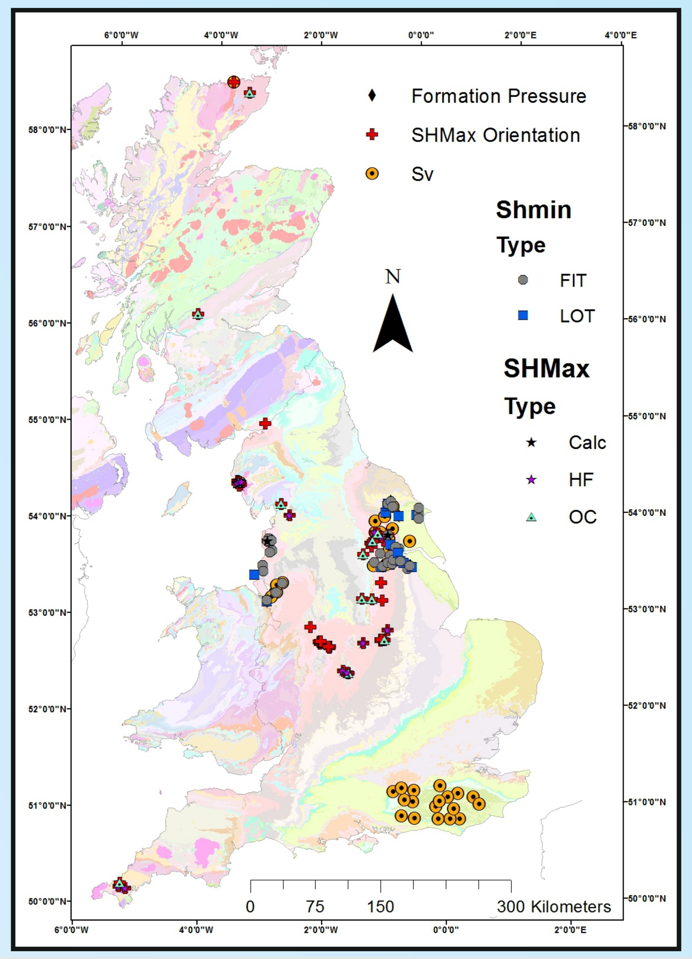


Figure 1A, *Above Left*: : Map of the UK showing those boreholes with stress magnitude data from the WSM 2016 release (Heidbach et al., 2016). Stress magnitude data source from Hydraulic Fracturing (HF) and Overcoring (OC). The shaded zone shows the area of interest from the BGS/DECC Bowland-Hodder Shale study, Andrews et al. (2013).
Figure 1B, *Above Right*: Map showing geographical location of borehole data available to characterise the UK stress field: FIT – Formation Integrity Test; LOT- Leak Off Test; HF – Hydraulic Fracturing; OC – Overcoring; Calc – S_{HMax} Calculated from borehole breakouts and DIFs.
Contains British Geological Survey materials ©NERC 2017, From Fellgett et al., 2017.

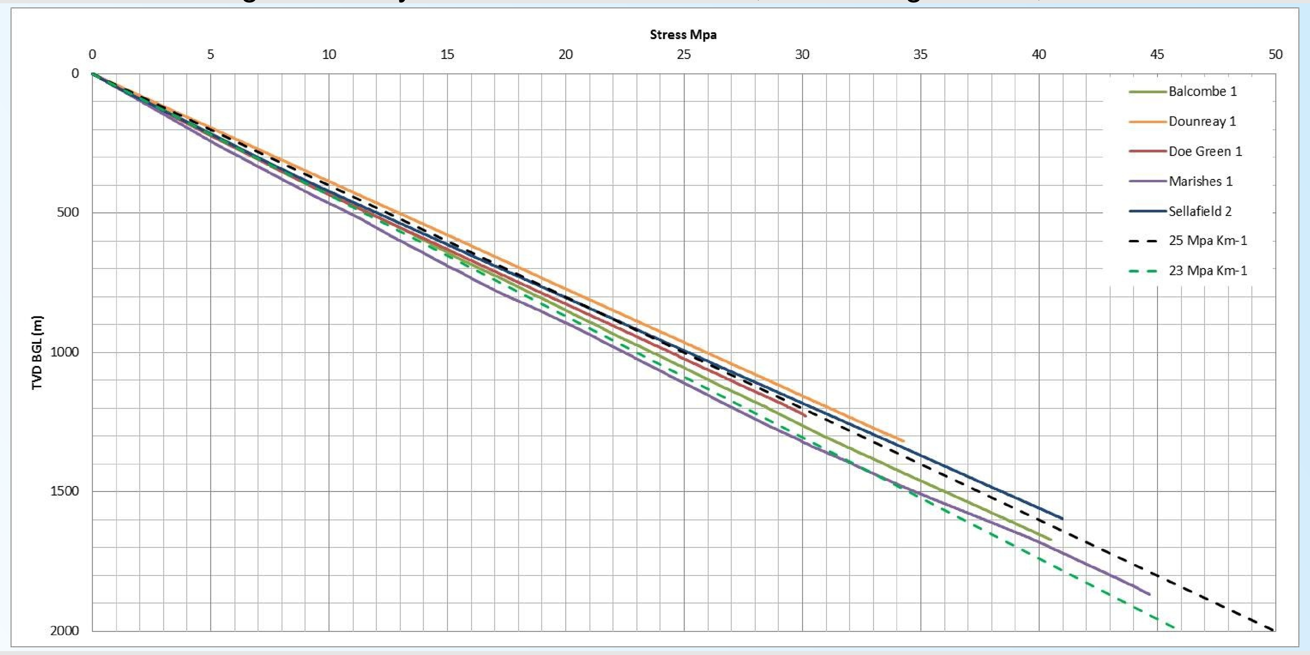


Figure 2: Vertical stress gradients for a variety of UK Regions. Dashed lines representing gradients of 23 and 25 MPakm-1 are included for reference. Balcombe 1 is a well from the Weald, Marishes 1 is from North Yorkshire, Doe Green 1 is from Lancashire, Sellafield 2 was drilled in Cumbria and Dounreay 1 was drilled on the North Coast of Scotland. From Fellgett et al., 2017.

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Minimum Horizontal Stress

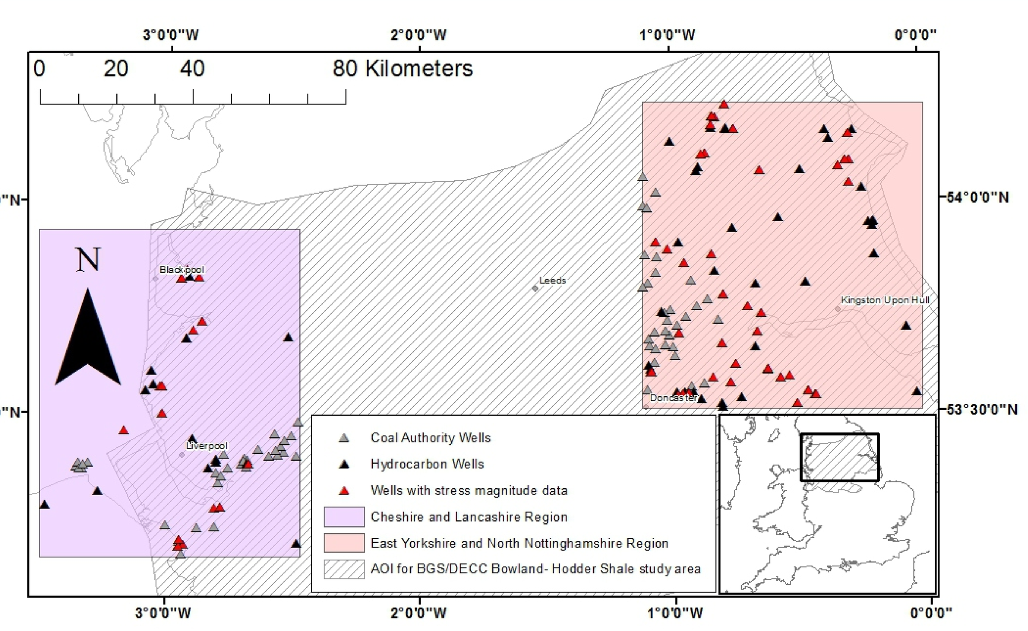
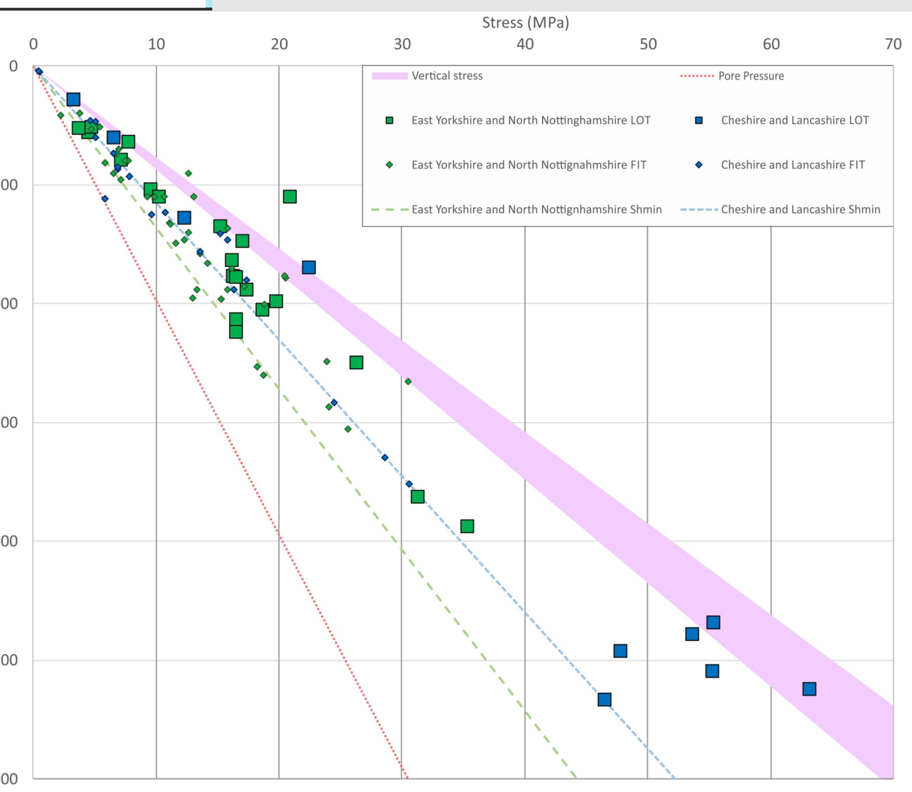


Figure 3A, *Top Left*: Map showing two regions of the UK where stress magnitudes have been investigated. Deep boreholes, shown as triangles, are the predominant source of stress field information. Boreholes in red have sufficient information to characterise stress magnitude. Hatched zone corresponds to the area of interest from the Bowland Shale (Andrews et al., 2013).

Figure 3B, *Right Below*: Graph showing results from FIT and LOT with regional estimates of the minimum bound of S_{hmin} for the two regions shown in Fig. 3A. Regional estimates are derived from LOTs after Addis et al. (1998). Range of S_v (values between 23 – 26 MPakm^{-1}) in purple.

To examine trends in the Minimum horizontal stress (S_{hmin}) Leak Off Test (LOT) and Formation Integrity Test (FIT) data were collected from two UK regions east ad west fo the Pennine Hills and used to estimate S_{hmin} (Fig. 3A).

This demonstrated that in both regions S_{hmin} is consistently lower than the Vertical Stress (S_v) (Fig. 3B). It also shows the gradient of S_{hmin} is 2.6 MPakm^{-1} higher in boreholes to the west of the Pennine Hills compared with those to the east.

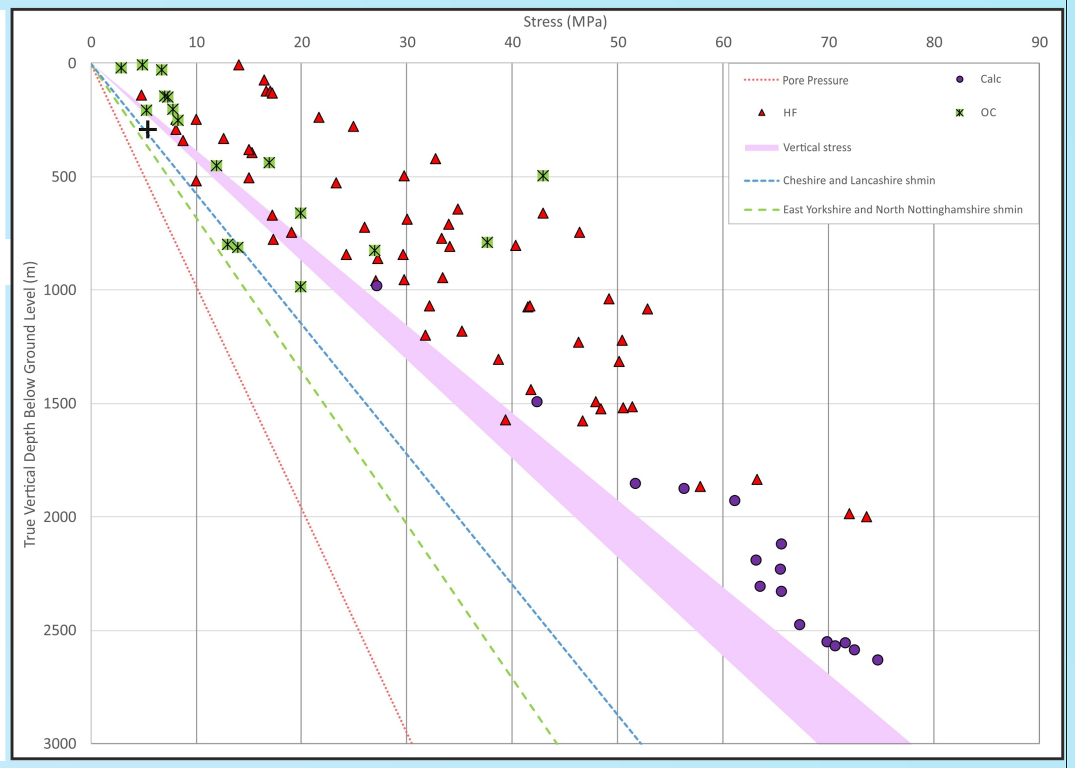


Faulting Regime

To examine trends in the Maximum Horizontal Stress (S_{HMax}) legacy HF and OC data were collected from across the UK (Fig. 4A).

These data showed S_{HMax} as consistenly higher than the estimated S_V indicating that the UK is predominantly a strike-slip faulting environment.

Some legacy S_{hmin} data plotted at/above estimates of S_v indicating a reverse faulting environment but that these may have been affected by other factors including stratigraphy, lithology and depth of collection quarries (Fig. 4B).



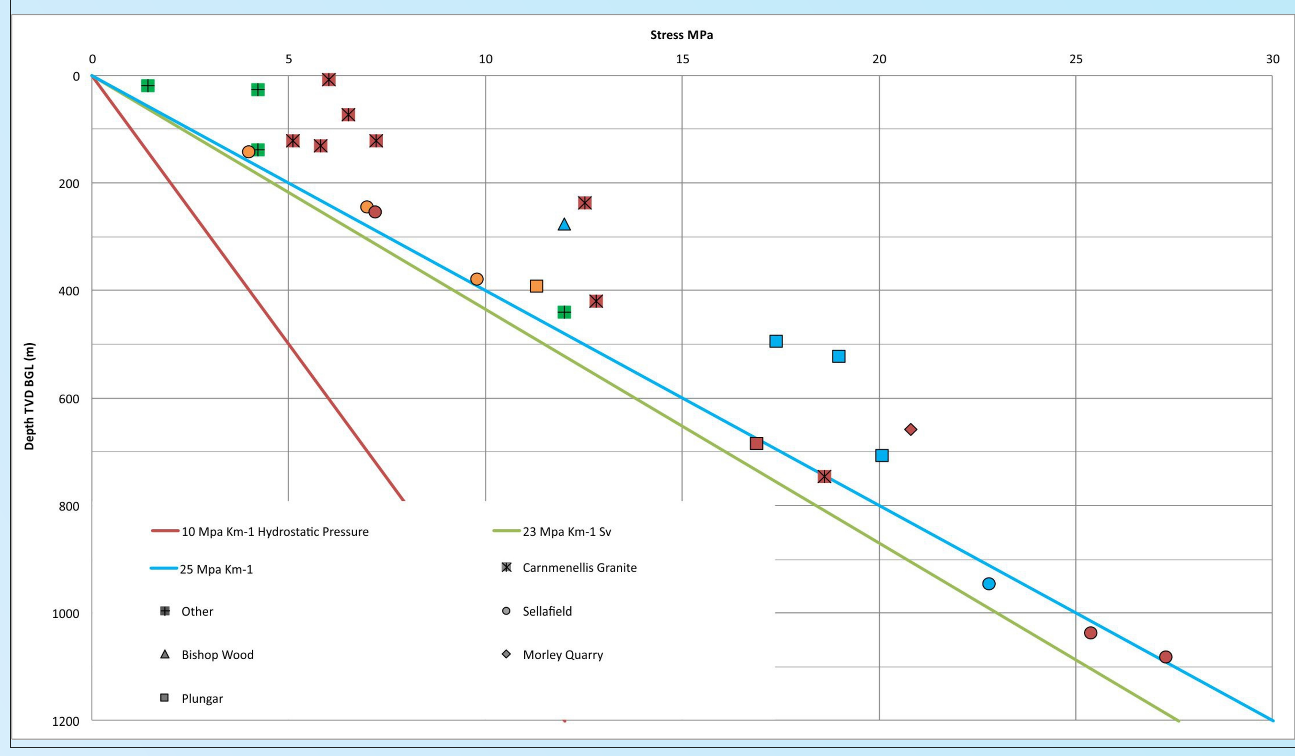


Figure 4A, *Above:* observations of S_{HMax} from legacy data including HF, OC and those calculated from borehole wall failure (Calc). Range of S_v 23 – 26 MPakm-1 in purple.

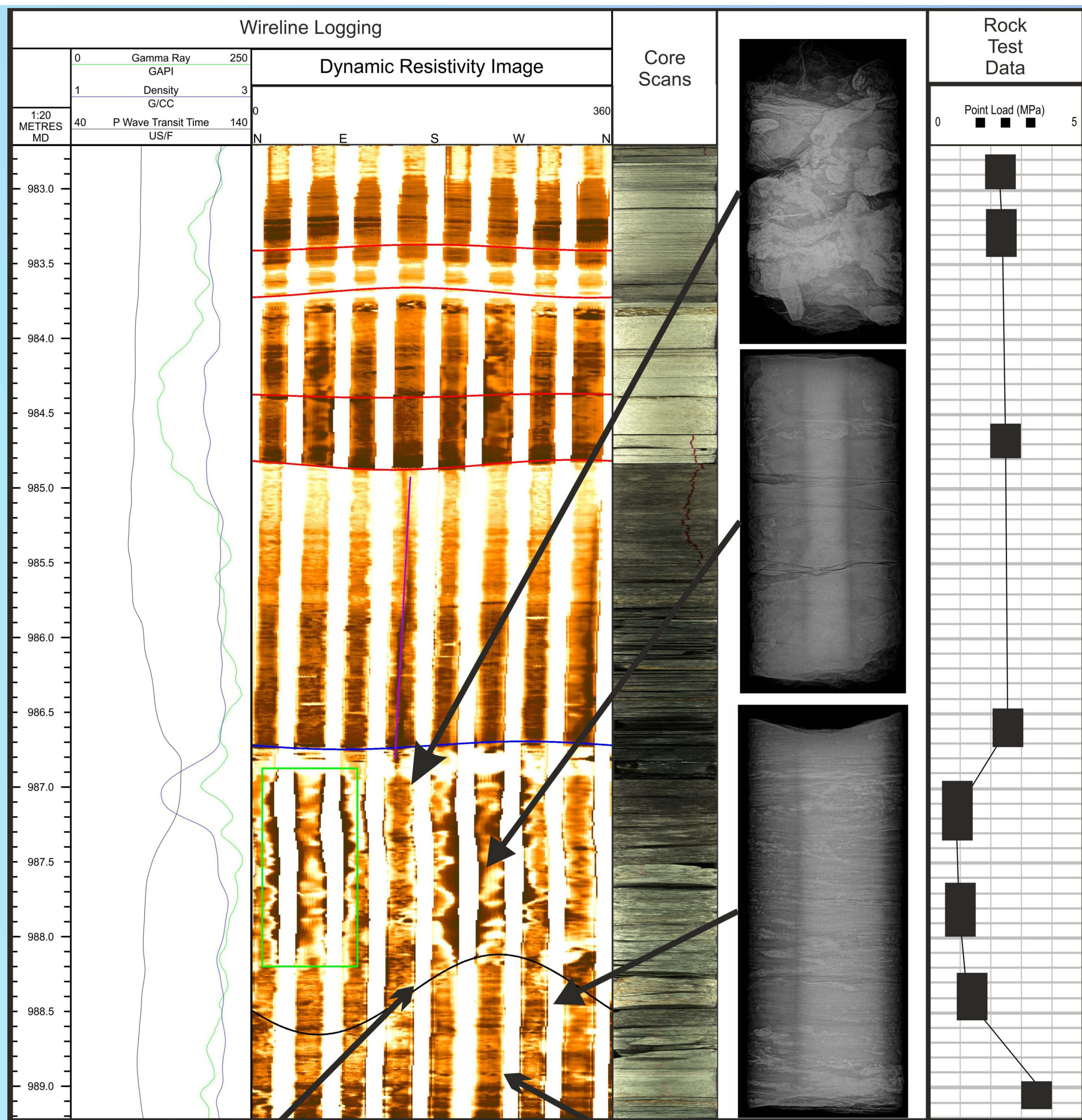
Figure 4B, *Left*: S_{hmin} values which exceed the S_v gradient of 23 MPakm-1 indicate possible reverse faulting regimes. S_{hmin} values derived from HF and OC. Values shaded by lithology and age:
Green: unknown age & lithology
Red: Igneous rocks
Orange: Triassic sediments,
Blue: Carboniferous sediments.
From Fellgett et al. 2017.

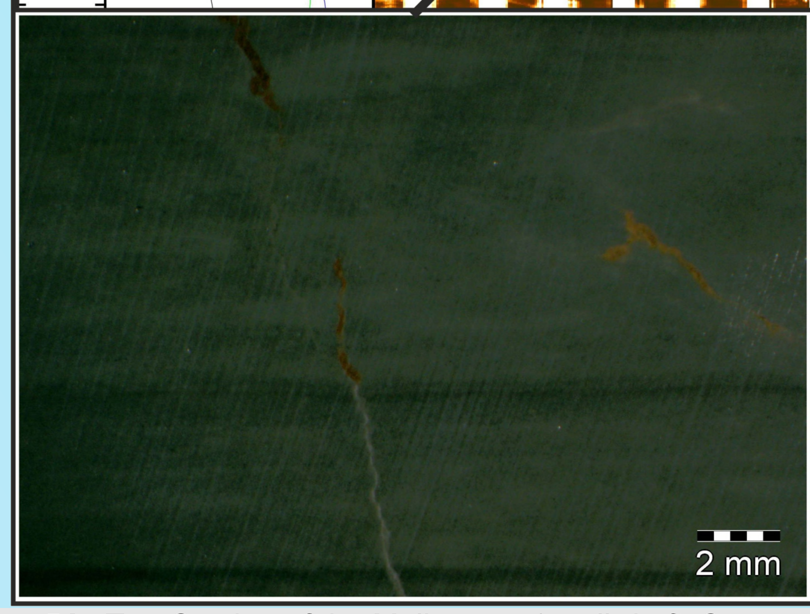
Rock Failure On Decimetre scale

In order to examine which physical processes cause wellbore failure a breakout in the Carboniferous Pennine Middle Coal Measures from the Melbourne 1 well was selected for detailed study. The core was analysed using a series of non-destructive sore scanning techniques tests (carried out by Geotek Ltd.) and destructive point load testing (Fig.5a).

X-ray radiography (Fig. 5a) shows the complete breakdown of sedimentary structures at the base of a thin coal at 986.9 m, with sedimentary structures becoming more prominent towards 989 m) that corresponds to an increase in rock tensile strength.

Photographs from core specimens show the growth of secondary iron mineralisation in the incipient fractures present in the rock at 988.5 m (Fig. 5B). Towards the base of the studied section (990 m) iron nodules can be seen growing between sedimentary laminations (Fig. 5C) suggesting that this mineralisation is limiting breakout length.





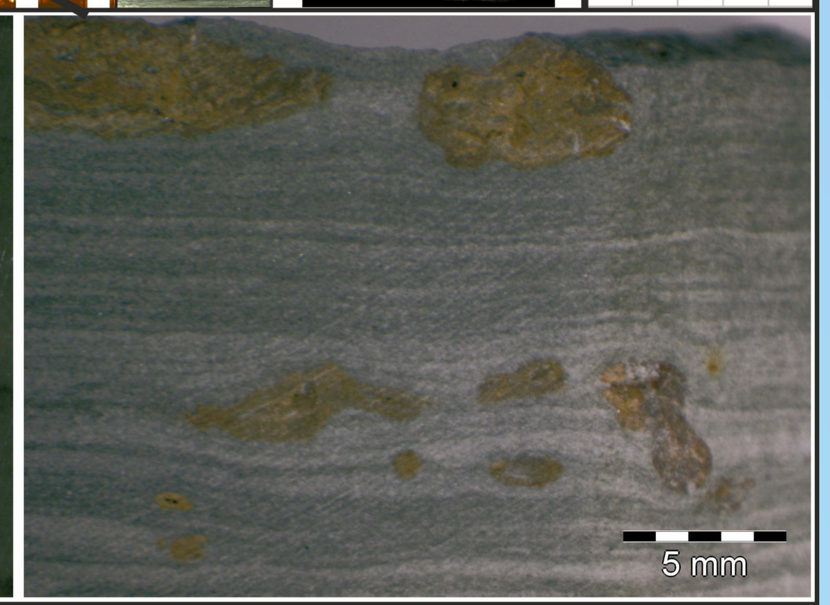


Figure 5A, *Top*: Section of the Melbourne 1 well. *Left*: Conventional geophysical logs including density, sonic and gamma ray. *Centre Left*: Borehole imaging showing breakouts and drilling induced tensile fractures with representative bedding picked. *Centre*: High resolution core scans depth matched against borehole imaging. *Centre Right*: 3D X-ray radiography (Trevor Plimmer and Michael Mills of Intertek NDT Services Ltd). *Right*: Tensile strength from Point Load Testing.
Figure 5B, *Bottom Left*: Optical Micrograph showing a microfracture with an Fe-rich precipitate.
Figure 5C, *Bottom Right*: Optical Micrograph showing horizontal laminations and Fe nodules

The Authors gratefully acknowledge Geotek Ltd for access to core scanners which provided data used here.