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New UK in-situ stress orientation for northern England and controls on borehole wall deformation identified using borehole imaging

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The nascent development of a UK shale gas industry has highlighted the inadequacies of previous in-situ stress mapping which is fundamental to the efficacy and safety of potential fracturing operations. The limited number of stress inversions from earthquake focal plane mechanisms and overcoring measurements of in-situ stress in prospective areas increases the need for an up-to-date stress map.

Borehole breakout results from 36 wells with newly interpreted borehole imaging data are presented. Across northern England these demonstrate a consistent maximum horizontal stress orientation (SHmax) orientation of 150.9° and circular standard deviation of 13.1°. These form a new and quality assured evidence base for both industry and its regulators.

Widespread use of high-resolution borehole imaging tools has facilitated investigation of micro-scale relationships between stress and lithology, facilitating identification of breakouts as short as 25 cm. This is significantly shorter than those identified by older dual-caliper logging (typically 1-10+ m). Higher wall coverage (90%+ using the highest resolution tools) and decreasing pixel size (down to 4mm vertically by 2° of circumference) also facilitates identification of otherwise undetectable sub-centimetre width Drilling Induced Tensile Fractures (DIFs).

Examination of borehole imaging from wells in North Yorkshire within the Carboniferous Pennine Coal Measures Group has showed that even though the stress field is uniform, complex micro-stress relationships exist. Different stress field indicators (SFI) are significantly affected by geology with differing failure responses from adjacent lithologies, highlighted by borehole imaging on sub-metre scales.

Core-log-borehole imaging integration over intervals where both breakouts and DIFs have been identified allows accurate depth matching and thus allows a synthesis of failure for differing lithology and micro-structures under common in-situ conditions. Understanding these relationships requires detailed knowledge of the rock properties and how these affect deformation. Strength and brittleness of the facies are indicative of their likely failure-modes which are in turn controlled by their lithology, diagenesis and clay mineralisation, often highlighting dm-scale stress rotations around lithological boundaries. Breakouts are seen to concentrate within “seatearths” (palaeosol intervals directly under the coals), whereas intervals immediately above coals are marked disproportionately by DIFs. In-situ stress magnitude data information is not yet available for these wells, further work is required to quantify the geomechanical properties.

New UK in-Situ Stress orientation for Northern England and controls on borehole wall deformation identified using borehole imaging

British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

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UK in-situ stress field

Shale gas exploration highlighted inadequacies in understanding of the UK stress field.

Borehole image logs show high-resolution colour images based on physical property contrasts (eg resistivity).Image logs are now widely available across Northern England (Figure 1A) and can be used to identify stress field indicators such as Borehole Breakouts and Drilling Induced tensile Fractures (DIF's), as shown in Figure 1B. Newly available imaging has been used to identify breakouts to re-interpret the UK stress orientation (Kingdon et al., 2016), replacing previous work based on dual-caliper log data (Evans and Brereton, 1990).

Mapped breakouts interpreted from borehole imaging show a highly uniform maximum stress orientation (eg Figure 2A for Yorkshire area). Uncertainty in the maximum stress orientation has been radically reduced (Figure 2B).

The review of borehole imaging showed that breakouts are highly discontinuous with breakout formation and length highly constrained by lithology (Figure 2A).

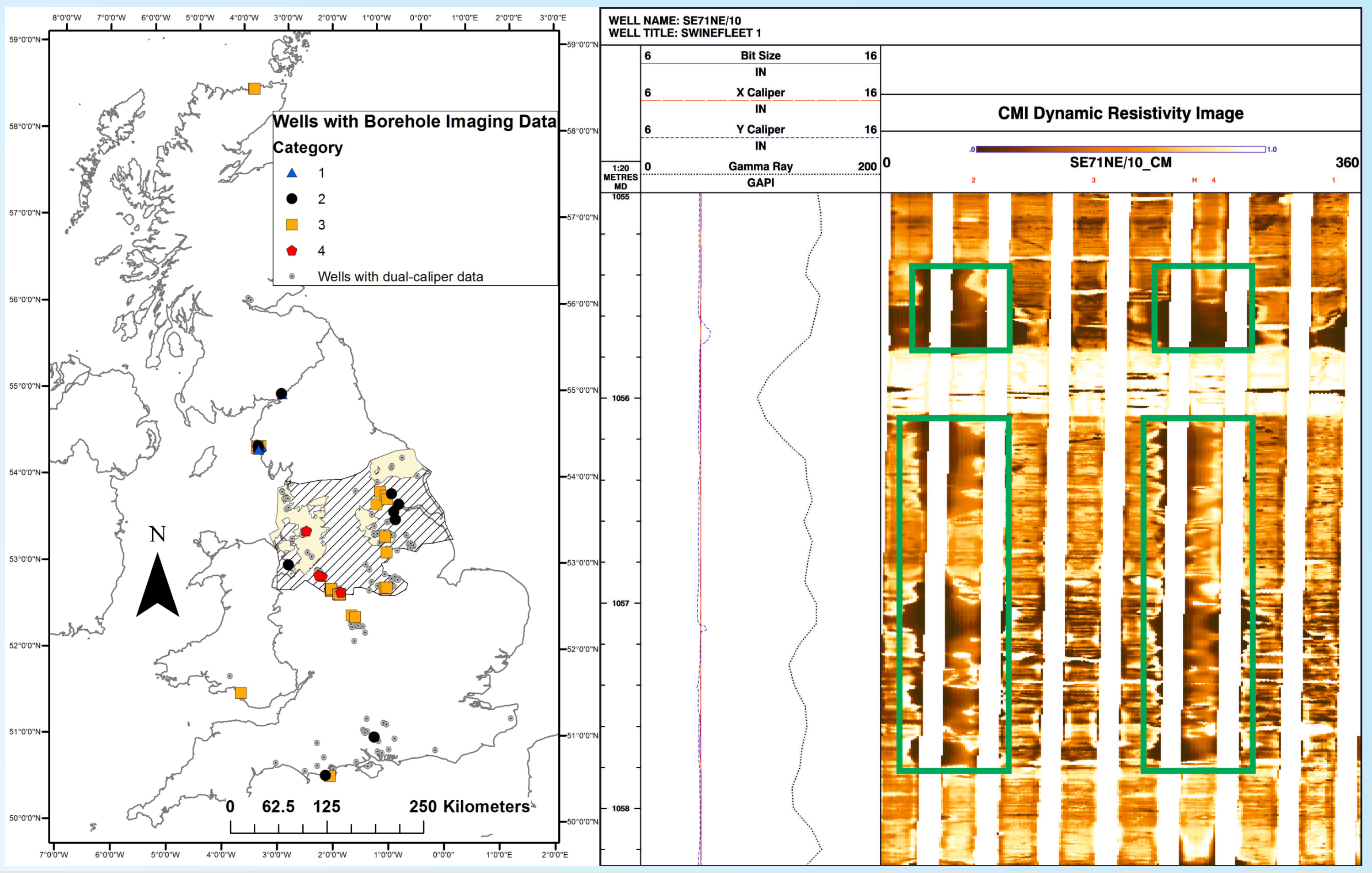
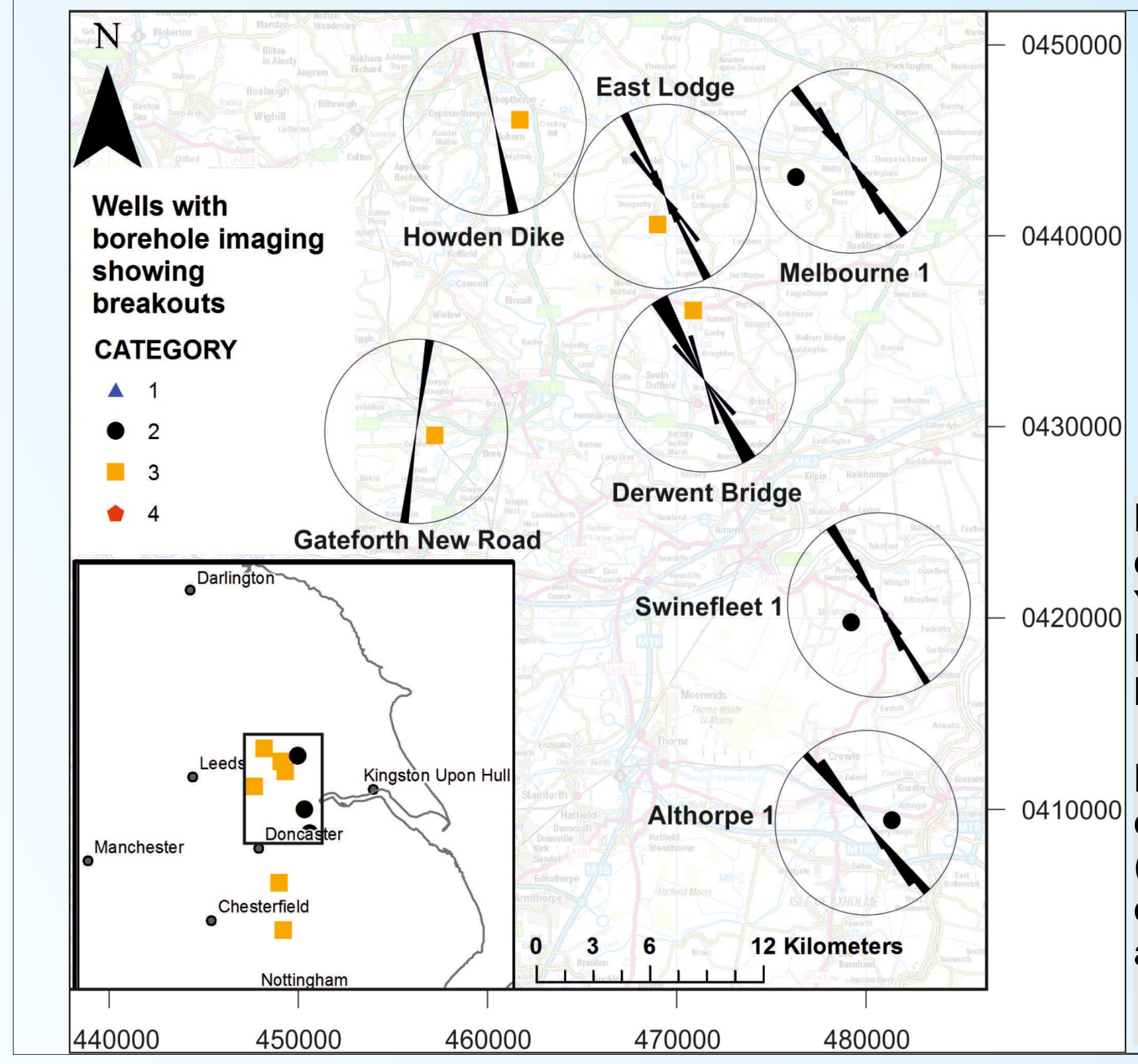


Figure 1A, *Left*: Map showing availability of dual-caliper and borehole imaging data across the UK. Hatched area shows Bowland Shale subcrop, shading highlights prospective zones. Categories show the resolution of available borehole imaging tools (Kingdon et al, 2016).

Figure 1B, *Right*: Resistivity borehole wall image from borehole Swinefleet 1 (unwrapped clockwise from north). Highlighting clear breakouts (green box) show as two parallel zones of borehole wall failure 180° apart.



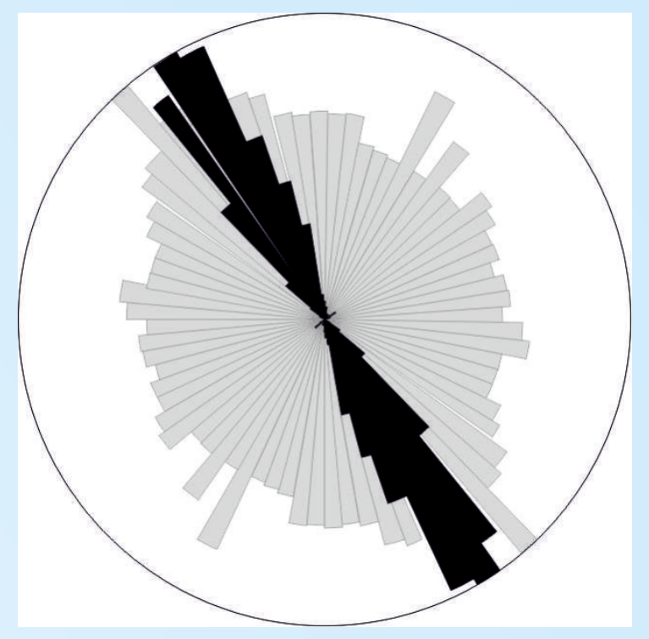


Figure 2A, *Left*: Map showing in-situ stress orientations for seven wells in the North Yorkshire area. Roses indicate the maximum horizontal stress orientations (SH$_{MAX}$) from breakouts identified on image logs.

Figure 2B, *Top*: Comparison of all SH$_{MAX}$ observations. Grey petals show dual caliper (Evans and Brereton,1990) black those derived from borehole imaging (Kingdon et al, 2016).

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References:

Evans, C.J., and Brereton, N.R., 1990, In situ crustal stress in the United Kingdom from borehole breakouts, in Hurst, A., Lovell, M.A., and Morton, A.C., eds., Geological applications of wireline logs: Geological Society of London Special Publication No. 48, p. 327-338. doi: 10.1144/GSL.SP.1990.048.01.27

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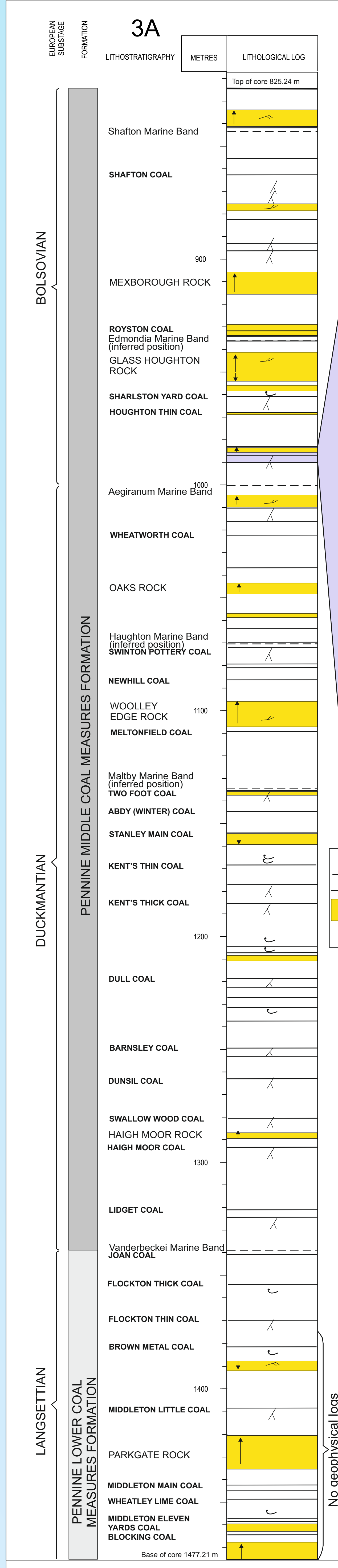
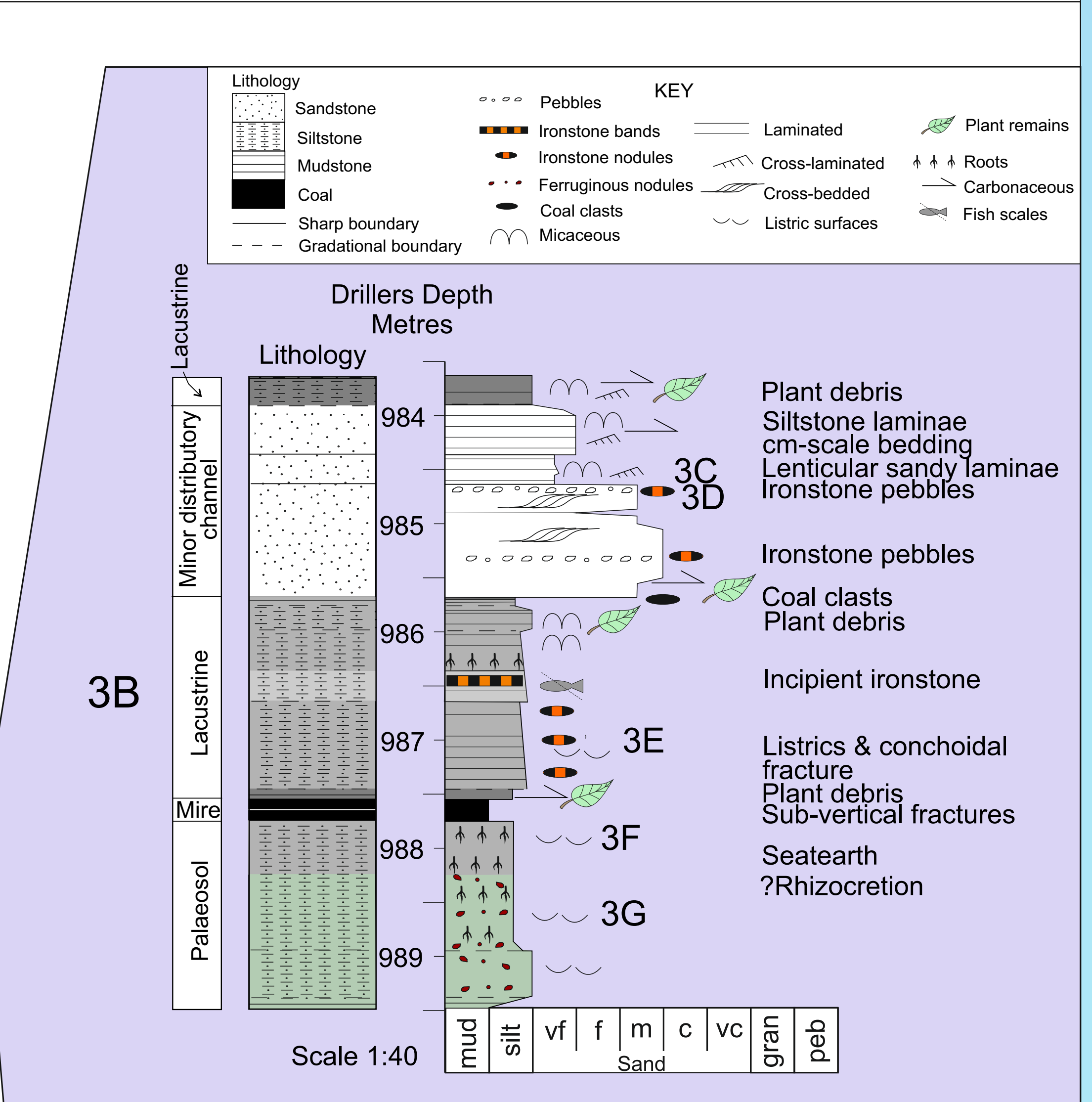
Stratigraphy of Melbourne 1





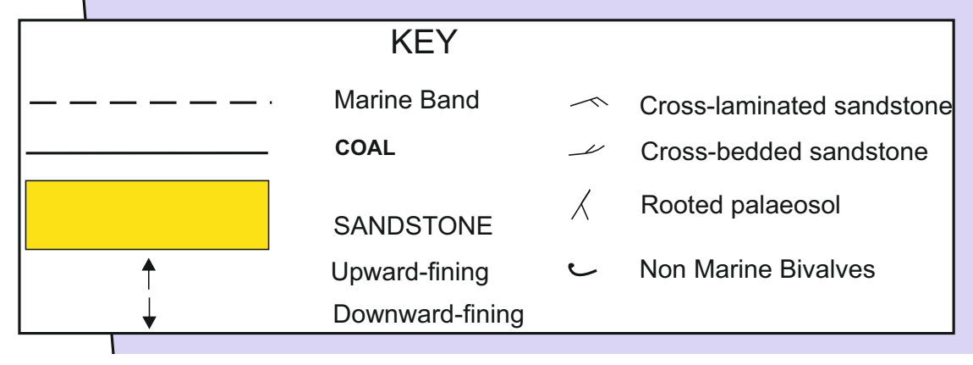
3C
985.00m
Cross-laminated sandy siltstone with muddy partings

3D
985.16m
Rounded ironstone pebbles within sandstone matrix

3E
987.53m
Ironstone nodule within muddy siltstone showing deformed laminae

3F
988.36m
Polished listric surface and dark root traces in seatearth

3G
989.10m
Polished listric surfaces and ferruginous nodules in seatearth



'COAL MEASURES' SEDIMENTOLOGY

The Pennine Coal Measures Group of northern and central England is a fluvio-lacustrine succession comprising cyclic sequences, each tens of metres thick. This interval includes parts of two such cycles, present immediately above a major flooding event (recognised as the Aegiranum Marine Band) which shows this interval to be of earliest Bolsovian age.

The main distributary channels of the Coal Measures, were filled by sharp-based upward-fining sands (e.g. Mexborough Rock, Woolley Edge Rock, Parkgate Rock). A minor distributary channel present in the studied interval shows a sharp base with initial infill by medium sands with common ironstone pebbles, reworked from adjacent lacustrine muds (**Photo 3D**), grading up to very fine, cross-laminated sands (**Photo 3C**). Between the channels were freshwater lakes where laminated carbonaceous mudstones were deposited, rich in drifted plant material, with secondary development of clayband ironstone nodules developed (**Photo 3E**). Upward-coarsening siltstones to sandstones, deposited as small deltas and crevasse splays, filled the lakes. As these infilled with sediment, emergent surfaces were colonised by plants and became swamps or raised peat bogs. These formed coals following burial.

Rooted horizons (**Photo 3F**) developed in argillaceous sediments beneath the mires, forming unleached grey palaeosols (seatearths), formed where water tables were at, or above, ground level for prolonged periods. In addition to the loss of primary sedimentary fabric, a common feature of such seatearths is polished 'listric' surfaces or pedogenic slickensides (**Photo 3F and 3G**). These convex-concave surfaces form during expansion/contraction of clay-rich vertisols where vertical movement is confined, typically during an initial better-drained phase of soil formation. Resultant strong alignment of clay minerals causes reactivation during subsequent tectonic deformation.

Rock Failure On Decimetre scale

Melbourne 1 well in North Yorkshire was selected to study this. The well has high quality borehole imaging data in addition to several hundred metres of continuous core and conventional logs. The 10m section shown (Figure 4) is from the Carboniferous Pennine Middle Coal Measures.

'To examine how lithology affects deformation a selection of whole round core samples were non-destructively scanned using a Multi-Sensor Core Logger (MSCL) by GEOTEK Ltd. Sensors include gamma , density and P-wave, X-Ray, CT, XRF & magnetic susceptibility. Testing to determine rock strength is ongoing.

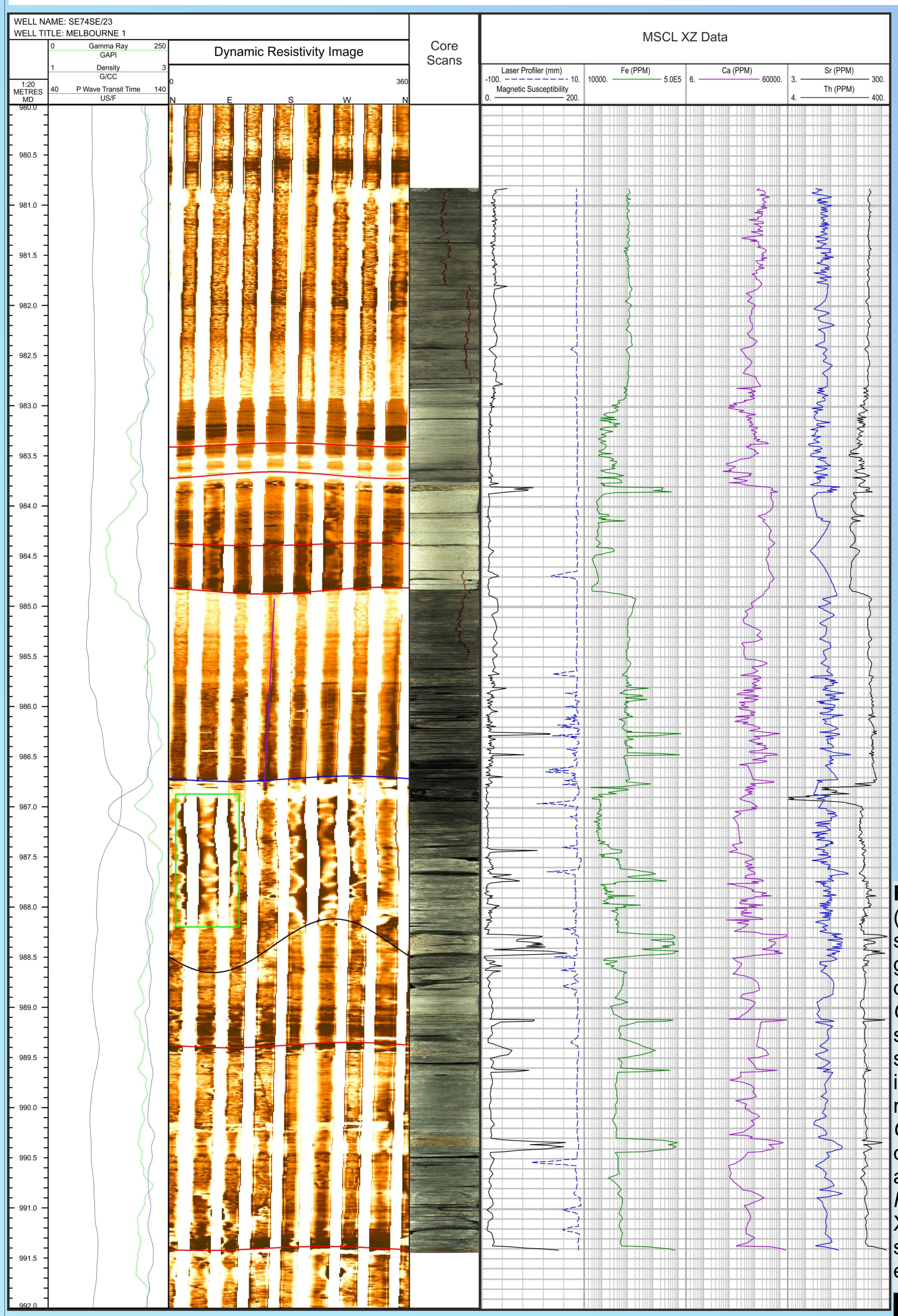


Figure 4 shows that conventional wireline logs are not sufficent to analyse these units in detail.

The MSCL-XZ data (Figure 4) has identified a significant decrease in iron between the Lacustrine Siltstone (984.85 m - 986.7 m) which contains DIF and a Palaeosol (986.7 m - 989.5 m) with a clear breakout.

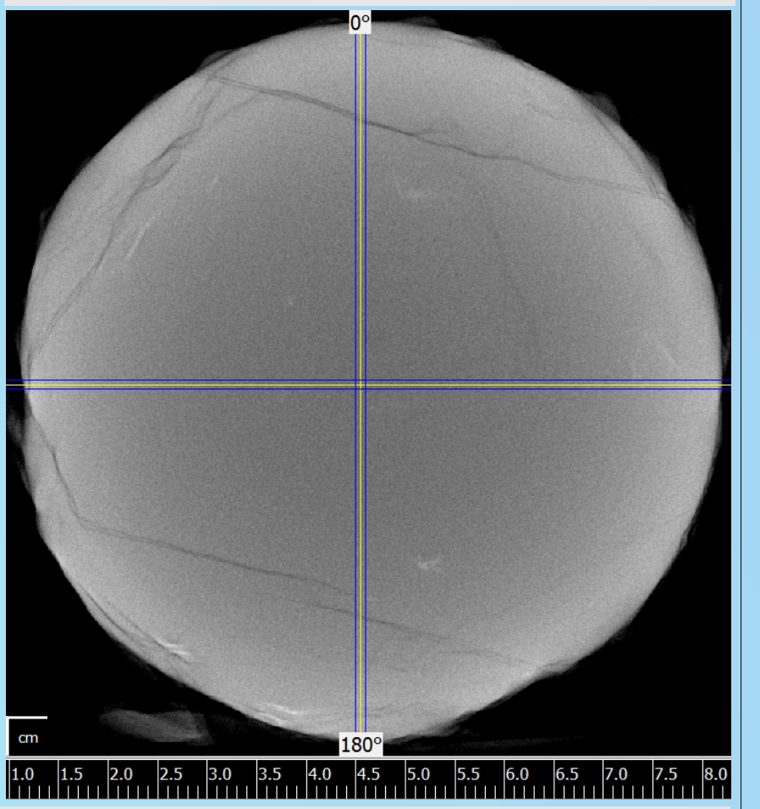
However CT scans (Figure 5) highlight discontinuities cross cutting the core. Figures 5B and 5C clearly show the cross cutting fracture 2 cm into the scan however the two vertical feature seen on Figure 5C do not appear on Figure 4B suggesting that the discontinuous micro-scale features may affect rock failure.

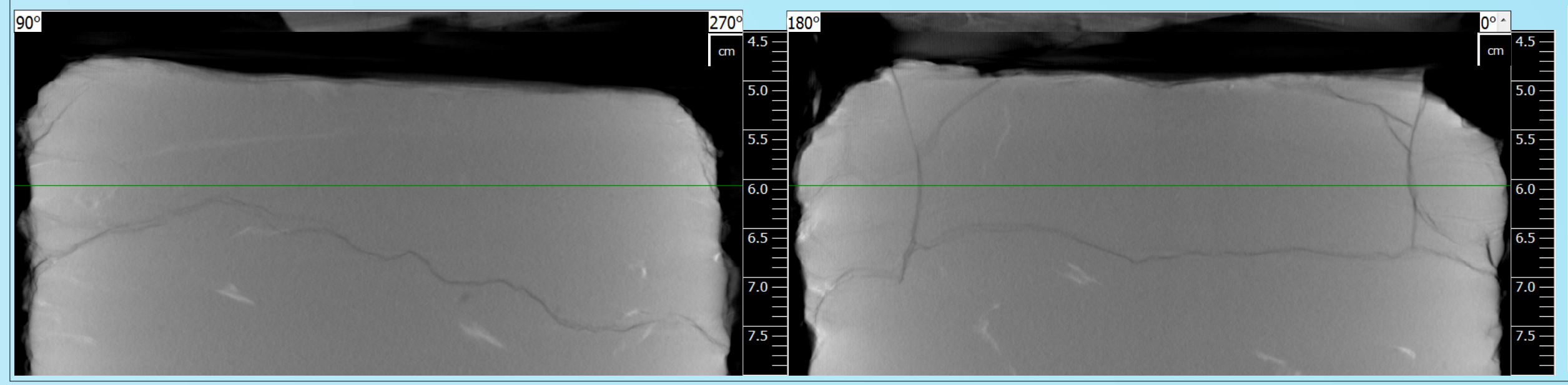
Figure 4, Plot for Melbourne 1 (1:20 scale) *Left*: Track showing conventional geophysical logs including density and gamma ray. *Centre Left*: Twelve metre section of borehole imaging showing breakouts, drilling induced tensile fractures with representative bedding picked. *Centre Right:* High resolution core scans depth matched against borehole imaging. *Right:* Output from the MSCL-XZ showing magnetic susceptibility, core profile and element abundances in ppm.

Further research is needed to investigate whether incipient micro-fractures or compositional changes control rock failure.

Only high resolution studies using: borehole imaging, rock testing and core scanning can resolve the dominant control on rock failure.

Conclusions: First indications are that breakout formation is controlled by zones of incipient micro-features





CT Scans of Palaeosol 986.9 m - 986.94 m
Figure 5A: *(Top)*: X-section . **Figure 5B:** *(Bottom Left)***:** Orthogonal view (90- 270°) **Figure 5C:** *(Bottom Right*) Orthogonal view (0-180°) Green line corresponds to the cross section shown in Figure 5A.