OR/17/048 Characterising the UK stress field and in-situ stresses

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Zoback et al. (2003)[1] states that stress is a tensor with six independent components but it can be assumed that at depth it is resolved to three principle stresses: a vertical stress (S_v = lithostatic pressure), a minimum horizontal stress (S_{hmin}) and a maximum horizontal stress (S_{HMax}). The other component required to fully characterise the stress field is the direction of S_{HMax} which is perpendicular to S_{hmin}. The magnitudes of the principle stress relative to each other determine which faulting regime is dominant (Table 1).

Table 1 Table showing the principle stresses in different faulting regimes and their relationship to S_{HMax}, S_{hmin} and S_v

Faulting environment	**Principle stress**				
	σ1		**σ2**		**σ3**
In Normal Faulting	S_v	≥	S_{HMax}	≥	S_{hmin}
In Strike Slip	S_{HMax}	≥	S_v	≥	S_{hmin}
In Reverse Faulting	S_{HMax}	≥	S_{hmin}	≥	S_v

Standard downhole geophysical logging and borehole tests can be used to estimate the magnitude of the principle stresses. Stress data is typically available from deep coal and hydrocarbon exploration wells in addition to a small number of boreholes drilled as part of the Sellafield project (Nirex 1997[2]) and other research boreholes. Figure 1 shows the available Coal, Oil and Radioactive Waste boreholes across the UK landmass.

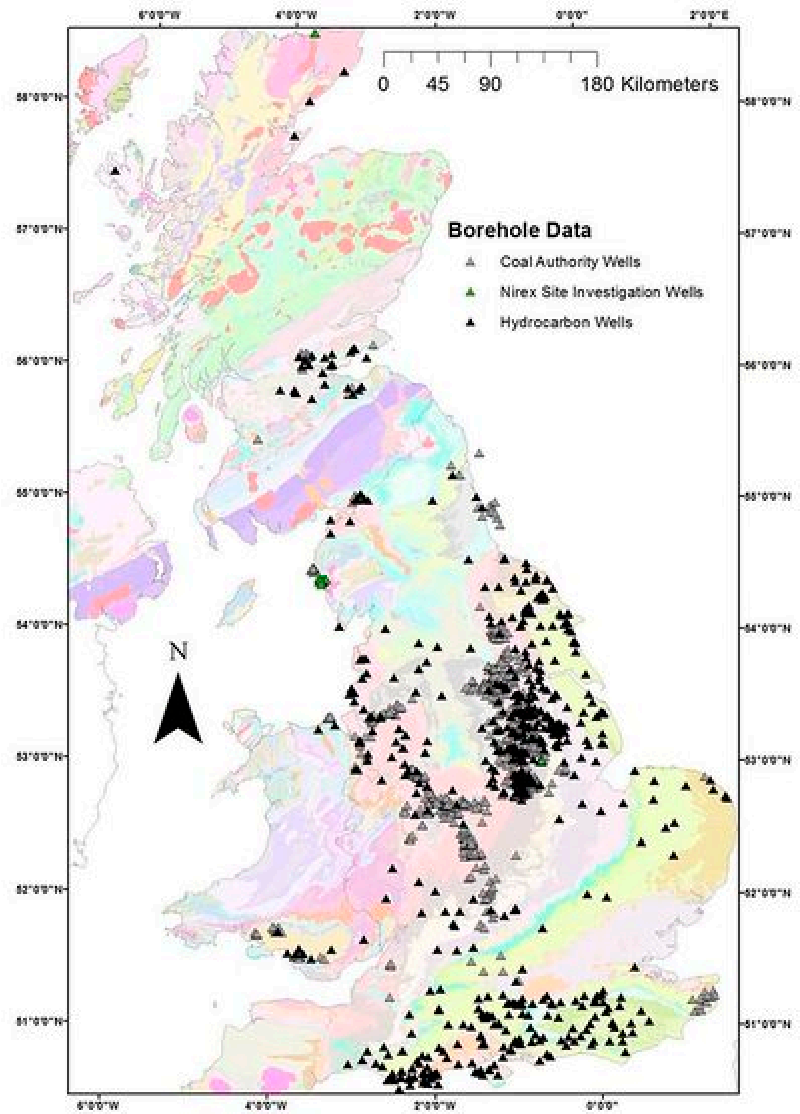

Figure 1 Map of the UK Landmass showing the distribution of: Wells drilled by the Coal Authority, Site investigation wells drilled by NIREX and Onshore hydrocarbon wells with digital geophysical log data. Note the low density of wells across central and Northern Wales, North Scotland and parts of the UK e.g. Devon and Cornwall. Contains British Geological Survey materials. © NERC 2017.

Figure 1 illustrates that for areas of the UK e.g. North Scotland, Central and Northern Wales there is a lack of data in the form of boreholes to quantify the in-situ stress field. It is also the case that even where deep boreholes have been drilled the necessary data required to characterise the stress field may not have been acquired. For example, between 1950 and 1995, Coal Authority data were often collected using non-standard tool, often with minimal metadata. The data available from onshore hydrocarbon wells were largely collected from 1960 to the present day, with the quality and variety of information available depending upon the operator, age and classification of the well. Because of this heterogeneity only a subset of the wells shown in Figure 1 will enable detailed characterisation of the principle stresses and the stress field orientation.

Vertical stress

The vertical stress is often used to predict fracture gradients and pore pressure in the absence of downhole, in-situ data (Tingay et al., 2003a[3]). In a sedimentary basin with no supporting information it is common to assume a vertical stress gradient of 23 MPakm^{-1} or 1 psift^{-1} (e.g. Dickenson, 1953[4]; Tingay et al., 2003a[3]). This corresponds to a basin with a layer-cake stratigraphy, an average density of 2.3 gcm^{-3} and 15% porosity (Zoback et al., 2003[1]). However, this is based on data from the Gulf of Mexico and specifically for Tertiary deltas (Tingay et al., 2003a[3]). Multiple studies document that the state of stress can be highly variable and where possible the vertical stress should be determined using in-situ data (e.g. Tingay et al., 2003a[3]; Verweij et al., 2016[5]; Williams et al., 2016[6]).

Estimating vertical stress

The vertical stress can be estimated from wireline density logs using the method of Zoback et al (2003)[1]. This method integrates density logs from surface to total depth (TD). The method for estimating vertical stress is given in Equation 1:

$$S_v = \int_0^z \rho(z) g \, dz \approx \bar{\rho} g z$$

Where $\bar{\rho}$ is the mean overburden density, ρ(z) is the density as a function of depth and g is the acceleration due to gravity (this study is limited to the UK landmass, thereby negating the need to correct for water depth). Density logging of hydrocarbon wells is often only collected through the strata of economic interest. The density log method requires densities information to the surface, this requires the user to estimate densities in the shallow sub-surface which are not sampled by the density tools. For wells drilled a body of water (usually offshore wells) the water depth must also be included.

Original native digital data for hydrocarbon wells is often unavailable, hardcopy logs can be machine digitised in a process known as vectorisation. This vectorised data has been shown to be a good match to native digital data (Figure 2), though quality is dependent on the quality of the scan of the original log data.

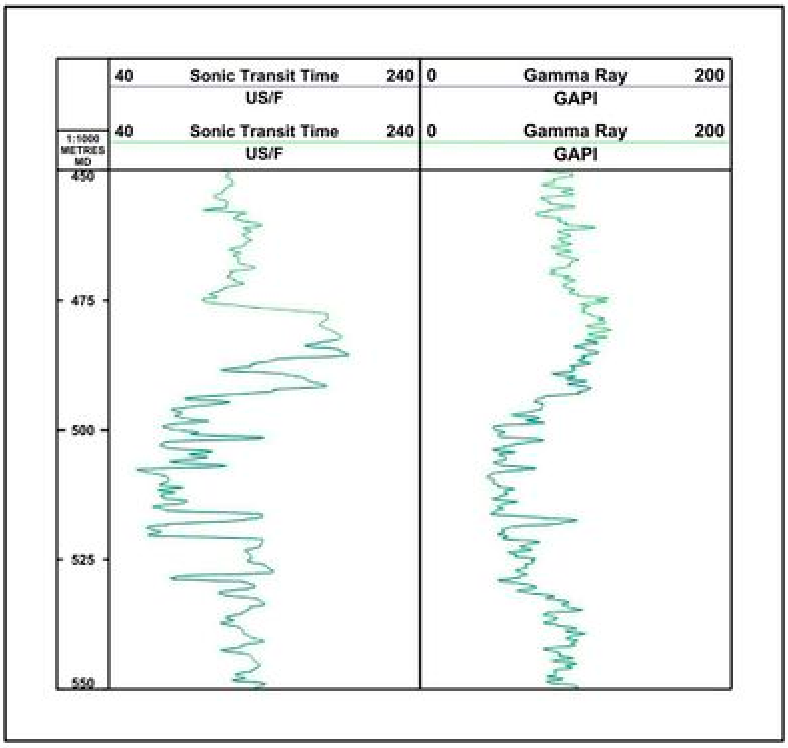

Figure 2 A 100 metre section of an onshore hydrocarbon well showing native digital data in blue and machine digitised (vectorised) data in green. Note the vectorised data is almost a perfect match for the native digital data.

In some cases the quality of the hardcopy log can cause problems and effect log data quality as shown in Figure 3. Even though the density log goes off scale at 4470 ft there is no backup/wrap-around on the scan. As a result the curve is 'top and tailed', degrading the signal quality and making it unsuitable for use in this work.

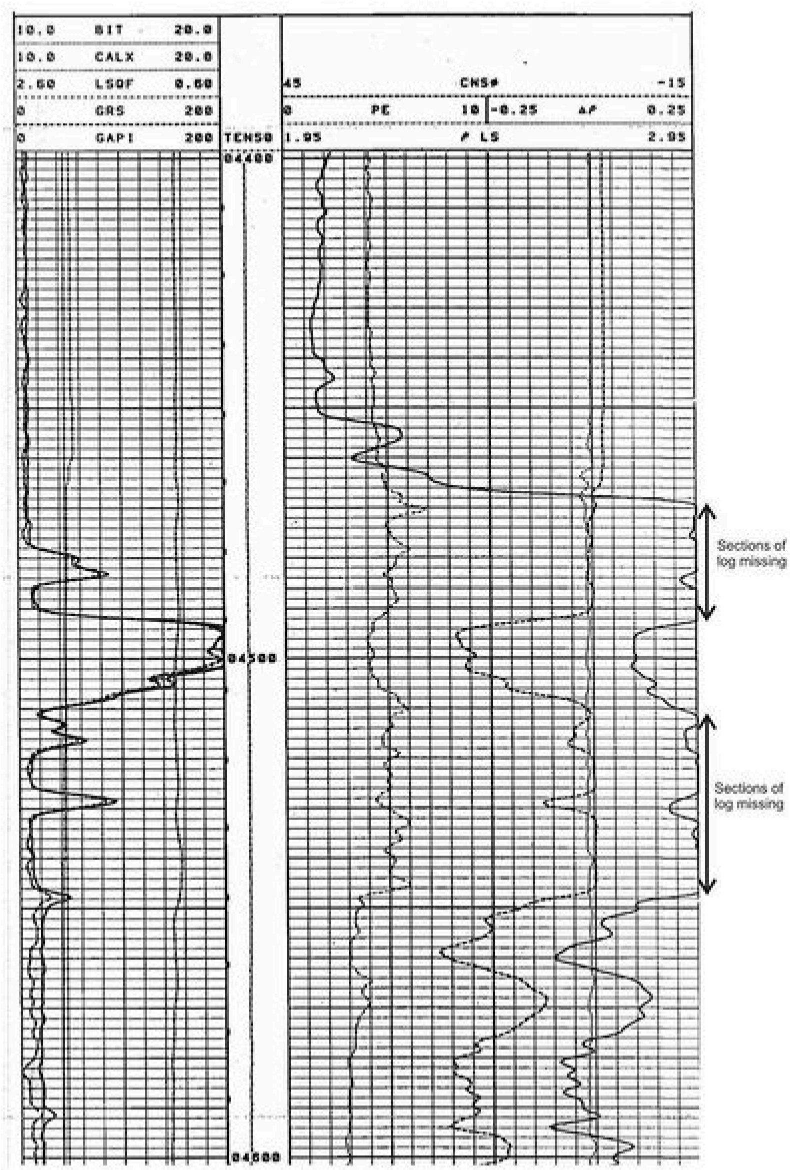

Figure 3 Section of a wireline log plot from a UK oil well (depth in feet), the density trace (Right hand panel, solid black line) is cut off at 2.95 gcm^{-3}, because of this vectorisation could not reproduce the source digital data accurately.

Often density logs from Coal Authority wells were collected from near surface making them useful for estimating the shallow subsurface density values. However, many were logged with non-standard tools which returned densities in counts per second (CPS). Conversion factors between CPS to gcm^{-3} cause errors and often there is no record of the conversion factor. For this report, no density log in CPS has been converted to gcm^{-3} by the authors, where data had already been converted it was reviewed before being incorporated.

Minimum horizontal stress

The minimum horizontal stress (S_{hmin}) is also the minimum principle stress (σ3) in both normal and strike slip environments. Baptie (2010)[7] demonstrated that the UK is predominately a strike slip/reverse environment with NW–SE compression driven by the Mid Atlantic Ridge. The magnitude of σ3 (Table 1) is important for any hydraulic fracturing operation as this is the value that needs to be exceeded to induce a hydraulic fracture. The magnitude of σ3 is also important to minimise the likelihood of inducing hydraulic fractures during the drilling process. In normal and strike-slip environments, these fractures occur when the weight of the mud used to drill the hole exceeds S_{hmin}. A detailed knowledge of S_{hmin} allows drillers to alter the weight of the drilling mud and reduce the chances of inducing a hydraulic fracture.

In boreholes S_{hmin} can be determined by a specific type of hydraulic fracture known as a leak-off test (LOT). These tests are typically carried out below casing shoes and multiple tests can be carried out in individual boreholes. To carry out a leak-off test the well is shut in and the pressure is increased. If pumping occurs at a constant rate then the pressure should increase linearly with time (Zoback et al., 2003[1]). At a specific point (known as the leak-off point) this linear relationship breaks down and the drilling mud is said to be 'Leaking off' due to the formation of a hydraulic fracture, into which the fluid moves/invades. If the well is pressured but not taken to leak-off, then it is known as a Formation Integrity Test (FIT) or Limit Test (LT; Zoback et al., 2003[1]). As a result FIT's are considered a lower bound for S_{hmin}, with LOT's giving a more reliable estimate of the magnitude of S_{hmin}. LOT's are a function of S_{hmin} and rock tensile strength, they can be effected by drilling fluids and pre existing fractures. The most reliable estimates of S_{hmin} come from extended Leak-off Tests (XLOT's) which are fully completed LOT's. However no XLOT's were available for this study and are not discussed further here. For a more detailed discussion of LOT's and XLOT's see: Addis et al., 1998[8]; White et al., 2002[9].

LOT and FIT data are recorded either in units of psi, specific gravity or as an equivalent mud weight, for this study all values have been converted to MPa. They are typically found in well reports, mud logs and composite plots, but there is no consistent standard for their reporting. Collecting LOT's/FIT's in all boreholes is not standard industry practice. In a small hydrocarbon field it is typical to collect FIT/LOT data from one or two wells for characterisation purposes. In some cases, tests were performed but the mud weight not recorded (Figure 4).

3 ¾" Hole Section

MWD RUN	07
Interval Drilled	7508 ft – 7694 ft
Tool Type	NaviTrak
Operational status	Performed to Specification

MWD / RWD Service	Percentage Logged		MWD / RWD Service	Percentage Logged	
	MWD	RWD		MWD	RWD

The 3 ¾" section was drilled using a 3 ⅛" NaviTrak with a 2 ⅞" National mud motor.

The cement and casing shoe were drilled out with no problems, formation was drilled from 7508 ft to 7519 ft then an FIT was performed. The rest of the 3 ¾" section was drilled with no major events. Well TD was called at 7694 ft 50 ft TVD into the Kirkham Abby formation.

Figure 4 Extract from an End of Well Report from a UK hydrocarbons well. The text states that an FIT was preformed but does not state a value.

Pore pressure

Pore Pressure (P_p) relates to the pressure of the fluids within the pores of a rock. Usually this equates to the pressure of a water column from the depth of interest to the surface, also known as hydrostatic pressure. When the density of water is approximately 1 gcm^{-3} hydrostatic pressure increases at a rate of 0.44 psi/ft or 10 $MPakm^{-1}$ (Zoback et al., 2003[1]).

Pore pressure is typically recorded downhole in permeable formations using a number of conventional tools including: Formation Multi Tester (FMT), Repeat Formation Tester (RFT) and Modular Formation Dynamics Tester (MDT). In impermeable formations such as shales, geophysical logging tools fail. When this occurs, laboratory test data is often used to estimate pressure (Zoback, 2010[10]).

Whilst pore pressure is not in itself a principle stress, it effects on S_{HMax} and is directly coupled to S_{hmin} (Hillis, 2000[11]). In a porous elastic rock the behaviour is controlled by the effective stress (Zoback, 2010[10]). The concept of effective stress was first noted by Terzaghi, (1923) and represents the difference between internal pore pressure and externally applied stresses (Zoback, 2010[10]). By making assumptions about faults in bodies of rock at depth the concept of effective stress can be used to predict the magnitudes of the principle stresses at depth (Zoback et al., 2003[1]).

Section Maximum horizontal stress discusses the role of Pore Pressure in estimating S_{HMax} in the presence of well bore failure. S_v is unaffected by changes in pore pressure, however some changes can be indicative of processes which can affect S_v such as undercompaction and overpressure (Hillis, 2000[11]; Tingay et al., 2003a[3]). The ratio between the change in S_{hmin} and the change in P_p can also be used to evaluate whether increases in P_p will result in tensile fractures or fault reactivation (Tingay et al., 2003b[12]).

Stress field orientation

The orientation of the stress field is an important component of subsurface characterisation as in normal and strike-slip environments it constrains the orientation of any hydraulic fracture. Hydraulic fractures propagate perpendicular to σ3 as this is the least energy configuration (Zoback et al., 2003[1]). In the vertical plane the orientation of these features will be parallel to S_{HMax} (Brudy and Zoback, 1999[13]).

There are two types of deformation that occur at the borehole wall which indicate the orientation of S_{hmin} or S_{HMax}: borehole breakouts and drilling-induced tensile fractures (DIFs). Stress concentrations at the borehole wall can lead to compressive failure which is termed a borehole breakout (Bell and Gough, 1979[14]). Plumb and Hickman (1985)[15] were able to demonstrate that these failures were orientated in the direction of S_{hmin} which in vertical boreholes is perpendicular to the direction of S_{HMax}. DIFs are the result of tensile fractures induced by the drilling process. These features are orientated in the direction of S_{HMax} (Moos and Zoback, 1990[16]). Figure 5 shows a borehole breakout and its relationship to S_{HMax} and S_{hmin}.

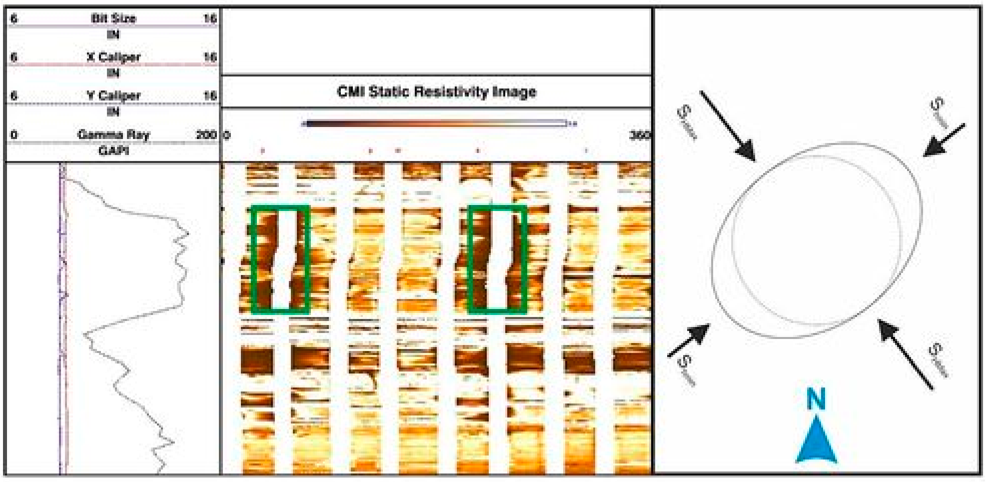

Figure 5 Image and diagram showing an example of a borehole breakout and its relationship to the principle horizontal stresses. *Left panel* conventional logs including perpendicular dual-caliper and gamma-ray log.
Centre: Unwrapped circumferential resistivity borehole imaging (CMI) (clockwise from north), breakouts highlighted by green boxes (orientation 54°). *Right panel:* Diagram showing the plan view of the breakout and the principle stresses, dotted circle represents the original hole/bit size; solid line represents the borehole wall.

Borehole breakouts and DIFs are most reliably characterised using borehole imaging tools (see Figure 6 after; Kingdon et al., 2016[17]). These generate high resolution false colour images using physical properties e.g. P-wave velocity or electrical resistivity. They can provide borehole wall coverage of 20%–95% with a vertical resolution of up to 2.5 mm (Kingdon et al., 2016[17]). Four-arm caliper tools can be used to identify breakouts, however, the use of these tools can increase uncertainty in the orientation of S_{HMax} (Kingdon et al., 2016[17]).

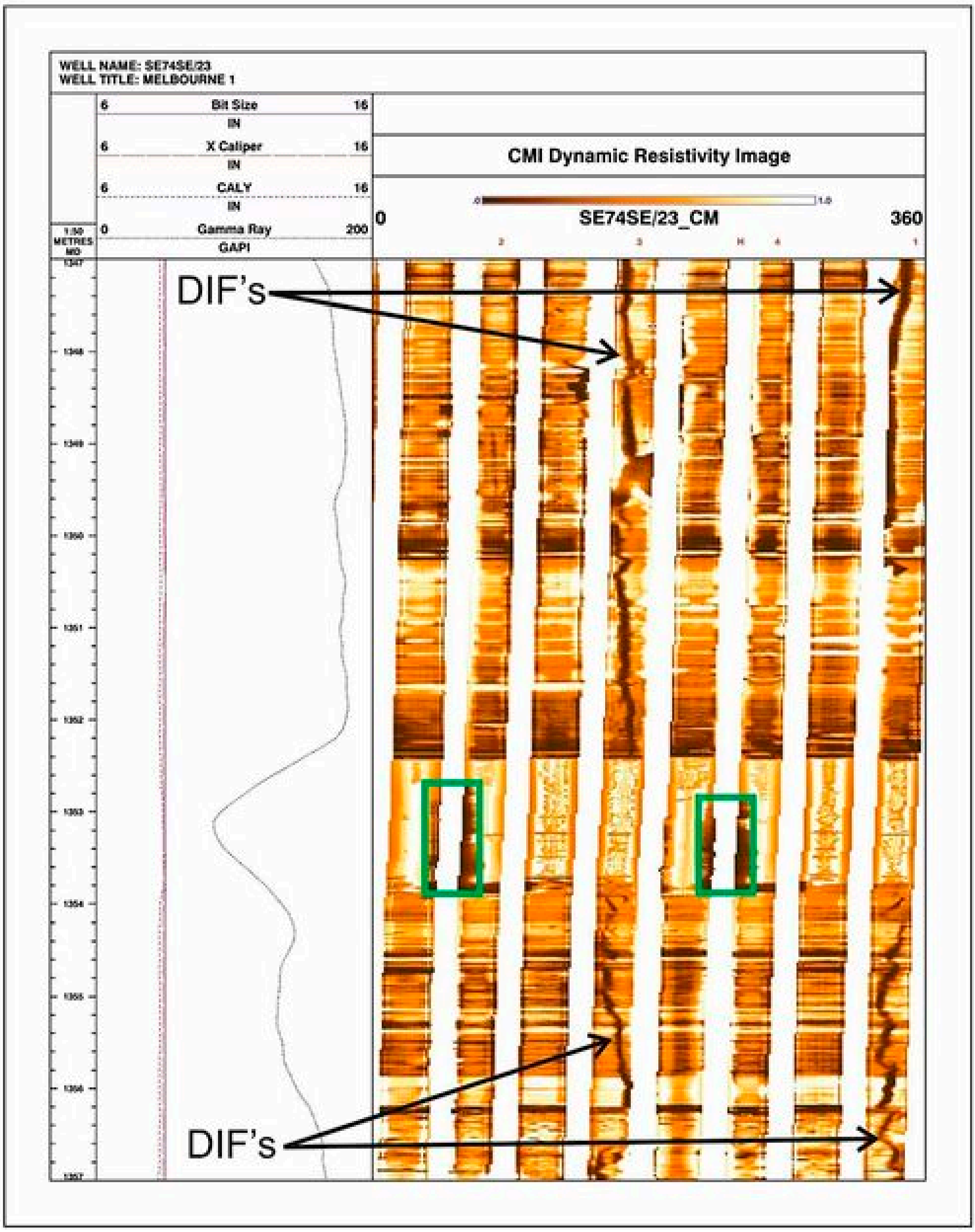

Figure 6 A 10 m section of borehole imaging from Melbourne 1 in North Yorkshire showing both borehole breakouts and DIFs (after Kingdon et al., 2016[17]). Left panel; conventional wireline logs including 4-arm caliper. Right Panel; Unwrapped Compact Micro Imager (CMI) resistivity image (clockwise from North), breakouts highlighted by green boxes indicate an Shmin orientation of NE–SW.

For a detailed explanation of characterising breakouts and DIFs from 4-arm caliper logs and breakouts see: Reinecker et al. (2003)[18] and Tingay et al. (2008)[19]. For a review of the UK stress field orientation see Kingdon et al. (2016)[17].

Maximum horizontal stress

The maximum horizontal stress (S_{HMax}) is the most difficult principle stress to characterise as it requires estimates of: P_p, S_{hmin}, rock tensile strength and depending on the technique you use: formation breakdown pressure or Unconfined Compressive Strength (UCS).

At shallow depths in mines and tunnels overcoring can be used to estimate the magnitude of S_{HMax}. This method involves the drilling of a pilot hole, and the insertion of a strain gauge, fixed in place with resin (Leeman and Hayes, 1966[20]; Becker and Davenport, 2001[21]). Both the strain gauge and a section of rock are then drilled out in a larger core. The strain gauge will then measure the stress relaxation of the rock. However the resin used to fix the gauge in place can have unreliable setting properties and poor adhesion (Farmer and Kemeny, 1992[22]). In addition to this the process of drilling the gauge can induce heating which causes cell expansion. These measurements also require knowledge of the elastic rock properties, which can lead to large uncertainties and errors in the value of S_{HMax}.

Hydraulic fractures were utilised by the Coal Authority to estimate S_{HMax} in the late 80’s, some of which were incorporated into the World Stress Map database release (Heidbach et al., 2016[23]). However, no standards exist for systematic recording of these data. Consequently, there is no way to easily identify boreholes where these data were collected and if data were preserved. In addition to this Zoback (2010)[10] questioned the use of hydraulic fractures to calculate S_{HMax} as the method was best suited to low temperatures; typically above 2 km and in rocks where borehole wall failure is not observed. Hydraulic fractures yield the most reliable results in smooth holes with no pre-existing fractures; however this is very rarely verified prior to conducting a hydraulic fracturing test (Zoback, 2010[10]). The most serious problem with this method is that it is almost impossible to detect the pressure at which a fracture forms at the well bore wall (Zoback, 2010[10]).

S_{HMax} can be estimated from observations of breakouts and DIFs on borehole imaging using Equation 2 and Equation 3 after: Barton and Zoback (1988)[24]; Moos and Zoback (1990)[16]; Zoback et al., (2003)[1].

For borehole breakouts:

$$S_{HMax} = \frac{(C_0 + 2P_P + \Delta P + \sigma^{\Delta T}) - S_{hmin}(1 + 2\cos 2\theta_b)}{1 - 2\cos 2\theta_b}$$

$$\text{Where } 2\theta_b = \pi - W_{bo}$$

In Equation 2 C_0 is the rock strength usually from UCS tests, W_{bo} is the breakout width, ΔP is the difference in pressure between the pore fluid pressure and the pressure exerted by a column of mud in the well bore. The thermal stress induced by the difference in temperature between the drilling fluid and formation fluid is: $\sigma^{\Delta T}$

For DIFs:

$$S_{HMAX} = 3S_{hmin} - 2P_p - \Delta P - T_0 - \sigma^{\Delta T}$$

Where T_0 is the rock tensile strength.

Due to the difficulties in determining stress either through unsuitable techniques or uncertainties in calculations there are almost no readily available, reliable measurements of S_{HMax} in the UK.

Well data quality control

All well data is typically recorded in measured depth (MD) downhole, typically relative to Kelly Bushing (KB) or Rotary Table (RT) in metres (m) or feet (ft). The KB or RT tends to be several metres above ground level. To calculate the stress at depth all observations are converted to true vertical depth below ground level in metres (TVD BGL).

To calculate TVD BGL the effect of borehole deviation must be taken into account. For FIT, LOT and RFT data where borehole deviation was >10° from vertical, deviation surveys were collected. These are often held in ASCII formats, or tabulated in end of well reports (EOWRs). True vertical depth is usually recorded but in a small number of cases was calculated using the minimum curvature method from borehole deviation and hole azimuth. If the borehole deviation was <10° the well was assumed to be vertical.

To assess S_v using the density log method, vertical wells were prioritised. It is common practice for vertical characterisation wells to be drilled to assess a potential resource target prior to development. These characterisation wells often have greater coverage of density logs over more stratigraphic units. As a result these characterisation wells were prioritised for calculating S_v. Wireline density tools require good contact with the borehole to record accurate densities. Loss of contact with the borehole wall results in the density tool recording the density of drilling muds and leads to anomalously low values. Due to the number of wells with density logs in the regions where large washouts were found the data from the well was removed from the interpretation.

References

1. ↑ [1.0] [1.1] [1.2] [1.3] [1.4] [1.5] [1.6] [1.7] [1.8] Zoback, M D, Barton, C A, Brudy, M, Castillo, D A, Finkbeiner, B R, Grollimund, B R, Moos, D B, Peska, P, Ward, C D, and Wiprut, D J. 2003. Determination of stress orientation and magnitude in deep wells. International Journal of Rock Mechanics & Mining Sciences., 40, 1049–1076.
2. ↑ Nirex, 1997. Sellafield Geological and Hydrogeological Investigations: Assessment of In-situ Stress Field at Sellafield. Nirex Report S/97/003.
3. ↑ [3.0] [3.1] [3.2] [3.3] [3.4] Tingay, M R P, Hillis, R R, Morley, C K, Swarbrick, R E, and Okpere, E C. 2003a. Variation in vertical stress in the Baram Basin, Brunei: tectonic and geomechanical implications. Marine and Petroleum Geology, 20, 1201–1212.
4. ↑ Dickinson, G. 1953. Geological aspects of abnormal reservoir pressure in the Gulf Coast Louisiana. Bulletin of the American Association of Petroleum Geologists, 37, 410–432.
5. ↑ Verweij, J M, Boxem, T A P, and Nelskamp, S. 2016. 3D spatial variation in vertical stress in on- and offshore Netherlands; integration of density log measurements and basin modelling results. Marine and Petroleum Geology. 78. 870-882. DOI: 10.1016/j.marpetgeo.2016.06.016
6. ↑ Williams, J D. O, Fellgett, M W, and Quinn, M F. 2016. Carbon dioxide storage in the Captain Sandstone aquifer: determination of in situ stresses and fault-stability analysis. *Petroleum Geoscience*, 22, 211–222. DOI: 10.1144/petgeo2016-036
7. ↑ Baptie, B. 2010. Seismogenesis and state of stress in the UK. *Tectonophysics*, 482 (1–4). 150–159.10.1016/j.tecto.2009.10.006
8. ↑ Addis, M, Yassir, N, Willoughby, D, and Enever, J. 1998. Comparison off leak-off test and extended leakoff test data for stress estimation. SPE/ISRM Eurock'98, Trondheim, Norway.
9. ↑ White, A J, Traugott, M O, and Swarbrick, R E. 2002. The use of leak-off tests as means of predicting minimum in-situ stress. Petroleum Geoscience, 8, 189–193.
10. ↑ [10.0] [10.1] [10.2] [10.3] [10.4] [10.5] Zoback, M D. 2010. Reservoir Geomechanics. Cambridge University Press.
11. ↑ [11.0] [11.1] Hillis, R. 2000. Pore pressure/stress coupling and its implications for seismicity. Exploration Geophysics, 31, 448–454.
12. ↑ Tingay, M R P, Hillis, R R, Morley, C K, Swarbrick, R E, and Okpere, E C. 2003b. Pore pressure and stress coupling in Brunei Darussalam — implications for shale injection. In: Van Rensbergen, P, Hillis, R R, Maltman, A J, and Morley, C K. (eds) 2003. Subsurface Sediment Mobilization. Geological Society, London, Special Publications, 216, 369–379.
13. ↑ Brudy, M, and Zoback, M D. 1999. Drilling-induced tensile wall-fractures: Implications for determination of in-situ stress orientation and magnitude. *International Journal of Rock*

Mechanics, 36, 191–215.
14. ↑ Bell, J S, and Gough, D I. 1979, Northeast-Southwest Compressive Stress. In: Alberta: Evidence From Oil Wells, Earth and Planetary Science Letters, 45, 475–482.
15. ↑ Plumb, R A, and Hickman, S H. 1985. Stress-Induced Borehole Elongation: A Comparison Between the Four-Arm Dipmeter and the Borehole Televiewer in the Auburn Geothermal Well. *Journal of Geophysical Research*, 90(B7), 5513–5521.
16. ↑ [16.0] [16.1] Moos, D, and Zoback, M D. 1990. Utilization of observations of well bore failure to constrain the orientation and magnitude of crustal stresses: Application to continental, Deep Sea Drilling Project, and Ocean Drilling Program boreholes. *Journal of Geophysical Research*, 95(B6), 9305–9325, doi:10.1029/JB095iB06p09305.
17. ↑ [17.0] [17.1] [17.2] [17.3] [17.4] Kingdon, A, Fellgett, M W, and Williams, J D O. 2016. Use of borehole imaging to improve understanding of the in-situ stress orientation of Central and Northern England and its implications for unconventional hydrocarbon resources. *Marine and Petroleum Geology*, 73, 1–20. DOI: 10.1016/j.marpetgeo.2016.02.012
18. ↑ Reinecker, J, Tingay, M, and Müller, B. 2003. Borehole breakout analysis from four-arm caliper logs, World Stress Map Project. WSM website: http://dc-app3-14.gfz-potsdam.de/pub/guidelines/WSM_analysis_guideline_breakout_caliper.pdf
19. ↑ Tingay, M, Reinecker, J, and Müller, B. 2008. Borehole breakout and drilling-induced fracture analysis from image logs [online], in World Stress Map Project—Guidelines: Image Logs, Helmholtz Cent. Potsdam, GFZ German Research Centre for Geosciences, Potsdam, Germany. (Available at: http://dc-app3-14.gfz-potsdam.de/pub/guidelines/WSM_analysis_guideline_breakout_image.pdf).
20. ↑ Leeman, E R, and Hayes, D J. 1966. A technique for determining the complete state of stress in rock using a single borehole. Proceedings of the 1st congress of the international society of Rock Mechanics, Lisbon, Part 2, 17–23.
21. ↑ Becker, A, and Davenport, C A. 2001. Contemporary in situ stress determination at three sites in Scotland and northern England, J. Struct. Geol., 23, 407–419.
22. ↑ Farmer, I W, and Kemeny, J M. 1992. Deficiencies in rock test data. In: Hudson, J A. (ed), Rock Characterisation: Proceedings of the International Symposium on Rock Stress, Chester, United Kingdom, 298–303.
23. ↑ Heidbach, O, Rajabi, M, Reiter, K, Ziegler, M, and WSM Team (2016). World Stress Map Database Release 2016. GFZ Data Services. http://doi.org/10.5880/WSM.2016.001
24. ↑ Barton, C A, and Zoback, M D. 1988. In-situ stress orientation and magnitude at the Fenton Geothermal Site, New Mexico, determined from wellbore breakouts. Geophysical Research Letters, 15, 467–470.

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