Marine and Petroleum Geology 97 (2018) 24–31

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo

Research paper

Stress magnitudes across UK regions: New analysis and legacy data across potentially prospective unconventional resource areas

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ARTICLE INFO

Keywords:
In-situ stress
Stress magnitude
Pore pressure
Unconventional resources
Hydraulic fracturing

ABSTRACT

Stress magnitude data across the UK is limited spatially and stratigraphically with information available for only 21 sites in the latest release of the World Stress Map. This information is largely derived from geothermal resource exploration and radioactive waste storage site assessment. Active exploration of unconventional resources in the UK has highlighted a lack of information to adequately characterise the stress field, in particular in regions underlain by potentially prospective shale formations. Understanding the in-situ stress conditions is critical to the planning of sub surface operations and the potential extraction of unconventional resources.

Legacy stress magnitude data from 75 sites is combined with new analysis of wireline data to re-characterise the stress field across two regions which are underlain by the Bowland Shale Formation which has resource potential for unconventional hydrocarbons. These regions are: East Yorkshire and North Nottinghamshire, and Cheshire and Lancashire.

Vertical stress gradients vary between 23 and 26 $MPakm^{-1}$ for the regions studied. Pore pressure is similar for both regions and is hydrostatic with a gradient of 10.19 $MPakm^{-1}$. Lower bounds for the minimum horizontal stress have been estimated from the available data and show that the magnitude of the minimum horizontal stress is 2.6 $MPakm^{-1}$ higher to the east of the Pennines.

The compiled legacy data show that the Maximum Horizontal Stress is consistently greater than the vertical stress, which in turn is greater than the minimum horizontal stress, indicating that at depth within the two regions, the faulting regime is predominantly strike-slip.

1. Introduction

Knowledge of the in-situ stress field is a key constraint in the exploitation of the subsurface and development of any subsurface resources including, storage of carbon dioxide, radioactive waste disposal, mining, unconventional hydrocarbon exploration, civil engineering and fault stability (Nirex, 1997; Zoback et al., 2003; Tingay et al., 2005; Williams et al., 2016). In particular, the stress field is critical to understanding fracture mechanics. This is highly important as the UK investigates the possibility of developing unconventional hydrocarbon resources which require stimulation of the rock mass through hydraulic fracturing. Controversy around the use of hydraulic fracturing in the UK intensified following tremors associated with the first hydraulic fracturing operations to test shale gas resource at the Preese Hall borehole in 2011 (Green et al., 2012; Younger, 2016). Since 2012 there have been renewed efforts to understand the UK's in-situ stress field in response to the recommendations of the Royal Society and Academy of Engineering (Mair et al., 2012) that "the British Geological Survey should implement national surveys to characterise in-situ stresses and to identify faults affecting prospective UK shale plays".

This research highlights the state of existing published knowledge of the UK in-situ stress field, and in particular the limited database of stress magnitude data across the UK. The knowledgebase is then extended with calculation of the stress magnitude from newly derived data sources to give a more complete understanding of the stress field in those regions which are potentially prospective for shale gas.

1.1. *The in-situ stress field*

At depth within the subsurface the in-situ stress field can be resolved to three principle components (Amadei and Stephansson, 1997; Zoback et al., 2003). The vertical stress component (S_v), also known as lithostatic or overburden stress, the minimum horizontal stress (S_{hmin}) and the maximum horizontal stress (S_{HMax}) and their respective orientations which are orthogonal to each other. The final component of the in-situ stress field is the pore pressure (P_p), the pressure of the fluid

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https://doi.org/10.1016/j.marpetgeo.2018.06.016
Received 17 November 2017; Received in revised form 27 April 2018; Accepted 14 June 2018
Available online 18 June 2018

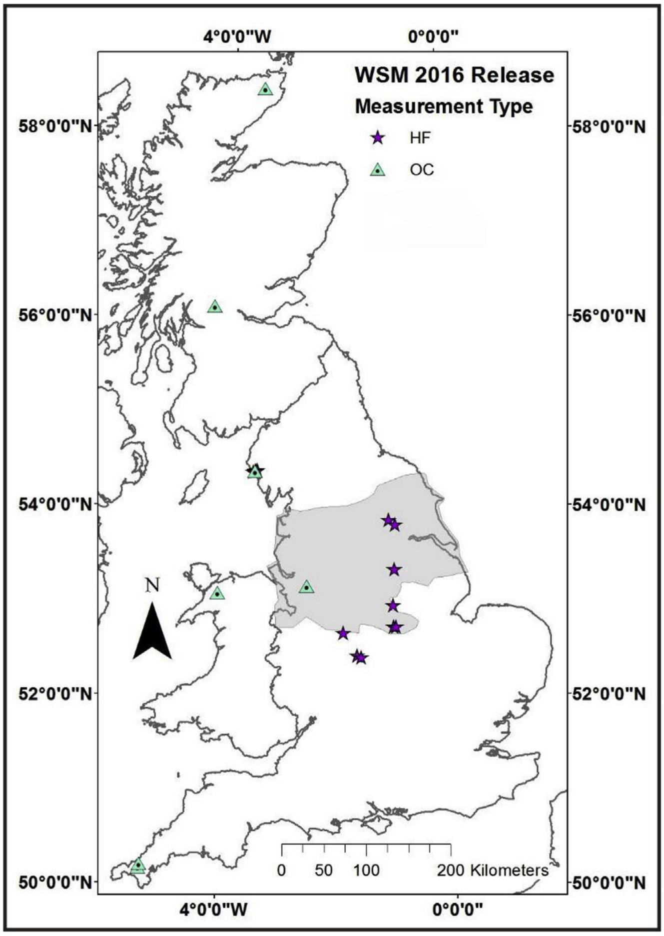

Fig. 1. Map of the UK showing those boreholes with stress magnitude data from the WSM 2016 release (Heidbach et al., 2016). Stress magnitude data source from Hydraulic Fracturing (HF) and Overcoring (OC). The shaded zone shows the area of interest from the BGS/DECC Bowland-Hodder Shale study, Andrews (2013).

within the rock mass. The relative magnitudes of the three principle stresses can also be used to determine the predominant faulting regime within a region (Zoback et al., 2003); normal faulting where $S_v \geq S_{HMax} \geq S_{hmin}$; strike slip $S_{HMax} \geq S_v \geq S_{hmin}$; and reverse faulting $S_{HMax} \geq S_{hmin} \geq S_v$.

The latest edition of the World Stress Map (WSM) includes all of the current openly available stress data for the UK (Heidbach et al., 2016) which has been greatly expanded by recent studies (Williams et al., 2015, 2016, 2018; Holford et al., 2016; Kingdon et al., 2016). Information from the WSM has previously been used to estimate stress magnitudes (Zang et al., 2012). Fig. 1 shows the 24 borehole sites for which stress magnitude information is available from the WSM (Heidbach et al., 2016) and also the technique from which the stress magnitude was derived, either by over-coring (Bigby et al., 1992) or hydraulic fracturing. The majority of this information was collected between 1982 and 1997, by the National Coal Board, site characterisation records from the previously proposed nuclear waste repository at Sellafield (Nirex, 1997), or from research projects such as the Hot Dry Rock Project (Parker, 1999). Since these projects there has been comparatively little work on the magnitude of the principle stresses at depth onshore in the UK.

There is little information regarding UK stress magnitudes, particularly in those areas and depths of current interest for unconventional resources. To address this the authors have undertaken a reinterpretation of the stress field across two UK regions using legacy information from boreholes drilled for hydrocarbon exploration, or boreholes drilled by the National Coal Board, to better constrain the magnitude of the stress field in key UK regions. Such data includes reported outputs of measurement techniques, often without acquisition parameters or raw data records from sources including: peer review publications, well reports, composite logs etc.

Due to lack of data in the two regions, SHMax magnitude data have been compiled from across the UK in order to evaluate the stress state. This information has been sourced from: peer-review publications, data referenced in the WSM database (Fig. 1), and records identified in the UK National Geoscience Data Centre (NGDC) hosted by the British Geological Survey (BGS).

2. Stress field information

Information collected during drilling, logging and testing of boreholes can be used to characterise the stress field. In practice in the UK, stress field information is most commonly available from coal or hydrocarbon exploration and appraisal boreholes (Fellgett et al., 2017a). In excess of 3000 coal or hydrocarbon boreholes have been drilled across the UK during the last two centuries. This makes the archive extremely variable and relevant information is only available for a small subset of these boreholes, between 25% and 30% in the regions investigated. For a full description of borehole data across the UK and how it can be used to characterise the stress field see Fellgett et al. (2017a).

2.1. Vertical stress

In most cases it can be assumed that vertical stress (S_v) is solely related to the overburden (Amadei and Stephansson, 1997). S_v can then be calculated by integrating bulk density logs with depth (Equation (1); Zoback et al., 2003):

$$S_v = \int_0^z \rho(z) g dz \approx \bar{\rho} g z \tag{1}$$

where $\rho(z)$ is the density as a function of depth, $\bar{\rho}$ is the mean overburden density and g is the acceleration due to gravity. This method requires knowledge of the density from the surface, and as a result when using logs from hydrocarbon boreholes (which often only collect density logs through the reservoir sections) requires estimates of densities through unlogged sections. The National Coal Board however, would often run density tools from surface, reducing the uncertainty associated with estimation of density at shallow depths.

2.2. Minimum horizontal stress

In boreholes the magnitude of the least principle stress (S_{hmin}) can be estimated using leak-off tests (LOT), which are typically carried out beneath casing shoes. These tests are carried out in a short section of open hole where the borehole is shut in and the pressure is increased at a constant rate. This causes a linear increase in pressure with time, which at a critical threshold (known as the leak off point), breaks down as a fracture is induced in the formation (Zoback et al., 2003). The pressure required to induce leak off can be measured and thereby used to approximate the magnitude of S_{hmin}. If the formation is pressurised but not taken to leak off then the test is referred to as a formation integrity test (FIT) or a limit test (LT) (Zoback et al., 2003). These tests can be used on a regional scale to provide an approximation of S_{hmin} but should not be used to determine its magnitude. There are many factors which can affect the leak off pressure including borehole stability, tensile strength and drilling fluids. For this study leak off tests were collated from drilling reports which often record these tests as a single pressure value for the leak off point without the pressure curves. This results in uncertainties in the determination of S_{hmin} as it is not clear if the test has been taken to leak off or which pressure has been recorded.

Extended leak off tests (XLOTs) allow for a more reliable estimate of S_{hmin} (Zoback et al., 2003) however no records have been found of these tests being conducted in the study area. For a full description of leak off tests and how they can be used to estimate S_{hmin} see (Addis et al., 1998; White et al., 2002).

2.3. Pore pressure

Pore pressure relates to the pressure of fluids within the pores of a rock. Where no information is available it is often assumed that the pressure is hydrostatic, meaning the pressure in the pores equates to the pressure of a column of water from the surface to the unit of interest. When the density of the pore water is 1 gcm^{-3}, hydrostatic pressure increases at 10 $MPakm^{-1}$ or 0.44 $psift^{-1}$ (Zoback et al., 2003). Pore pressure measurements can be taken by wireline formation testing tools such as the repeat formation tester (RFT), or can be taken during drill stem tests (DST).

2.4. Maximum horizontal stress

In boreholes S_{HMax} is extremely difficult to estimate as the techniques require knowledge or assumptions of: pore pressure, rock strength (tensile or unconfined compressive strength), formation breakdown pressure and S_{hmin}.

There are three main techniques used to estimate S_{HMax} in boreholes: hydraulic fracturing, overcoring and borehole failure mechanisms. Determining S_{HMax} from hydraulic fracturing uses a similar process to a leak off test however these are conducted in isolated sections of borehole after drilling rather than as the borehole is being drilled. The test pressurises a borehole to what is termed the formation breakdown pressure (P_b), the pressure at which a hydraulic fracture propagates away from the borehole wall. This pressure can be related to the principle stresses for impermeable rocks using Equation (2) and permeable rocks using Equation (3) (Hubbert and Willis, 1957; Haimson and Fairhurst, 1967, 1970; Amadei and Stephansson, 1997; Zoback, 2010):

$$P_b = 3\ S_{hmin} - S_{HMax} - P_p + T_0 \tag{2}$$

$$P_b = \frac{3\ S_{hmin} - S_{HMax} + T_0}{2 - \alpha\left(\frac{1-2\nu}{1-\nu}\right)} + P_p \tag{3}$$

where: T_0 is the rock tensile strength, ν is the rock poisons ratio and α is the Biot constant. Both techniques assume an isotropic medium and by multiplying S_{hmin} by three triples the error on this parameter which can lead to errors in excess of $\pm$ 6 MPa (M Tingay personal communication, April 2018).

Overcoring is a technique which is typically used in mine and shaft walls though it can also be used in boreholes. For a full description of this method see Leeman and Hayes (1966); Becker and Davenport (2001). The method involves drilling a vertical or horizontal pilot hole into the rock and inserting a strain gauge which is fixed in place with resin. The strain gauge and a section of the rock are then drilled out as part of a larger core. The strain gauge measures the stress relaxation of the rock which can be used to estimate the magnitudes of the principle stresses. There are several issues associated with this technique including poor adhesion of the resin to the rock and the generation of friction heat when extracting the core (Farmer and Kemeny, 1992).

Hydraulic fracturing has been used to determine the magnitude of S_{HMax} for a number of sites across the UK including: Morley Quarry, Rosemanowes Quarry and the Wray borehole (Evans, 1987; Parker, 1999; Heidbach et al., 2016). This method was also utilised by the coal industry for a number of boreholes drilled across the UK between 1980 and 1992. There are several issues associated with the use of hydraulic fractures to measure S_{HMax}; hydraulic fracturing operations need to be carried out in smooth circular holes with no pre existing fractures but this is not always verified (Zoback, 2010). However the biggest problem with this technique is uncertainty in the pressure at which a hydraulic fracture forms at the borehole wall (Zoback, 2010), which can lead to uncertainties in excess of 10 MPa as documented in Pine et al. (1983).

Borehole failure mechanisms include borehole breakouts and drilling induced tensile fractures (DIFs) which are predominantly used to characterise the orientation of the horizontal stresses (Plumb and Hickman, 1985; Tingay et al., 2008; Heidbach et al., 2016). However they can also be used to calculate S_{HMax} using equations (2) and (3) (Barton and Zoback, 1988; Moos and Zoback, 1990; Zoback et al., 2003).

For borehole breakouts:

$$S_{HMax} = \frac{(C_0 + 2P_P + \varDelta\ P + \sigma^{\varDelta T}) - S_{hmin}(1\ +\ 2\cos 2\theta_b)}{1 - 2\cos 2\theta_b} \tag{4}$$

where $2\theta_b = \pi - W_{bo}$ where C_0 is the rock strength usually from uniaxial compressive strength (UCS) tests, though it can be estimated using wireline log data if it is correlated to core (Chang et al., 2006). W_{bo} is the breakout width, $\varDelta P$ is the difference in pressure between the pore fluid pressure and the pressure exerted by a column of mud in the borehole. The thermal stress induced by the difference in temperature between the drilling fluid and formation fluid is: $\sigma^{\varDelta T}$. An alternative method of estimating horizontal stresses in granite using breakout width and depth was proposed by Shen (2008).

For DIFs:

$$S_{HMAX} = 3S_{hmin} - 2P_p - \varDelta\ P - T_0 - \sigma^{\varDelta T} \tag{5}$$

Both Equations (4) and (5) have significant uncertainties associated with them including the assumption that there are no variations in downhole pressure during drilling (Ramirez and Frydman, 2006). The use of breakout width been shown to overestimate S_{HMax} by up to 18% (Ramirez and Frydman, 2006).

Despite the numerous studies identifying borehole wall failure (breakouts and DIFs) there is insufficient information available to estimate S_{HMax} across the UK as rock strength or an estimate of rock strength is required. There are laboratory studies of rock strength and strength criterions which are used to estimate rock strength for specific lithologies (Chang et al., 2006), however the UK strata from which majority of the stress field information is available, is highly heterogeneous and a single strength criterion would not be representative of the rock strength across the area of Interest.

2.5. Orientation of the UK stress field

The orientation of the UK and UKCS stress field has been studied extensively (Williams et al., 2015, 2016, 2018; Holford et al., 2016; Kingdon et al., 2016; Fellgett et al., 2017b)). Kingdon et al. (2016) reported that the orientation of S_{HMax} across the UK landmass is $150.9^\circ \pm 13.1^\circ$, which is the result of ridge-push forces associated with the Mid Atlantic Ridge (Klein and Barr, 1986; Gölke and Coblentz, 1996).

3. Areas of interest

Two regions were chosen for the initial compilation of stress field information: East Yorkshire and North Nottinghamshire, and Cheshire and Lancashire (Fig. 2). This was based on the numbers of deep boreholes available and the resource potential for unconventional resources, highlighted by Andrews (2013).

The areas and available borehole data are shown in Fig. 2. Over 180 boreholes across the two regions were identified as potentially having stress field information available (Fig. 2), with stress magnitude data available for 75 of these.

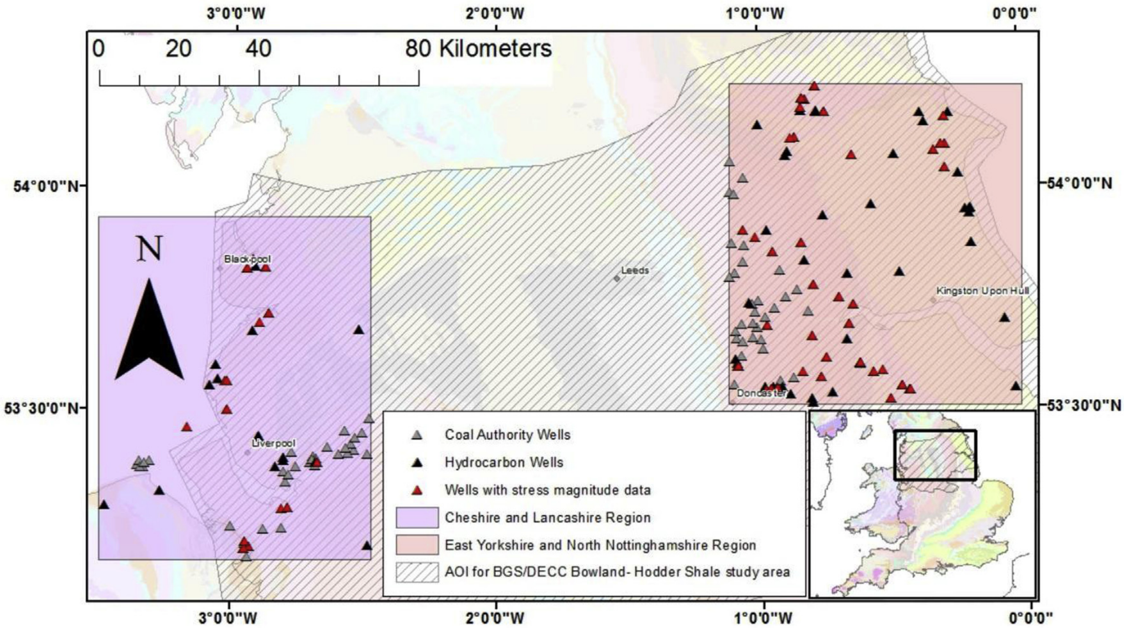

Fig. 2. Map showing the two areas of interest and the available deep borehole data. Boreholes shown in red have information to characterise stress magnitude data. The hatched zone shows the area of interest from the BGS/DECC Bowland-Hodder Shale study, Andrews (2013). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4. Results and discussion

When no stress field information is available it is common to assume a vertical stress gradient of 23 $MPakm^{-1}$ (Tingay et al., 2005) and a hydrostatic pore pressure with a gradient of 10 $MPakm^{-1}$, however these figures correspond to the Tertiary Deltas of the Gulf of Mexico (Tingay et al., 2003). Due to variability in the stress field this information should always be validated using in-situ stress data (Tingay et al., 2003).

Results from the density log inversion method (Fig. 3) show the vertical stress is between 23 and 26 $MPakm^{-1}$ with the average gradients increasing by two $MPakm^{-1}$ from East Yorkshire and North Nottinghamshire to Cheshire and Lancashire. This may be a result of the stratigraphy sampled by each of the borehole rather than a regional trend. In East Yorkshire and North Nottinghamshire the deepest borehole: Marishes 1 contains a thick sequence of Jurassic and Triassic sediments. The Carboniferous strata are found at depths of ≈1700 m. In contrast the Ince Marshes borehole in Cheshire and Lancashire typically intersects Carboniferous strata at significantly shallower depths of ≈400 m.

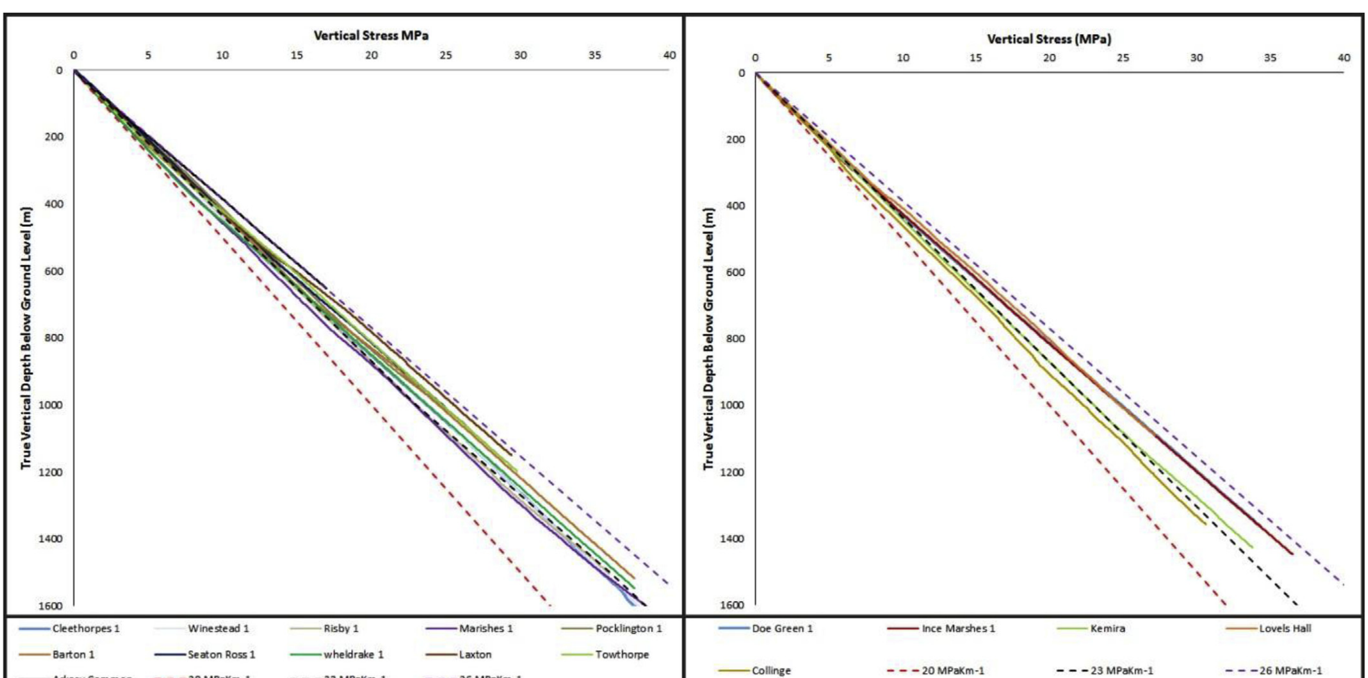

Fig. 3. Vertical Stress results from density log inversion method of Zoback et al. (2003), dashed black lines correspond to a gradient of 23 $MPakm^{-1}$. Left; results from East Yorkshire and North Nottinghamshire. Right; results from boreholes in Cheshire and Lancashire. After Fellgett et al. (2017a).

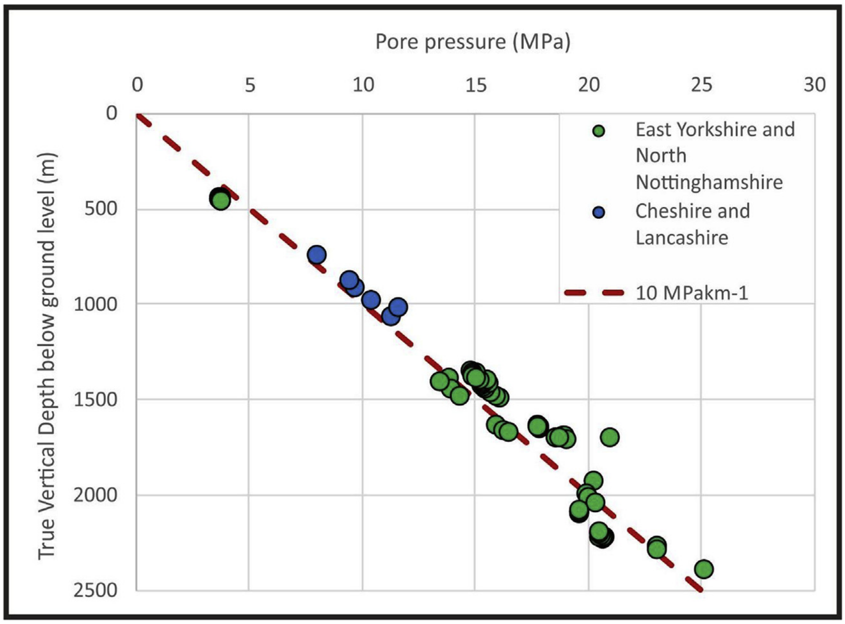

Fig. 4. Pore pressure measurements for the areas of interest from drill stem test and repeat formation tests for the regions of interest. Pore pressure values are hydrostatic and plot close to the 10 $MPakm^{-1}$ line.

The results of the density logs and pore pressure measurements show no evidence of overpressure in either region (Fig. 4). The majority of the pore pressure measurements are close to hydrostatic pressure, 10 $MPakm^{-1}$.

Values of S_{hmin} from LOT and FIT data from 91 tests across the two regions are shown in Fig. 5. Eighty of the LOT and FIT tests show that $S_{hmin} < S_v$. Eleven of the LOT and FIT measurements exceed the lower bound of S_v, 23 $MPakm^{-1}$. Of these 11 measurements nine were taken in the highly heterogeneous Permo – Triassic strata which may be a factor in the variation in S_{hmin} due to variations in lithology and rock strength (Fellgett et al., 2017a).

Linear gradients representing regional estimates of a lower bound for S_{hmin} were calculated from LOT data using the method of Addis et al. (1998) and may not be representative of S_{hmin} values at specific sites (Fig. 5). For information on determining in-situ stress at specific sites see: Zang and Stephansson (2010); Stephansson and Zang (2012).

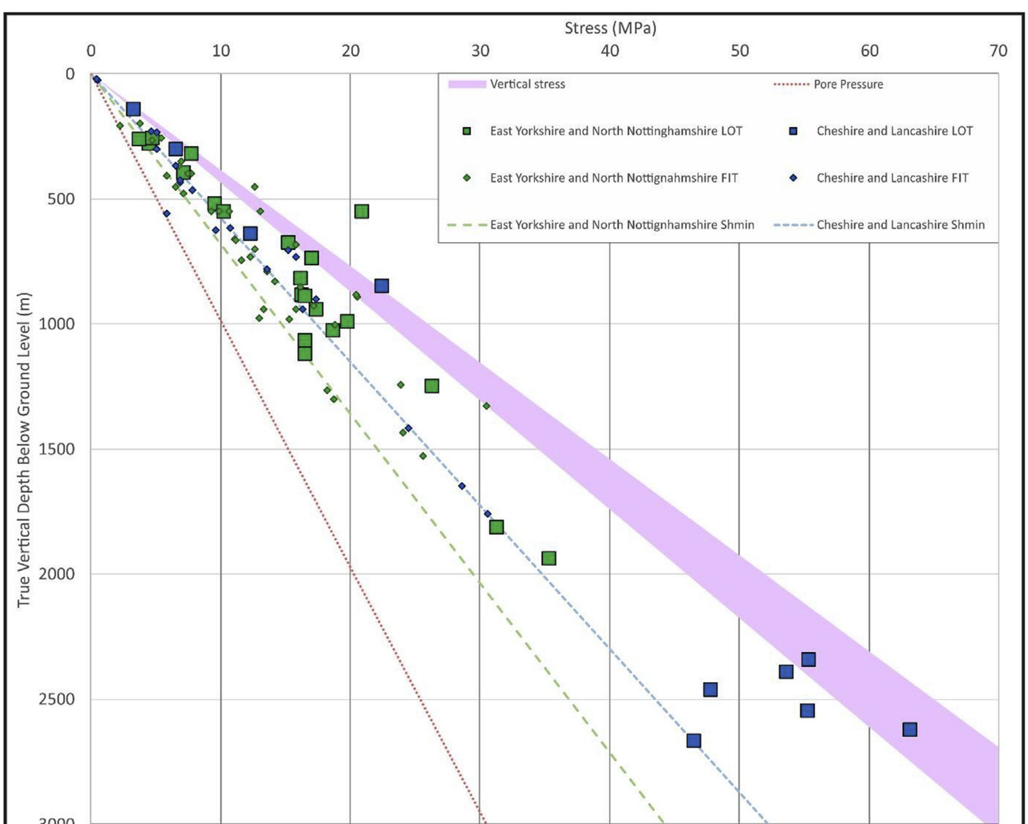

Fig. 5. Graph showing all S_{hmin} estimates in the areas or interest from FIT and LOT tests with regional estimates of the minimum bound of s_{hmin} for both Cheshire and Lancashire and East Yorkshire and North Nottinghamshire. The regional estimates are derived from the leak off tests for each region using the method of Addis et al. (1998). Range of vertical stress values from 23–26 $MPakm^{-1}$ shaded in purple. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

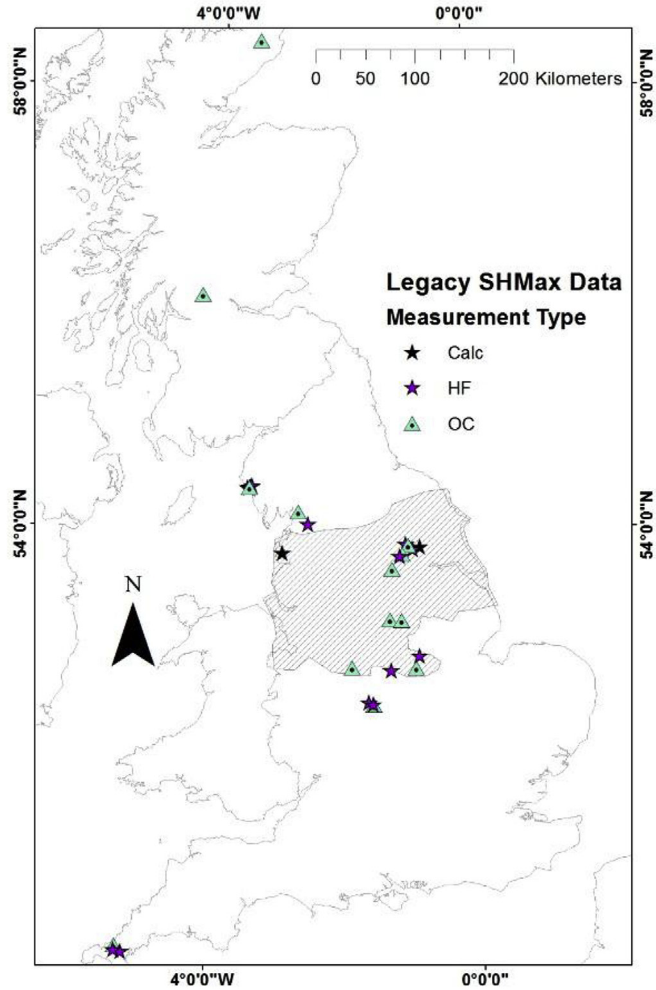

Fig. 6. Map of the UK showing those boreholes with SHMax magnitude data across the UK. Stress magnitude data is sourced from Hydraulic Fracturing (HF) and Overcoring (OC). The hatched zone shows the area of interest from the BGS/DECC Bowland-Hodder Shale study, Andrews (2013).

These gradients show a similar trend to the vertical stress gradients with the magnitude of the least principle stress 2.6 MPa per kilometre higher in Cheshire and Lancashire (17.42 $MPakm^{-1}$) compared to East Yorkshire and North Nottinghamshire (14.75 $MPakm^{-1}$).

There are only four sites across the two regions where the magnitude of S_{HMax} has been determined. To characterise the faulting regime required the use of legacy data to assess S_{HMax}, S_{hmin} and S_v. Legacy S_{HMax} data were collected from 33 sites across the UK (Fig. 6), these sites have variable lithology and stratigraphic successions so cannot be used to estimate the magnitude of S_{HMax} within the two regions. These data were collected using overcoring, borehole wall failure and hydraulic fracturing (Fig. 7). There are several studies which look at combining and interpreting data from these techniques (Ask, 2006; Zang and Stephansson, 2010). These studies require the use of raw data records to derive a standard deviation for each measurement. Due to the nature of the legacy data compiled this information was not available. Consequently Fig. 7 provides a qualitatively assessment of the relationship between SHMax, S_{hmin} and S_v. rather than the determination of the magnitude of S_{HMax}.

With five exceptions all of the S_{HMax} data plots above the minimum bound of S_v (23 $MPakm^{-1}$) with only ten results plotting below the upper Sv boundary of 26 $MPakm^{-1}$, indicating that $S_{HMax} > S_v$. As the S_{hmin} approximated from LOT and FIT indicates that $S_v > S_{hmin}$, the overall stress state of $S_{HMax} > S_v > S_{hmin}$ characterises the UK as a predominantly strike-slip faulting environment. However at depths of < 1 km there is greater uncertainty in the relation between Sv, Shmin and SHMax and SHMax estimates in particular can be highly unreliable at shallow depths. Stress magnitude data from the Triassic appears to show a greater variation than data from Carboniferous successions (Fellgett et al., 2017a).

Earthquake focal plane mechanisms in the UK show a predominantly strike slip/reverse faulting regime (Baptie, 2010) which supports the overall stress state of $S_{HMax} > S_v > S_{hmin}$. Earthquake focal plane mechanisms have shown wider evidence of thrust faulting in areas of Lincolnshire and central Wales (Baptie, 2010). These areas are outside the regions of interest and are from considerably greater depths of 3–18 km. As a result they may not be representative of the stress state in the area of interest and at depths less than 2 km. Stress detachments have been observed offshore (Williams et al., 2015) and proposed onshore (Evans, 1987) though detachments are not expected within the study area.

5. Conclusions

Density log inversion methods show the vertical stress to be between 23 and 26 $MPakm^{-1}$ for the two regions, with vertical stress values two $MPakm^{-1}$ higher in the Cheshire and Lancashire region to the west of the Pennines when compared with East Yorkshire and North Nottinghamshire region to the east. This trend is also reflected in the lower bounds of S_{hmin} calculated for the two regions with gradients of 17.42 $MPakm^{-1}$ in Cheshire and Lancashire compared to 14.75 $MPakm^{-1}$ in East Yorkshire and North Nottinghamshire.

Formation testing data have shown that the pore pressure is hydrostatic with a gradient of 10.19 $MPakm^{-1}$ with little difference between the two regions. S_{HMax} magnitude data were only available for five locations across the two regions and more information is required to better characterise it.

The combination of legacy data with newly calculated stress component data highlights that within the two regions the faulting regime is predominantly strike-slip. This has implications for borehole stability and hydraulic fracturing operations. A strike-slip stress state implies that any induced fractures will propagate vertically and will strike in the orientation of S_{HMax} (150.9° ± 13.1°; Kingdon et al., 2016). Therefore horizontal boreholes should optimally be deviated SW-NE to maximise the surface area of those fractures. This in turn has implications for borehole stability which will need to be monitored with great care during the drilling process with particular attention paid to mud weights etc. The regional-scale information available for stress field characterisation described in this study is, however, constrained both geographically and stratigraphically. This data is only indicative of the subsurface stress within the areas of interest and is not predictive of the principle stresses at greater depths. Detailed site specific data is required for a more detailed assessment of individual sites.

To gain a more complete understanding of the stress field requires extended leak-off test data to provide better estimates of S_{hmin}. When combined with core, utilising borehole imaging for core log-integration this would allow for a more detailed study of the magnitude of S_{HMax} and its variation with depth.

Acknowledgments

This paper is published with the permission of the Executive Director of the British Geological Survey. It was funded by BGS National Capability funding from NERC. Contains Ordnance Survey data © Crown copyright and database rights. All rights reserved [2015] Ordnance Survey [100021290 EUL], Use of this data is subject to terms and conditions. Contains British Geological Survey materials ©NERC 2017.

The authors would like to thank Dr Mark Tingay and an anonymous reviewer for constructive comments to improve this manuscript along

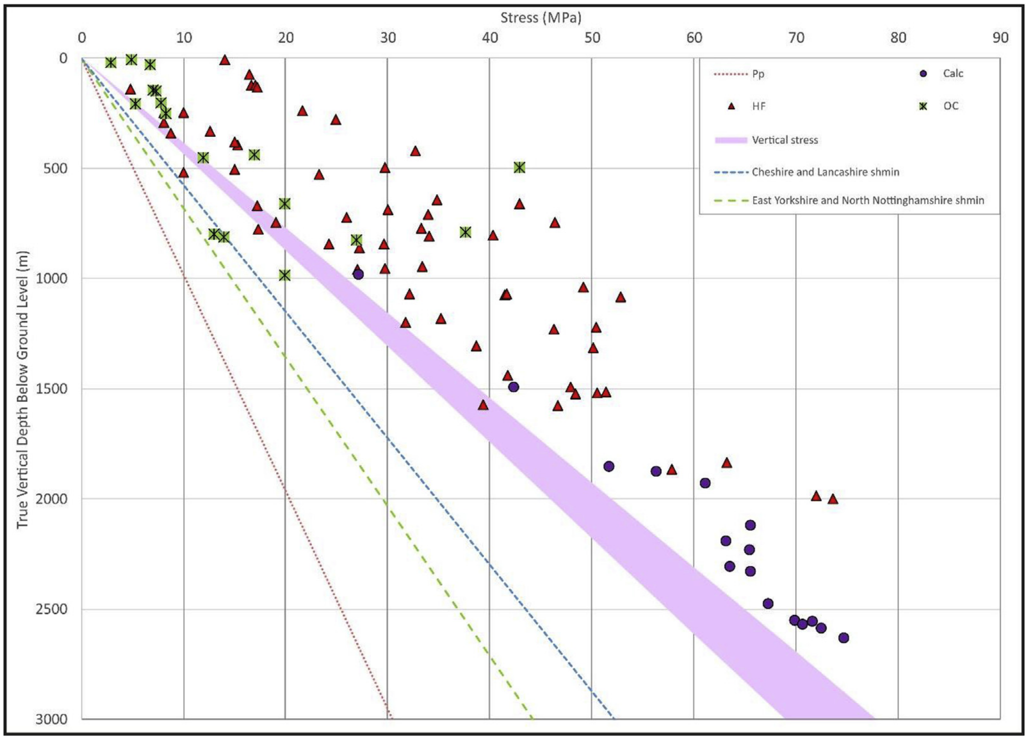

Fig. 7. Graph showing all S_{HMax} observations from legacy information from: hydraulic fracturing (HF), overcoring (OC) and calculations based on borehole wall failure (Calc). Range of vertical stress values from 23–26 MPakm^{-1} shaded in purple. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

with David Evans and Richard Haslam. The authors would also like to thank the BGS records team and Library team, in particular Catherine Oldham and Lesley Gerrett for help in collating the legacy stress field information from the Coal Authority and the Hot Dry Rock Project.

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