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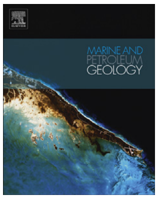

Research paper

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

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ABSTRACT

New interest in the potential for shale gas in the United Kingdom (UK) has led to renewed exploration for hydrocarbons in the Carboniferous age Bowland–Hodder shales under Central and Northern England. Following an incidence of induced seismicity from hydraulic fracturing during 2010 at Preese Hall, Lancashire, the publically available databases quantifying the in-situ stress orientation of the United Kingdom have shown to be inadequate for safe planning and regulation of hydraulic fracturing. This paper therefore reappraises the in-situ stress orientation for central and northern England based wholly on new interpretations of high-resolution borehole imaging for stress indicators including borehole breakouts and drilling-induced tensile fractures. These analyses confirm the expected north northwest – south southeast orientation of maximum horizontal in-situ stress identified from previous studies (e.g. Evans and Brereton, 1990). The dual-caliper data generated by Evans and Brereton (1990) yields a mean S_{Hmax} orientation of 149.87° with a circular standard deviation of 66.9°. However the use of borehole imaging without incorporation of results from older dual-caliper logging tools very significantly decreases the associated uncertainty with a mean S_{Hmax} orientation of 150.9° with a circular standard deviation of 13.1°.

The use of high-resolution borehole imaging is thus shown to produce a more reliable assessment of in-situ stress orientation. The authors therefore recommend that the higher resolution of such imaging tools should therefore be treated as a de-facto standard for assessment of in-situ stress orientation prior to rock testing. Use of borehole imaging should be formally instituted into best practice or future regulations for assessment of in-situ stress orientation prior to any hydraulic fracturing operations in the UK.

1. Introduction

1.1. In-situ stress and unconventional hydrocarbons reservoirs

The first exploration well of a prospective shale-gas reservoir in the United Kingdom (UK) was drilled at Preese Hall (Lancashire) in 2010 to test the productivity of the Carboniferous Bowland Shale Formation (Andrews, 2013; Smith et al., 2010). Induced seismicity was experienced following hydraulic fracturing, culminating in a magnitude 2.3 ML earthquake (Green et al., 2012). Following this event, the UK government imposed a temporary suspension of the use of hydraulic fracturing whilst a review of safety and best practice was undertaken. Simultaneously, the Royal Society and Royal Academy of Engineering (Bickle et al., 2012) undertook a study of the state of knowledge around economic development of shale gas in the UK. A key conclusion of this review was that "the British Geological Survey should implement national surveys to characterise in-situ stresses and to identify faults affecting prospective UK shale plays". This statement recognised the poor state of knowledge of the in-situ stress in the UK, and identified the requirement for the review of data from which detailed information may be derived. The research reported in this paper is a direct response to that recommendation and is intended to establish best practice for future acquisition of data to fully understand in-situ stress orientations in the UK.

Understanding of the in-situ stress field is essential for successful and safe production of remaining UK hydrocarbon resources, particularly to the development of unconventional

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reservoirs and shale horizons (Bickle et al., 2012). Knowledge of the in-situ stress orientation is important for understanding borehole stability, fluid flow in naturally-fractured reservoirs, and hydraulic fracture stimulation (Fuchs and Müller, 2001). Shale gas production typically involves hydraulic fracturing in deviated wells to increase the volume of produced gas (Bickle et al., 2012). The growth in gas and oil production from shale rocks that has taken place in the United States in the 21st century, has been a direct consequence of utilising hydraulic fracturing in deviated or horizontal wells. This creates a complex conductive fracture network allowing for an improvement in the well performance.

Shale gas production has potentially much greater impact on the population of the UK than in the US. Many of the major shale gas basins in the US are in sparsely populated areas. For example the Bakken Shale has predominantly been developed in North Dakota which has a population of 739,482 in 2014 with a population density of just 3.83 people/km^2 (U.S. Census Bureau, 2014). In contrast the much smaller area of northern and central England which overlies the potentially prospective Bowland Shale Formation includes several of England's largest cities with a total population of more than 14.6 million people, a population density of 502.7 people per km^2, over 100 times greater (Cartwright, 2015; Office for National Statistics, 2011). Any attempt to develop these resources in the UK therefore has the potential to affect a far greater number of people. Thus, improved understanding of the in-situ stress orientation in these parts of the UK is essential if shale gas exploitation is even to be considered, and should form any part of future regulations.

1.2. *In-situ stress orientation*

A critical factor in hydraulic fracturing operations is the orientation of the in-situ principal stresses. Hydraulic fracturing will propagate along the path of least resistance and create width in a direction that requires the least force. Therefore, hydraulic tensile fractures propagate parallel to the maximum horizontal stress (SHmax) in the vertical plane (Brudy and Zoback, 1999). Consequently, in order to maximise recovery with minimal energy input it is necessary to drill horizontal wells parallel to the minimum horizontal stress (S_{hmin}) direction. As a result hydraulic tensile fractures will propagate parallel to the maximum horizontal stress (S_{Hmax}) in the vertical plane (Brudy and Zoback, 1999). Understanding the orientation of the in-situ stress is therefore imperative prior to drilling in order to ensure that wells are deviated favorably with respect to the in-situ stress.

Previous work relating to UK in-situ stress orientation (Evans and Brereton, 1990) has been critically assessed as part of this study. This older study was undertaken using dual-caliper (also known as four arm caliper) logs analysed for the presence of borehole breakouts and will be shown to be inadequate for current needs. This paper therefore includes the first published account of the use of borehole image logs to characterise the orientation of S_{Hmax} onshore in the UK, across northern and central England, where borehole image logs are now available.

Fig. 1 shows the distribution of borehole imaging data across the UK, which by fortunate coincidence corresponds very closely to the area of the UK that is sub-cropped by the potentially economic Bowland–Hodder Shale. This also shows the dual-caliper data distribution across the UK.

1.3. *Identifying stress field indicators*

Bell and Gough (1979) noted that stress concentrations around vertical boreholes can cause caving, also known as a borehole breakout. Plumb and Hickman (1985) were able to show that the orientation of the elongations, or breakouts which result in a compressive failure of the well take place in the orientation of S_{hmin}, orthogonal to S_{Hmax} in vertical boreholes. For a more detailed description of breakout formation see Zoback et al. (1985). There are several wireline tools which can be used to identify borehole breakout which are discussed below.

1.3.1. *Dual caliper logging*

Dual-caliper logging, usually undertaken in conjunction with dipmeter tools typically measure four points on the borehole circumference with a vertical resolution of between 25 and 154 mm. Guidelines for breakout identification from caliper logs is detailed in Reinecker et al. (2003). The tool rotates as it is pulled up the wall however when it encounters a zone of borehole elongation the rotation will cease. The tool locks into an elongation zone which, with the aid of the other tool outputs, can be interpreted as a breakout (Reinecker et al., 2003).

1.3.2. *Borehole imaging tools*

Borehole imaging tools provide high resolution borehole images based on (generally) either ultrasonic velocity or resistivity. These tools and their origins are described in Paillet et al. (1990) and Prensky (1999). Borehole imaging tools provide wall coverage of between 20% and 95%, depending on the tool specification and borehole diameter. Table 1 describes the specific tool types used in this study and the details of their resolution (Ekstrom et al., 1987; Gaillot et al., 2007).

Tingay et al. (2008) investigated analysing borehole breakouts using image logging. They characterised borehole breakouts from resistivity image logs as parallel poorly resolved conductive zones that appear 180° apart on opposite sides of the borehole wall. However, the resolution of borehole breakouts is dependent on the width of the pad compared to the width of the breakout (Tingay et al., 2008). In a limited number of cases, resistivity images are accompanied by ultrasonic borehole images (e.g. Schlumberger's UBI™ tool) which circumferentially record both the amplitude and travel time of the returning wave form. These tools have lower vertical and angular resolution than the resistivity tools.

However, the travel time waveform (TTWF) images from acoustic logs are useful as they are more sensitive to changes in the borehole radius. In TTWF images breakouts appear as broad zones of increased borehole radius observed at 180° from one another (Tingay et al., 2008). Fig. 2 shows an example of resistivity (FMI) image and an acoustic (UBI) travel time image from the Sellafield 13A in Cumbria, highlighting the differences between the way these two types of tool show borehole breakout. In the absence of acoustic images, breakouts are therefore identified by darker (less conductive) patches on opposite sides of borehole images and a simultaneous disturbance to the spacing between the imaging pads.

1.4. *Drilling induced tensile fractures*

Whilst most fractures identifiable in boreholes are formed naturally, drilling induced tensile fractures (DIF's) result from tensile failure directly induced by the drilling process. These fractures form parallel to the orientation of the greatest far field horizontal stress (S_{HMAX}) (Moos and Zoback, 1990). These features occur when the sum circumferential stress concentration and the tensile strength are exceeded by the pressure in the well (Moos and Zoback, 1990). As DIF's have widths of only a few mm they can only be identified from high-resolution borehole image logs as they are not associated with any borehole enlargement (Tingay et al., 2008). They are generally narrow well defined features which are slightly inclined or sub-parallel to the borehole axis and form perpendicular to breakout orientation (Tingay et al., 2008). Fig. 3