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The role of fault gouge properties on fault reactivation during hydraulic stimulation; an experimental study using analogue faults

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ABSTRACT

During the hydraulic stimulation of shale gas reservoirs the pore pressure on pre-existing faults/fractures can be raised sufficiently to cause reactivation/slip. There is some discrepancy in the literature over whether this interaction is beneficial or not to hydrocarbon extraction. Some state that the interaction will enhance the connectivity of fractures and also increase the Stimulated Reservoir Volume. However, other research states that natural fractures may cause leak-off of fracturing fluid away from the target zone, therefore reducing the amount of hydrocarbons extracted. Furthermore, at a larger scale there is potential for the reactivation of larger faults, this has the potential to harm the well integrity or cause leakage of fracturing fluid to overlying aquifers.

In order to understand fault reactivation potential during hydraulic stimulation a series of analogue tests have been performed. These tests were conducted using a Bowland Shale gouge in the Angled Shear Rig (ASR). Firstly, the gouge was sheared until critically stressed. Water was then injected into the gouge to simulate pore fluid increase as a response to hydraulic stimulation. A number of experimental parameters were monitored to identify fracture reactivation. This study examined the effect of stress state, moisture content, and mineralogy on the fault properties.

The mechanical strength of a gouge increases with stress and therefore depth. As expected, a reduction of moisture content also resulted in a small increase in mechanical strength. Results were compared with tests previously performed using the ASR apparatus, these showed that mineralogy will also affect the mechanical strength of the gouge. However, further work is required to investigate the roles of specific minerals, e.g. quartz content. During the reactivation phase of testing all tests reactivated, releasing small amounts of energy. This indicates that in these basic conditions natural fractures and faults will reactivate during the hydraulic stimulation if critically stressed. Furthermore, more variables should be investigated in the future, such as the effect of fluid injection rate and type of fluid.

1. Introduction

The extraction of natural gas and oil from unconventional shale source rocks has become a key onshore energy source (Arthur et al., 2008). In 2014 approximately 48% of the total U.S dry natural gas was produced by this method, with that number predicted to rise to 69% by 2040 (EIA, 2016). The European Union Energy Roadmap 2050 forecasts a similar trend in natural gas production from unconventional reservoirs in Europe (EU, 2011). Shale gas is a critical energy source as Europe transitions from coal-powered electricity generation to a more environmentally friendly energy mix. However, the hydraulic fracturing technique associated with shale gas production has geological, engineering and environmental challenges and concerns associated with it. These need to be overcome to create an efficient, cleaner, and socially acceptable shale gas industry in Europe.

Hydraulic fracturing involves drilling a deviated well within a shale formation at depths of up to 5 km (Geol.Soc., 2013). The deviated well is perforated within the target area and high pressure fluid is injected into the formation to create a fracture network with enhanced permeability. The fluid is pumped in at a pressure that overcomes the tensile strength of the shale, thus producing a hydraulic fracture network. Several overviews of the hydraulic fracturing process are available in the literature (e.g. API, 2009; Cuss et al., 2015; Mair et al., 2012). Shale is a naturally heterogeneous rock and can contain many discontinuities (fractures, faults, joints, bedding planes) at a range of scales (e.g. Ougier-Simonin et al., 2016; Gale et al., 2014). Therefore, during the hydraulic fracturing process it is likely that the man-made fracture network will interact with naturally occurring discontinuities within

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the shale. The interaction of fracture networks is a key area of research identified by a number of studies (Fisher and Warpinski, 2012; Arthur et al., 2008; Cuss et al., 2015; Rutqvist et al., 2013; Davies et al., 2012). There is disagreement over whether the interaction of man-made fractures with natural fractures will enhance hydrocarbon recovery or not (Gale et al., 2007; Montgomery et al., 2005). The area over which the hydraulic fracture network is produced is commonly referred to as the Stimulated Reservoir Volume (SRV). It is generally assumed that the larger the SRV the higher the volume of hydrocarbons extracted. The SRV could be enhanced by the interaction with natural fractures, resulting in more hydrocarbons being produced. However, some studies indicate that natural fractures lead to the fracturing fluid flowing away from the target area and therefore reducing the impact of the hydraulic fracturing process.

Injection of pore fluids at an elevated magnitude compared with in situ pore pressure can result in changes of in situ conditions; this is likely to be manifest as a change in pore pressure within the reservoir. This perturbation, if sufficient in magnitude, may result in the reactivation of pre-existing fault systems that are close to the point of failure. It is believed that hydraulic stimulation at the Preese Hall site in Lancashire UK, resulted in the reactivation of a large, previously unidentified fault (Clarke et al., 2014). Two seismic events, of a magnitude $M_L = 2.3$ and 1.5 on the Richter scale were observed. These relatively small seismic events were attributed to the injection of fracturing fluid onto the fault zone (De Pater and Baisch, 2011). It must be noted that these can be considered relatively large when discussing shale gas exploitation. The majority of seismic events associated with production of the Barnett Shale in the US are typically less than $M_L = 1$ (Maxwell et al., 2006); therefore the detected events at Preese Hall are considered to be relatively large. Earthquakes of this magnitude as experienced at Preese Hall have the potential to damage well integrity and have the potential to result in leakage of fracturing fluid into shallow aquifers through loss of well integrity. It is therefore important to understand the role of hydraulic stimulation on fault reactivation/fracture slip. It should be noted that during this study the terms ‘fracture’ and ‘fault’ will be used interchangeably with the assumption of the observations will be observed over a range of scales.

Complex hydro-mechanical interactions occur during the hydraulic fracturing process. The injection of the fracturing fluid into the unconventional reservoir locally raises the pore pressure. This results in a reduction of effective stress as pore pressure acts in the opposing direction to confining stress (Terzaghi, 1943):

$$\sigma' = \sigma - u \quad [1]$$

where u is pore pressure, σ is confining stress and σ' is effective stress. Hubbert and Rubbey (1959) recognised that this theory applies to faults. The increase in pore pressure and resultant reduction in effective stress on a fault can lead to reactivation, as illustrated by Equation (2). The increase in pore pressure from the injection of the hydraulic fracturing fluid therefore has the potential to cause reactivation of natural pre-existing faults. The point at which reactivation will occur can be defined by the Mohr-Coulomb failure criterion:

$$\tau_f = C + \mu\sigma_n' = C + \mu(\sigma_n - u) \quad [2]$$

where C is cohesive strength of the fault, μ is coefficient of friction, σ_n is normal stress on the fault, u is pore pressure and σ_n' denotes effective normal stress. Therefore, an increase in pore pressure may result in the loss of frictional strength on a pre-existing discontinuity (fracture, fault, joint etc.), resulting in movement along that discontinuity.

In order to define the potential for reactivation within a potential shale formation a number of characteristics must be defined. As can be seen in Fig. 1, the angle of the fault (θ) with respect to the stress field determines if the fault is critically stressed and therefore prone to reactivation. The material within the fracture, often referred to as the gouge, is also an important control on the potential for reactivation. Gale et al. (2014) review many of the natural fractures found within the major US shale formations. Many were filled with calcite, although some quartz-filled fractures were observed. Montgomery et al. (2005) regard calcite-filled fractures as barriers to fluid flow. However, Gale et al. (2007) oppose this view and argue the low tensile strength of the cement in comparison to the protolith means that reactivation will occur and therefore not act as a barrier to fluid flow. Gale and Holder (2008) also showed that calcite filled fractures have half the strength of intact rock. These contrasting views highlight the importance of understanding the effect that the fracture gouge can have on the hydro-mechanical properties of the fault and the potential for reactivation.

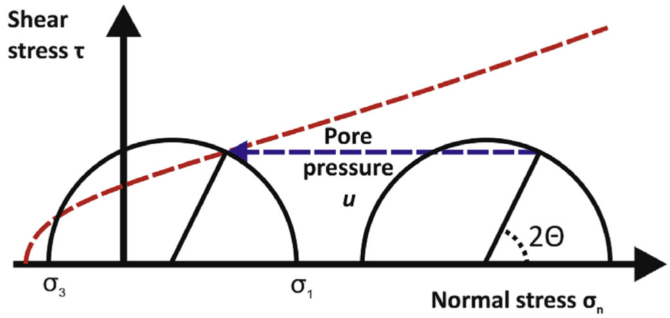

Fig. 1. Mohr circle diagram showing the stress state of a fault and the subsequent effect of an increase in pore pressure (u). The fault is orientated at 2θ and becomes critically stressed once it crosses the failure envelope (dashed line).

Another controlling factor on reactivation potential is the water content of the gouge. Water content, or degree of saturation, has been shown to have a specific weakening effect on rock strength when compared with dry conditions (Paterson, 1978). This behaviour has been observed in many laboratory tests, e.g. uniaxial, triaxial and hydrostatic deformation testing (Dyke and Dobereiner, 1991; Hawkins and McConnel, 1992; Serdengecti and Boozer, 1961; Rutter, 1972; Zhu and Wong, 1997). However, many of these tests were conducted on common reservoir and aquifer rocks such as sandstones (Cuss, 1999; Boozer et al., 1963). Thus meaning there is paucity in data describing the effect of saturation on shale strength. A study by Ikari et al. (2007) showed that moisture content can have a significant effect on the mechanical properties of faults. Therefore, it is important to understand how varying moisture content could effect the potential for fault reactivation in natural discontinuities within shale.

This study presents results from a series of analogue tests carried out with the aim of simulating reactivation of a critically stressed fault/fracture through increases in pore fluid pressure as a result of hydraulic stimulation. The Bowland Shale has been highlighted as a potential shale resource formation in northern England. Previous analogue studies have used the same methodology and demonstrated that mineralogy has an effect on both the mechanical properties of faults and fault reactivation (Cuss and Harrington, 2016; Cuss et al., 2016). The current study aimed to advance previously studies and apply observations to the shale gas industry. The main objectives of the study were to investigate:

- mechanical properties of a Bowland Shale filled fault gouge;
- reactivation potential of a Bowland Shale filled fault gouge;
- effect of moisture content on the mechanical properties and reactivation potential of the fault gouge.

These objectives were achieved through a series of analogue fault gouge experiments. The analogue tests would recreate a basic fault system with the ability to increase the pore pressure on the fault. This would therefore simulate pore pressure perturbations as a result of hydraulic stimulation and provide information relevant to fault strength and fault reactivation potential within an unconventional reservoir.