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An experimental study of the potential for fault reactivation during changes in gas and pore-water pressure

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ABSTRACT

The injection of CO_2 into a depleted reservoir will alter the pore pressure, which if sufficiently perturbed could result in fault reactivation. This paper presents an experimental study of fault reactivation potential in fully saturated kaolinite and Ball Clay fault gouges. Clear differences were observed in fault reactivation pressure when water was injected, with the addition of mica/illite in Ball Clay seen to reduce the pressure necessary for reactivation. Slip occurred once pore-pressure within the gouge was sufficient to overcome the normal stress acting on the fault. During gas injection localised dilatant pathways are formed with approximately only 15% of the fault observing an elevated gas pressure. This localisation is insufficient to overcome normal stress and so reactivation is not initiated. Therefore faults are more likely to conduct gas than to reactivate. The Mohr approach of assessing fault reactivity potential gave mixed results. Hydro-mechanical coupling, saturation state, mineralogical composition and time-dependent features of the clay require inclusion in this approach otherwise experiments that are predicted to be stable result in fault reactivation.

1. Introduction

The capture of CO_2 from large point source emitters and storage in the form of a super-critical fluid within geological formations has been identified as a key technology in tackling anthropogenic climate change (Haszeldine, 2009; Bickle, 2009). To achieve a reduction in emissions, significant quantities of CO_2 need to be injected into suitable geological formations capable of containing the fluid for thousands of years. It has been estimated that approximately 30 billion barrels of CO_2 need to be injected annually (Zoback and Gorelick, 2012). Several demonstration projects have been conducted injecting megatonne scale CO_2 into depleted hydrocarbons reservoirs, such as at Sleipner (Norwegian North Sea; Arts et al., 2008), Weyburn (Saskatchewan Province, Canada; Wilson and Monea, 2004) and In Salah (Algeria; Mathieson et al., 2010). Storage of CO_2 in depleted reservoirs offers the security of storage with an effective top-seal that previously acted as a seal to hydrocarbons.

The use of a depleted reservoir will play a role in the performance of the storage facility. During depletion, pore pressure within the reservoir will have been lowered during hydrocarbon extraction and as a result the reservoir will have subsided. The injection of super-critical fluid into a depleted reservoir will result in the opposite, with pore pressure increased and heave of the reservoir. The use of injection and extraction boreholes can minimise this effect, with water injected at a rate similar to the extraction rate of the hydrocarbon during drawdown, and extraction of aquifer water at a similar rate to CO_2 injection during carbon sequestration. Local deformation will still occur though if the two boreholes are well spaced, as seen during the In Salah CO_2 storage project in Algeria (Mathieson et al., 2010). Perturbations of the reservoir pore fluid pressures are required in order to initiate flow out of, or into the reservoir. These changes in pore pressure, and as a result the stress state, may result in undesired geomechanical deformation that could affect the integrity of the overlying seal. Zoback and Gorelick (2012) identified the risk to security from a geomechanical point of view, while Economides and Ehlig-Economides (2009) showed that an upper pressure limit exists for CCS, above which the seal is potentially compromised due to the formation of fractures. However, Vilarrasa and Carrera (2015) state that large earthquakes are unlikely to be triggered during CO_2 injection in sedimentary basins and therefore leakage is not likely to be induced. Verdon et al. (2013) examined the deformation observed at injection sites and noted that the geomechanical response was complicated and non-intuitive at Weyburn, small at Sleipner due to the high permeability of the reservoir, and uplift and microseimic activity was noted at In Salah. Therefore, reservoirs need to be con-

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sidered on an individual basis based on their geometry and the properties of the geology present.

Hydraulic and mechanical interactions play a critical role in reactivating faults at various scales in the Earth's upper crust (Scholz, 1990). Injection of fluid and the resulting changes in the stress-state can result in the reactivation of existing faults (Cappa and Rutqvist, 2011; Segall and Rice, 1995), which can result in felt seismicity. This has occurred in geothermal projects (e.g. Bachmann et al., 2012; Gan and Elsworth, 2014), waste water injection during shale gas exploration (e.g. Ellsworth, 2013), during hydraulic fracturing (e.g. Clarke et al., 2014; Holland, 2013), and by natural gas injection at the Castor storage site in Spain (Cesca et al., 2014). However, only micro-seismicity has been observed during Carbon Capture and Storage (Verdon et al., 2013).

Faults with high clay content within the fault core may have a permeability as low as 10^{-22} m^2 (Faulkner and Rutter, 2000). Such flow barriers within a reservoir may increase overpressure locally, which could result in fault reactivation (Rutqvist et al., 2007; Rinaldi et al., 2015). This may create an open migration pathway for CO_2 to escape from the reservoir (Zoback and Gorelick, 2012), although no correlation between seismicity and leakage was found in numerical modelling (Rinaldi et al., 2014a,b). Experimental work related to fault reactivation has tended to look at mechanical controls using analogue sand-box experiments (Krantz, 1991; Richard and Krantz, 1991; Dubois et al., 2002; Bellahsen and Daniel, 2005; Del Ventisette et al., 2006) or examining the flow properties of fault gouge and inferring fault weakness on geomechanical response (Crawford et al., 2008; Faulkner and Rutter, 2000, 2001).

Modelling studies of fault reactivation potential, or slip tendency, have been conducted by several workers; some of which are summarised here, see Rutqvist (2012) for a more comprehensive summary of numerical modelling. Streit and Hillis (2004) estimated fault stability for underground storage of CO_2 based on the Mohr-Coulomb approach of predicting individual fault strength. A similar approach using slip tendency analysis using the 3-dimensional Mohr-space has been proposed by Leclère and Fabbri (2013). Williams (2015) calculated slip tendency based on the ratio of shear to normal stress for faults within the Moray Firth, North Sea, to determine which were critically stressed. A critically stressed fault is one where the shear stresses acting upon the fault is at the limit of the frictional strength of the fault, i.e. as soon as stress is increased on the fault it will result in slip. They found that pore fluid increases as modest as several kPa were sufficient to cause reactivation for certain fault segments, with a maximum pore pressure of 20 MPa. However, Zhang et al. (2015) used a coupled geomechanical–fluid flow modelling approach and demonstrated that reactivation wasn't likely in the South West Hub of Western Australia. Coupled reservoir-geomechanical numerical modelling (Rutqvist, 2011) has been used to simulate fault/fracture zone reactivation induced by CO_2 injections (Cappa and Rutqvist, 2012; Rinaldi and Rutqvist, 2013) to assess the potential for fault instability and shear failure (Cappa and Rutqvist, 2011). Gan and Elsworth (2014) modelled the role of both pore fluid change and temperature drawdown on fault reactivation in relation to geothermal projects and showed that temperature variations needed to be considered when examining fault stability.

A fault will remain locked as long as the applied shear stress is less than the strength of the contact. Karl Terzaghi first showed in 1923 that pore-fluid under pressure has a profound effect on the physical properties of porous solids (Terzaghi, 1943). In a saturated porous system, the fluid supports some proportion of the applied load lowering the overall stress exerted through grains. Strength is therefore determined not by confining pressure alone, but by the difference between confining and pore-pressures. Hubbert and Rubey (1959) showed this applies to faults; a pore pressure of P_f reduces the frictional strength of faults (τ), which can be represented by a criterion of Coulomb form:

$$\tau_f = C + \mu\sigma_n' = C + \mu\left(\sigma_n - P_f\right) \quad (1)$$

where C is the cohesive strength of the fault, μ is the coefficient of friction, σ_n, is the normal stress on the fault, and ' denotes effective stress. Byerlee (1978) showed that μ ranges between 0.6 and 1.0, but can be approximated as 0.75 ± 0.15 (Sibson, 1994). Fault reactivation can therefore occur when shear stress along the fault (τ) equals τ_f. This condition can occur through an increase in shear stress, decrease in normal stress, or an increase in fluid pressure.

This paper presents results from an experimental study aimed at evaluating fault reactivation potential within the laboratory in two fault gouges. The current study represents the second stage of a three-part investigation of the potential for fault reactivation during the sequestration of carbon dioxide. The three parts of the study were; (1) the role of stress history on fault flow properties, as reported in Cuss et al. (2016); (2) quantification of fault reactivation potential as a result of elevated pore pressure (the current study); and (3) the role of stress history on fault reactivation. The scenario being investigated is for a static boundary condition for stress acting on a fault with an increase in pore pressure initiating fault reactivation; therefore directly simulating an increase in pore pressure in response to the injection of CO_2 during sequestration. The objectives of the study were:

- Investigate whether fault reactivation could be detected using a shear apparatus with an angled fault-plane within the laboratory;
- Investigate the mechanical properties of two clay gouges during shear;
- Variation in fault reactivation behaviour between two clay gouges;
- Variation in fault reactivation potential as a result in elevation of gas or water pressure.

In order to simulate a critically stressed fault, gouge material was sheared to a stress representative of the residual shear strength before pore pressure was elevated. This ensured that the fault plane was actively stressed. Eq. (1) shows that the coefficient of friction dictates the strength of a fault, although cohesion also contributes to fault strength. Two clay gouges were selected so as to determine whether different material properties would alter the potential for fault reactivation, or whether a single parameter could be used to estimate the stress state at failure for different gouge compositions. The primary aim of the study was to establish maximum pore pressure perturbations that could be employed during carbon sequestration.

Previous experimental work at the British Geological Survey (BGS) on fracture transmissivity in Opalinus clay (Cuss et al., 2011, 2014a,b) and kaolinite gouge (Sathar et al., 2012) showed that hydraulic flow is a complex, focused, transient property that is dependent upon stress history, normal stress, shear displacement, fracture topology, fluid composition, and clay swelling characteristics. The current experimental programme aimed to extend this knowledge by investigating the potential for fault reactivation by elevating pore pressure within gouge filled discontinuities.

2. Experimental setup

All experiments were performed using the bespoke Angled Shear Rig (ASR, Fig. 1) designed and built at the BGS. Previous experiments conducted on Opalinus Clay (Cuss et al., 2009, 2011, 2014b) showed that fracture topology is a key parameter in controlling fluid flow along fractures. In order to reduce the number of variables required to fully understand flow, an analogue discontinuity