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Research paper

Permeability and frictional properties of halite-clay-quartz faults in marine-sediment: The role of compaction and shear

Bryan M. Kaproth [a, b], Marek Kacewicz [c], Sankar Muhuri [c], Chris Marone [a, *]

[a] Department of Geosciences, and Energy Institute Center for Geomechanics, Geofluids, and Geohazards, The Pennsylvania State University, University Park, PA, USA
[b] Noble Energy Corporation, Denver, CO, USA
[c] Chevron Corporation, Houston, TX, USA

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ABSTRACT

Faults in marine-sediment basins often dictate fluid flow and act as petroleum traps or seals. Permeability contrasts between these zones and the surrounding country rock can be large, depending on fault composition, stress, and strain history. Despite the importance of such faults, our understanding of their frictional properties and permeability is relatively poor. Here we report on a suite of laboratory experiments to assess the roles of fault composition, stress, and shear strain for dictating poromechanical properties of fault. Experiments were conducted at room temperature on synthetic fault gouge composed of quartz, halite, and clay (illite shale or Ca-montmorillonite). We sheared layers that were 5–7 mm thick and measured fault permeability at effective normal stresses from 2 to 6 MPa for hydrostatic conditions and after shear strains from 2 to 10. We find that fault permeability is highly sensitive to clay content, with permeabilities spanning 2–4 orders of magnitude under otherwise identical conditions. Permeability decreased up to 2 orders of magnitude with imposed shear strain >1 and ~1 order of magnitude with increasing normal stress from 2 to 6 MPa. During shear, halite deformed via both ductile flow and brittle failure, while quartz and clay particles formed force chains that spanned the layers and defined shear localization fabrics. Samples with higher halite content exhibited greater permeability reduction, perhaps by plastic flow and pressure solution. Our results suggest that the permeability of faults in marine sediment is dictated by clay content, and that the most dramatic permeability changes occur with relatively small fault throw (shear strain from 2 to 5). This highlights the importance of understanding minor faults and fault sets when estimating subsurface fluid flow and potential reservoir compartmentalization.

1. Introduction

Faults represent significant geologic features for subsurface fluid flow and are important in numerous transport processes within sedimentary basins where they affect petroleum reservoir quality, hydrocarbon migration, and groundwater flow (Smith, 1966; Aydin and Johnson, 1983; López and Smith, 1995; Evans et al., 1997; Aydin, 2000; Kim et al., 2004; Baud et al., 2004). Fault permeability and poromechanical properties can impact deformation style in reservoir rocks and a variety of tectonic environments (e.g., Arch and Maltman, 1990; Caine et al., 1996; Caine and Forster, 1999; Crawford, 1998; Zhang et al., 1999; Fisher et al., 2001; Chuhan et al., 2003; Wibberley and Shimamoto, 2003; Odling et al., 2004; Mitchell and Faulkner, 2008, 2012; Ikari et al., 2009a,b; Balsamo and Storti, 2010; Faulkner et al., 2010; Foroozan et al., 2012; Carruthers et al., 2013; Gomila et al., 2016). In particular, faults can act as fluid conduits in impermeable environments (e.g., shales, granites, basalts, etc.), fluid barriers in permeable environments (e.g., sandstones), and they may act to redirect flow in cases where faults develop significant permeability anisotropy (Knipe, 1992; Evans et al., 1997; Fisher and Knipe, 1998, 2001; Zhang and Tullis, 1998; Bos and Spiers, 2000; Shipton et al., 2005; Benson et al., 2006; Fossen and Bale, 2007; Takahashi et al., 2007; Daniel and Kaldi, 2008; Crawford et al., 2008; De Paola et al., 2009; Faulkner et al., 2010; Savage and Brodsky, 2011; Ballas et al., 2012; Ikari and Saffer, 2012; Faoro et al., 2012, 2013; Olierook et al., 2014;

* Corresponding author.
E-mail address: cjm38@psu.edu (C. Marone).

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Scuderi et al., 2015; Seebeck et al., 2015).

Fault permeability can be significantly lower than the wall rock, especially in marine sediment environments where clay is integrated into fault zones (Caine et al., 1996; Evans et al., 1997; Gibson, 1998; Crawford et al., 2008; Ikari et al., 2009a; Faulkner et al., 2010; Ishibashi et al., 2012; Mitchell and Faulkner, 2012; Harding and Huuse, 2015). In these environments, faults juxtapose and mix clays from shale along with sands and silts from other horizons (e.g, Bjùrlykke and Hùeg, 1997; Billi et al., 2003; Faulkner et al., 2010). Important processes include abrasional mixing, clay smearing, and pore throat clogging. Fault permeability is often dictated by pore conduit connectivity or narrow crack apertures, depending on mineralogy and development of shear fabric (Revil et al., 2002; Takahashi et al., 2007; Crawford et al., 2008; Ikari et al., 2009b; Niemeijer et al., 2010; Cheung et al., 2012; Scuderi et al., 2015). Indeed, small increases in clay concentrations can dramatically reduce fault permeability in sandy faults (Revil et al., 2002; Crawford et al., 2008; Faulkner et al., 2010). For example, Crawford et al. observed a four order of magnitude permeability reduction as clay content increased from 0 to 50% under otherwise identical conditions. While much work has been done to quantify the roles of clay content, load, and strain on fault permeability (e.g., Bentley and Barry, 1991; Antonellini and Aydin, 1994; Revil et al., 2002; Lothe et al., 2002; Wibberley and Shimamoto, 2003; Sternlof et al., 2004; Fortin et al., 2005; Crawford et al., 2008; Mondol et al., 2008; Tueckmantel et al., 2010; Ballas et al., 2012; Skurtveit, 2013; Scuderi et al., 2015), our understanding of the relationship between fault strength and permeability remains relatively poor.

Here, we focus on complex mixtures of synthetic fault gouge to illuminate the role of shear, fabric development and ductile flow, with application to faults found in association with salt domes and surrounding country rock. One goal of this work is to provide input for geomechanical models of salt bodies, which require information on both permeability and friction constitutive properties of the salt-clay-sediment mixtures that often bound them.

Impermeable salt domes (Peach and Spiers, 1996) often have associated faults, and these features can act in concert to seal reservoirs (Jackson et al., 1994; Rowan et al., 1999; Hudec and Jackson, 2007; Fort and Brun, 2012). In these cases, the fault zones often integrate halite from the salt dome as well as nearby salt layers. Halite undergoes a range of deformation behaviors depending on the chemistry, composition, materials it mixes with, stress, and strain history on the fault, and thus its role for fault zone permeability is complex. Under fast slip conditions halite tends to deform brittlely (e.g., Shimamoto, 1986; Bos et al., 2000a,b; Niemeijer et al., 2010; Wong and Baud, 2012) and should behave as a framework grain. During slower deformation and for transient slip, halite likely accommodates shear via a combination of brittle and ductile deformation and/or pressure solution (Rutter, 1983; Shimamoto, 1986; Bos et al., 2000a,b; Niemeijer et al., 2008, 2010).

The purpose of this paper is to present results from a comprehensive laboratory study of the permeability and frictional properties of marine-sediment faults as a function of composition, stress, and shear strain. We studied synthetic faults composed of quartz, halite, and illite shale or smectite clay. We report on frictional properties and fault-normal permeability as a function of strain and effective normal stress, focusing primarily on low effective stress (<6 MPa) relevant for overpressured environments.

2. Methods and materials

We measured permeability and frictional properties of simulated fault zones as a function of normal stress and shear strain. We conducted experiments in the double-direct shear configuration under true triaxial stress conditions (e.g., Ikari et al., 2009a; Samuelson et al., 2009; Kaproth and Marone, 2014; Carpenter et al., 2015). The experimental geometry is shown in Fig. 1. To simulate faults in marine-sediment basins we conducted experiments on mixtures of quartz sand, illite shale or smectite clay (Ca-montmorillonite), and halite (Table 1 and Fig. 2). Our sample compositions were designed to span the transition between clast-supported and matrix supported fault gouge, where fault zone porosity is lowest and permeability changes are strongest (e.g., Faulkner et al., 2010). We used commercial silt-sized quartz foundry sand (F110) and Ca-montmorillonite (sieved to <125 μm). Illite shale and pure halite were ground in a rotary mill and sieved to <125 μm. The illite shale is primarily illite with some quartz, plagioclase, and minor kaolinite (Ikari et al., 2009a). Our experiments were carried out under conditions where pressure solution and ductile deformation of halite is operative at low strain rates and during holds, but halite and the other minerals deform via brittle deformation for the shearing rates used (e.g., shear displacement rate of 10 μm/s or shear strain rate of ~ 2×10^{-3} s^{-1}). Our pore fluid was a saturated NaCl brine, 35.7 g/ml, obtained by adding pure NaCl to deionized water. We ensured NaCl saturation by regularly adding salt grains to the brine bath.

We deformed synthetic faults as layers in the double direct shear configuration under constant effective stress normal to the layers (Fig. 2). In this configuration, two identical layers of fault-gouge are sandwiched between three forcing blocks (Fig. 1). All stresses, displacements, and other measurements reported here are given for one layer of the double direct shear geometry. Shear displacement at the fault boundary is imposed by driving the central block with a hydraulic ram, inducing shear within the fault gouge layers. We arranged the true triaxial apparatus for constant confining pressure, with normal stress and shear stress applied to the sample directly via hydraulic pistons (Fig. 1). All stresses and fluid flow rates were maintained by fast-acting, servo-hydraulic control. Strain gauge load cells, accurate to ±0.1 kPa, measured applied stresses. Direct current displacement transducers (DCDTs), accurate to ±0.1 μm, measured shear and normal displacement on the faults. Pressure transducers, accurate to ±7 kPa, measured the confining and pore pressure. Stresses, pressures, and displacements were digitally recorded at 10 kHz with a 24 bit system, and were averaged to 10–100 Hz for storage.

Fault layers were constructed to specific initial thicknesses from 5 to 7 mm. To ensure reproducibility of the tests we weighed the sample material used to construct each layer. Layer thickness was measured carefully on the bench during sample construction and then again in the testing machine once a small normal load was applied. These measurements were accurate to ±50 μm. Layer thickness was also measured at the end of the run, prior to unloading, which allowed us to check and verify the thickness and thickness change compared to that measured via the DCDT. We calculated average shear strain γ within the layer as the sum of dx/h, where dx is a given shear displacement increment (normally <1 μm for our digital sampling rates) and h is the measured layer thickness, which is updated continuously during shear.

Porous steel frits act as the interface between the steel forcing blocks and the sample layers, distributing the pore pressure and allowing linear flow across the sample (parallel to σ_n; Fig. 1C). The sample assemblies were sealed with flexible latex jackets to isolate the sample from the confining oil (Fig. 1D). Pore pressures were applied to the sample through the forcing blocks, with upstream pressure (P_PA) applied through the center block to both sample layers and downstream pressure (P_PB) applied simultaneously to the two side blocks of the double direct shear configuration (Kaproth and Marone, 2014).

Fig. 3 shows representative shear stress curves for three