



Frictional properties of simulated anhydrite-dolomite fault gouge and implications for seismogenic potential



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ABSTRACT

The frictional properties of anhydrite-dolomite fault gouges, and the effects of CO₂ upon them, are of key importance in assessing the risks associated with CO₂ storage in reservoir formations capped by anhydrite-dolomite sequences, and in understanding seismicity occurring in such formations (such as the Italian Apennines). Therefore, we performed velocity-stepping direct-shear experiments on simulated dolomite, anhydrite and 50:50 anhydrite/dolomite gouges, at representative in-situ conditions (120 °C and $\sigma_n^0 = 25$ MPa). They were conducted under vacuum, or else using water or CO₂-saturated water as pore fluid ($P_f = 15$ MPa). Friction coefficients varied between 0.55 and 0.7. All dry samples exhibited velocity-weakening behavior, whereas all wet samples exhibited velocity-strengthening behavior, without or with CO₂. This is consistent with trends previously reported for such gouges. A compilation of literature data shows that the transition from velocity-strengthening to velocity-weakening occurs in these materials between 80 and 120 °C when dry, and between 100 and 150 °C when wet. This implies little seismogenic potential for wet dolomite, anhydrite and mixed gouges under CO₂ storage conditions at 2–4 km depth. Seismic slip in the Italian Apennines at depths of ~6 km and beyond may be explained by the velocity-weakening behavior expected in anhydrite and especially dolomite at temperatures above 150 °C.

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1. Introduction

Many hydrocarbon fields are capped by evaporites, the base of which often contains tens or even hundreds of meters of interbedded anhydrite and dolomite (respectively CaSO₄ and (Ca,Mg)CO₃). Such thick layers are usually deposited in a deep basin setting, and examples include the Zechstein sequence that overlies many of the Rotliegend gas fields in the Netherlands and North Sea area (Geluk, 2000, 2007), the Sudair Formation overlying many of the Qatar gas fields (Alsharhan and Nairn, 1994; Bai and Xu, 2014), and the Midale and Muskeg Formations, that overlie respectively the Weyburn and the Zama oil fields in Canada (Smith et al., 2011; Bennion and Bachu, 2013). Once depleted, the hydrocarbon reservoirs offer attractive options for CO₂ storage. To ensure safe and effective CO₂ storage, it is important to evaluate the geomechanical

stability of faults that crosscut the caprock. Such faults are known to be preferential leakage pathways in natural reservoirs (Miocic et al., 2013) and when cross-cutting an anhydrite caprock, they will generally contain anhydrite-rich fault gouges, with variable amounts of dolomite. A thorough understanding of the frictional properties not only of anhydrite but also of dolomite and mixed fault gouges is therefore needed, as well as knowledge of any possible effects of CO₂-bearing fluids. Such data is also relevant to understanding natural seismicity in tectonically active regions dominated by carbonate/anhydrite evaporite formations, of which the Italian Apennines are a well-studied example. There, the M-6 Colfiorito sequence (1997–1998) and the destructive M-6 L'Aquila earthquake (2009) nucleated in respectively the interbedded anhydrite/dolomite formation (Mirabella et al., 2008; Collettini et al., 2009) and a thick dolomite sequence (Speranza and Minelli, 2014), with nucleation depths lying between 5 and 10 km. Moreover, this region is characterized by major CO₂ degassing from deeper levels (e.g. Chiodini et al., 1999; Collettini et al., 2008; Improta et al., 2014), so that data on the effects of CO₂-bearing fluids on the frictional properties of carbonate/anhydrite fault rocks are also directly relevant here.

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One of the mechanisms by which a fault can generate an earthquake lies in its capacity to weaken as motion accelerates, via “velocity-weakening behavior”. Even without velocity weakening, marked slip weakening, i.e. weakening with increasing displacement, can also lead to accelerating slip and hence seismogenesis (c.f. Ikari et al., 2013; Ohnaka, 2013). On the other hand, if a fault becomes stronger with increasing slip and/or increasing slip velocity (e.g. via “velocity-strengthening” behavior), it is not capable of generating accelerating slip. In the current paper we will focus on the velocity dependence of friction. This is classically described by the rate-and-state friction (RSF) equations (Dieterich, 1978, 1979; Ruina, 1983), which have been successful in describing and explaining natural seismicity (Sone and Shimamoto, 2009; Barbot et al., 2012; Noda and Lapusta, 2013; den Hartog and Spiers, 2014; Niemeijer and Vissers, 2014). The Dieterich-type RSF equation describes fault strength evolution upon a velocity step as follows:

$$\mu = \mu_0 + a \ln\left(\frac{V}{V_0}\right) + b \ln\left(\frac{V_0\theta}{d_c}\right), \quad \text{with} \quad \frac{d\theta}{dt} = 1 - \frac{V\theta}{d_c}. \quad (1)$$

Which at steady state reduces to:

$$(a - b) = \frac{\Delta\mu}{\ln(V/V_0)} \quad (2)$$

Here μ_0 and μ are the friction coefficients measured before and after individual velocity steps, V_0 and V represent the sliding velocities imposed before and after each step, a represents the magnitude of the direct effect of changing velocity on the friction coefficient μ , b represents the subsequent evolution of μ , θ is a state variable (generally interpreted as reflecting the average lifetime of load supporting contact points or asperities), and d_c is the slip distance necessary to establish a new steady state strength and internal structure (i.e. to renew the population of load supporting contact points). Positive values of $(a-b)$ describe velocity-strengthening behavior, whereas negative values of $(a-b)$ describe velocity-weakening behavior.

In contrast to quartz and clay, carbonates like dolomite and calcite, and sulphates, like anhydrite, are ionic solids, characterized by a crystal structure displaying distinctive brittle cleavage properties (e.g. Johnsen, 2004) and similar indentation and Mohs hardness (e.g. Mohs, 1820; Taylor, 1949; Tabor, 1956, 1970; Johnsen, 2004). They also show a transition from brittle to plastic behavior at relatively low temperatures compared to silicates (from cataclasis to pressure solution, twinning and dislocation glide, see Müller and Siemes, 1974; Rutter, 1974; Wenk and Shore, 1975; Barber et al., 1981; Müller et al., 1981; Schmid et al., 1987; Dell’Angelo and Olgaard, 1995; Bruhn et al., 1999; Davis et al., 2008; Delle Piane et al., 2008) and they show a decrease in solubility with increasing temperature (e.g. Langmuir, 1997). Additionally, through their relatively high solubility at low temperatures, they are prone to deformation by fluid-assisted diffusive processes such as pressure solution. Indeed, pressure solution has been shown to be an important deformation mechanism in both anhydrite (Pluymakers and Spiers, 2015; Pluymakers et al., 2014a) and calcite aggregates (Zhang and Spiers, 2005; Zhang et al., 2010) under upper crustal conditions.

On this basis, carbonate and anhydrite fault gouge can be expected to show similarities in their frictional behavior at upper crustal conditions, while differing significantly from silicate gouges at similar pressures and temperature. Previous work on the velocity-dependence of friction in wet anhydrite gouges, at P-T conditions relevant to CO₂ storage, has demonstrated velocity-strengthening behavior, both without and with supercritical CO₂ (Pluymakers et al., 2014b; Pluymakers and Niemeijer, 2015).

However, limited data recorded by Scuderi et al. (2013), on 50:50wt % mixtures of anhydrite and dolomite tested wet at 75 °C, suggests that $(a-b)$ may decrease compared to the end-member compositions, and may produce velocity-weakening (Scuderi et al., 2013). If $(a-b)$ decreases in mixed anhydrite-dolomite gouges such that marked velocity-weakening behavior occurs under CO₂ storage conditions, this may have important consequences with respect to induced seismicity and risk assessment. Data on the frictional behavior of mixed anhydrite-dolomite fault gouges under upper crustal pressure and temperature conditions are very few, despite intimate mixing inferred from field and borehole studies (e.g. De Paola et al., 2008; Collettini et al., 2009; Trippetta et al., 2013; Hangx et al., 2014), and no published data exist on how the friction of dolomite and dolomite/anhydrite aggregates is affected by the presence of CO₂-bearing fluids.

To fill this knowledge gap, we have performed direct-shear experiments on simulated gouges of anhydrite, dolomite and on 50:50wt% anhydrite/dolomite mixtures. The experiments were performed at a temperature of 120 °C and an effective normal stress of 25 MPa with the pore fluid system under vacuum (dry testing conditions) or else pressurized with water or with CO₂-saturated water. These conditions were chosen to be as close as possible to those expected in anhydrite/dolomite-capped CO₂ storage reservoirs at 2–4 km depth (assuming hydrostatic pore fluid pressure), as well as to natural seismicity in the Italian Apennines (Mirabella et al., 2008; Collettini et al., 2009). The expected in-situ normal stresses may be as low as 20 MPa due to the high fluid pressures, up to 85% of lithostatic pressure (Collettini et al., 2009; Trippetta et al., 2013). To investigate the robustness of our findings for a wider, more realistic range of conditions relevant to CO₂ storage and to seismicity in the Apennines, we compare our results with previous data on the frictional properties of dolomite and anhydrite at a range of different pressure and temperature conditions.

2. Experimental methods

We conducted velocity-stepping, direct shear experiments on simulated fault gouges consisting of crushed dolomite (labeled D in all Figures and in Table 1), of crushed anhydrite (labeled A) or of a 50:50wt% mixture (labeled 50:50). Runs were performed dry, with the pore fluid system under vacuum (labeled dry or VAC), or with the pore fluid system pressurized with water (labeled wet or W), or using pre-wetted samples pressurized with supercritical CO₂ (labeled wet + CO₂ or WC). The temperature used in all experiments was 120 °C, and the effective normal stress (σ_n^e) was 25 MPa. When using a pore fluid phase, its pressure was 15 MPa. All experiments and corresponding conditions are listed in Table 1.

The dolomite gouge used was prepared by crushing cleaved single crystals from Butte, Montana, obtained commercially through Ward’s Natural Science. Anhydrite gouge was prepared by crushing core material retrieved from a borehole in Overijssel, the Netherlands (courtesy of Shell Global Solutions), where it was taken from the Permian Zechstein 1 Anhydrite Member, at 2–3 km depth (see for a detailed description Hangx et al., 2014). After crushing, the powders were sieved to obtain simulated end-member gouges with a grain size smaller than 50 μm. Laser particle size analyses indicated a similar initial maximum grain size of 50 μm and a mode grain size of ~32 μm for all samples. The sieved powders were further analyzed using ThermoGravimetric Analysis (TGA) and/or X-Ray-Diffraction (XRD), which confirmed the anhydrite gouge to be > 95 wt% anhydrite with trace amounts of dolomite. The dolomite gouge consisted of >90 wt% dolomite with trace amounts of calcite, albite and quartz. For the experiments on the 50:50 wt% mixtures, we mixed a single batch of 8 g of the anhydrite with 8 g of the dolomite powder.

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