Frictional behavior of simulated anhydrite fault gouge and the effects of temperature and supercritical CO_2

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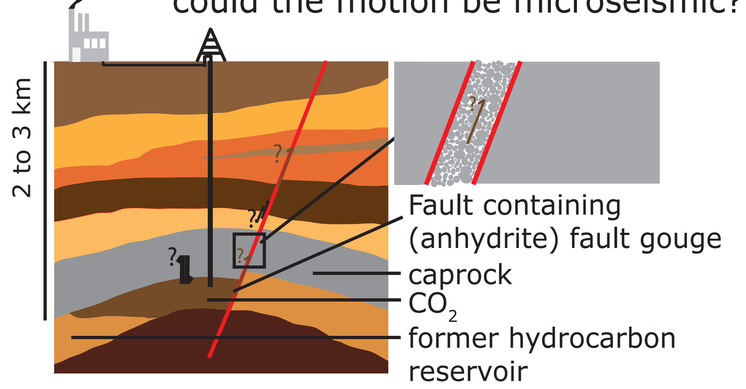
1. INTRO

In many climate mitigation plans storing anthropogenic CO_2 in the Earth's subsurface forms a considerable part of the targeted reduction in CO_2 emissions. Possible geological storage sites include aquifers, unmineable coal seams and depleted hydrocarbon reservoirs. The latter form desirable storage sites because of their well-known geology, the existing infrastructure and their large storage potential. In the Netherlands many gas reservoirs are capped by Zechstein anhydrite.

Testing the frictional properties of faults within and adjacent to potential reservoirs is necessary to ensure safe storage and to avoid leakage of CO2. Leakage could be caused by reactivation-induced permeability changes. It is needed to determine the conditions under which reservoir-bounding faults might be reactivated, and if this would have the potential to be microseismic.

Our aim is to determine both the influence of temperature and of supercritical CO_2 on the frictional strength and stability (i.e. microseismic potential) of anhydrite filled fault zones. To this end we have conducted direct shear experiments on simulated fault gouge in two different triaxial testing machines. Experiments are conducted at constant normal stress and, in those cases in which a pore fluid was present, constant pore fluid pressure. Experiments were conducted dry, and under water-wet, dry CO_2 and wet CO_2 conditions at temperatures ranging from 80 to 150ºC.

1. How frictionally strong are the faults?
2. If the fault is reactivated, could the motion be microseismic?



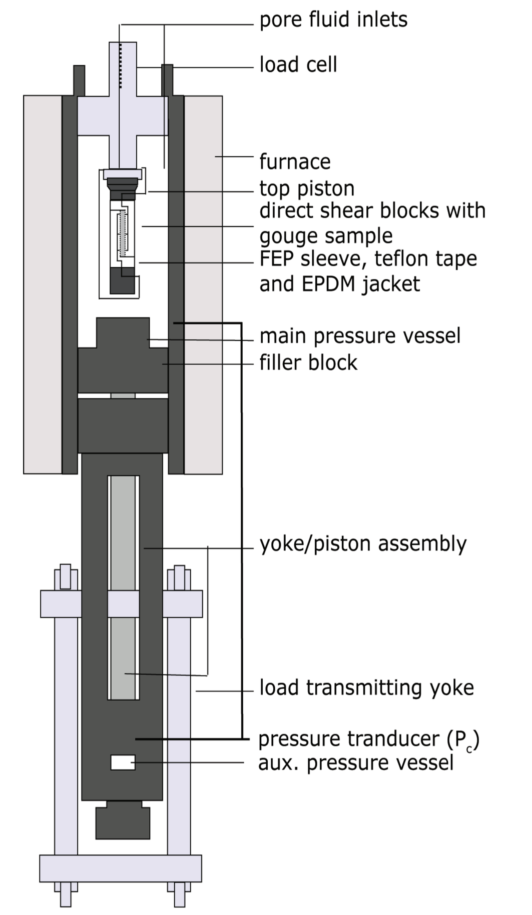
2. METHODS

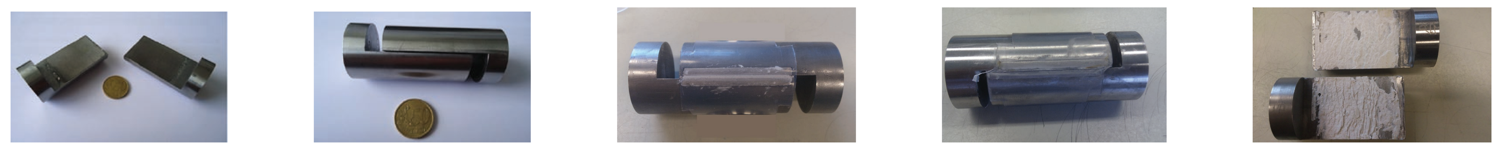
Direct shear experiments are conducted on simulated anhydrite fault gouge using two different triaxial machines which both use oil as a confining medium.

Material:
- Zechstein anhydrite from Hardenberg well, Groningen, the Netherlands
- Material is crushed and sieved at a grain size <50μm
- Dry experiments: gouge layer is dried at T~110ºC in vacuum furnace overnight before sample assembly

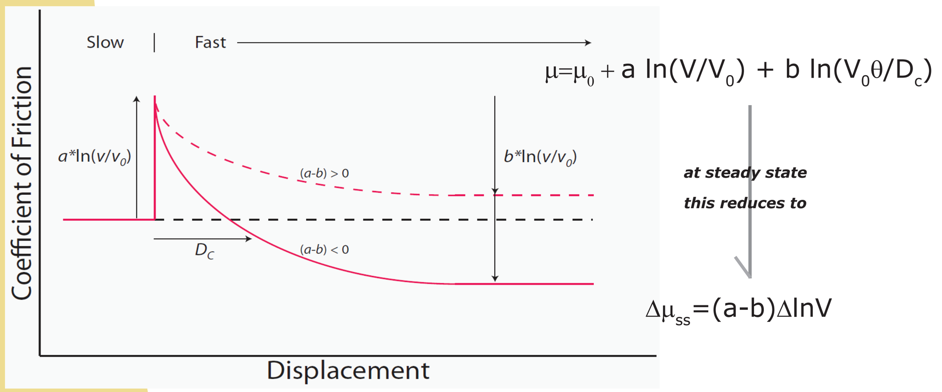
Experimental conditions:
- *dry*, P_c = σ' = 25 MPa
- *wet*: saturated & pressurized with DI water, σ'= 25 MPa, P_f= 15 MPa
- *dry CO_2*: pressurized with CO_2, σ' = 25 MPa, P_{CO2}= 15 MPa
- *wet CO_2*: saturated with DI water and pressurized with CO_2, σ' = 25 MPa, P_{CO2}= 15 MPa

Temperature range:
80ºC - 100ºC - 120ºC - 135ºC - 150º





3. THEORY



Rate and state friction. In order to generate earthquakes two conditions must be met: the material should exhibit velocity weakening behavior and the stiffness of the system should be less than a certain critical stiffness. It is the first condition that is investigated in our current set of experiments.

A material is velocity weakening if after an up step in velocity the steady state friction coefficient is lower than before the velocity step, i.e. when the rate and state friction parameter (a-b) < 0. (see figure above) Vice versa, a material is velocity strengthening if the steady state friction coefficient is higher after an up step in velocity, i.e. (a-b)>0. If there is long-term strain hardening (or weakening) during an experiment the (a-b) value can still be derived by removing the long-term trend, since the fraction of $\delta\mu/\delta\ln(V/V_0)$ is independent of slope.

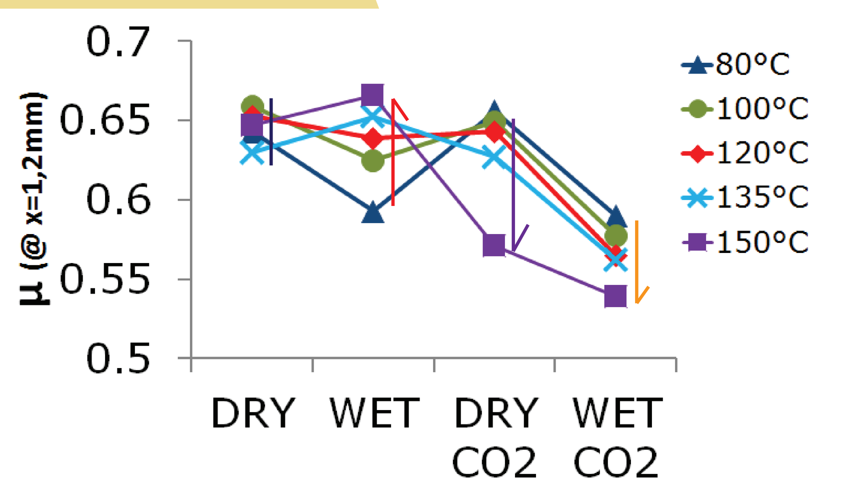


Fig. 5 Friction coefficient at a fixed shear displacement of 1.2 mm at all temperatures vs. the different conditions. Strength does not vary much for the dry samples. For the wet experiments strength increases with T, whereas in the presence of CO_2 there is a slight decrease.

4. RESULTS

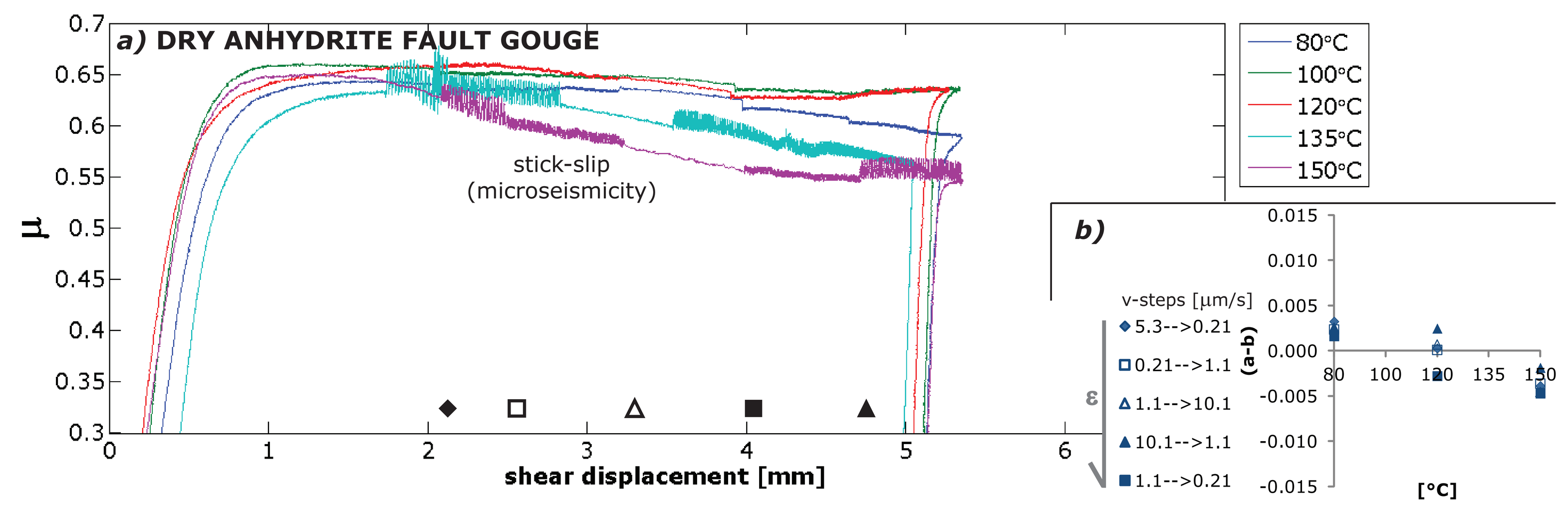


Fig. 1 Frictional properties as a function of temperature for dry anhydrite fault gouge. **a)** friction coefficient vs shear displacement [mm]. Friction coefficient between 0.55-0.65. Note how the increase in temperature leads to stick-slip behavior **b)** (a-b) values as a function of temperature. Increasing temperature leads to a negative (a-b) value, indicating increasing potential for microseismicity

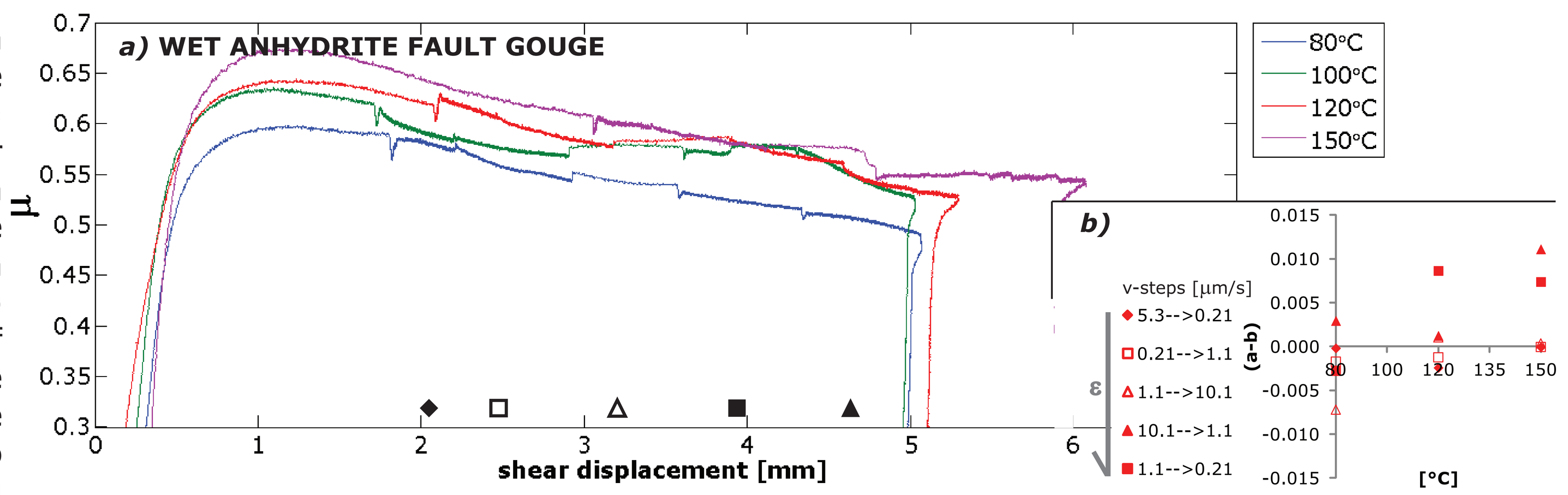


Fig. 2 Frictional properties as a function of temperature for gouge pressurized with DI water **a)** friction coefficient vs shear displacement [mm]. Friction coefficient between 0.55-0.67. The friction coefficient increases with increasing temperature **b)** (a-b) values as a function of temperature. Decreasing temperature leads to negative (a-b) value, indicating a transfer to stable sliding behavior with rising temperature

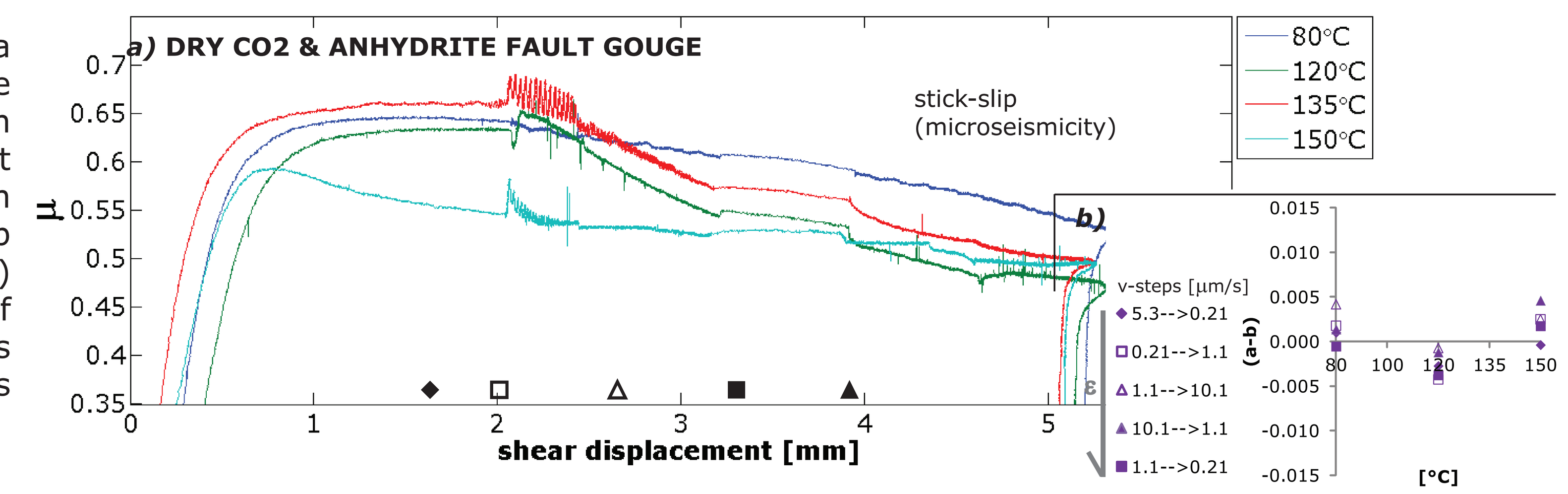


Fig. 3 Frictional properties as a function of temperature for gouge pressurized with dry CO_2 **a)** friction coefficient vs shear displacement [mm]. Friction coefficient between 0.52-0.67. Note the sticks-slip events at intermediate T **b)** (a-b) values as a function of temperature. Negative (a-b) values for intermediate temperatures concur with the unstable sliding

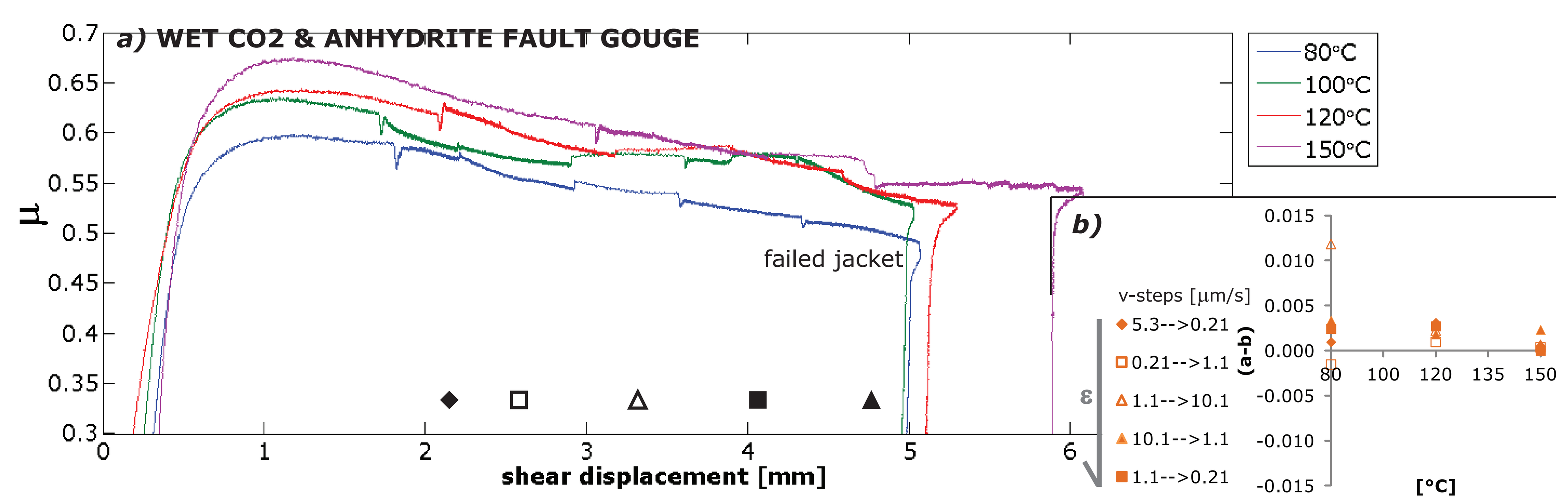


Fig. 4 Frictional properties as a function of temperature for water-wet gouge pressurized with CO_2 **a)** friction coefficient vs shear displacement [mm]. Friction coefficient between 0.47-0.57. (Peak) friction decreases with increasing temperature **b)** (a-b) values as a function of temperature. (a-b) values are positive over the investigated temperature range

5. DISCUSSION

Observations	Implications
DRY	
Increasing temperature leads to a negative (a-b)	increasing T increases risk for unstable behavior/ increased risk for microseismicity
T = 135°C & T =150°C: stick-slip if v<5 μm/s	confirms negative (a-b) / unstable sliding
T = 135°C & T =150°C: continuous ε weakening	If this is a material property, the measured friction coefficient is an upper limit when comparing to nature
WET	
Increasing temperature leads to a positive (a-b)	increasing T leads to stable sliding: diminishing likelihood for earthquakes
with increasing ε (a-b) becomes positive	High strain fault zones with well-developed fabric may have positive (a-b)
Continuous ε weakening for all T	If this is a material property, the measured friction coefficient is an upper limit when comparing to nature
DRY CO_2	
T = 80°C : (a-b) > 0 T = 120°C : (a-b) < 0 T = 150°C : (a-b) mostly > 0	Dry anhydrite fault gouge pressurized with CO_2 only shows velocity weakening behavior at intermediate temperatures
T = 120°C: stick slip behavior at low v; at high ε also at medium v	confirms negative (a-b) at intermediate temperature
WET CO_2	
(a-b) > 0 at all T	for $\sigma_{n,eff}$ = 25 MPa the presence of CO_2 in wet anhydrite fault gouge decrease the potential for microseismicity, independent of T

Overall:

- Without CO_2 there is some potential for microseismicity. This potential increases when there is no water present and with increasing temperature. However, the presence of water and CO_2 decrease the potential for microseismicity; independent of temperature.
- Frictional strength is independent of temperature for dry experiments. Wet anhydrite fault gouge becomes slightly stronger with temperature. Gouges with CO_2 become slightly weaker, though this is most pronounced under wet + CO_2 conditions.

Further research
- Investigate microstructures where possible
- Determine importance of strain weakening
- Determine the influence of normal stress

6. SUMMARY

How strong are faults filled with anhydrite fault gouge?

Under the investigated experimental conditions, anhydrite has a friction coefficient of approximately 0.6.

It is sensitive to temperature when pore fluid is present, and it also depends on the type of pore fluid (water/CO_2/water + CO_2).

In general variations are within 0.60±0.05. Wet anhydrite is slightly weaker than dry anhydrite. The strength of dry anhydrite is not influenced by temperature, whereas wet anhydrite becomes slightly stronger at high temperatures. At 80°C the presence of CO_2 does not effect the strength, but with increasing temperature both wet and dry gouge become weaker when pressurized with CO_2, with μ~0.55 for both at 150°C.

If the fault is reactivated, could the motion be microseismic?

Our data indicate that

NO, microseismicity will not occur in wet gouge with or without CO_2 in the investigated temperature range, except possibly in wet gouge at 80°C

YES, there is a potential for microseismicity in dry gouge with and without CO_2 at temperatures of 135 and 150°C.