

Velocity dependence of strength and healing behaviour in simulated phyllosilicate-bearing fault gouge

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Received 11 July 2005; received in revised form 14 March 2006; accepted 24 March 2006

Available online 22 September 2006

Abstract

Despite the fact that phyllosilicates are widespread in fault zones, little is known about the strength of phyllosilicate-bearing fault rocks under brittle–ductile transitional conditions. In this study, we explored the steady state strength and healing behaviour of a simulated phyllosilicate-bearing fault rock, i.e. muscovite plus halite and brine, at room temperature, normal stresses of 1–9 MPa, atmospheric fluid pressure and sliding velocities of 0.001–13 $\mu\text{m/s}$, using a rotary shear apparatus. While 100% halite and 100% muscovite samples exhibit rate-independent frictional/brittle behaviour, the strength of mixtures containing 10–50% muscovite is both normal stress and sliding velocity dependent. At low velocities ($<1 \mu\text{m/s}$), strength increases with increasing velocity and normal stress, and a mylonitic foliation develops. This behaviour results from pressure solution in the halite grains, which accommodates frictional sliding on the phyllosilicate foliation. The pervasive muscovite foliation, which coats all halite grains, prevents significant healing. At high velocities ($>1 \mu\text{m/s}$), velocity-weakening frictional behaviour occurs, along with the development of a structureless, intermixed, cataclastic microstructure. The steady state porosity of samples deformed in this regime increases with increasing sliding velocity. We propose that this behaviour involves competition between dilatation due to granular flow and compaction due to pressure solution. Towards higher sliding velocities, dilatation increasingly dominates over pressure solution compaction, so that porosity increases and frictional strength decreases. During periods of zero slip, pressure solution compaction occurs, causing a significant strength increase on reshearing. Our results imply that cataclastic overprinting of mylonitic rocks in natural fault zones does not require any changes in temperature or effective pressure conditions, but can simply result from oscillating fault motion rates. Our healing data suggest that foliated, aseismically creeping fault segments will remain weak and aseismic, whereas segments that have slipped seismically will rapidly re-strengthen and remain in the unstable, velocity-weakening regime.

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Keywords: Deformation; Faults; Healing; Phyllosilicates; Seismogenesis

1. Introduction

In the past few decades considerable experimental effort has been focused on quantifying the frictional behaviour of faults. Results from room temperature and/

or dry sliding experiments on bare rock interfaces and simulated gouge-filled faults have typically shown static and dynamic sliding friction at 0.6–0.9 times the applied normal stress (e.g. Byerlee, 1967; Dieterich, 1972; Jackson and Dunn, 1974; Byerlee, 1978). Early experiments on bare rock surfaces by Dieterich (1972) and many others (e.g. Byerlee, 1967; Byerlee and Summers, 1975; Rummel et al., 1978; Ruina, 1983) have shown an increase in static friction, that is the maximum friction

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following a “hold” period of zero slip, with increasing hold duration. These experiments also show a decrease in dynamic friction with increasing sliding velocity, a phenomenon known as velocity-weakening. By contrast, simulated fault gouges (e.g. Marone et al., 1990; Chester and Higgs, 1992; Chester, 1994; Blanpied et al., 1995) in general show a lower rate of increase in static friction with hold duration. Moreover, they show an increase in dynamic friction with increasing sliding velocity for pervasive shear over a wide range of sliding velocities, i.e. a velocity-strengthening effect. With ongoing shear displacement, however, simulated fault gouges exhibit a transition from velocity-strengthening to velocity-weakening behaviour associated with localization of shear.

Reduction of dynamic friction through velocity-weakening behaviour is a requirement to produce unstable slip on a fault, i.e. a stick–slip event in the laboratory or an earthquake in nature, and is therefore of major interest in relation to seismogenesis. Increasing static friction during periods of zero slip, otherwise known as strength recovery or fault healing, is also of major interest in relation to understanding the earthquake cycle (e.g. Marone et al., 1995; Becker and Schmeling, 1998). A coupled description of static and dynamic friction in relation to fault slip behaviour was first established with the development of the rate- and state-friction (RSF) laws by Dieterich (1979) and Ruina (1983). These have been successfully applied to quantify the effects seen in numerous rock friction experiments and have shown that static friction and its time dependence represent a special case of velocity-dependent friction.

Significantly, most previous studies of friction on bare fault surfaces and simulated gouge-filled faults have focused on room temperature experiments (e.g. Dieterich, 1978, 1979; Marone et al., 1990; Kilgore et al., 1993; Beeler et al., 1994; Beeler et al., 1996; Mair and Marone, 1999). Such experiments exclude the hydrothermal fluid–rock interactions that are known to be important in the upper to middle crustal depth range corresponding to the seismogenic zone and its base at the brittle–ductile transition (e.g. Imber et al., 2001; Rutter et al., 2001). Effects of fluid–rock interaction have been demonstrated in several experimental studies on gouge-filled faults (e.g. Chester and Higgs, 1992; Chester, 1994; Cox, 1994; Tullis, 1994; Blanpied et al., 1995; Karner et al., 1997; Kanagawa et al., 2000; Nakatani and Scholz, 2004) and have a clear influence on the sliding and healing behaviour. These effects include stabilization of sliding behaviour (i.e. a transition from velocity-weakening to velocity-strengthening) and a stronger healing propensity often attributed to solution transfer effects (e.g. Olsen et al., 1998; Nakatani and Scholz, 2004). However, there

is a lack of systematic analysis and quantification of these effects, and the number of studies of the micromechanical processes involved and their relevance to nature is limited. Indeed, most experiments performed on simulated gouge under wet, reactive conditions have focused on pure single phase materials or else are influenced by incomplete mineral reactions. They are also limited in the duration and in the total amount of strain that could be reached, so that the internal microstructural development is highly immature (Blanpied et al., 1991; Cox, 1994; Blanpied et al., 1995; Karner et al., 1997; Olsen et al., 1998; Kanagawa et al., 2000; Nakatani and Scholz, 2004). By contrast, natural fault rocks often contain a significant proportion of weak phyllosilicates, either inherited from the host rock or formed by mineral reactions, which form an interconnected network or foliation indicative of high shear strain. Such foliations have often been suggested as an explanation for the observed weakness of some faults, such as the San Andreas Fault and others (e.g. Wintsch et al., 1995; Imber et al., 2001; Holdsworth, 2004), though it remains unclear how these weak faults may be capable of producing large earthquakes.

Recent large strain, rotary shear experiments, performed by Bos, Niemeijer and Spiers (Bos et al., 2000a,b; Bos and Spiers, 2000, 2001, 2002a,b; Niemeijer and Spiers, 2005) on rock analogue materials consisting of halite plus phyllosilicate mixtures have shown large effects of phyllosilicate content and foliation development. These experiments were done under simulated brittle–ductile transitional conditions where cataclasis and solution transfer operate in the halite, without the operation of plastic processes such as dislocation creep. At low sliding velocities, combined slip on the developing phyllosilicate foliation and solution-transfer of intervening halite clasts yield velocity-strengthening behaviour plus slow healing characteristics. A microphysical model for the inferred deformation process predicts low steady state fault strength and aseismic slip in mature phyllosilicate-bearing faults at mid-crustal depths (Bos and Spiers, 2002b; Niemeijer and Spiers, 2005).

Similar experiments performed by Niemeijer and Spiers (2005) on wet halite/muscovite mixtures, but at higher sliding velocities, have recently revealed dramatic velocity-weakening behaviour, not seen in the two end-member compositions. Such behaviour may also be important in natural fault rocks containing phyllosilicates. If so, it could play a significant role in controlling seismogenesis and the entire the seismic cycle on faults under the reactive hydrothermal conditions of the brittle–ductile transition. However, the microphysical

mechanisms underlying the observed velocity-weakening behaviour are not yet understood. Moreover, the healing behaviour in the velocity-weakening regime is unknown and the relevance to nature is unverified.

In this study, we have investigated the large strain sliding and the healing behaviour of simulated faults containing halite–muscovite gouges at velocities covering both the velocity-strengthening and velocity-weakening regimes. Under the chosen conditions, pressure solution, cataclasis and phyllosilicate foliation development and destruction are active, as anticipated for nature under brittle–ductile transitional conditions (e.g. Imber et al., 2001; Holdsworth, 2004). Our aim is to determine the healing behaviour of the mixtures as a function of sliding velocity and to explain the microphysical mechanisms responsible for the observed velocity-weakening and healing effects. Finally, we speculate on the possible implications of our results for natural faults, assuming that the processes observed in our experiments also occur in natural fault zones.

2. Experimental method

The experiments were performed at room temperature on simulated, muscovite–halite fault gouges, using a rotary shear apparatus located in an Instron 1362 loading frame to apply normal load to the simulated fault. Tests were done both dry and in the presence of brine. The apparatus has been described in detail elsewhere (Bos et al., 2000a; Niemeijer and Spiers, 2005). In brief, the sample assembly consists of a pair of toothed stainless steel rings (the wall rock rings of Fig. 1, teeth height = ~ 0.1 mm) sandwiching a layer of halite–muscovite gouge. The assembly is sealed, using O-rings, between an inner steel confining ring and an outer steel confining ring, which houses a pore fluid inlet and outlet. Within the rotary-shear machine, the sample assembly is rigidly gripped by a stationary upper forcing block and a lower forcing block linked to a servo-controlled drive system. The servo-controlled drive is used to apply rotational sliding velocities of 0.001 – 10 $\mu\text{m/s}$ to the gouge with a resolution of 0.0003 $\mu\text{m/s}$. Shear displacement is measured using a potentiometer with a resolution of 0.001 mm, geared to the lower (rotating) forcing block. Shear stress on the gouge is measured using a torque gauge couple, with a resolution of 0.01 MPa, mounted on the upper forcing block. Normal stress is applied using the Instron loading ram and can be held constant to within ~ 0.02 MPa. Most of the present experiments were conducted under a normal stress of 5 MPa. Displacement occurring normal to the fault zone is measured using a Linear Variable Differential Trans-

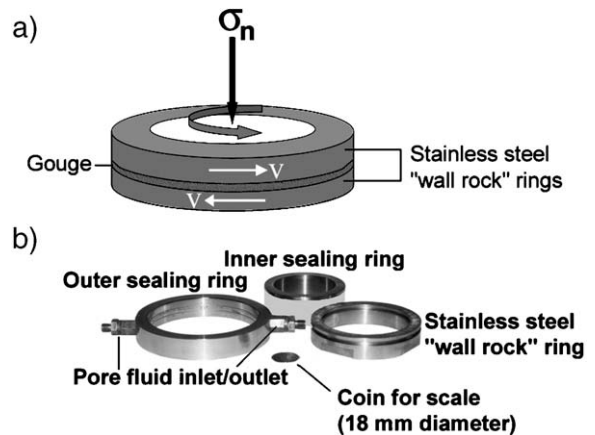


Fig. 1. (a) Schematic diagram of the rotary shear sample assembly used in this study. Granular fault gouge is sheared between annular stainless steel wall rock rings at controlled velocity v and normal stress σ_n . Gouge dilatation/compaction is measured using an LVDT located in the centre of the sample assembly. (b) Photograph of the wall-rock rings and the sealing rings that constitute the sample assembly.

former or LVDT (1 mm full scale, 0.01% resolution) located in the centre of the sample assembly.

Sample material consisted of mixtures of granular halite with a median grain size of 100 μm (determined using a Malvern particle sizer), plus 10 – 80 wt.% muscovite with a median equivalent spherical diameter of 13 μm (as stated by the supplier, Internatio B.V., Zutphen, the Netherlands). Pure halite and pure muscovite samples were used as control experiments. In setting up each run, about 8 g of material were loaded into the sample assembly, yielding an initial gouge thickness of ~ 2 mm. All samples were then subjected to dry compaction, under a normal load of 1 MPa for ~ 15 min. Except where otherwise specified (Table 1), samples were subsequently dry-sheared to a displacement around ~ 50 mm at a velocity of 1 $\mu\text{m/s}$ and 5 MPa normal stress. This was done to produce a reproducible microstructure. In most experiments, the pore fluid system was then connected to the sample assembly, which was in turn evacuated and flooded with saturated brine (i.e. saturated with respect to the NaCl in the gouge). The pore fluid was subsequently kept at atmospheric pressure by means of evaporation-proof draining to air.

Two broad categories of experiments were performed to investigate the effects of sliding velocity, composition and normal stress.

- Continuous sliding experiments carried out in velocity stepping mode, normal stress stepping mode, or at constant velocity and constant normal stress.
- Slide–hold–slide experiments, performed using different sliding velocities and constant normal stress.

Table 1

List of the 26 velocity-stepping, constant velocity and normal stress stepping experiments performed plus corresponding experimental conditions

Sample code	Composition muscovite:halite	Dry run-in displacement(mm)	Fluid	σ_n stepping sequence (MPa)	Velocity-stepping sequence (μ m/s)	Total shear displacement *	Final gouge thickness (mm)
Hal1	0%:100%	0	brine	1, 0.5, 2, 3, 1	1	29.38	n.d.
Mus1	100%:0%	69	brine	5, 7, 9, 5, 3, 1	1, 10, 0.1, 1, 0.03, 1	40.01	1028
Mus2	10%:90%	59	brine	5, 9, 1, 5	1, 10, 0.1, 1, 0.03, 1	44.18	1470
Mus3	20%:80%	49	brine	5	0.8, 0.5, 1, 0.1, 0.03, 0.3, 1, 0.01, 0.003, 0.008, 0.3	44.96	1318
Mus4	20%:80%	61	brine	5	1, 3, 5, 7, 9, 11, 13, 11, 9, 7, 5, 3, 1, 5, 10	171.04	975
Mus5	20%:80%	50	brine	5	0.03	35.35	967
Mus6	20%:80%	50	brine	5	1	30.10	1142
Mus7	20%:80%	50	brine	5	5	30.11	1135
Mus8	20%:80%	53	brine	5	13	30.05	1295
Mus9	20%:80%	0	brine	5, 4, 3, 2, 1	1	32.43	1212
Mus10	20%:80%	0	brine	5, 4, 3, 2, 1	5	38.87	1361
Mus11	20%:80%	0	brine	5, 4, 3, 2, 1, 2, 3, 4, 5	10	60.14	1376
Mus12	20%:80%	0	silicon oil	5	1, 10, 0.1, 1, 0.03, 1, 3, 5, 1, 0.1	44.62	1007
Mus13	20%:80%	0	none	5	1, 10, 0.1	38.05	n.d.
Mus14	30%:70%	45	brine	5	1, 10, 0.1, 1, 0.03, 1, 3, 5, 10, 1	33.72	n.d.
Mus15	30%:70%	66	brine	5	1, 10, 0.1, 1, 0.03, 1, 10, 1, 3, 1, 0.01	50.53	997
Mus16	20%:80%	0	none	5	1, 10, 0.1, 1, 0.03, 1, 10, 1, 0.1	38.46	1555
Mus17	20%:80%	0	brine	5	1, 0.001	8.27	880
Mus20	0%:100%	54.8	brine	5	10, 0.1, 1, 0.03, 1, 3, 5, 7, 9, 11, 13, 11, 1, 0.01, 0.00	106.51	1100
Mus21	80%:20%	50.3	brine	5	1, 10, 0.1, 1, 0.03, 1, 0.00	30.91	793
Mus22	50%:50%	55.5	brine	5	1, 10, 0.1, 1, 0.03, 1, 0.01	47.05	955
Mus23	20%:80%	49.5	brine	5	0.1	30.3	1026
Mus24	20%:80%	51.8	none	5	1	—	1568
Mus25	20%:80%	0	brine	5, 4, 3, 2, 1	0.03	30	1300

Note that σ_n is the normal stress on the fault. n.d. not determined, * total shear displacement after the dry run-in stage.

The continuous sliding experiments consisted of 24 separate experiments. These included a series of 11 velocity-stepping experiments performed on brine-flooded samples of different composition (0, 10, 20, 50, 80 and 100 wt.% muscovite). The tests were carried out by shearing at a constant sliding velocity of 1 μ m/s until a steady state shear stress level was attained, usually after a displacement of $\sim$ 3 mm. The velocity was then stepped up or down and the new sliding velocity held constant until a new steady state shear stress level was reached. The aim of this series of experiments was to determine the rate dependence of steady state shear strength for a range of gouge compositions. Most of these tests were carried out at a constant normal stress of 5 MPa, though the normal stress was also stepped in a few cases to determine its effect on gouge shear strengths. In addition, four stress-stepping experiments were performed at constant sliding velocity on wet samples with 20 wt.% muscovite using the same experimental procedure, but without the dry run-in phase. A further series of 5 large displacement experi-

ments was carried out on wet samples with 20 wt.% muscovite at a constant sliding velocity of 0.03, 0.1, 1, 5 and 13 μ m/s and at a constant stress of 5 MPa (including a dry run-in phase). These were done to investigate the high strain microstructure (shear strain of 30). The remaining continuous sliding tests consisted of 4 control experiments, performed dry and using silicone oil instead of brine. For more details, we refer to our previous paper dealing with velocity-stepping experiments on the same material (Niemeijer and Spiers, 2005).

The slide–hold–slide (SHS) experiments (Table 2) were carried out with the aim of investigating the transient and healing behaviour of mixtures containing 80 wt.% halite and 20 wt.% muscovite plus brine at different sliding velocities. This series of 5 tests involved the same initial dry compaction and shearing procedure described above, followed by a wet “run-in” sliding stage at 1 μ m/s, until a steady state shear stress level was reached. The sliding velocity was then stepped to a chosen SHS reference sliding velocity until a new steady state shear stress

Table 2

List of slide–hold–slide experiments performed plus corresponding experimental conditions

Sample code	Composition muscovite:halite	Dry run-in displacement (mm)	Fluid	Normal stress (MPa)	Velocity-stepping sequence (μ m/s)	Hold periods (s)	Total wet shear displacement	Final gouge thickness (mm)
shs1	20%:80%	51.3	brine	5	1*, 3, 5, 0.05*, 10, 1, 5	60, 600, 60	95.27	1077
shs2	20%:80%	55.61	brine	5	1*, 0.1, 0.01	600, 1200, 6000	27.73	1008
shs3	20%:80%	50.5	brine	5	10, 5	60, 600, 6000	60.22	1015
shs4	20%:80%	57.6	brine	5	1*, 0.03, 0.1, 1, 0.1*, 5	60, 600, 6000	86.49	903
shs5	20%:80%	50.12	brine	5	1*, 0.1*, 2, 0.1*, 10	60, 600, 6000	82.49	963

* Sliding interval without hold.

was reached. The rotary drive was then halted and the sample allowed to “stress relax” for a chosen hold time. We measure no displacement or back lash when the motor was halted. After the desired hold, sliding was restarted at the same reference velocity, by switching on the motor, and continued until steady state was re-attained. This slide–hold–slide procedure was repeated 2 or 3 times for reference SHS sliding velocities of 0.01, 0.03, 0.1, 1, 2, 3, 5 and 10 μ m/s, using hold periods of 60 s, 600 s, 1200 s and 6000 s. We employed slide–hold–slide cycles at different reference velocities within individual tests in order to avoid any effects of sample variability and to investigate the influence of increasing displacement (shear strain). An exception to the above SHS procedure is test shs3, which was slid directly after the dry run-in stage at the desired reference sliding velocity of 10 μ m/s. The shear stiffness of the machine was measured using a dummy sample of steel. It was found that the stiffness varied from 0.02–0.08 MPa/ μ m and stress relaxation curves were accordingly corrected.

At the end of all experiments, sliding was halted and the normal load was removed. Residual brine was flushed rapidly from the sample assembly with hexane and the entire assembly was removed from the testing machine and dried at 50 °C for $\sim$ 2 h. Finally, the sample was extracted and impregnated with blue-stained epoxy resin. Standard thin sections were cut parallel to the sliding direction and normal to the shear plane.

The final porosities of the gouge samples studied in all constant velocity tests (Mus5, Mus6, Mus7, Mus8, Mus23) and all slide–hold–slide tests were determined by image analysis of thin sections and Thermo Gravimetric Analysis of propylene carbonate-saturated samples. Porosity determination using image analysis was done by defining a pixel threshold for detecting pores filled with blue-stained resin in 10 microstructural images at the same magnification. The images were converted to a black-and-white image using the UTHSCA ImageTool and a manual grey scale threshold. The porosity was obtained from the relative proportion of black pixels, yielding an area-based

porosity. Porosity determinations using TGA were conducted by evacuating of about 0.1 g of sample material and subsequently impregnating this with propylene carbonate. Propylene carbonate is a liquid with a high boiling point (240 °C) which does not dissolve halite in significant amounts. The sample was then placed in a DuPont Instruments 1090 Thermal Gravimetric Analyzer and heated at a rate of 10 °C/min up to a temperature of 130 °C at which point significant evaporation starts. It was then kept at this temperature for 40 min, while the weight loss was continuously measured. The porosity was determined by assuming a constant surface evaporation rate at 130 °C, so that deviations from a linear weight loss must be due to evaporation from the pores. The weight loss due to evaporation from the pores was then used to determine the porosity of the sample. Measurements for each sample were repeated three times. The absolute standard error in our TGA porosity determination is about 1.5%. Values obtained from TGA agree well with those available from image analysis.

Table 3

List of porosity values determined for a selected number of experiments from the experimental data (porosity Exp), image analysis (porosity I.A.) and mercury porosimetry (porosity Hg) plus their standard deviations (S.D.)

Experiment	Velocity (μ m/s)	Porosity exp	Porosity IA	S.D.	Porosity TGA	S.D.
shs1	1*, 3, 5, 0.05*, 10, 1, 5	10.73	n.d.	n.d.	9.91	0.02
shs2	1*, 0.1, 0.01	0.30	n.d.	n.d.	1.85	0.11
shs3	10, 5	8.31	n.d.	n.d.	7.65	0.20
shs4	1*, 0.03, 0.1, 1, 0.1*, 5	3.52	n.d.	n.d.	5.38	1.26
shs5	1*, 0.1*, 2, 0.1*, 10	5.79	n.d.	n.d.	6.33	1.26
mus5	0.03	1.58	n.d.	n.d.	1.37	0.28
mus23	0.1	3.27	n.d.	n.d.	3.14	1.24
mus6	1	4.82	n.d.	n.d.	5.26	1.52
mus7	5	8.66	9.05	1.42	8.99	2.16
mus8	13	12.46	13.37	4.50	12.15	0.76

3. Results

Table 1 lists the 24 continuous sliding experiments, along with corresponding data on dry run-in displacement, normal stress, sliding velocity, total wet displacement and final gouge thickness (cf. Niemeijer and Spiers, 2005). A similar list of the 5 slide–hold–slide experiments and supporting data is given in Table 2.

3.1. Porosity data

The final porosities of the samples obtained from our constant velocity tests (Mus5, Mus6, Mus7, Mus8 and Mus23) and slide–hold–slide tests, as measured using image analysis and TGA, are listed in Table 3. The final porosity of the gouges was also calculated from our mechanical compaction data, obtained using the LVDT, and using the gouge density and the measured initial thickness of the sample assembly. However, in numerous cases we found negative values for the final porosity calculated in this way, probably due to minor material loss from the edges of the samples during the experiments. We accordingly corrected our mechanical compaction data for material loss, using a linear fit of compaction strain versus displacement obtained from experiment Mus12 in which silicone oil was used as the pore fluid. Pressure solution compaction does not occur under these conditions, because halite is not soluble in silicone oil. The porosity (Porosity–Exp) values listed in Table 3 are the values obtained from the thus corrected compaction data. They agree well with the porosities determined using both image analysis and TGA. Note that the final porosity of the gouges increases systematically with increasing sliding velocity (Fig. 2).

3.2. Velocity-stepping data

We present data from a typical velocity-stepping experiment (Mus2) in Fig. 3a. In all such experiments, upon a change in sliding velocity, an instantaneous effect on the measured shear stress (strength) was observed. This was followed by a gradual approach to a new steady state strength as seen in conventional rate- and state-dependent friction experiments (Dieterich, 1979; Ruina, 1983; Marone, 1998b; Scholz, 1998). Sample compaction rate was observed to increase sharply upon a step down in velocity and to decrease and even become negative upon a step up in velocity.

Representative results from the complete set of velocity-stepping tests, showing the dependence of steady state shear strength of our gouge samples on sliding velocity, are presented in Fig. 3b. Reproducibility between experiments performed at the same conditions was good, showing differences in shear strength up to $\sim 10\%$. The pure muscovite sample (Mus1) showed no measurable velocity-dependence of steady state shear strength (~ 1.8 MPa) over the entire velocity range (0.03 – 10 $\mu\text{m/s}$) investigated. The pure halite sample showed a very slight velocity dependence, with the steady state shear strength increasing from a value of ~ 4.3 MPa at a velocity of 0.003 $\mu\text{m/s}$ to a maximum of ~ 5.2 MPa at 3 $\mu\text{m/s}$. At higher velocities, the steady state strength decreased slightly, falling to around 4.6 MPa at the highest velocity (13 $\mu\text{m/s}$).

In contrast to the pure end-members, all mixed muscovite–halite samples show a pronounced dependence of steady state shear strength on sliding velocity, reaching a maximum strength at ~ 1 $\mu\text{m/s}$ (Fig. 3b). In addition, strength clearly decreases with increasing muscovite-content. All halite–muscovite mixtures are weaker than

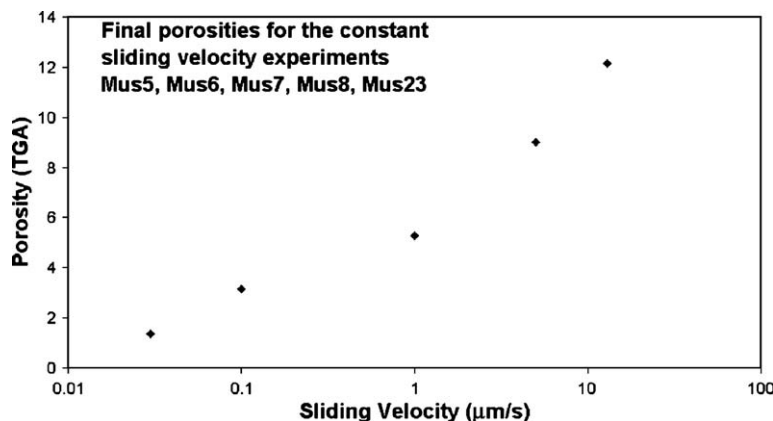


Fig. 2. Plot showing measured final porosity (TGA) versus sliding velocity for the five constant sliding velocity experiments (Mus5, Mus6, Mus7, Mus8 and Mus23).

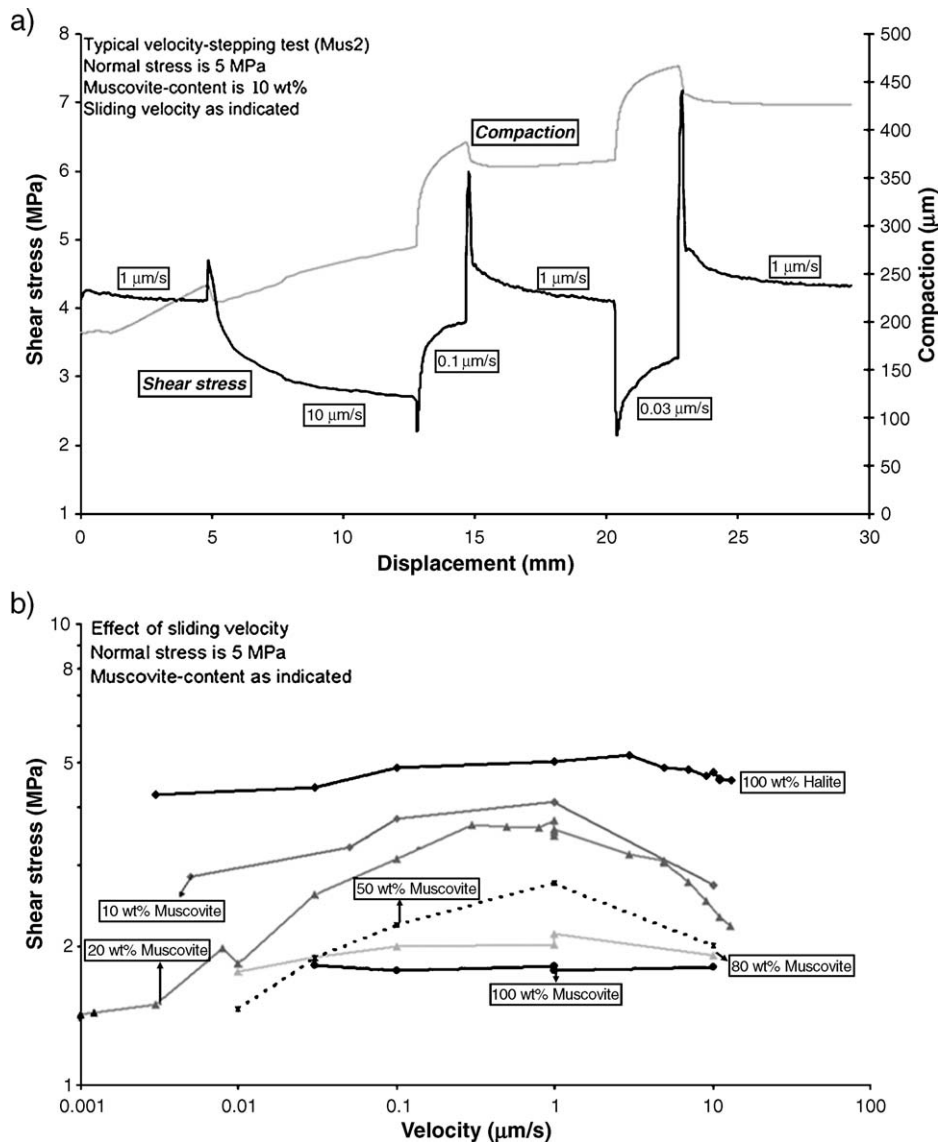


Fig. 3. (a) Measured shear stress (strength) and fault normal compaction versus sliding displacement for a 10 wt.% muscovite sample (Mus2), subjected to velocity stepping at a normal stress of 5 MPa. (b) Measured steady state shear stress (strength) versus sliding velocity data from the complete set of velocity-stepping experiments (Table 1; cf. Niemeijer and Spiers, 2005).

the pure halite sample over the entire velocity range investigated, while at the lowest sliding velocities investigated, samples with 20–50 wt.% muscovite are even weaker than the pure muscovite sample. The velocity dependence of shear strength is most pronounced in mixtures with low to intermediate muscovite content (i.e. 10 wt.% to 50 wt.%). The samples with 20 wt.% muscovite increased over 250% in strength, from a minimum value of ~ 1.4 MPa at $0.001 \mu\text{m/s}$ to a maximum of ~ 3.7 MPa at $1 \mu\text{m/s}$. At higher sliding velocities, the steady state strength decreased again, reaching a value of ~ 2.2 MPa at $13 \mu\text{m/s}$. Two regimes of behaviour could thus be

distinguished for the halite–muscovite samples, namely a velocity-strengthening regime at low sliding velocities ($< 1 \mu\text{m/s}$) and a velocity-weakening regime at high sliding velocities ($\geq 1 \mu\text{m/s}$).

3.3. Slide–hold–slide data

In Fig. 4, we present typical shear stress and normal displacement versus time data sets extracted from the complete sequence of SHS cycles performed within experiments shs2 and shs5 (see Table 2). Note that the experimental data shown are for displacements beyond

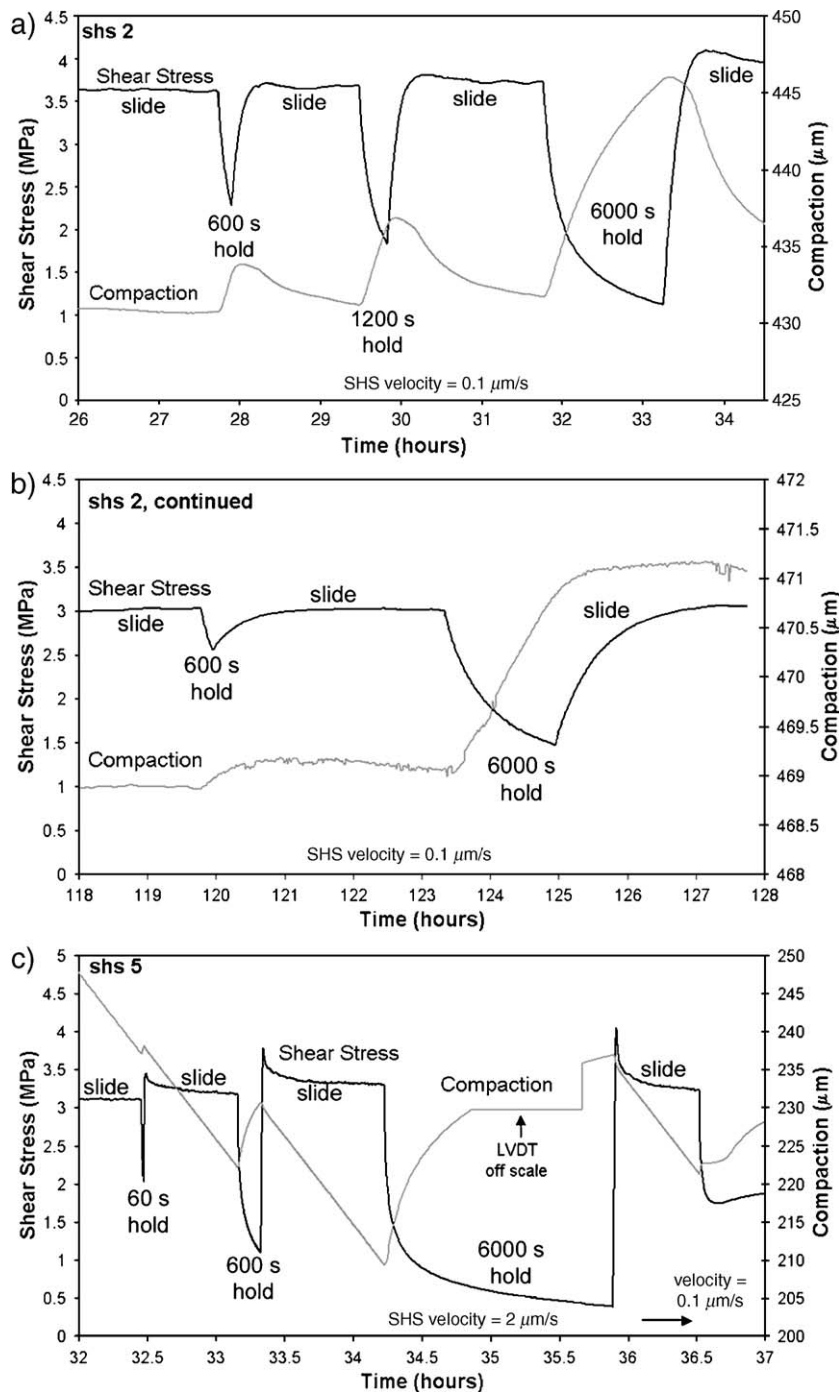


Fig. 4. Typical shear stress and compaction versus time data obtained for SHS cycles performed within experiments shs2 (a, b) and shs5 (c, d). Note that the slide periods are characterized by near steady state stress levels, while the intervening hold periods show stress relaxation and enhanced compaction. Compaction is represented in micrometer of displacement measured normal to the fault zone. Normal stress is 5 MPa and muscovite-content is 20 wt.% in all cases.

both the dry and wet run-in stages. The steady state sliding behaviour obtained prior to and between hold periods was generally similar to that observed in the

velocity-stepping experiments, both in terms of steady state shear stress levels and in terms of strain weakening and transient response to velocity-steps. An exception

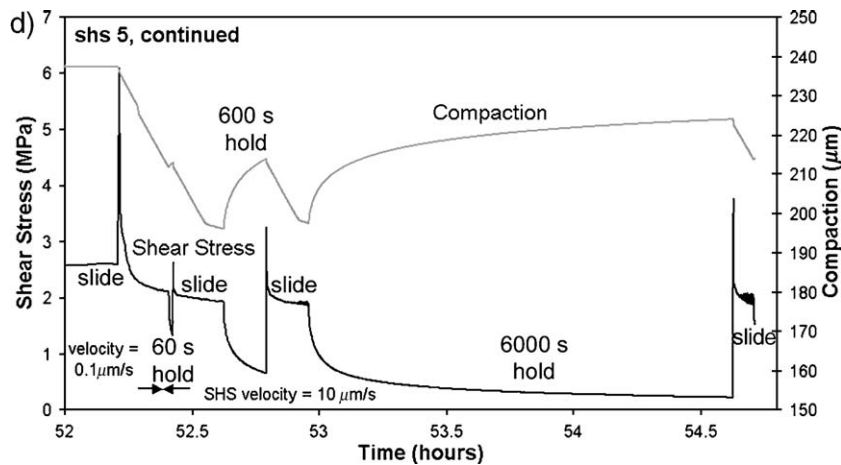


Fig. 4 (continued).

was sample shs3 (wet run-in at $10 \mu\text{m/s}$), which showed significantly lower steady state shear stress values ($\sim 30\%$) than those determined in the velocity-stepping series, as well as regular stick–slip cycles during sliding at $10 \mu\text{m/s}$.

All SHS cycles showed rapid shear stress relaxation from the instant that the drive motor was halted (see Figs. 4 and 5). In addition, significant compaction and shear displacement were observed during the hold periods. At low SHS reference velocities ($<1 \mu\text{m/s}$), the shear stress drops at a low rate, and only small amounts of horizontal and vertical displacement are accumulated. With increasing SHS reference velocity, the shear stress relaxation rate during individual hold periods increases, with a maximum observed at $1 \mu\text{m/s}$ (though the lowest shear stress level was observed in the sample deformed at $10 \mu\text{m/s}$). Both horizontal (shear) and vertical (compaction) displacement accumulated during hold periods increase with increasing SHS reference velocity. Shear displacement, for example, is approximately half an order of magnitude larger at a SHS reference velocity of $10 \mu\text{m/s}$ than at $0.1 \mu\text{m/s}$, while compaction is even one order of magnitude larger.

Upon re-shear, distinctly different behaviour was observed for SHS cycles performed in the velocity-strengthening regime (sliding velocity $<1 \mu\text{m/s}$) than for SHS cycles in the velocity-weakening regime (sliding velocity $\geq 1 \mu\text{m/s}$). When sliding was re-started in the low velocity regime, a more or less gradual increase in shear stress occurred until a steady state shear stress was achieved at a similar level to the shear stress prior to the hold period (see Fig. 4a and b). Dilatation, recovering about 80% of the compaction that occurred during the hold, was observed upon re-shear. In the high velocity

regime, on the other hand, a sharp peak in shear stress was observed upon re-shear, accompanied by significant dilatation usually recovering all of the compaction that occurred during the hold (Fig. 4c and d). Also, the absolute amount of compaction and dilatation was much larger in the high velocity regime. After the peak, the shear stress rapidly decreased to a steady state level similar to that prior to the hold period.

3.4. Microstructural observations

The starting microstructure of the samples prior to brine addition was investigated using a sample extracted from an experiment that was terminated directly after the dry run-in stage, i.e. after a dry shear strain of ~ 40 (sample Mus24, Niemeijer and Spiers, 2005 — see Fig. 6). In this sample, halite clasts with a size close to the starting grain size fraction ($60\text{--}110 \mu\text{m}$) are obvious and represent $\sim 30 \text{ vol.}\%$ of the gouge. These appear to be little affected by deformation, since they are mostly equiaxed. However, the matrix of the sample consists of a fine-grained mixture of halite and muscovite. Some regions of the gouge ($\sim 20 \text{ vol.}\%$, especially near the edges of the gouge) are relatively enriched in muscovite and contain fewer halite clasts than other regions. Such regions sometimes form narrow poorly defined zones lying in the Riedel shear orientation, i.e. inclined at $20\text{--}30^\circ$ to the shear direction. Locally, the matrix also shows a weak foliation orientated at 30° to the fault zone boundary (Fig. 6b), defined by muscovite grains interleaved with comminuted halite grains, some of which show a weak elongation within this foliation. A sharp, continuous, $5\text{--}15 \mu\text{m}$ wide boundary-parallel shear band, mainly consisting of aligned muscovite flakes, is

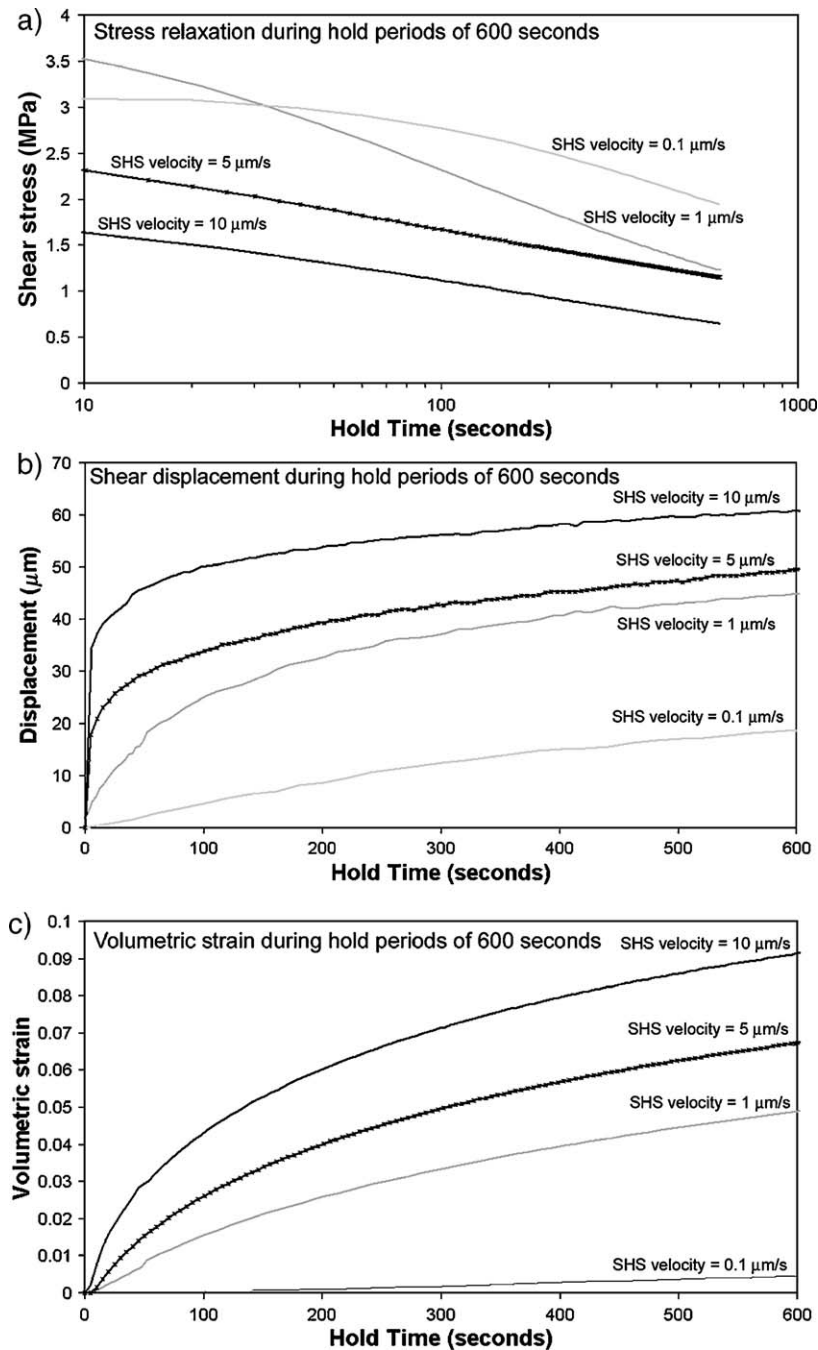


Fig. 5. Hold period data. Evolution of shear stress (a), shear displacement (b) and volumetric strain (c) during hold periods of 600 s for samples containing 20 wt.% muscovite and 80 wt.% halite tested in SHS mode at different SHS reference velocities (samples shs4 and shs5).

observed near the lower shear zone boundary of sample Mus24 (see arrows, Fig. 6a and b). It was inferred in an earlier paper (see Niemeijer and Spiers, 2005) that this shear band was probably produced during the last part of the dry run-in, since at this time stick-slip cycles occurred which are well-known to be associated with shear

localization (Chester and Logan, 1990; Marone, 1998b; Bos et al., 2000b).

In Figs. 7a–c and 8a–c, we show the microstructures developed in three constant sliding velocity (0.03, 5 and 13 $\mu\text{m/s}$) experiments in which the samples were deformed wet to a shear strain of ~ 30 . Sample Mus5,

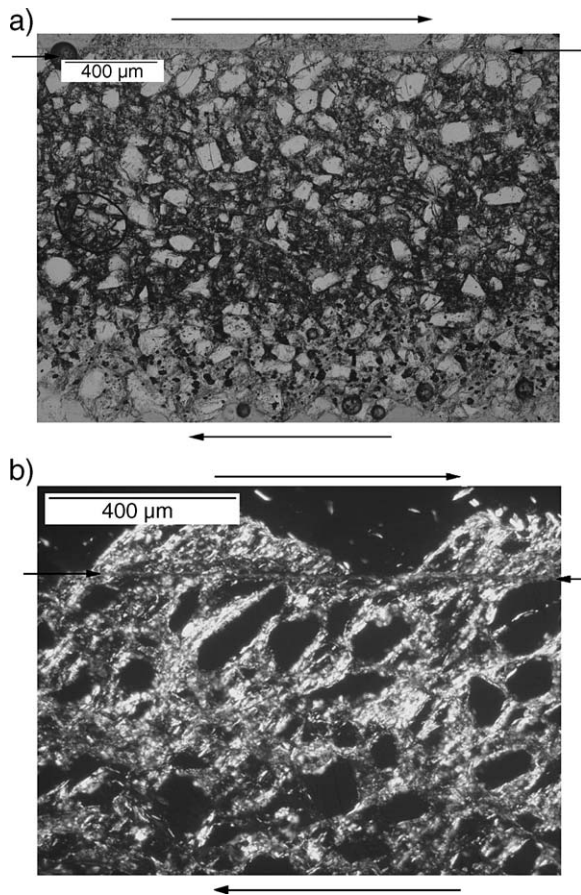


Fig. 6. Optical micrographs showing microstructures developed in the initial dry run-in stage of deformation, sample Mus24 (20 wt.% muscovite, shear strain is ~ 40). (a) Plane polarized light: note the chaotic structure with halite clasts embedded in a fine halite-muscovite matrix. A boundary parallel Y-shear is evident (small arrows). Shear sense as indicated. (b) Crossed polarized light: note weak foliation and Y-shear developed at the boundary of the gouge (small arrows). Shear sense as indicated. See also Niemeijer and Spiers, 2005.

deformed at $0.03 \mu\text{m/s}$, shows a wavy foliation defined by aligned muscovite flakes plus intervening halite grains (see Fig. 7a). The overall grain size of the halite is significantly reduced in comparison with the starting material, although numerous larger clasts are still present. These larger clasts consist of elongated grains often with long tails that sometimes show trails of fluid inclusion (Fig. 8a), suggesting the presence of an overgrowth. The matrix makes up approximately 80 vol.% of the gouge and consists of a foliated intercalation of muscovite flakes and fine halite grains. No apparent porosity is visible in the thin section, indicating that it is very low (see also Table 3).

Samples Mus7 and Mus8, deformed wet at higher sliding velocities (5 and $13 \mu\text{m/s}$) are relatively struc-

tureless on the microscopic scale and show a large variation in halite grain size (Fig. 7b–c). The larger clasts in these samples are blocky and irregular compared to the clasts in the low velocity sample. The matrix muscovite

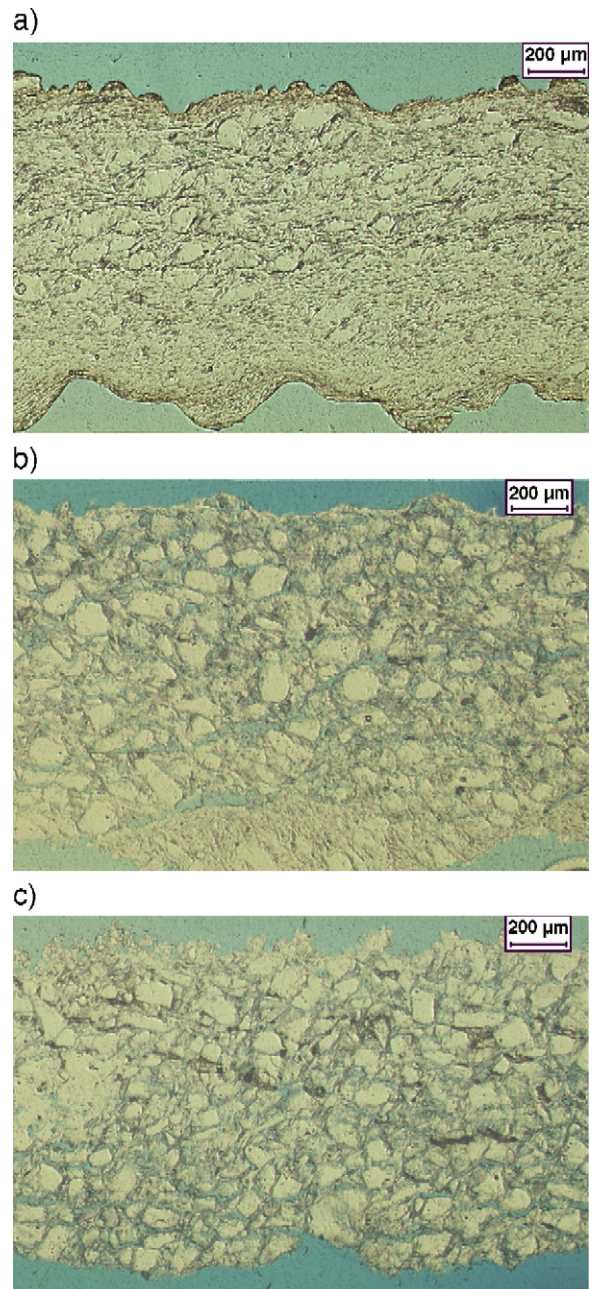


Fig. 7. Optical micrographs showing microstructures developed in the constant sliding velocity tests, samples Mus5, Mus7 and Mus8 (20 wt.% muscovite, shear strain is ~ 30). (a) Plane polarized light, sliding velocity is $0.03 \mu\text{m/s}$, shear sense as indicated. (b) Plane polarized light, sliding velocity is $5 \mu\text{m/s}$, shear sense as indicated. (c) Plane polarized light, sliding velocity is $13 \mu\text{m/s}$, shear sense as indicated.

grains do not define a clear foliation. They usually coat the smaller halite grain boundaries but not the entire surface of larger clasts. In contrast to the low velocity samples, considerable porosity is developed, especially at the highest velocity (Mus8, see Table 3). The porosity

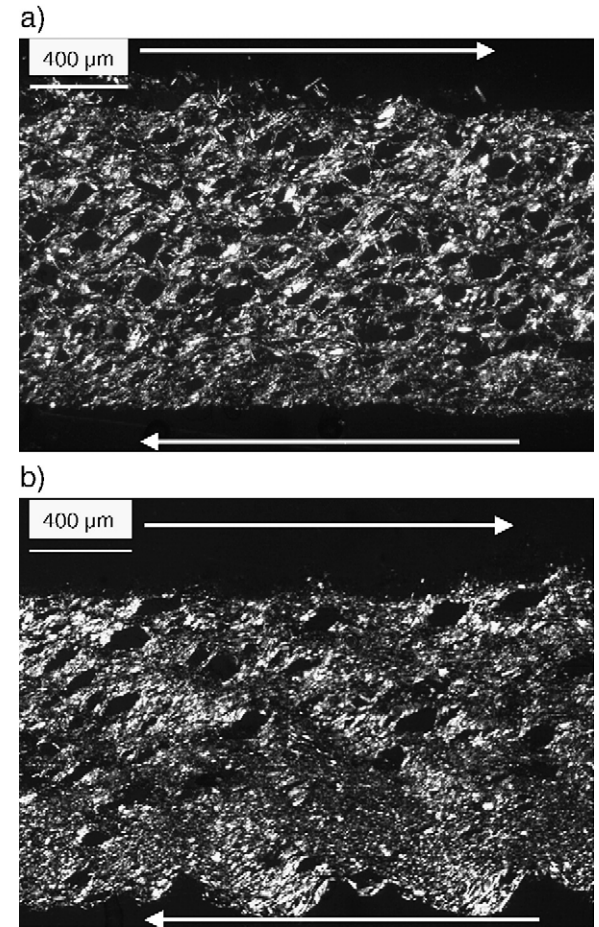
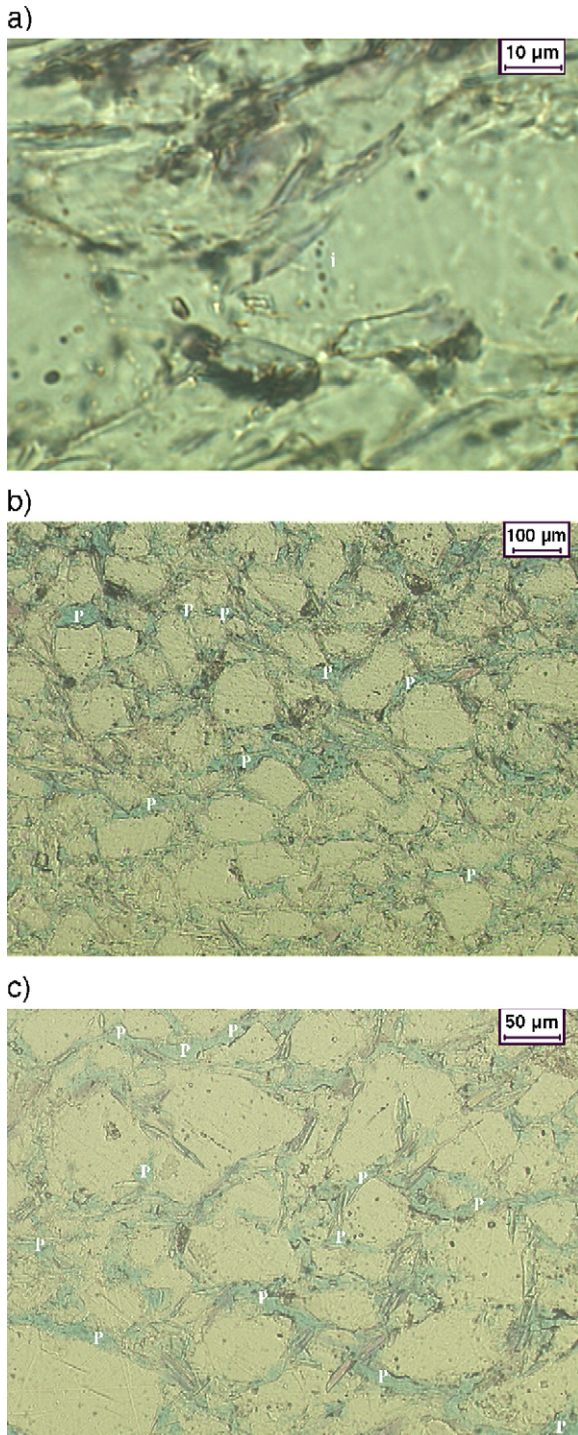


Fig. 9. Crossed polarized light optical micrographs showing microstructures developed in SHS tests shs2 and shs4. (a) Sample shs2. Note foliation orientated at an angle of $\sim 20^\circ$ to the fault zone boundary. Numerous asigmoidally shaped halite clasts, showing long tails are evident. Shear strain is ~ 25 and shear sense as indicated. (b) Sample shs4. Note heterogeneous appearance of the gouge, with zones of fine-grained mixtures of halite and muscovite and zones with larger halite clasts embedded in muscovite. The wavy foliation is orientated at an angle of $\sim 10^\circ$ to the fault zone boundary. Shear strain is 85 and shear sense as indicated.

is both distributed over the sample as well as locally clustered to form zones of higher porosity. Besides the difference in porosity, there is little further difference in the microstructures of sample Mus7 (5 $\mu\text{m/s}$, Figs. 7b and 8b) and Mus8 (13 $\mu\text{m/s}$, Figs. 7c and 8c).

Fig. 8. Optical micrographs showing details of the microstructures developed in the constant sliding velocity tests, samples Mus5, Mus7 and Mus8 (20 wt.% muscovite, shear strain is ~ 30). (a) Plane polarized light, sliding velocity is 0.03 $\mu\text{m/s}$, shear sense as indicated. Note the trail of fluid inclusions (i), indicative of the presence of an overgrowth. (b) Plane polarized light, sliding velocity is 5 $\mu\text{m/s}$, shear sense as indicated. Note the high porosity (P). (c) Plane polarized light, sliding velocity is 13 $\mu\text{m/s}$, shear sense as indicated. Note the high porosity (P).

In Figs. 9a and 10a, we show the microstructure of slide–hold–slide sample shs2, which was deformed to a shear strain of ~ 28 in the low-velocity regime ($< 1 \mu\text{m/s}$). The microstructure is relatively homogeneous and consists of a matrix of highly intercalated halite and muscovite grains, with numerous tailed or sigmoidally shaped halite clasts. A clear, anastomosing foliation can be observed, which is mostly defined by the muscovite flakes and the shape of the intervening halite clasts. Almost all halite grain boundaries are coated with muscovite flakes. The sample shows no evidence for boundary-parallel shear bands.

Figs. 9b and 10b show the microstructure of sample shs4 which was deformed to a shear strain of ~ 85 in both

velocity regimes. The appearance of this gouge is very heterogeneous. The overall halite grain size is significantly reduced in comparison to sample shs2. However, there are still a number of larger, sigmoidally shaped or tailed halite clasts present. Some of these clasts show intragranular fractures (Fig. 10b). The matrix consists of regions of very fine-grained mixtures of halite and muscovite and regions with less muscovite and more porosity. Some of the more porous zones appear aligned in a poorly defined Riedel shear orientation.

4. Discussion

The aim of the present work is to investigate the large strain slip and healing behaviour of halite–muscovite fault gouges in both the velocity-strengthening and in the velocity-weakening regimes, to explain any differences in behaviour in terms of the microphysical mechanisms involved, and to speculate on the possible implications of our results for natural fault zones. In order to set about interpreting our results, we begin by considering a number of important theoretical concepts relating to the strength and healing of gouge-filled faults. We then proceed to consider the microphysical mechanism that might be responsible for the observed velocity-weakening under steady state conditions. We go on to compare and mechanistically analyse the strength recovery behaviour seen in slide–hold–slide experiments performed in both the velocity-strengthening and the velocity-weakening regimes. Finally, we will discuss some of the implications that our work may have for deformation of natural phyllosilicate-bearing fault zones under hydrothermal conditions.

4.1. Theoretical considerations

Following Lehner (1995) and Bos and Spiers (2000, 2002a), and taking into account possible changes in grain boundary and pore wall surface areas, the combined energy and entropy balance for a representative volume of fault rock during deformation can be written as:

$$\tau \dot{\gamma} + \sigma_n \dot{\epsilon} = \dot{f} + \dot{\Delta} + \dot{A}_{gb} \gamma_{gb} + \dot{A}_{sl} \gamma_{sl} \quad (1)$$

assuming a closed system with respect to solid mass. In this relation, τ is the shear stress acting on the fault rock, $\dot{\gamma}$ is the shear strain rate, σ_n is the effective normal stress on the fault (compressive positive), $\dot{\epsilon}$ is the normal strain rate (compaction positive), $\dot{f}$ is the rate of change of Helmholtz free energy of the solid phase per unit volume, $\dot{\Delta}$ denotes the volume specific energy dissipation rate by all irreversible processes, $\dot{A}_{sub}$ gb is the rate of change in

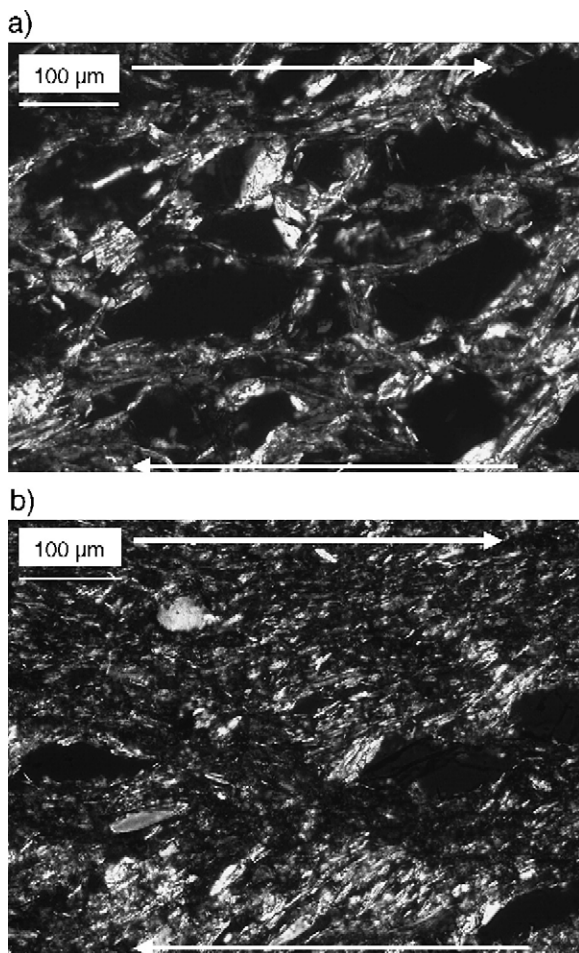


Fig. 10. Crossed polarized light optical micrographs showing details of microstructures developed in SHS tests shs2 and shs4. (a) Sample shs2. Note long tails in most halite grains. All halite grains are coated with muscovite flakes. Shear strain is ~ 25 and shear sense as indicated. (b) Sample shs4. Note small grain size of halite grains in the matrix. Large halite clasts show several intragranular fractures. Shear strain is 85 and shear sense as indicated.

grain boundary surface area per unit volume, γ_{gb} is the grain boundary surface energy, $\dot{A}_{sl}$ is the rate of change of solid–liquid interfacial area per unit volume and γ_{sl} is the solid–liquid interfacial energy. For clarity, note that the left-hand side of Eq. (1) represents the rate at which work is done on unit volume of fault rock by the externally applied stresses. The right-hand side represents the sum of the energy dissipation rates of all microscale processes operating per unit volume ($\dot{A}$), plus changes in the Helmholtz free energy stored in the solid part of the system, plus changes in surface energy caused by changes in grain boundary and pore wall area. Dividing now by $\dot{\gamma}$ (Bos and Spiers, 2000, 2002a), the measured shear stress or shear strength can be written:

$$\tau = \tau_x - d\varepsilon/d\gamma\sigma_n \quad (2)$$

where $\frac{d\varepsilon}{d\gamma}$ represents an instantaneous dilatation angle $\tan \Psi = \frac{d\varepsilon}{d\gamma}$ analogous to that familiar in soil mechanics (e.g. Paterson, 1995), and where

$$\tau_x = \frac{d\dot{f}}{d\dot{\gamma}} + \frac{d\dot{A}}{d\dot{\gamma}} + \frac{d\dot{A}_{gb}}{d\dot{\gamma}}\gamma_{gb} + \frac{d\dot{A}_{sl}}{d\dot{\gamma}}\gamma_{sl} \quad (3)$$

The quantity τ_x can be interpreted as representing the contribution to measured shear stress of all energy dissipation and storage processes operating in the gouge. Ignoring minor changes in Helmholtz free energy, it is evident from (5.2) and (5.3) that strengthening of a homogeneously deforming granular fault gouge may occur for three basic reasons. First, gouge compaction may increase the packing density so that upon reshearing the gouge needs to dilate, requiring work against the normal stress ($\frac{d\varepsilon}{d\gamma}\sigma_n$). Second, the gouge may strengthen through an increase in contact bonding between particles in the gouge. The increased bonding may increase the grain boundary friction coefficient and/or the grain boundary cohesion. This then increases the average contact sliding strength in the gouge and thereby the total frictional dissipation ($\frac{d\dot{A}}{d\dot{\gamma}}$) due to intergranular slip on re-shearing. Third, the gouge may strengthen by an increase in grain contact area (relative to pore wall area) which may be disrupted on re-shear. This increases strength only when the sliding contact has a cohesive strength. In general, fault gouge healing will be a combination of the three.

4.2. Steady state behaviour: velocity-strengthening versus velocity-weakening

Our results from the velocity-stepping experiments have shown two clear regimes of steady state behaviour for the

halite–muscovite mixtures: velocity-strengthening at velocities below 1 $\mu\text{m/s}$ and velocity-weakening at velocities above 1 $\mu\text{m/s}$. We have shown here and in our previous work (Bos and Spiers, 2002b; Niemeijer and Spiers, 2005) that the velocity-strengthening regime is associated with intense phyllosilicate foliation development. In our previous paper, we presented strong evidence that this regime is characterized by a steady state flow mechanism involving frictional sliding on the foliation accommodated by pressure solution of the intervening halite grains. A microphysical model was presented that is capable of predicting the observed velocity-strengthening behaviour. The model is based on a steady state microstructure (Fig. 11), where the phyllosilicate foliation wraps around elongate halite grains. The shear stress supported by the gouge at a particular sliding velocity is then the sum of the shear stress for sliding on the foliation plus the shear stress taken up by driving pressure solution. The strengthening with increasing velocity is caused by an increasing influence of pressure solution on the total shear stress, i.e. increasing dissipation by pressure solution.

We argue here that the switch to velocity-weakening behaviour occurs when the rate of pressure solution is too slow to accommodate the imposed shear displacement and the gouge has to dilate to accommodate slip, causing the

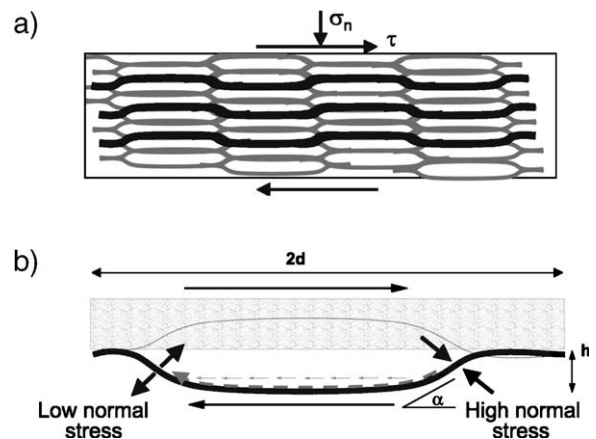


Fig. 11. (a) Schematic diagram of the model microstructure proposed by Bos and Spiers (2002b), showing a contiguous, anastomosing network of phyllosilicates surrounding elongate grains of a soluble solid. The shear strength of the gouge is determined by the combined resistance to shear offered by the serial transport processes of frictional sliding on the phyllosilicate foliae, pressure solution in the halite and dilatation on the foliation (work done against the normal stress). (b) Schematic drawing of representative grain element of matrix, showing an active sliding surface in black. Shear sense is right-lateral. The diffusive mass flux from source to sink regions is indicated by a dashed arrow. The foliation waves have amplitude h , the grains have long axis d . The leading edge of the grain is inclined at an angle α to the horizontal (Figure from Bos and Spiers, 2002b).

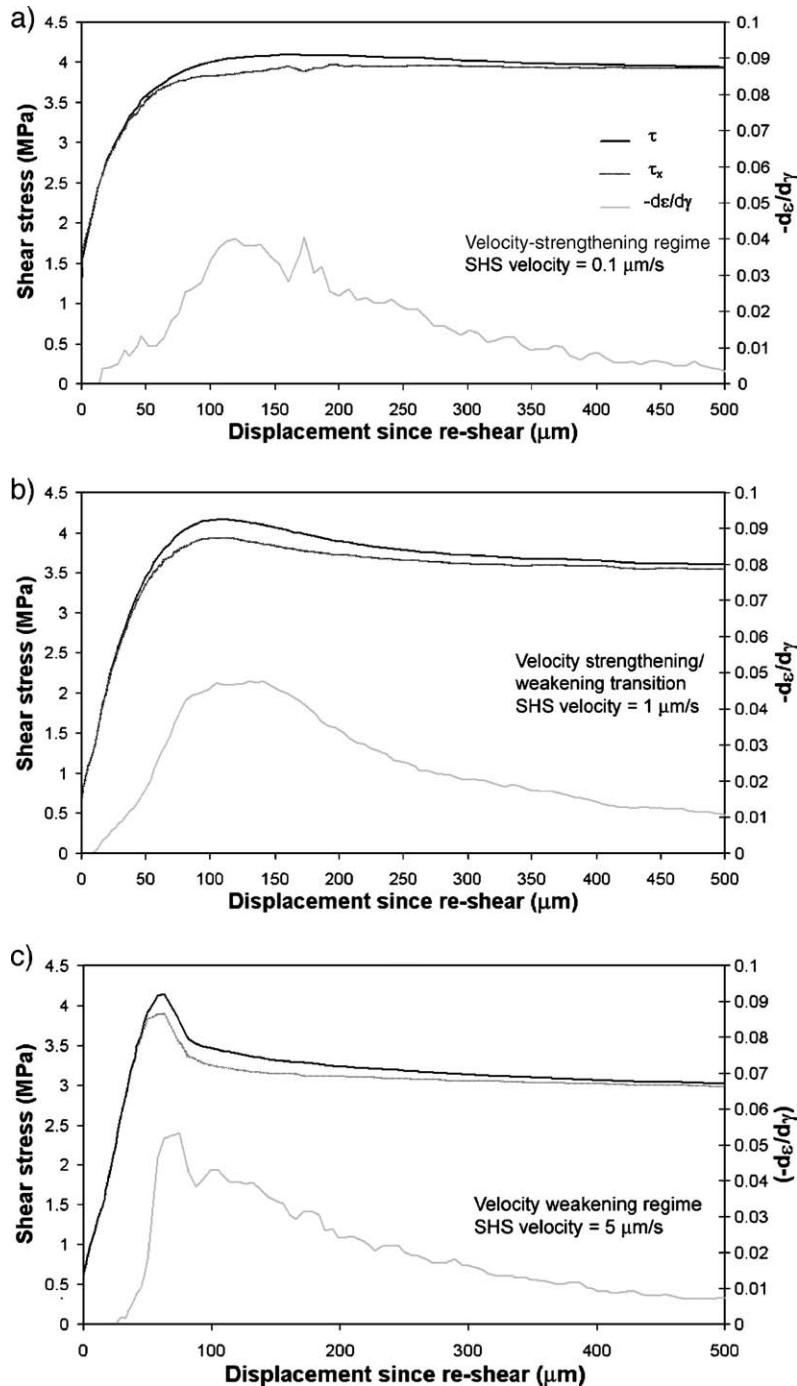


Fig. 12. Plots showing the evolution of shear stress, τ , and dilatation rate $-d\epsilon/d\gamma$ versus displacement since re-shear after a hold period of 6000 s for samples containing 20 wt.% muscovite, 80 wt.% halite plus brine (shs4 and shs5). (a) SHS reference velocity of 0.1 $\mu\text{m/s}$. (b) SHS reference velocity of 1 $\mu\text{m/s}$. (c) SHS reference velocity of 5 $\mu\text{m/s}$. (d) SHS reference velocity of 10 $\mu\text{m/s}$.

onset of cataclasis. This argument is based on the observation that the velocity-weakening regime is associated with a chaotic cataclastic microstructure (see Fig. 7b,c and 8b,c). However, purely cataclastic deformation is

not expected to show a strong rate-dependence, whereas we have found a marked, inverse dependence of steady state shear strength on velocity (Fig. 3b). This velocity weakening effect could potentially be explained by severe

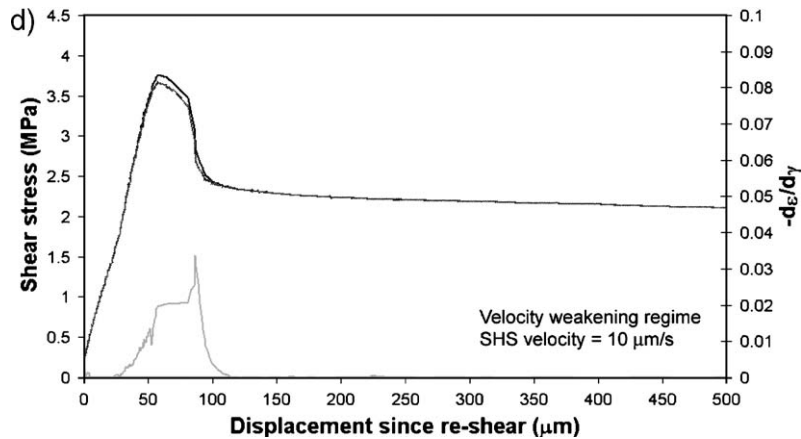


Fig. 12 (continued).

grain size reduction in the halite with increasing velocity, thus enhancing pressure solution rates in the halite and reducing the stress required for pressure solution to accommodate slip on phyllosilicates. However, since the velocity weakening behaviour that we observe is reversible with velocity-stepping direction (see Fig. 4a), we believe that an effect of grain size reduction thereby enhancing pressure solution rates, can be ruled out. Another possibility is that the proportion of healed, cohesive contacts decreases with increasing sliding velocity, due to a shorter average contact lifetime (*cf.* Dieterich-type healing). However, if this is the explanation of the velocity-weakening, the same would occur in the pure halite sample, but we did not observe a strong velocity-weakening in this sample. Moreover, the lack of healing observed in halite–kaolinite samples (Bos and Spiers, 2000) and in our low velocity samples, implies that phyllosilicate–halite contacts do not heal readily. Therefore, we believe that a Dieterich-type healing mechanism cannot explain the observed strong velocity-weakening.

On the basis of the chaotic, intermixed, cataclastic microstructures, we propose instead the hypothesis that the velocity-weakening regime is due to competition between a) shear-induced dilatation caused by granular flow of the gouge and b) compaction of the gouge through pressure solution of the halite. Such a mechanism should lead to an increase in porosity with increasing shear rate, at steady state, as granular dilatation becomes more effective compared to compaction by pressure solution. This will produce a decrease in mean grain contact area and intergranular slip-surface inclination/amplitude (dilatancy angle for granular flow). A decrease of the average inclination of actively sliding grain contacts (*i.e.* the dilatancy angle for granular flow) will lower the normal force on the contacts, thereby reducing the friction on the

contacts. Focusing first on the steady state behaviour, the proposed mechanism should thus lead to:

1. Increasing steady state porosity with increasing steady state velocity
2. Zero compaction rate at mechanical steady state
3. A decrease in granular dilatancy angle with increasing steady state sliding velocity.

The first of these is confirmed by the porosity measurements made on samples deformed at constant sliding velocity, *i.e.* at 0.03, 0.1, 1, 5 and 13 $\mu\text{m/s}$ and 5 MPa normal stress (see Fig. 2). The final porosity of these samples increases from near-zero at the lowest sliding velocity to $\sim 13\%$ at the maximum sliding velocity. Zero compaction rate was almost never measured, however. This could be due to the fact that we did not achieve true steady state in our experiments, or more likely because of minor but ongoing material loss from the simulated fault zone. Direct determination of the granular dilatancy angle from our compaction data is not possible because our volumetric data are a combined signal of compaction by pressure solution and dilatation by granular flow. We therefore evaluate our hypothesis further by qualitatively testing its implications versus our observations in slide–hold–slide tests.

4.3. Slide–hold–slide and healing behaviour — velocity-strengthening regime

Our SHS results for the velocity-strengthening regime ($< 1 \mu\text{m/s}$), characterized by foliation development, show an increase in compaction rate and gradual shear stress relaxation during the hold periods plus a gradual increase in shear strength upon re-shear accompanied by significant

dilatation (Figs. 4a, b and 5a). The re-shearing behaviour has been analysed by calculating the dilatation rate $\frac{d\epsilon}{d\gamma}$ and τ_x for an SHS reference velocity of 0.1 $\mu\text{m/s}$ and a hold period of 6000 s (Fig. 12a). This shows that there is hardly any peak discernible for the shear stress (τ) or for τ_x , whereas the dilatation rate $\frac{d\epsilon}{d\gamma}$ shows a broad maximum. This implies that most of the strength recovery was due to dilatational work done against the normal stress. This behaviour resembles that for foliated clay-bearing synthetic fault gouges reported earlier by Bos and Spiers (2000). These authors explained the observed compaction and stress relaxation as caused by the operation of pressure solution. The absence of a peak strength upon re-shear was explained by a low proportion of healing-prone halite–halite grain contacts due to the presence of a pervasive phyllosilicate foliation. The absence or low amount of healing of these gouges was thus attributed to the absence of contact strengthening and/or increase during the hold periods. Since the behaviour seen in our SHS tests in the velocity-strengthening regime is identical, the same explanation would seem to apply.

4.4. Slide–hold–slide and healing behaviour — velocity-weakening regime

Our SHS results for the velocity-weakening regime ($\geq 1 \mu\text{m/s}$, samples shs1, shs4 and shs5) show increasing syn-hold compaction with increasing SHS reference velocity (Fig. 5c), as well as rapid shear stress relaxation during hold periods (Fig. 5a) and a strong increase in shear strength on re-shearing (Fig. 12b–d). This results in a peak strength which gradually decays to a steady state value, the peak being accompanied by only minor dilatation. If we assume that the steady state velocity-weakening behaviour is

indeed due to the mechanism of compaction versus dilatation inferred in Section 4.2, then in the SHS experiments, the faster syn-hold compaction observed for higher SHS reference velocities (Fig. 5c) can be explained by a higher porosity being maintained during faster steady state sliding. This would result in a higher pressure solution compaction rate than at low sliding velocity, due to the smaller grain contact area and the higher grain contact stress (e.g. Niemeijer et al., 2002; Spiers et al., 2004).

Support for our hypothesis that gouge behaviour is controlled by competition between pressure solution compaction and dilatation due to granular flow can be obtained by a comparison of pre-hold and syn-hold compaction behaviour. Our qualitative model implies that 1) the compaction rate at the start of and during individual hold periods should increase systematically with increasing gouge porosity and SHS reference velocity and 2) the granular dilatation rate (i.e. the granular dilatancy angle) just prior to the hold period should increase with pre-hold steady state porosity and hence SHS reference velocity. The granular dilatation rate just prior to the hold can be obtained by subtracting the volumetric strain rate just after the start of the hold from the volumetric strain rate just before the start of the hold. The results are shown in Fig. 12 and indeed show an increasing compaction rate and dilatation rate with increasing SHS sliding velocity.

We now analyse the effects of reshearing on strength seen in the velocity-weakening regime. To do this we again use the measures of strength τ and τ_x introduced in Section 4.1. In Fig. 12b–d, we show representative data on the evolution of τ , τ_x and the measured dilatation rate ($-\frac{d\epsilon}{d\gamma}$) with displacement for three different sliding velocities after a hold period of 6000 s. The curves for τ_x

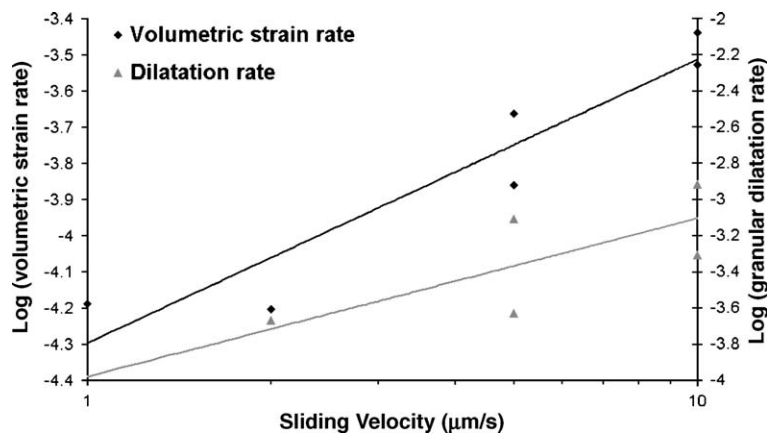


Fig. 13. Plot of volumetric strain rate at the start of hold periods of 6000 s and granular dilatation rates just prior to hold periods of 6000 s as a function of SHS reference velocity. Data are derived from experiments shs4 and shs5.

correspond to the measured shear stress τ almost perfectly at all SHS velocities. This means that dilatational work ($\sigma_n \cdot \dot{\epsilon}$) contributes negligibly to strength evolution and that strength is determined by dissipative processes or changes in stored energy within the system. Note that the

peak in dilatation rate consistently postdates the peaks in τ and τ_x by $\sim 20 \mu\text{m}$ in displacement, which again implies that dilatation contributes almost negligibly to strength evolution (Fig. 13). Instead, virtually all strengthening is caused by an increase in τ_x .

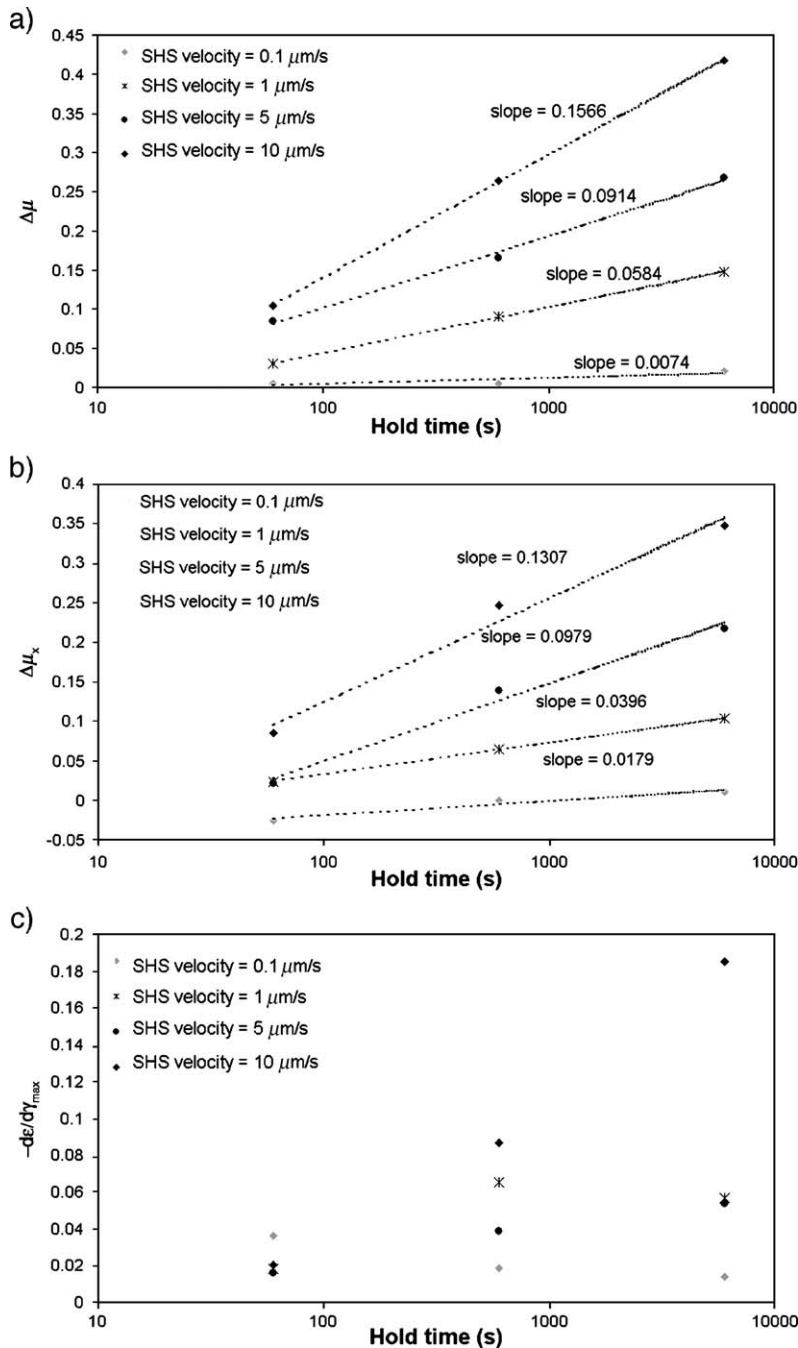


Fig. 14. Plots showing extent of healing for different hold times and SHS reference velocities. (a) Plot of $\Delta\mu$ versus hold time for different SHS reference velocities. (b) Plot of $\Delta\mu_x$ (see Eq. (2)) versus hold time for different SHS reference velocities. (c) Plot of maximum dilatation versus hold time for different SHS reference velocities. (d) Plot of the three healing parameters as a function of SHS reference velocity for a hold period of 6000 s.

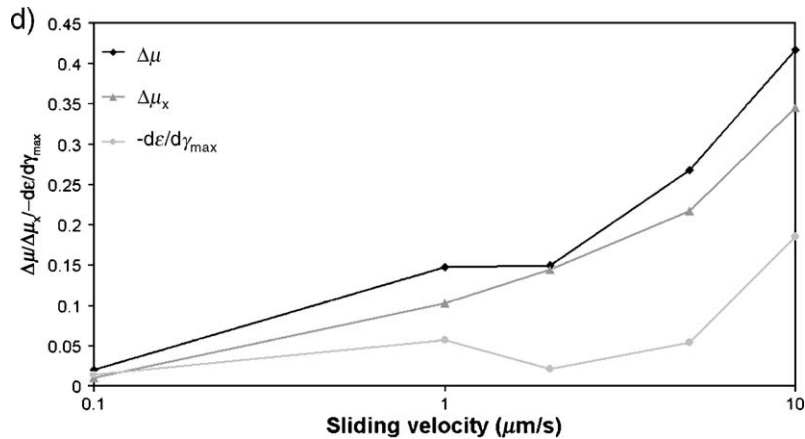


Fig. 14 (continued).

As explained earlier, this implies that strengthening was either due to an increase in average contact strength, thereby increasing the amount of frictional dissipation through intergranular slip, or due to an increase in average grain contact area relative to pore wall area. We cannot distinguish between the two on the basis of our mechanical results, although the increase of the amount of compaction during hold periods with increasing SHS velocity might indicate a larger increase in contact area with increasing SHS velocity. The observed increase in strengthening with increasing SHS velocity might be explained by an increase in contact area during hold periods.

In analysing SHS tests, it is customary to define the degree of restrengthening or healing ($\Delta\mu$) as the difference between the peak shear stress and steady state shear stress prior to each hold period, normalized with respect to the applied normal stress. Fig. 14a shows how this depends on hold time for our complete set of SHS experiments (with the exception of SHS reference velocities of 0.01 and 0.03 $\mu\text{m/s}$, which were similar to the results for 0.1 $\mu\text{m/s}$ and of test shs3). The linearised healing rate ($\Delta\mu$ per order of magnitude of healing time, i.e. the slope in Fig. 14a) is also indicated. The healing rate is observed to increase steadily with increasing pre-hold sliding velocity, with the healing rate at 10 $\mu\text{m/s}$ being almost 1.5 orders of magnitude higher than at 0.1 $\mu\text{m/s}$. In Fig. 14b we show the dependence of $\Delta\mu_x$ (the difference between the peak and steady state values of τ_x , normalized by the normal stress) as a function of hold time. Again, an increase in healing rate is observed with increasing sliding velocity. In Fig. 14c we show the maximum measured dilatation rate ($-d\varepsilon/d\gamma$) as a function of hold time. No clear dependence of maximum dilatation rate on hold time or sliding velocity is visible, although dilatation rate tends to be higher after longer

hold times. Fig. 14d shows the dependence of $\Delta\mu$, $\Delta\mu_x$ and $-(d\varepsilon/d\gamma)_{\max}$ on SHS sliding velocity for a fixed hold period of 6000 s. This illustrates that with increasing SHS sliding velocity, healing rates increase as a result of faster compaction due to higher steady state porosity being sustained at high SHS sliding velocity.

In summary, Fig. 12 and 14 show that at low sliding velocities, post-hold strengthening is minor and mostly due to dilatation. We infer that changes in τ_x , i.e. in contact friction and/or strength, are unimportant and do not influence strengthening in the low velocity regime. This is because there are few halite–halite contacts to be disrupted, as concluded by Bos and Spiers (2000) for NaCl plus kaolinite. At high sliding velocities, however, restrengthening is almost entirely ($\sim 90\%$) due to an increase in τ_x (or $\Delta\mu_x$, see Fig. 12b–d and Fig. 14b). This is due to a decrease in porosity which causes an increase in the dilatancy angle for granular flow, hence an increased contact friction. Increased cohesive strength at halite/halite contacts may also play a role in this regime.

We will now discuss sample shs3. In this case, there was no initial wet sliding stage at low sliding velocity and stick–slip cycles occurred after a short amount of slip. The absence of initial slow sliding is likely to have resulted in a loose gouge where localization could easily be achieved, as evidenced by the occurrence of stick–slip. This is similar to the deformation behaviour observed during part of the dry run-in stage (Niemeijer and Spiers, 2005).

4.5. Effects of muscovite versus kaolinite

It is evident from the above that our results for the halite–muscovite mixtures in the velocity strengthening

regime are similar to the results reported by Bos and Spiers (2000, 2001, 2002a) and Bos et al. (2000) for halite plus kaolinite. However, there are some important differences. The main difference between the present experiments and the previous work of Bos and coworkers lies in the effect of using of muscovite instead of kaolinite as the phyllosilicate phase. Surprisingly, the different phyllosilicate phase and grain size has led to a different mechanical behaviour in the high velocity regime. Firstly, our muscovite-bearing mixtures have clearly shown velocity-weakening behaviour at high velocities, whereas Bos et al. (2000a,b, 2001) reported only a slight velocity-effect at sliding velocities above 1 $\mu\text{m/s}$ for salt–kaolinite mixtures. The microstructures of the salt–kaolinite mixtures deformed at high sliding velocities are similar to those deformed at low sliding velocity and show only minor porosity (Bos and Spiers, 2001). Secondly, our samples heal significantly faster than kaolinite-bearing samples, in the velocity-weakening regime, even when there is no foliation present in the kaolinite–salt mixtures (Bos and Spiers, 2002a). The explanation of these marked differences in mechanical behaviour may lie in the fact that Bos used a sub micron grain size for his kaolinite phase and we used muscovite grains with a median grain size of 13 μm . In the kaolinite-bearing samples dilatation is less effective, since the sub micron kaolinite grains are easily bent and smeared out, whereas in the muscovite-bearing samples the large muscovite flakes form true barriers for granular flow, so that dilatation is much more effective. Therefore, a larger amount of porosity is created and sustained in the muscovite-bearing samples during steady state shearing. The presence of more porosity results in higher restrengthening for these samples.

4.6. Implications

Many natural fault zones exhumed from brittle–ductile transitional depths contain significant amounts of phyllosilicates. Moreover, pressure solution and cataclasis are known to be important deformation mechanisms in fluid-rich rocks at such depths (e.g. Rutter and Mainprice, 1979; Passchier and Trouw, 1996; Holdsworth et al., 2001; Imber et al., 2001). The present results accordingly imply a possible influence of phyllosilicate content, foliation development, cataclasis and pressure solution on mid-crustal fault mechanics, including both steady state and transient aspects. We therefore speculate upon the following possible implications of our present work,

although we are aware that a microphysical model, and/or experiments under hydrothermal conditions on real fault rock materials such as quartz plus muscovite, are needed to validate extrapolation of our results to nature.

A first and obvious implication is that the occurrence of brittle deformation textures (i.e. cataclases) together with ductile deformation textures (i.e. mylonites) does not necessarily imply a change in deformation temperature or effective pressure conditions. Equally, our results indicate that an increase in shear strain rate, through an increase in fault displacement rate or a decrease in fault zone width, can create chaotic, cataclastic gouges by causing a transition from velocity-strengthening (stable) fault creep to a granular flow process accompanied by pressure solution compaction. Because this process is velocity-weakening, self-enhancing behaviour is initiated leading to an instability and possibly a seismic event. Similarly, oscillating fault motion rate can easily produce multiple cataclastic overprinting of mylonitic rocks.

Secondly, it is worth noting that the healing rates we measured at the highest sliding velocity are about one order of magnitude higher than healing rates of quartz–feldspar gouges determined at room temperature and/or dry (e.g. Dieterich, 1972; Beeler et al., 1994; Marone, 1998a). A direct comparison of our healing data with estimates of fault-healing rates based on earthquake stress drop observations would not be appropriate. However, since the same mechanisms operate under upper to mid-crustal conditions, healing of natural fault zones can be expected to be dominated by solution-transfer processes and the transition from velocity-strengthening to velocity-weakening would also occur when pressure solution is too slow to accommodate the imposed displacement.

Finally, the present data on the rates of restrengthening of our simulated fault gouges in the velocity-strengthening and velocity-weakening regimes imply a strong effect of the velocity history of a fault gouge on its healing rate and seismicity. A mature phyllosilicate-bearing fault rock can be expected to slip aseismically at low rates with low friction and a low healing propensity forming a mylonitic fault rock. At high strain rates, however, the same fault rock might slip seismically with high friction and a high healing propensity, forming a chaotic, cataclastic fault rock. In such a scenario, the geometry and heterogeneity of the fault zone, together with pore fluid pressure and/or composition, will initially determine which parts of the fault zone can slip aseismically and which parts might

slip seismically. With ongoing displacement, stably sliding portions will tend to remain weak and stable, while unstable portions will rapidly heal and thus remain strong and unstable.

5. Conclusions

In this study, we have investigated the large strain sliding and healing behaviour of simulated fault gouge using a muscovite–halite system under room temperature conditions, normal stresses of 1–9 MPa, atmospheric fluid pressure and sliding velocities of 0.001–13 $\mu\text{m/s}$. Under these conditions pressure solution, cataclasis and phyllosilicate foliation development and/or destruction are active, as anticipated for nature under the brittle–ductile transitional conditions. We investigated the steady state sliding behaviour and performed a series of slide–hold–slide tests to investigate the transient behaviour of the gouges in both the velocity-weakening and velocity-strengthening regimes reported previously. Our aim was to explain the observed velocity-weakening and healing behaviour in terms of a microphysical mechanism. We also aimed to speculate on the possible implications of our work for phyllosilicate-bearing natural fault zones under hydrothermal conditions.

The following conclusions were reached:

1. Synthetic fault gouges composed of muscovite plus halite are characterized by a strong velocity-dependence of shear strength, showing velocity-strengthening behaviour at low velocities ($<1 \mu\text{m/s}$) and velocity-weakening at high velocities ($\geq 1 \mu\text{m/s}$).
2. In the low velocity regime, halite–muscovite gouges develop a mylonitic microstructure and deform by slip on the muscovite foliation with accommodation by pressure solution of the intervening halite grains. These gouges show little or no healing in slide–hold–slide tests, probably due to the low porosity (low compaction potential) of these samples and the absence of halite–halite contacts that can heal by solution transfer processes.
3. In the high velocity regime, halite–muscovite gouges develop a chaotic, intermixed, cataclastic microstructure due to deformation by granular flow involving pervasive intergranular sliding plus competition between intergranular dilatation and pressure solution controlled compaction. A higher porosity develops towards higher sliding velocities due to an increase in the relative importance of dilatation compared to compaction. The increase in porosity at high sliding velocity causes reduced intergranular friction due to a

lower inclination of sliding grain contacts (i.e. dilatancy angle for granular flow) which leads to the observed velocity-weakening.

4. Gouges deformed in the high velocity regime exhibit strong, velocity-dependent healing in slide–hold–slide tests, as a result of compaction during the hold period. This increases the inclination of sliding contacts (i.e. dilatancy angle) and increases intergranular friction. Increases in cohesive strength of halite–halite contacts through cementation might also play a role in the restrengthening.
5. The overprinting of mylonitic rocks by cataclasites does not necessarily require a history of uplift, since such overprinting relations can be formed by changing the strain rate in the fault zone. Multiple overprinting of cataclasites and mylonites more likely implies a history of highly variable fault displacement rates than a complex uplift history.
6. The large difference between healing rates in the low velocity and high velocity regimes observed in the present experiments implies that mature phyllosilicate-bearing fault zones might slip aseismically where a mylonitic foliation with a low healing and low restrengthening potential is developed. In contrast, other parts of the fault zone, where a cataclastic microstructure is developed with a high healing and high restrengthening potential, will tend to slip seismically.

Acknowledgements

We thank Eimert de Graaff, Gert Kastelein and Peter van Krieken for help in the laboratory and technical support. We also thank the reviewers, C. Marone and T. Tullis, for their constructive reviews which helped improve this paper.

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