



Experimental investigation of the brittle-viscous transition in mafic rocks – Interplay between fracturing, reaction, and viscous deformation



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ARTICLE INFO

Keywords:

Rock deformation experiments
Brittle-viscous transition
Dissolution-precipitation
Grain boundary sliding
Polyphase rheology

ABSTRACT

Rock deformation experiments are performed on fault gouge fabricated from 'Maryland Diabase' rock powder to investigate the transition from dominant brittle to dominant viscous behaviour. At the imposed strain rates of $\dot{\gamma} = 3 \cdot 10^{-5} - 3 \cdot 10^{-6} \text{ s}^{-1}$, the transition is observed in the temperature range of ($600 \text{ }^\circ\text{C} < T < 800 \text{ }^\circ\text{C}$) at confining pressures of ($0.5 \text{ GPa} \leq P_c \leq 1.5 \text{ GPa}$). The transition thereby takes place by a switch from brittle fracturing and cataclastic flow to viscous dissolution-precipitation creep and grain boundary sliding. Mineral reactions and resulting grain size refinement by nucleation are observed to be critical processes for the switch to viscous deformation, i.e., grain size sensitive creep. In the transitional regime, the mechanical response of the sample is a mixed-mode between brittle and viscous rheology and microstructures associated with both brittle and viscous deformation are observed. As grain size reduction by reaction and nucleation is a time dependent process, the brittle-viscous transition is not only a function of T but to a large extent also of microstructural evolution.

1. Introduction

Relatively little is known about the rheology of fault rocks undergoing the brittle-viscous transition (BVT). However, fault zones are assumed to sustain the highest differential stress values near the BVT, and thus it constitutes a key regime controlling the dynamics of lithospheric fault systems. Here, the term 'viscous' refers to temperature and rate sensitive deformation mechanisms such as dislocation and diffusion creep (including pressure solution creep). The onset of viscous deformation within the Earth's crust (or, alternatively, a decreasing α -factor for the effective pore pressure law, according to Hirth and Beeler, 2015) is generally associated with the disappearance of earthquake rupture (e.g. Sibson, 1982, 1984). At the BVT, both, time-dependent viscous mechanisms and relatively time-independent brittle mechanisms significantly contribute to the deformation and thus several processes are competing: fracturing, frictional sliding, crystal plasticity, and diffusive mass transfer. Given the number of parameters controlling the deformation, the BVT is a complex system where temperature, pressure, fluid availability, grain size, strain rate, microstructure, rock composition (i.e. mineral assemblage), and chemical environment control the rheology. As a consequence, it is not surprising that there is

a lack of laboratory data characterising the BVT in detail, despite pioneering seminal works by, e.g., Griggs et al. (1960); Heard (1960); Byerlee (1968); Tullis and Yund (1977); Kirby and Kronenberg (1984); and review by Paterson and Wong (2005) and references therein.

In the absence of flow laws for most crustal minerals, the viscous strength of the continental crust was first estimated using a dislocation creep flow law for quartz (Brace and Kohlstedt, 1980). However, large proportions of the lower continental crust, and most of the oceanic crust are of mafic composition. Strength estimates for these crustal parts could only be assessed once flow law parameters for plagioclase and pyroxene became available (e.g. Mackwell, 1991; Raterron and Jaoul, 1991; Bystricky and Mackwell, 2001; Rybacki and Dresen, 2000; Rybacki et al., 2006; Chen et al., 2006; Dimanov et al., 2003, 2007; Dimanov and Dresen, 2005). Most of the data, however, is applicable to high temperature deformation, and experimental studies for mafic rocks at lower temperatures are scarce (e.g. Kronenberg and Shelton, 1980; Shelton et al., 1981; Rutter et al., 1985; Hacker and Christire, 1991; Tullis and Yund, 1987; Getsinger and Hirth, 2014).

One important aspect of the BVT is the development of the rheology of sheared rock over time or during a strain history. Strain-dependent microstructural evolution of fault- and shear zones may cause a strain-

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<https://doi.org/10.1016/j.jsg.2017.10.011>

Received 18 July 2017; Received in revised form 29 October 2017; Accepted 30 October 2017
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Table 1

Composition of Maryland Diabase starting material. EDS measurements as oxide wt.-% and calculated to stoichiometric mineral formula.

wt.-%	Plagioclase		Pyroxene	
	core	rims	Cpx	Opx
SiO ₂	51.86	55.67	51.58	52.61
Al ₂ O ₃	29.92	27.72	1.77	0.75
CaO	13.39	10.57	14.71	1.44
Na ₂ O	3.63	5.11	0.28	0.00
K ₂ O	0.26	0.37	0.00	0.00
MgO	0.00	0.00	14.03	19.36
TiO ₂	0.00	0.00	0.76	0.28
FeO	0.94	0.55	16.40	25.55
MnO	0.00	0.00	0.48	0.00
Cr ₂ O ₃	0.00	0.00	0.00	0.00
Total:	100.0	100.0	100.0	100.0

	Atoms per 8 oxygen		Atoms per 6 oxygen	
Si	2.36	2.51	1.95	1.99
Al	1.61	1.47	0.08	0.03
Ca	0.65	0.51	0.60	0.06
Na	0.32	0.45	0.02	0.00
K	0.02	0.02	0.00	0.00
Mg	0.00	0.00	0.79	1.09
Ti	0.00	0.00	0.02	0.01
Fe	0.04	0.02	0.52	0.81
Mn	0.00	0.00	0.02	0.00
Cr	0.00	0.00	0.00	0.00
Total	5.00	4.97	4.00	3.99

	An	Ab	Or	En	Fe	Wo
	0.66	0.32	0.02	0.42	0.27	0.31
	0.52	0.46	0.02	0.42	0.27	0.31
	0.52	0.46	0.02	0.42	0.27	0.31

dependent strength evolution. One of the resulting consequences is that stresses different from final steady state strengths are required to initiate fault- and shear zones. It is frequently seen from natural examples that brittle and viscous deformation can occur cyclically (e.g. Gratier et al., 2011; Price et al., 2012) or sequentially in time (e.g. Simpson, 1986; Fitz Gerald and Stünitz, 1993; Trepmann and Stöckert, 2003; Mancktelow and Pennacchioni, 2005; Fousseis and Handy, 2008; Goncalves et al., 2016; Bukovská et al., 2016).

Significant amounts of the global seismic moment occur along faults within the oceanic crust and along subduction zones. A better understanding of the behaviour of mafic rocks at the BVT is therefore key to our understanding of earthquake distribution and seismic hazard in these regions.

2. Methods

2.1. Experimental procedure

2.1.1. Sample material

Experiments are performed on Maryland Diabase (Table 1; Kronenberg and Shelton, 1980) with a modal composition (by volume) of ~ Plagioclase (Pl): 57%, Clinopyroxene (Cpx): 32%, Orthopyroxene (Opx): 8%, accessories (Qz, Kfs, Ilm, Mag, Bt, Ap): 3% (mineral abbreviations after Whitney and Evans, 2010). Pieces of Maryland diabase were crushed with a hand-press and subsequently crushed with an alumina hand-mortar. The resulting powder was dry-sieved to extract a grain size fraction of $\leq 125 \mu\text{m}$.

2.1.2. Experimental setup and sample assembly

Experiments are performed using two modified Griggs-type

Table 2

List of experiments and experimental conditions.

Exp. Nr	T [°C]	Pc [MPa]	peak τ [MPa]	flow τ [MPa]	γ_a	strain rate [s^{-1}]
375	300	549	1022	951	2.6	3.3E-05 ^a
418	300	551	978	872	3.4	3.4E-05 ^a
442	300	530	963	876	3.9	3.4E-05 ^b
444	300	558	937	899	2.9	3.3E-04 ^b
446	500	1007	875	777	2.9	2.9E-05 ^b
				746		2.3E-05 ^b
				853		2.7E-04 ^b
				771	3.2	3.5E-05 ^b
367	600	587	620	451	2.0	3.2E-05 ^a
373	600	538	614	429	2.8	3.1E-05 ^a
399	600	1027	930	743	3.0	3.2E-05 ^a
501	600	1041	903	659	3.1	3.7E-05 ^a
393	700	572	606	288	2.4	3.1E-05 ^a
413	700	604	541	–	3.6	3.3E-05 ^a
365	700	1097	759	658	2.6	2.8E-05 ^a
416	700	1038	722	624	3.1	3.0E-05 ^b
531	700	1093	798	732		2.4E-05 ^b
				636		8.3E-06 ^b
				460		2.7E-06 ^b
				609	4.5	9.2E-06 ^b
473	700	1556	872	872	2.9	3.1E-05 ^a
436	700	1515	846	846	1.9	2.8E-05 ^a
414	800	1045	407	192	4.2	3.7E-05 ^b
468*	800	1061	348	348	0.7	–
484	800	1041	371	316		2.8E-05 ^b
				234	2.0	1.3E-05 ^b
489	800	1080	428	286	2.8	3.0E-05 ^a
490	800	1059	350	297		3.5E-05 ^b
				245		1.9E-05 ^b
				130	4.5	4.1E-06 ^b
492	800	1077	468	197	6.8	4.8E-05 ^a
449	800	1504	479	337	4.1	3.5E-05 ^a
470*	800	1477	446	–	0.9	–

* peak stress experiments. Pc is determined as mean between start to end.

^a Strain rate determined as mean between gammas 1.5 to end.

^b Strain rate determined as mean between variable gammas.

deformation apparatus at the University of Tromsø, Norway, at confining pressures (Pc) of ~0.5, 1.0 and 1.5 GPa, temperatures (T) of 300, 500, 600, 700 and 800 °C and with constant displacement rates of $\sim 10^{-8}$ to 10^{-9} m s^{-1} (resulting in bulk strain rates of $\sim 3 \cdot 10^{-5}$ to $3 \cdot 10^{-6} \text{ s}^{-1}$). See Table 2 for a list of experiments and conditions.

Salt is used as confining medium. Inner salt pieces are fabricated from potassium iodide (KI) for experiments at $T \leq 600 \text{ °C}$ and sodium chloride (NaCl) for experiments at $T \geq 700 \text{ °C}$. KI is mechanically weaker than NaCl but shows partial melting at $T > 600 \text{ °C}$ at the experimental pressures. Outer salt pieces are always fabricated from NaCl. The sample consists of a thin shear zone, produced by placing 0.11 g of Maryland Diabase powder + 0.2 μl H₂O (equals 0.18 wt%) between the Al₂O₃ forcing blocks along a 45° pre-cut (Fig. 1). Forcing blocks are cylindrical with a diameter of 6.33 mm. The sample and forcing blocks are placed in a weld-sealed platinum jacket (0.15 mm wall thickness) with a 0.025 mm nickel foil insert. The amount of added water was chosen such that sufficient water is present for solution mass transport processes and mineral reactions, while not inducing mechanical pore pressure effects. Pore pressure effects were inferred to be absent for contents up to 0.5 wt % H₂O by Kronenberg and Tullis (1984) and up to 0.3 wt % H₂O by Negrini et al. (2014).

During the experiments, ~84% of the inelastic axial displacement by the σ_1 -piston is accommodated by shear strain parallel to the piston-sample interface and ~16% by plane strain thinning of the shear zone. The initial shear zone thickness is measured from a pressurized but undeformed experiment and is assumed to be the same for all other experiments. The final thickness of each experiment is measured in the thin sections after the experiment (Table 2; Appendix).

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