Chapter 8

GENERAL CONCLUSIONS AND SUGGESTIONS FOR FUTURE RESEARCH

8.1. Conclusions

In this thesis, the results of an experimental study, aimed at investigating the effects of intergranular pressure solution (IPS) and phyllosilicates on slip and compaction behaviour of gouge-bearing faults, have been reported. The general aims of the work were a) to characterize IPS compaction in quartz and quartz-muscovite aggregates, b) to investigate the sliding and healing behaviour of simulated fault rock analogue materials, c) to test and improve microphysical models of frictional-viscous flow and d) to experimentally investigate the high strain shearing behaviour of simulated fault gouges of quartz under hydrothermal conditions. In relation to these aims, I reach the following main conclusions.

1. Experimental characterization of intergranular pressure solution (IPS) in quartz.

Isostatic compaction experiments on quartz sands under hydrothermal conditions up to 600 ºC, a confining pressure of 300 MPa and fluid pressures of 150-250 MPa have indicated that IPS is controlled by quartz dissolution at grain contacts under these conditions. Existing microphysical models for this process show reasonable agreement with the experimental results, at least down to porosities of ~15%. At lower porosities, rates slow dramatically as a result of either a switch in rate-controlling mechanism, internal healing of the grain boundary structure or due to contamination of the pore fluid by dissolution of the copper capsules used in our experiments. Our findings imply that IPS compaction under natural conditions is most likely to be controlled by dissolution within grain contacts and that pore fluid chemistry will thus have a strong effect on IPS compaction rates.

2. Effect of muscovite on IPS compaction rates in quartz

Similar isostatic compaction experiments performed on quartz-muscovite mixtures under hydrothermal conditions have demonstrated that the presence of muscovite in amounts of 5-20 wt% hinders IPS compaction rate by a factor of 3-10. This retardation is believed to be the result of either dissolution of the mica, releasing Al^{3+} into the pore fluid and thus hindering the dissolution of quartz, or possibly a reduction in precipitation area by the presence of muscovite in the pores.

3. Steady state mechanical behaviour of halite-muscovite fault gouge analogue

High strain, rotary shear experiments, on halite-muscovite mixtures flooded with saturated brine have demonstrated distinctly different sliding behaviour for different sliding velocities. A low sliding velocity regime has been identified, where a strong muscovite foliation develops. In this regime, frictional-viscous deformation occurs by frictional sliding in/on the muscovite foliation, with accommodation by pressure solution of the intervening halite grains, in a manner similar to that reported for halite-kaolinite gouges by Bos and coworkers (2000, 2001, 2002). The steady state strength of the gouge in this regime increases with increasing sliding velocity (velocity-strengthening). A high sliding velocity regime has also been identified, where deformation involves granular (cataclastic) flow, producing a relatively chaotic granular microstructure. The mechanical behaviour seen in this regime is determined by competition between shear-induced intergranular dilatation and pressure solution controlled compaction. The steady state strength of the gouges in this regime decreases with increasing sliding velocity (velocity-weakening). This is due to an increase in porosity and thus a decrease in dilatancy angle for granular flow, which in turn reduces grain boundary shear resistance. In contrast, pure halite and pure muscovite samples did not show a significant velocity dependence. The results imply that phyllosilicates may be capable of producing marked velocity weakening effects in natural quartz-rich fault rocks. In addition, they imply that, if in natural fault rocks a cataclastic microstructure is observed in the vicinity of a mylonitic microstructure, this does not necessarily mean a change in pressure and temperature conditions. A change in strain rate can just as easily produce the two different microstructures.

4.Healing behaviour of halite-muscovite fault gouge analogue

Aside from the above steady state tests, slide-hold-slide tests on simulated fault rocks, consisting of halite-muscovite mixtures, have demonstrated an important effect of sliding velocity on the observed healing (i.e. strength recovery) rate. In the low velocity regime, healing is virtually zero, due to the low porosity and presence of a pervasive muscovite foliation, which inhibits compaction and cementation of the halite grains. In the high velocity regime, healing is significant and healing rate increases with increasing sliding velocity. This is due to the higher steady state porosity sustained at higher sliding velocity. The higher porosity enhances IPS compaction rates during periods of zero slip (hold periods), thereby enhancing healing effects through compaction and contact cementation during hold periods. If similar microphysical processes operate in natural phyllosilicate bearing fault gouges, the observed increase in healing rate with increasing sliding velocity implies a strong effect of the velocity history of a fault gouge on its healing and restrengthening behaviour. This in turn implies that, an aseismically creeping fault segment will not restrengthen, while a seismically slipping segment will.

5. Microphysical modelling

The microphysical model put forward by Bos and Spiers for the type of mechanism inferred for the low velocity regime seen in our halite-muscovite experiments (i.e. describing frictional-viscous flow of foliated fault rock) has been reformulated and extended to include the possibility of crystal plastic flow in the phyllosilicates. The model predictions agree well with our experimental data for the halite-muscovite system under room temperature conditions where plasticity in the muscovite plays no role. Extrapolation of the model to quartz-phyllosilicate fault rock under mid-crustal depth conditions predicts a significant truncation of classical strength profiles (factor 2-5), as pressure solution enables low stress slip on/in the phyllosilicate foliation at depths greater than 3-5 km. In addition, a completely new microphysical model has been developed, describing the steady state competition between shear-induced dilatation and pressure solution controlled compaction in phyllosilicate-bearing fault gouge deforming in the velocity weakening regime seen in our experiments. The model predictions compare reasonably well with our experimental data for the halite-muscovite system. Extrapolation of the model to natural conditions for quartz-phyllosilicate fault rocks predicts a significant velocity weakening effect at depths of 5-10 km for strain rates larger than 10^{-6} s^{-1}, due to the presence of phyllosilicates and the operation of pressure solution. This effect is much larger than velocity weakening effects reported earlier in friction experiments on quartz/granite gouges and may have significant implications for seismogenesis. Also, the model predicts average static stress drops (maxima) for earthquakes, which are within the range inferred from seismological observations.

6. Sliding behaviour of simulated quartz gouges under hydrothermal conditions

Rotary shear experiments have been performed on simulated quartz gouges (initial grain size of 5 to 22 µm) under hydrothermal conditions at temperatures of 400-600 ºC, effective normal stresses of 20-100 MPa, a fluid pressure of 200 MPa and sliding velocities of 0.01-1 µm/s. Shear strains γ up to 25 or even 50 were reached, which is well beyond the maximum values of ~1-5 previously achieved. The results show a broad yield/peak stress at γ is 0.6-1.8, followed by steady slip weakening (up to 30%) towards near steady state values at shear strains γ of 10-15. Steady state friction coefficients obtained from stress-stepping at a velocity of 1 μm/s lie between 0.5 and 0.7. The friction coefficient is observed to increase with decreasing temperature and grain size. On the basis of microstructural observations and previous work by other authors, we infer that the observed slip weakening is most likely caused by localisation of deformation along a boundary parallel Y-shear. Bulk deformation is mostly cataclastic, probably with some pressure solution acting to weaken the Y-shear slip surface at higher temperatures and lower sliding velocities. Our experiments show that even in quartz gouge that show initial slip hardening behaviour at shear strains up to 1.5, significant strain softening occurs at higher strains. This implies that chemical effects can act together with cataclastic processes to significantly weaken fault gouges at higher strains. These should be taken into account in future experimental and modelling studies of fault behaviour.

8.2. Suggestions for future research

The experiments described in this thesis leave behind a number of unsolved questions and new problems. These are summarized below and suggestions are made on how these may be addressed in future.

1. As seen in the present work on quartz sands, microphysical models for IPS compaction depend on knowing the kinetics of the three serial processes of dissolution, diffusion and precipitation. Present results have shown dissolution reaction control for quartz under the specific experimental and chemical conditions used, but we also found evidence for retardation by other effects at porosities <15%. Better quantification of the kinetic processes controlling IPS in a granular aggregate under realistic natural conditions, and the evolution of such processes with ongoing compaction, is therefore still needed, with special attention for effects of pure fluid chemistry. Several approaches can be taken to tackle this problem. First, geochemical experiments at high temperatures (e.g. 300 ºC) and fluid pressures (e.g. up to 100 MPa) can be done to quantify the dissolution and precipitation rates of natural quartz, systematically checking the influence of common pore fluid impurity ions. Second, internal grain boundary structure, dissolution kinetics and diffusive properties might be investigated by performing electrical resistivity and dissolution rate measurements on bi-crystal contacts during IPS (cf. De Meer et al., 2002; Spiers et al., 2004). Third, high resolution compaction experiments on ultra fine granular quartz sands can be performed under conditions where the results can be directly applied to determine the kinetics of the rate-controlling process. By systematically varying the grain size, it should be possible to quantify the kinetics of the three serial processes as a function of

temperature, fluid pressure and confining pressure, following the approach adopted here in Chapter 2.

2. While present results show a retarding effect of phyllosilicates on IPS compaction rates in quartz, the effect is still not unambiguously explained and our results contradict expectations from earlier work. The main problem is that the effect of phyllosilicates in compaction experiments might be chemical or physical. In order to devise more diagnostic experiments, careful consideration must be given to separating these effects. Purely chemical effects of phyllosilicate dissolution could be identified in future isostatic compaction experiments on pure granular quartz sands by externally equilibrating the pore fluid with respect to the phyllosilicate phase, and by comparing the results with those of control experiments done using pure water as pore fluid. Varying the pore fluid chemistry by addition of IPS-enhancing cation such as Ca^{2+}, K^{+} and Na^{+} and IPS-retarding cations such Al^{3+} or Fe^{3+} would also be useful. When straightforward chemical effects of phyllosilicate dissolution have been clearly identified or eliminated, physical effects of the presence of phyllosilicates within the samples can be investigated. Again, bi-crystal quartz-quartz and quartz-phyllosilicate experiments might be useful here, following the methods suggested under point 1.

3. The present study has shown that experiments on rock analogue materials are very useful to study microphysical processes under easily accessible conditions. However, systematic, high strain rotary shear experiments on quartz-phyllosilicate mixtures, under hydrothermal conditions, are still needed to establish whether low and high sliding velocity regimes of behaviour seen in our halite-muscovite mixtures also occur in more realistic fault gouge materials, under appropriate conditions. If so, the experimental results can then be compared to the predictions of the present microphysical models for steady state slip in the velocity strengthening and velocity weakening regimes, and any modifications or extension of the existing models carried out. If the models successfully reproduce the experimental data for realistic fault rocks, under steady state conditions, the geodynamical and seismological implications of the models need to be carefully investigated.

4. Given the relevance of velocity weakening to seismogenesis, a microphysical model should be constructed for the transient behaviour seen in the high velocity or velocity weakening regime of our halite-muscovite experiments. The present steady state model for this regime can be extended to the transient case, by obtaining expressions for porosity and dilatancy angle evolution under non steady state conditions. The results of such a model should enable us obtain a microphysical basis for predicting rate- and state friction parameters. Like the

steady state model, such a model should also be tested against experiments on natural systems. This would involve high strain, slide-hold-slide experiments on natural materials (e.g. quartz-muscovite mixtures) in a rotary shear set-up under hydrothermal conditions.

5. The microphysical models developed here for the low and high velocity regimes of behaviour of phyllosilicate-bearing fault gouge, require input data not only on the kinetics of IPS (see also point 1), but also on the sliding properties of grain contacts. The latter are not well known for quartz-phyllosilicate systems. Systematic sliding experiments are therefore needed to clarify and quantify the grain contact slip behaviour of quartz-quartz, quartz-phyllosilicate and phyllosilicate-phyllosilicate contacts under hydrothermal conditions. This will constrain the input parameters of the models for extrapolation to nature. Aside from the frictional slip behaviour expected at low temperatures and pressures, care should be taken in such work to account for other processes that might play a role at high temperatures, such as thermally activated grain boundary sliding, fluid film effect or pore fluid pressurization.

6. Upscaling of laboratory results to natural fault zones requires the internal structure, rock properties and structural evolution of such fault zones to be taken into account. Future numerical models of faulting and seismogenesis should aim to take the heterogeneity and anastomosing structure of fault zones into account, computing the macroscopic fault behaviour using microphysical models, such as those obtained here, to describe the rheology of the various internal fault rock segments.