Summary

Deformation of the Earth's crust and crust-lithosphere system is for a large part concentrated in localised faults or fault zones. The mechanical behaviour and evolution of these faults are important in controlling a wide range of geological and geodynamical processes, ranging from rifting and seismogenesis to basin evolution and hydrocarbon trapping, and to orogenesis and ore emplacement. Modelling such processes relies heavily on descriptions of the rheology of fault rocks i.e. of the brittle/frictional, compaction and creep behaviour of fault rocks as derived from laboratory experiments. Laboratory experiments on bulk rock rheology have led to the construction of so-called crustal strength profiles in which upper crustal behaviour is described by laboratory-based fault friction laws with plastic flow dominating the lower crust. Assuming a direct relation between frictional behaviour and seismogenesis, these profiles seem to explain the depth distribution of crustal seismicity. However, fault localisation implies internal weakening and a considerable body of geological and geophysical evidence suggests that classical strength profiles significantly overestimate the long-term steady state strength of fault zones. Moreover, strength profiles describe only the steady state strength of fault rock, whereas for processes such as seismogenesis, transient effects such as fault healing and sealing are much more important.

Several explanations have been offered for the inferred weakness of major fault zones. First, it has been suggested that high internal pore fluid pressures are somehow maintained, thus reducing fault friction, but a mechanism allowing this is not clearly established. Another possible explanation is the development, through reaction, of weak phyllosilicates that align to form a pervasive foliation in many fault zones. Finally, it has been proposed that fluid-rock interactions, such as stress-induced dissolution and precipitation or pressure solution creep, can significantly weaken fault rocks. However, these processes can also lead to fault healing and sealing through compaction and cementation. Thus pressure solution effects seem to be able to both weaken and strengthen fault rocks through competing effects of shear versus compaction. Progress in understanding the effects of fluid-rock interaction on steady state and transient fault strength depends on understanding this competition and the role played by phyllosilicate foliation development.

This thesis aims to elucidate the effects of pressure solution and phyllosilicates on the compaction and shear behaviour of granular materials chosen to resemble or simulate granular fault gouge deforming under hydrothermal, brittle-ductile transitional conditions. To achieve my aims, I implemented three different experimental programs. The first experimental program consists of isostatic compaction experiments on both pure quartz sand and phyllosilicate-bearing quartz sand at temperatures of 400-600 ºC, a confining pressure of 300 MPa and fluid pressures of 150-250 MPa. These experiments were designed to quantify rates of compaction by intergranular pressure solution (IPS) and to determine the effects of phyllosilicates on the process. The results of these experiments are reported in Chapters 2 and 3. Clear evidence was found for compaction by IPS. The main conclusion is that IPS compaction under the conditions studied, is probably controlled by the rate of

dissolution of quartz within the grain contacts, at least down to porosities of 15%. The presence of muscovite hinders compaction, probably through a chemical retardation effect, on the dissolution rate, of aluminium ions dissolved in the pore fluid from the muscovite.

The second experimental program consists of high strain rotary shear experiments performed on simulated fault gouges consisting of brine-flooded, halite-muscovite mixtures. This mixture was chosen as a gouge analogue, since the processes of cataclasis, pressure solution and foliation development are known to occur in this material in room temperature experiments of a few days duration. The effects of these processes on gouge strength could therefore be easily investigated. Normal stresses explored were 1-9 MPa and sliding velocities ranged from 0.001 to 13 μm/s. A series of normal stress-stepping, velocity-stepping, constant sliding velocity and slide-hold-slide experiments were performed at room temperature, reaching shear strains in excess of 50. The results are reported in Chapters 4 and 5.

As described in Chapter 4, I observed velocity-strengthening behaviour up to a sliding velocity of ~0.3-1 μm/s, along with the development of an apparently mylonitic microstructure consisting of an anastomosing muscovite foliation enveloping elongate halite clasts. The deformation mechanism was one of frictional slip on the phyllosilicate foliation with accommodation by pressure solution of the intervening halite. I refine a previous microphysical model for this type of deformation mechanism in halite-kaolinite mixtures and extend it to include the possibility of plastic flow in the phyllosilicates. The model predictions compare well with the experimental results, and extrapolations of the model to natural quartz-phyllosilicate fault rocks under crustal conditions predict significant weakening (factor 2-5) with respect to classical crustal strength profiles. At higher sliding velocities, I observed a strong velocity weakening effect in the mixtures of halite and muscovite. This was accompanied by a cataclastic microstructure with no foliation but with significant porosity development. The porosity increased with increasing sliding velocity. I explain this behaviour in terms of a granular flow mechanism involving competition between shear-induced dilatation and pressure solution controlled compaction. The time-dependence of pressure solution compaction leads to higher porosities at higher sliding velocities. Higher porosity implies smaller grain contact areas, a lower dilatancy angle for granular flow and hence lower grain boundary shear resistance. Thus faster shear produces a lower macroscopic shear strength and velocity-weakening. Since velocity weakening is a prerequisite for an instability (i.e. an earthquake) to initiate, the marked, phyllosilicate-related velocity weakening effect observed in these experiments (one order of magnitude higher than previously observed) is potentially important in developing our understanding of the seismic cycle.

The marked difference in behaviour between the two velocity regimes seen in the salt-muscovite experiments is also associated with completely different healing and restrengthening behaviour as evidenced from the results of the slide-hold-slide experiments which are reported in Chapter 5. These experiments show that samples deformed in the low-velocity regime do not heal or restrengthen significantly on re-shear, while those deformed in the high velocity regime regain high strength. Static healing rates, recorded for the latter samples, increase with increasing pre-hold sliding velocity. This is explained by a higher steady state porosity being maintained during rapid steady state sliding, so that compaction is increased during hold periods. The increased compaction leads to an increased granular dilatancy angle and to higher intergranular friction, hence higher healing rates following rapid slip. If a similar mechanism operates under natural conditions, this implies that the velocity history of fault gouges will have a strong effect on the restrengthening potential of these gouges with unstable, seismogenic fault segments being prone to effective healing and recurrent failure.

The third experimental program consists of high strain rotary shear experiments on simulated quartz gouges under hydrothermal conditions. The experiments were performed in a purpose-built apparatus 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 and reached shear strain γ up to 50. I report the results of these experiments in Chapter 6. They show strain hardening up to a shear strain γ of 0.6-1.8, followed by strain weakening of up to 30% towards a steady state value at a strain γ of ~8-12. This strain weakening effect is much higher than previously reported for quartz gouge. The steady state shear strength increases with decreasing grain size, increasing sliding velocity, and decreasing temperature. The microstructure of the deformed quartz gouge is characterised by the presence of a through-going boundary-parallel Y-shear. Some samples also show Riedel shears oriented oblique to the shear zone boundary. Deformation in these tests was largely by cataclastic, with most displacement being accommodated along the boundary-parallel Y-shear, causing the strong weakening observed. Intergranular pressure solution did not contribute significantly to shear strain accommodation, but appears to play a role in smoothening and weakening the localised slip surface and in controlling gouge compaction.

Finally, I turn back to our rock-analogue experiments in Chapter 7, where I present a microphysical model predicting the steady state velocity-weakening behaviour reported in Chapter 4 for analogue samples deformed at high sliding velocities. The model is based on a quantitative description of the competition between shear-induced dilatation and IPS-controlled compaction processes. The aim was to assess whether the dramatic velocity weakening effect seen in the analogue system (Chapter 4) can be expected to occur in quartz-phyllosilicate fault rocks under upper to mid crustal conditions, where they might be important for seismogenesis. The model results agree favourably with the experimental results. Extrapolation of the model to natural conditions shows a velocity weakening effect which is an order of magnitude larger than previously seen in low strain experiments on quartz/granite gouges. Combining the model with that derived for the velocity strengthening regime in Chapter 4, yields curves describing the maximum static stress drop accompanying earthquakes, as a function of depth. The predicted stress drops agree favourably with static stress drop estimates inferred from seismological observations. This implies that if similar deformation mechanisms operate in quartz-phyllosilicate fault rocks, we will be able to provide a microphysical basis for extrapolating laboratory-derived rate and state dependent

fault friction parameters to natural conditions for numerical modelling of faulting and seismogenesis.