

Relations among porosity, permeability, and deformation in rocks at high temperatures

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The migration of fluids through the upper mantle and lower crust is important for a broad variety of issues in geology, geochemistry, and geophysics. Examples include the formation of the continental crust by upwelling magma along plate margins, the formation of oceanic crust along mid-ocean ridges, the alteration of reservoir rocks by diagenetic and metamorphic reactions, and the alteration of porosity by pressure solution processes. To understand the effect these processes have on the geochemistry and physical properties of the melts, it is necessary to understand relations among pore fluids, transport properties, and mechanical deformation.

Transport properties of rocks, including permeability, strongly influence and are influenced by deformation in a rich variety of ways. For example, pores can be produced by fracturing caused by thermal or pressure cycling, by volume changes during metamorphism, by nonhydrostatic stresses, or by interaction with an undersaturated pore fluid. Decreases in permeability might be caused by brittle pore collapse, pressure solution, crack healing, crack sealing, cementation of existing minerals, or precipitation of new minerals. If a pore fluid in which the solid components are soluble is present, then the shape and amount of porosity may be altered quite quickly. The driving forces for the porosity changes may be chemical (e.g. reactions), textural (e.g. capillary forces), or mechanical (e.g. brittle or plastic deformation). Kinetics laws for porosity changes need to be developed for each mechanism, and interactions between them delineated. Rates could then be compared, provided stresses, temperature, fluid chemistry, pore pressure, pore microstructure, and mineralogy were known.

Many microstructure studies indicate that rocks have extreme variability of the pore dimensions; it is also clear that the pore geometry of granular sedimentary rocks, and cracked crystalline rocks can be viewed as having a highly connected pore network with broad distribution of radii, apertures, and aspect ratios. Network modeling has emerged as a natural and simple method capable of explicitly incorporating any desired level of pore-scale heterogeneity into the prediction of transport properties. Two issues in particular need to be understood for each deformation mechanism: i.e. the evolution of the pore statistics, and the way that connectivity of the pore space is modified during deformation. In addition to improved observations, current research is focussing on developing predictive models for the effect of deformation on these statistics.

When the pore fluid is a melt, deformation and transport properties may couple to produce a variety of behaviors that depend on the porosity, the melt viscosity, the solid strength, the relative interfacial energies, temperature, pore fluid/melt pressure, and the stresses on the solid. To understand the effect of variations of melt pressure on the extraction of melt from some partially molten peridotites, we measured the rate of melt extraction from partially molten peridotites as a function of melt content, ϕ , melt viscosity, grain size, and effective pressure, P_{eff} , i.e. the difference between confining and melt pressure. Samples containing 30-40% melt were subjected to a confining pressure of 300 MPa at 1473 K. Three different melt compositions were used: melts

fluxed with lithium silicate, formed from MORB, or produced by melting albite glass. Melt pressure was controlled by connecting the sample to an argon reservoir; melt and confining pressures were maintained at $3 < P_{eff} < 50$ MPa. For comparison, densification and permeability measurements were also performed on porous olivine aggregates with argon as the pore fluid. Compaction rates always decreased with decreasing ϕ and increased with increasing P_{eff} , but they also showed an interesting relationship with melt viscosity. At the same P_{eff} and ϕ , olivine with MORB compacted fastest, aggregates made from olivine+lithium silicate had intermediate rates, bracketed by the two olivine+Ar experiments, and aggregates of olivine+albite compacted the slowest. Two regimes of melt segregation can be distinguished: one where solid compaction controls deformation, and a second where melt extraction is most important. In the olivine+lithium silicate and olivine+MORB systems, compaction was isotropic, i.e., the shape changes and melt content were homogeneous. The compaction rate at fixed T , P_{eff} , and ϕ is inversely proportional to grain size squared or cubed. When other variables are fixed, compaction rate is linearly proportional to P_{eff} . We suppose that matrix deformation dominates the melt extraction at the run conditions for both systems. Using Eq. 1, we can estimate the local stress enhancement, $f_{(\phi, \theta)}$. The coordination number of the solid grains increases with decreasing ϕ , thus decreasing the stress enhancement factor. Adding melt apparently provides a short circuit for diffusion since melt-added samples compact faster than melt-absent samples. In the olivine/albite system compaction was not isotropic, and ϕ continuously increases from the drained interface to the far end of the sample. The exponent relating compaction rate to P_{eff} appears to be larger than 1, even though the olivine grain size is smaller than that in the olivine+MORB and olivine+lithium silicate systems. We suppose that the heterogeneity of melt indicates that compaction is controlled by melt extraction.

Based on experiments on partially molten granites, *Arzi* [1978] and *van der Molen and Paterson* [1979] proposed that, above a critical ϕ , $\sim 25\%$, aggregate strength drops rapidly from that characteristic of the solid phase to that approaching the viscosity of the melt. *Rutter and Neuman* [1995] questioned the existence of this rheologically critical melt percentage (RCMP). One major difference was that the former studies added water to produce melt, and the latter did not. Thus, it seems likely that the viscosity of the melts produced differ greatly. We suppose that the apparent discrepancy owes to the fact that the RCMP is not a universal constant, but is related to volumetric strain, drainage conditions, and melt viscosity. The strain rate at which fluid pressure can be maintained constant within a rock volume is [*Fischer and Paterson*, 1989]

$$\dot{\epsilon}_{crit} \propto k / (\eta\beta_s)$$

Although approximate, Eq 3 predicts dilatancy hardening and compaction weakening in low temperature rocks quite well. By relating k and β_s to ϕ , we estimated the RCMP,

$$\phi_{crit} \propto (\dot{\epsilon}\eta\beta_f / d^m)^{1/(n'-1)}$$

where β_f is the melt compressibility, d the grain size, and m and n' relate permeability with grain size and ϕ , respectively. Applying this estimate to deformation of partially molten granites resolves the apparent conflicts between the three studies.

We also performed triaxial deformation tests on synthetic calcite aggregates containing 3-40% of eutectic melts in the $\text{CaCO}_3 + \text{Ca(OH)}_2$ or $\text{CaCO}_3 + \text{Li}_2\text{CO}_3$ systems, the Ca(OH)_2 melts being less viscous by 2-3 orders of magnitude. Experiments were carried out at $P_c=300$ MPa, at 973 to 1023 K (eutectic temperatures are ~ 935 K), both drained and undrained, either by connecting the sample to an Argon reservoir or fully encapsulating it. In drained experiments, melt pressures varied from 100 to 295 MPa. These experiments were complemented by tests on melt-free aggregates. Samples were shortened or elongated to axial strains of 5-35%. The strength of the partially molten aggregates was less than that of pure aggregates at the same conditions. Samples were stronger in compression than extension, and weakened with increasing ϕ . Strength always decreased with decreasing strain rate; but the apparent stress exponent in a power-law was a function of ϕ and drainage conditions. The stress exponent decreased with increasing ϕ for $\text{CaCO}_3 + \text{Ca(OH)}_2$ samples independent of drainage, and for $\text{CaCO}_3 + \text{Li}_2\text{CO}_3$ samples when drained, but not when the latter were undrained. At otherwise identical conditions, drained samples were weaker than undrained. The difference in strength decreased with increasing ϕ and decreasing strain rate, but increased with melt viscosity. In creep tests, undrained samples did not approach steady state, and the strain rate decreased from initial values similar to those expected for a drained experiment, to values expected for an undrained experiment. During deformation, melt is redistributed into pockets oriented subparallel to the maximum compressive stress. The dependence of strength and stress exponent on melt pressure is consistent with the idea of dilatancy hardening in brittle rock [Brace and Martin, 1968].

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