Deformation of Polymineralic Rocks by Replacement Creep

Dugald M. Carmichael
Queen’s University, Kingston ON K7L3N6, Canada <carmicha@geol.queensu.ca>

Experiments by Bruhn et al (1999, JGR 104, 707-724) show that the creep strength of synthetic calcite+anhydrite rock at 600°C is about one order of magnitude lower than that of pure calcite rock or pure anhydrite rock. Systematic curvature of the calcite/anhydrite interfaces supports my postulation that the predominant mechanism of deformation is replacement creep, a microstructural process governed by the rules of diffusion metasomatism. In this case, replacement creep approximates to constant-calcium replacement of anhydrite by calcite at interfaces normal to the maximum principal stress (σ1) and of calcite by anhydrite at interfaces normal to the minimum principal stress (σ3). Fundamental to replacement creep is a concept first explained by Wheeler (1992, JGR 97, 4579-4586): the creep strength of a rock may be greatly reduced if the slowest-diffusing element need not diffuse.

Field evidence shows clearly that greenschist-facies metapelites and calcshists have much lower creep strength than associated quartzite and marble. During prograde metamorphism, these rocks are optimally suited to deform by replacement creep. At a biotite/albite interface, for example, there is a continuum of possible diffusion-metasomatic reactions, the extremes being dissolution or growth of either grain without involvement of the other. However, due to the relatively low diffusivity of aluminum, a reaction approximating to constant-aluminum replacement may be favoured. Accordingly, simplifying the composition of biotite as K(Mg,Fe)AlSiO(OH)2 and of albite as NaAlSiO3, let us consider a reaction by which biotite could be replaced by albite without any mass transfer of aluminum:

\[
\text{biotite} + \text{NaCl} + 6\text{HCl} = \text{albite} + \text{KCl} + 3(\text{Mg,Fe})\text{Cl}_2 + 4\text{H}_2\text{O} \quad (1).
\]

This type of reaction is possible only in the presence of at least a small excess of intergranular H2O, which greatly facilitates the necessary grain-boundary diffusion. If the externally-controlled activities of NaCl, HCl, KCl, (Mg,Fe)Cl, and H2O are such as to drive this reaction from left to right, the albite grain will grow at the expense of the biotite grain, obtaining all of its aluminum directly from the adjoining biotite.

The molar volumes of albite and biotite are 100 and 152 cm³; hence the volume-change of reaction 1 is -34% (The solute species and the H2O molecules enter or leave the system in accord with reaction progress, so they make no contribution to the volume-change). For a rock under tectonic stress, this provides a thermodynamic prediction: Albite will tend to replace biotite at interfaces normal to σ1, and biotite will tend to replace albite at interfaces normal to σ3. That is to say, reaction 1 will tend to proceed in opposite directions on differently oriented interfaces, permitting axial shortening parallel to σ1 and axial extension parallel to σ3.

A planar biotite/biotite interface in the same rock would be stable if normal to σ1, but if normal to σ3 it is a likely site for nucleation and growth of albite, with concomitant axial shortening. An albite/albite interface would be stable if normal to σ1, but if normal to σ3 it is a likely site for nucleation and growth of biotite, with concomitant axial extension. To the extent that these and other local metasomatic reactions function as source and sink for one another, the rock can deform without change in its bulk composition, and with minimal need for grain-boundary diffusion of aluminum. To the extent that metasomatic differentiation may tend to create monomineralic domains (e.g, in the m-domains of crenulation cleavage or in high-strain zones flanking porphyroblasts), the creep strength of the rock will tend to increase.

In amphibolite facies, although higher T will facilitate diffusion, the creep strength of metapelites may actually increase due to larger grain size, growth of porphyroblasts, weaker cationic partitioning among the coexisting minerals, and higher concentration of titanium in biotite.

At the onset of cooling in either facies, the intergranular aqueous vapour is consumed by back-hydration, and the creep strength of most rock types is greatly increased.