MICROFABRICS OF DEFORMED ROCKS, A REVIEW

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Recent conferences on this subject were largely devoted to highly specialized work: experimental, theoretical and model work. Geologists very quickly learned to apply knowledge accumulated in materials science to geological materials. Although the application of this specialist work to specific field geological problems was not always immediately obvious, a series of specialist conferences, starting with Leiden in 1976, was necessary to provide a physical basis for useful microfabric work. For example, it is probably fair to say that the very time consuming petrofabric investigations on a U-stage were in no proportion to their usefulness until only a few years ago.

The concept of deformation mechanisms made geologists aware that there is a range of different physical processes leading to strain accumulation, each of them associated with a particular flow law and a diagnostic microfabric. The concept of deformation mechanisms has been very useful in the case of monomineralic rocks in order to plan relevant experiments and for a reliable extrapolation of laboratory data to geological conditions of strain rate. It was even hoped that microfabric criteria would eventually allow us to reconstruct the conditions of stress, strain rate and temperature in a geological environment, as the study of metamorphic assemblages helps to establish p-T conditions during metamorphism.

There are some problems, however, with such a straightforward application:

(i) Steady state conditions are assumed and strain does not appear as a variable on deformation mechanism maps. The strain may alter the microstructure sufficiently to induce work hardening or softening after an initial stage of steady state creep.

(ii) Some deformation mechanisms are non-additive, others are additive only near the mechanism boundary, due to the vastly different contributions to the bulk strain rate. Field observations however indicate that usually more than one mechanism operates at the same time. This is particularly true for pressure solution in combination with intracrystalline plasticity. Often this can be explained by the inhomogeneous composition of a real rock in terms of grain size and mineralogy. The notion of a single deformation mechanism breaks down in the case of polymineralic rocks.

(iii) As a result of the recently established dialogue between structural geologists and petrologists we all became aware of the interactions between phase changes and rheology. Mineral reactions may have an effect on deformation mechanisms (transformation plasticity). On the other hand, intracrystalline plastic strain may influence metamorphic reactions, both in terms of the kinetics and mineral equilibria (e.g. changes in solubility as a result of stored plastic energy).

Experimental deformation work on the most important rock forming minerals and monomineralic rocks provided the basic framework for a better understanding of experiments on polymineralic rocks, such as granite. From this new work on granites it appears that a particular mineral in the rock may largely determine the bulk rheological response of the polymineralic aggregate. Other experimentalists started to perform shearing experiments. This type of experiment is crucial for a better understanding of microfabric development and the rheology under non-coaxial conditions, commonly encountered in geology. Another advantage of this method is that large strains can be achieved under controlled boundary conditions. Recent high-temperature experiments on marble indicated that work softening sets in only after a shear strain of $\gamma > 1$, following a long initial stage of steady state flow. Some of the most spectacular insights into the microstructural development during deformation was gained from experiments on rock analogues. These experiments are relatively easy to perform and some of them allow for in-situ observations.

Allthough the extrapolation of laboratory determined flow laws gives a rough estimate of the flow stresses expected for different monomineralic rocks, such extrapolations are far from accurate. Paleostress determinations based on microstructural features (dislocation density, subgrain-size, recrystallized grainsize) gave us a more direct means of estimating the differential stress magnitude, so far the least known physical quantity during rock deformation. The use of the recrystallized grain size method was particularly useful because this microstructural feature is reasonably stable and because this method asks for an ordinary microscope only. At the same time, this method offers an illustration of the dangers of an uncritical application. It has been shown on rock salt and calcite that different mechanisms of recrystallization (e.g. subgrain rotation and grain boundary migration) lead to different grain sizes at the same level of differential stress. A better understanding of the mechanisms of recrystallization, both in the experiments used to calibrate the paleopiezometer and in the geological material under investigation is imperative.

The numerous studies on shear zones provided an insight into possible mechanisms of work softening and also provided us with useful tools to infer the shear sense in large scale shear zones, such as mylonite belts. It is often impossible to find offset marker horizons or systematically deflected schistosity patterns within mylonites. A number of criteria, such as asymmetrical augen structures, shear bands and recrystallized grains with their elongation direction oblique to the macroscopic foliation are best used in combination to give consistent results. In the case of the mylonites along the Insubric line these criteria, together with lattice preferred orientation studies, gave surprisingly consistent answers. In other cases inconsistent results are reported, calling for a more complicated deformation history or coaxial deformation on a large scale.

Several models of strain softening have been proposed. The most popular model is that of shear heating. Although this process can produce partial melting during high stress pulses, direct evidence for its effectiveness is scarse in the case of ductile shear zones and mylonites. Since the grain size in mylonites is commonly drastically reduced due to dynamic recrystallization the idea of softening associated with a change in deformation mechanism towards grain size sensitive flow laws is very attractive. There is good evidence for this type of softening in the case of limestone mylonites. In the case of quartz, however, a very strong lattice preferred orientation is commonly observed. The interpretation of these preferred orientation patterns in terms of end-orientations for easy slip calls for geometrical softening as a better model. The development of a mylonitic foliation is often accompanied by a rearrangement of the most ductile phase, namely quartz, into continuous layers. This may lead to foliation induced softening because the shearing displacements are now largely taken up by strain within the weakest mineral phase in the rock. The interaction between mineralogical changes and deformation were already mentioned. In many mylonite belts field observations indicate that mineralogical changes are a prerequisite for mylonitization and strain localization.

The increased interest in lattice preferred orientation is a good example of the influence material science concepts had on microfabric work. In the case of quartz mylonites two dominant types of of preferred orientation have emerged: The single c-axis girdle normal to the a-maximum close to the infered shear direction and the "type 1" c-axis crossed girdle with two a-maxima. The interesting fact that those patterns are observed whether or not there is extensive dynamic recrystallization asks for an explanation in terms of a model.

Such a general model for the development of preferred orientations, a microdynamical model, is desirable for two additional reasons: it would enable the rheology of the rocks to be established and it would enable preferred orientation to be used as an indicator of deformation history and conditions. The search for such a model has occupied many geologists for many years and various possibilities have been explored. Two main processes have been proposed for the development of preferred orientation: recrystallization and lattice rotation caused by dislocation movement:

Kamb proposed that orientations stable under recrystallization would be those for which the stored elastic strain energy was lowest. This model is not so satisfactory as it relates the preferred orientation to the stress and not to the deformation history.

Lattice rotation models include the model of Etchecopar and the Taylor-Bishop-Hill theory applied to quartzites by Lister. The Etchecopar model is primarily geometric but allows the calculation of preferred orientations for materials with one slip system. The Taylor-Bishop-Hill analysis has the advantages that it is rigorously derived and all the parameters have a physical meaning. A major problem in its application to quartz is that slip on the rhombs in the direction c + a must be permitted to make up the five independent slip systems necessary for the accomplishment of a general strain. When applied to the calculation of preferred orientation in quartzites deformed under simple shear or approximate simple shear conditions, this analysis gives fairly close agreement for c in the case of the "type 1" crossed girdles but less good simulations for the c-axis single girdles and for the a-axis distributions found in X-ray texture studies. An a-maximum close to the inferred shear direction is to be expected from Taylor-Bishop-Hill, but the two a-maxima symmetrical to the lineation observed for "type 1" crossed girdle fabrics is not.

Both models based on lattice rotations caused by dislocation movements do not take into account the effects dynamic recrystallization may have on the build up of preferred orientation. Kamb, on the other hand, invoked recrystallization of a different type. We suggest a Kamb-type model adapted to crystal plastic deformation and associated dynamic recrystallization. Such a model proposes that stable orientations are those for which the imposed deformation causes the minimum dissipation of energy by the active glide systems. Reorientation by glide induced lattice orientations would be greatly enhanced by recrystallization. Grains which have an unstable orientation more rapidly build up distortional lattice energy and, as a consequence, are selectively eliminated by recrystallization. Such a model would explain why the preferred orientation in fully recrystallized mylonites can still be interpreted in terms of stable orientations for easy glide. In such a model, recrystallization would assist geometrical softening.