The role of microcracking and grain boundary dilation during retrograde reactions.

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Veined metamorphic rocks are common, and give evidence of fracture-controlled fluid flow. However, the processes involved in fluid infiltration in domains between fractures is rarely well established. Reaction products concentrated at grain boundaries give an indication that diffusion of elements along grain boundaries may be important, and linear fluid inclusion trails provide evidence of grain-scale microcracking. Despite these common observations, the relative importance of grain boundary processes and microcracking at different metamorphic grades is not well characterised. Etheridge et al. (1983) developed a metamorphic porosity model comprising grain boundary ‘bubbles’ and ‘tubules’ of White & White (1981), but also incorporating dilatant grain boundaries and intra-grain tensile cracks. Variations in the local granular stress state will initiate transient micro-cracking and grain boundary dilatancy, promoting enhanced porosity, permeability and grain-scale fluid infiltration. This in turn causes retrogression, the extent to which it develops being influenced by the degree of connectivity of the dilatant cracks and grain boundaries, and whether, for particular P-T-X conditions, the infiltrating fluid is at equilibrium (or not) with the host being infiltrated.

With reference to examples of greenschist facies retrogression from Troms (Norway) and South Harris (Scotland), this study establishes that the processes of microcracking and grain-boundary dilatancy are highly heterogeneous at thin-section scale. In examples where reaction products are not related to mutual contact of specific phases, it is shown that the development of reaction products varies according to grain boundary orientation and density of microcracks.

An example from Norway shows a quartz-rich garnet-mica-schist where a centimetre-scale brittle fracture has induced extensive microcracking and fluid infiltration in the adjacent matrix. Fluid inclusions defining healed microcracks (perpendicular to schistosity) have H₂O-CO₂ and hypersaline aqueous chemistries, typical of retrogressive fluids of the region. On one side of the fracture intense microcracking of quartz (75 microcracks/mm) extends up to 25mm from the fracture, whereas on the opposite side of the fracture such microcracking extends only 1–2mm, then diminishes rapidly. Almanditic garnets in the heavily microcracked zone are 100% retrogressed to chlorite (*biotite), and even when microcracking diminishes to 5 microcracks/mm, partial pseudomorphs with 50% garnet retrogression are recorded. At a greater distance from the fracture there is no visible microcracking and garnets are unaltered. However, a few garnets that are outside, but near to the zone of microcracking show significant retrogression, indicating that locally at least the fluid has gained access by a process other than microcracking; possibly grain-boundary dilatancy. It is rare to preserve such detailed evidence for retrogression due to fluid infiltration by microcracking because recrystallisation of quartz usually destroys much of the evidence. Uniquely preserved are the precise fluid pathways (healed microcracks) into and out of retrogressing garnets, together with the fluids involved; some being hypersaline aqueous fluids, others being CO₂-dominated.

The example from South Harris, Scotland is of a 90% scapolite rock. Some grain boundaries display reaction products (epidote + Fe-oxides, and sericite/illite + quartz), yet other boundaries show no evidence of reaction. Standard optical microscopy coupled with SEM imaging (backscatter mode & element mapping) has characterised specific reaction products at each grain boundary. A map depicting those boundaries with reaction products and those without indicates a microstructural rather than mineralogical control. Boundaries in some orientations display retrograde reaction products, whereas the same phase boundaries in other orientations do not. The relationship is interpreted in terms of subtle grain-scale dilatancy at greenschist facies or lower temperature conditions, allowing fluid access into grain boundaries oriented approximately perpendicular to principal extension, whilst tightening (closing) those boundaries perpendicular to principal compression. The differential stress responsible for this grain boundary dilatancy is considered relatively small since there is no evidence of intra-grain tensile microcracking. Nevertheless this example indicates that under certain conditions grain-boundary dilatancy can significantly enhance permeability of metamorphic rocks to allow grain-scale fluid infiltration and retrogression.

To simulate conditions that may account for the geometrical arrangement of reaction products, a 3mm length section of the polygonal scapolite aggregate was digitised and then Universal Distinct Element Code (UDEC) modelling (pioneered by Cundall, 1971) applied. UDEC modelling (which is 2-dimensional) has primarily been used for analysis of fracture patterns, fluid flow and permeability of large rock masses, and until now analysis of grain-scale processes in largely monomineralic aggregates has not really been exploited. UDEC modelling allows simulation of deformation both within grains and at grain boundaries, whilst permitting fluid flow between interfaces. A fully coupled mechanical-hydraulic analysis is performed in which mechanical deformation influences interface connectivity, but is itself influenced by interface hydraulic pressure. The model we have used sets maximum horizontal effective stress (Sv) = 330-240 MPa, minimum horizontal effective stress (Sh) = 270-240 MPa, and vertical stress (Sp) = 300-240 MPa. Initial pore fluid pressure (Pf) = 240 MPa is 0.8 times maximum Sv (300 MPa). It represents supra-hydrostatic fluid pressure
(not quite lithostatic), and is considered a reasonable approximation to low greenschist facies conditions. By using these values and appropriate estimates for grain and grain-boundary stiffness, a plot for 2-10 micron aperture (grain boundary) opening is produced. It shows good agreement with the map of boundaries showing reaction in the natural sample. Despite the limitations and assumptions made, including 2-D modelling of a 3-D natural example, this pilot study has given promising results to suggest that modelling of grain-boundary dilatancy and fluid infiltration may be realistic and could lead to an enhanced understanding of processes operating in natural rocks.

References