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Electron microscopy of alkali feldspars: reading the microtextural record of igneous events and fluid–rock interactions

Microscopía electrónica de feldespatos alcalinos: lectura del registro microtextural e interacciones fluido-roca

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Alkali feldspars have complex intracrystal microtextures which can provide a wealth of information about cooling history and fluid–mineral reactions from igneous growth to weathering. To understand them we must use transmission and scanning electron microscopy (TEM and SEM). The complexity arises because in alkali feldspars there are two types of phase transition, which interact with the exsolution process which leads to perthitic intergrowths of Ab- and Or-rich phases. The $C2/m$–$C\bar{1}$ phase transition in Ab-rich feldspars is fast and involves spontaneous shearing of theSi–Al–O framework; the transition from $C2/m$ sanidine to $C\bar{1}$ microcline in Or-rich feldspars is slow and involves ordering of Si and Al in the framework. Depending on bulk composition and conditions of formation perthites may be coherent (with a continuous Si–Al–O framework), semicoherent (spaced dislocations along the interface) or incoherent (no continuous framework). Regular perthites on scales of ≤1 mm are usually coherent or semicoherent and the orientation of the interfaces depends on the minimization of elastic coherency strains; they are said to be 'strain controlled'. Perthites coarser than a few mm are usually relatively irregular, largely incoherent, and record feldspar–fluid reactions; they can be called 'deuteric' intergrowths.

TEM work, mostly since 1980, has led to a much clearer picture of the reasons for the diversity of perthitic textures. Most crystals from plutonic rocks have a 'dual microtexture' in which some regions consist of strain-controlled intergrowths, with appreciable (~2.5–4 $kJmol^{-1}$) stored coherency strain energy, and other regions in which perthite has coarsened, become incoherent, and lost its coherency strain energy by interactions with aqueous fluids, a process called 'unzipping'. Orthoclase *sensu stricto* has a very fine 'tweed' microtexture, based on diffuse intersecting modulations, 5–10 nm thick, which are not fully ordered but which have ~1.8–3.7 $kJmol^{-1}$ of strain energy in the domain walls. Free energy lost by further ordering is balanced by a gain in strain energy in the walls, and orthoclase becomes kinetically stranded. Orthoclase too can be unzipped by fluid–feldspar reactions (and also by deformation) and this usually leads directly to nearly fully ordered microcline, with 'tartan' twins.

The evolution of strain controlled and deuteric intergrowths with bulk compositions near $Ab_{60}Or_{40}$ will be described in the hypersolvus Klokken intrusion. This has a layered syenite core, giving excellent stratigraphic control, enclosed by a compositionally zoned gabbro to syenite sidewall cumulate, giving wide chemical range. The feldspars in the layered series have 'braid' microtextures in which lozenges of Albite-twinned albite defined by {$\bar{6}\bar{6}1$} are enclosed by microcline. There are no periodic dislocations because coherency strains can be minimized by rotating initially straight lamellar interfaces into the {$\bar{6}\bar{6}1$} orientation. The periodicities of the exsolution microtextures vary systematically from ~40 nm near the roof of the intrusion to ~400 nm at the lowest exposures. Cooling was thus at the roof, and the coherent exsolution textures indicate relative cooling rates. The sidewall cumulates provide a range of feldspar bulk compositions evolving continuously from crypto-antiperthites (~$Ab_{59}Or_2An_{39}$) to crypto-mesoperthite ($Ab_{59}Or_{40}An_1$). The relationship of microtexture to composition can be understood in the light of known phase behaviour and the minimization of coherency strain energy.

Large amounts of coherency strain energy are stored in braid perthites, so that these feldspars show the unzipping effects of fluid–rock interaction particularly clearly. Two syenite types of essentially identical composition are present in the layered series. A fine-grained, dark-coloured granular type, with feldspars that are glass-clear in thin section, is interlayered with a coarser, white-coloured, laminated syenite, with feldspars that are variably turbid in thin section. The latter layers acted as aquifers in the cooling intrusion, and deuteric unzipping has produced an irregular, sub-mm strain-free mosaic of albite and microcline subgrains, which often have pores between them. It is micropores, usually empty of secondary minerals, that impart the white colour and translucency to many feldspars. Because we can be sure that the Klokken feldspars have all shared exactly the same thermal history over 1.16 Ga, the importance of fluid–feldspar reactions to their microtextural evolution is obvious. Radiogenic Ar is lost rapidly from microporous crystals but retained in pristine crystals with strain-controlled microtexture, which give $^{40}Ar/^{39}Ar$ ages near 1.12 Ga.

Alkali feldspars typical of subsolvus granites, with bulk compositions near $Ab_{25}Or_{75}$, will be described from Shap (NW England). As usual there is a dual microtexture. Strain-controlled volumes contain straight albite lamellae in tweed orthoclase along (601), with thicknesses ranging from a few µm to <20 nm. Almost all plutonic K-feldspars we have investigated with TEM, including many from granulite-facies metamorphic rocks, contain some cryptoperthite. Thicker lamellae have the shape of very long, flat lenses in three-dimensions, and are semi-coherent, with regularly-spaced edge-dislocation loops encircling them. These dislocations form during cooling as the lamellae coarsen and the structure stiffens. Lamellae cannot rotate into {661} because of the dominance of the monoclinic orthoclase host, coherency strains become insupportable, and, despite the large amount of free energy in dislocation cores, the total free energy of the crystal is lowered when dislocations form.

Unzipping reactions occurred at least three times: at >410°C, before the formation of the first dislocation loops, giving irregularly distributed turbid veins composed of subgrain mosaics of albite and microcline; at <<370°C when volumes of K-feldspar were replaced by externally-derived, very pure albite, guided by the dislocations; finally, semicoherent albite lamellae were infrequently replaced by microcline, giving a 'pseudoperthite' of microcline lamellae in orthoclase. This process continued during diagenesis, when clastic fragments of Shap feldspar phenocrysts found their way into an overlying conglomerate, giving crystals in which only fully coherent albite lamellae are preserved. The dislocation loops are also extremely important in the subsequent weathering behaviour of the feldspars in soil waters. Rapid dissolution occurs down the dislocation cores, followed by mechanical degradation of the surface. Thus microtextures developed during igneous cooling prove to be essential factors in the evolution of soil-water chemistry and clay mineral growth.