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Extreme ductility of feldspars from a mylonite, Parry Sound, Canada

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Abstract—Single feldspar crystals in mylonites, from the Grenville structural province of Canada, have accumulated extreme strains by ductile mechanisms. The samples studied are from a deep-crustal shear zone and were collected at Parry Sound, Ontario. The mylonites were derived from granite and leucogabbro, and the feldspar crystals originated in late syntectonic pegmatite dykes.

Optical and transmission electron microstructures of microperthitic alkali feldspars show evidence of syntectonic and synchronous dislocation climb (leading to recovery), Si/Al ordering, and Na/K interdiffusion. Evidence for the operation of these processes is, respectively, ubiquitous subgrains, development and coarsening of tweed texture and transition of monoclinic to triclinic K-feldspar, and exsolution domain reorganization. These processes occurred concurrently with extreme straining of the host crystals by dislocation and diffusion mechanisms.

The effects of ductile deformation preserved in these crystals are quite different from those usually observed in feldspars. The unusual microstructures are thought to be due to the conditions of high temperature and confining pressure which existed during deformation, in concert with a deformation-enhancing point defect chemistry, possibly associated with incorporation into the crystals of a species of 'water'.

INTRODUCTION

THE FELDSPAR minerals as a group exhibit a wide and complex range of crystal-chemical phenomena (Ribbe 1983a). Because of this complexity, their deformation behaviour is similarly complicated and poorly understood. Feldspars generally show: low-strain effects such as mechanical twinning, undulose extinction, and kinking (e.g., Berthé *et al.* 1979, Hanmer 1982, Tullis 1983); or fracturing and sub-critical cracking, both crystallographically and non-crystallographically controlled (for example, Boullier 1980, White & White 1983, Atkinson 1984); or recrystallization without extensive development of recovery substructures (e.g. White 1975, Burg & Laurent 1978, LaTour & Kerrich 1982). Although evidence for the operation of crystal–plastic deformation mechanisms is observed by transmission electron microscopy (e.g. Marshall & Wilson 1976, Borges & White 1980, Fitz Gerald *et al.* 1983), it is extremely rare that significant single-crystal distortion, or accumulation of finite strain, occurs (Goode 1978).

In medium- to high-grade rocks, recrystallization commonly destroys evidence of pre-existing states of feldspar grains (Tullis 1983); evidence that might show, for example, whether the grains deformed dominantly by dislocation or diffusion mechanisms, and whether they had accumulated large amounts of ductile strain prior to recrystallization. Recrystallization may also often erase any indication of what were the original chemical composition and structural state. The recrystallization process itself is not well understood, as original grains have usually been totally recrystallized, and intermediate steps in the process(es) are therefore not preserved.

Mylonites developed in major, deep-crustal shear zones from the western Grenville structural province of Ontario, Canada, contain highly deformed feldspar single crystals. Both alkali and plagioclase feldspars have suffered extreme ductile deformation, and preserve not only their finite strain states but also the internal strain gradients of the deformed crystals. Aspect ratios of more than 10:1 have been determined for alkali feldspar crystals, while albite-law twins in plagioclase crystals are folded through angles exceeding 120°. The crystals are only partially recrystallized, and the progressive microstructural transitions from deformed host to recrystallized material are preserved.

This occurrence represents a significant anomaly in reported feldspar deformation behaviour. In what follows, we describe the feldspar microstructures and discuss possible deformation mechanisms and their controls as a further contribution to the study of solid-state deformation processes in feldspars.

GENERAL GEOLOGY AND TECTONIC SETTING

The mylonites occur within a major ductile shear zone separating two discrete gneissic domains of the Grenville structural province (Fig. 1, Davidson *et al.* 1982): Parry Sound domain to the south-east, and Britt domain to the north-west. The shear zone formed as the Parry Sound domain was emplaced towards the north-west over the Britt domain. Evidence for this interpretation includes a characteristic assemblage of asymmetric structural features which occurs in the mylonites (for example, sheath folds, rotated 'porphyroclasts', shear band cleavage, Mawer in prep.).

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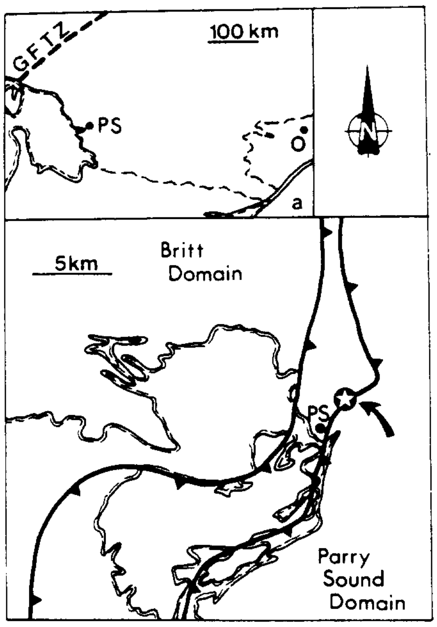

Fig. 1. Location map. Star indicates location of mylonite outcrops. Thick lines are approximate surface traces of boundaries of ductile shear zone, barbs point down-dip. PS, Parry Sound. Inset, Western Grenville structural province of Canada (shaded); a, Adirondack Mountains; O, Ottawa; PS, Parry Sound; GFTZ, Grenville Front Tectonic Zone.

Much of the Parry Sound domain is at granulite facies, whereas the Britt domain is at amphibolite facies (Davidson *et al.* 1982). Thus, across the bounding shear zone there exists an inverted metamorphic gradient. The outcrops occur towards the top of the boundary zone, at Parry Sound, Ontario (Fig. 1). Here, mylonitic granite and leucogabbro gneisses are in structural contact. Syntectonic metamorphic mineral assemblages indicate at least upper amphibolite facies temperatures for much of the mylonitization. Preliminary geobarometric calculations (A. Davidson, pers. commun., 1984) suggest pressures on the order of 900 MPa in both host rocks and shear zones from the Parry Sound and Britt domains.

The feldspar single crystals originated in pegmatite dykes, which were intruded and subsequently heterogeneously deformed and disaggregated (Davidson *et al.* 1982, Mawer in prep.) during the later stages of emplacement of the Parry Sound domain over the Britt domain. The pegmatites are considered to be derived from anatectic melts produced by ultrametamorphism, based on their simple mineralogy (feldspars, quartz, allanite, occasionally minor amphibole, Černý 1982).

Nearby, gneissic rocks at granulite facies are weakly deformed, and contain perthite and antiperthite, clinopyroxene and locally orthopyroxene, amphibole and quartz. All minerals are weakly to moderately deformed. The feldspars have subgrains and show undulose extinction, weak kinking and complex exsolution textures, as well as minor recrystallization at grain margins. The presence of small amounts of fine-grained syntectonic biotite, usually at amphibole grain margins, implies the presence of minor amounts of syntectonic hydrous fluids in these gneisses.

The mylonites in outcrop

Both granite and leucogabbro mylonites have a well-developed, generally SE-dipping foliation, with a SE-plunging mineral elongation lineation within this. Compositional layering is commonly parallel to the foliation in the leucogabbro mylonite. In both mylonites, numerous 'porphyroclasts' of alkali and plagioclase feldspars occur, up to 5 cm in diameter, in a finer-grained matrix. ('Porphyroclasts' are large, relict single crystals found in fault rocks. The term is in inverted commas because, in this case, these crystals have been derived solely by ductile processes, not brittle as the name might suggest. The term 'ductile', rather than the more specific 'crystal–plastic', is used when describing the feldspars as it is not mechanism-specific. 'Ductile' simply denotes the accumulation of strain without gross fracturing, whereas 'crystal–plastic' refers to permanent deformation by slip and twinning (Paterson 1978, p. 161, 174). Thus 'ductile' includes such mechanisms as crystal plasticity and diffusional flow, evidence for both of which is observed in the present samples). A qualitative strain gradient can be defined on the basis of the 'porphyroclasts', in that larger, rounded feldspars are less strained and smaller, elongate feldspars are more strained. This correlates with a similar, though less pronounced, strain gradient in the host mylonites, based on progressive grainsize reduction and quartz ribbon elongation. We have used these qualitative strain gradients as a reference framework in which to compare the behaviour of individual feldspar crystals.

The sequence of progressive deformation of the feldspar samples, then, is typified by the elongation and grainsize reduction of relict single crystals, in conjunction with the development of recrystallized grain trails which connect the relict crystals. With increasing elongation, these crystals can even become folded (Figs. 2a & b). This is some of the most compelling evidence for true single-crystal straining, as opposed to spurious geometrical effects caused by localized recrystallization.

METHODS OF ANALYSIS

Suites of samples of both granite and leucogabbro mylonites, showing various degrees of deformation, were collected. Orthogonal thin sections were cut from these oriented specimens, using lineation and foliation to define the reference axes. Initially, large, weakly deformed relict feldspar crystals were identified and characterized. These were then used as a standard state against which the more deformed material was compared. Deformed plagioclase relicts are more common in the leucogabbro mylonite, whereas in the granite mylonite, relicts of deformed alkali feldspar are more common. Overall, greater numbers of alkali feldspar 'porphyroclasts' occur, the plagioclase 'porphyroclasts' having been more completely recrystallized. The deformed plagioclase crystals have not yet been examined in detail, and are only briefly discussed below.

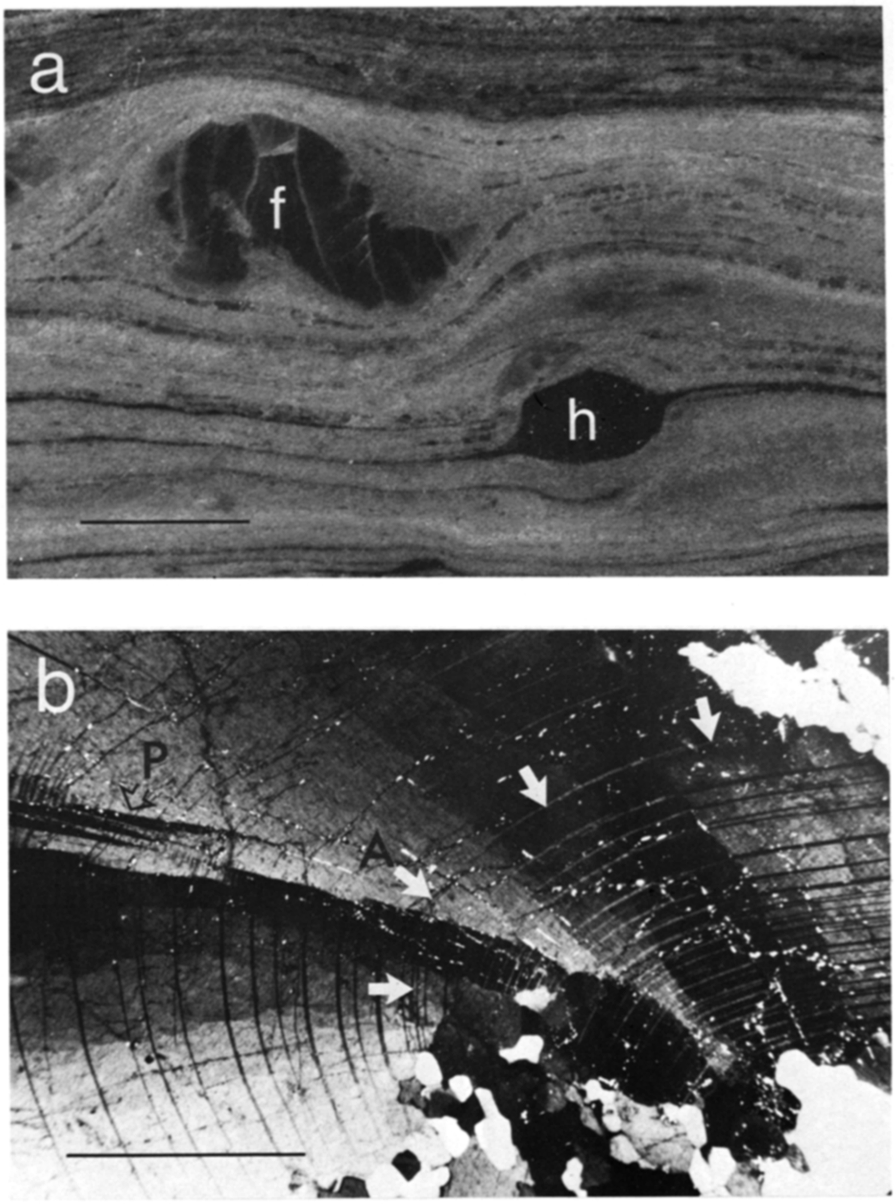

Fig. 2. (a) Folded alkali feldspar, f, and partially recrystallized hornblende, h, in granite mylonite. Scale bar—1 cm. (b) Folded plagioclase grain. Initially elongate parallel to the (010) planes, folding is outlined by albite-law twins, A. Note pericline-law twins, P, and kink-like structures developed in area of maximum crystal lattice curvature. Crossed polarizers. Scale bar—1 mm.

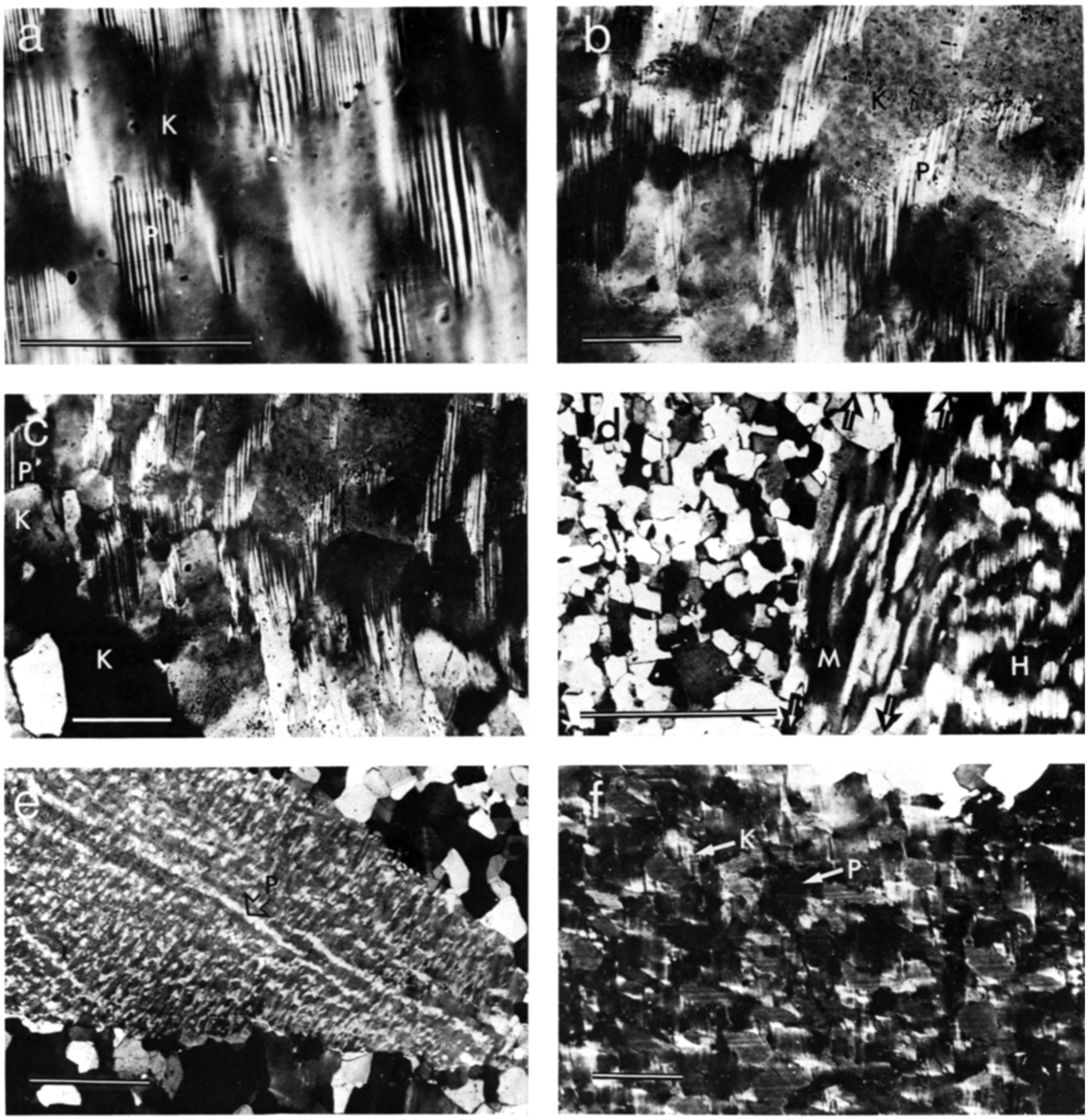

Fig. 3. (a) Relatively unstrained perthitic alkali feldspar 'porphyroclast' with orthoclase, K, and plagioclase, P, domains. Crossed polarizers. Scale bar—0.1 mm. (b) Grain mantle with intracrystalline distortion indicated by bending of plagioclase domains, P; an intermediate stage between (a) and (c). Foliation vertical. Crossed polarizers. Scale bar—0.1 mm. (c) Progressive development and subsequent misorientation of subgrains (from top to bottom of photograph) resulting in recrystallization of perthite into plagioclase, P, and K-feldspar grains, K, at alkali feldspar grain margin. Crossed polarizers. Scale bar—0.1 mm. (d) Contact between recrystallized grains (left) and highly deformed alkali feldspar host grain (right). Exsolution domains in deformed host mantle (M) are reoriented and elongated with respect to those in the centre of same grain (H). Crossed polarizers. Scale bar—0.5 mm. (e) Alkali feldspar grain elongate parallel to the trace of (010), showing elongate plagioclase exsolution domains, P, parallel to the host crystal long axis. Microscopic and field relations suggest that in this case grain elongation can be associated with intense deformation. Crossed polarizers. Scale bar—0.1 mm. (f) Development of incipient microcline cross-hatched twinning in K-feldspar subgrains, K, at boundary of a strongly deformed alkali feldspar grain. Crossed polarizers. Scale bar—0.1 mm.

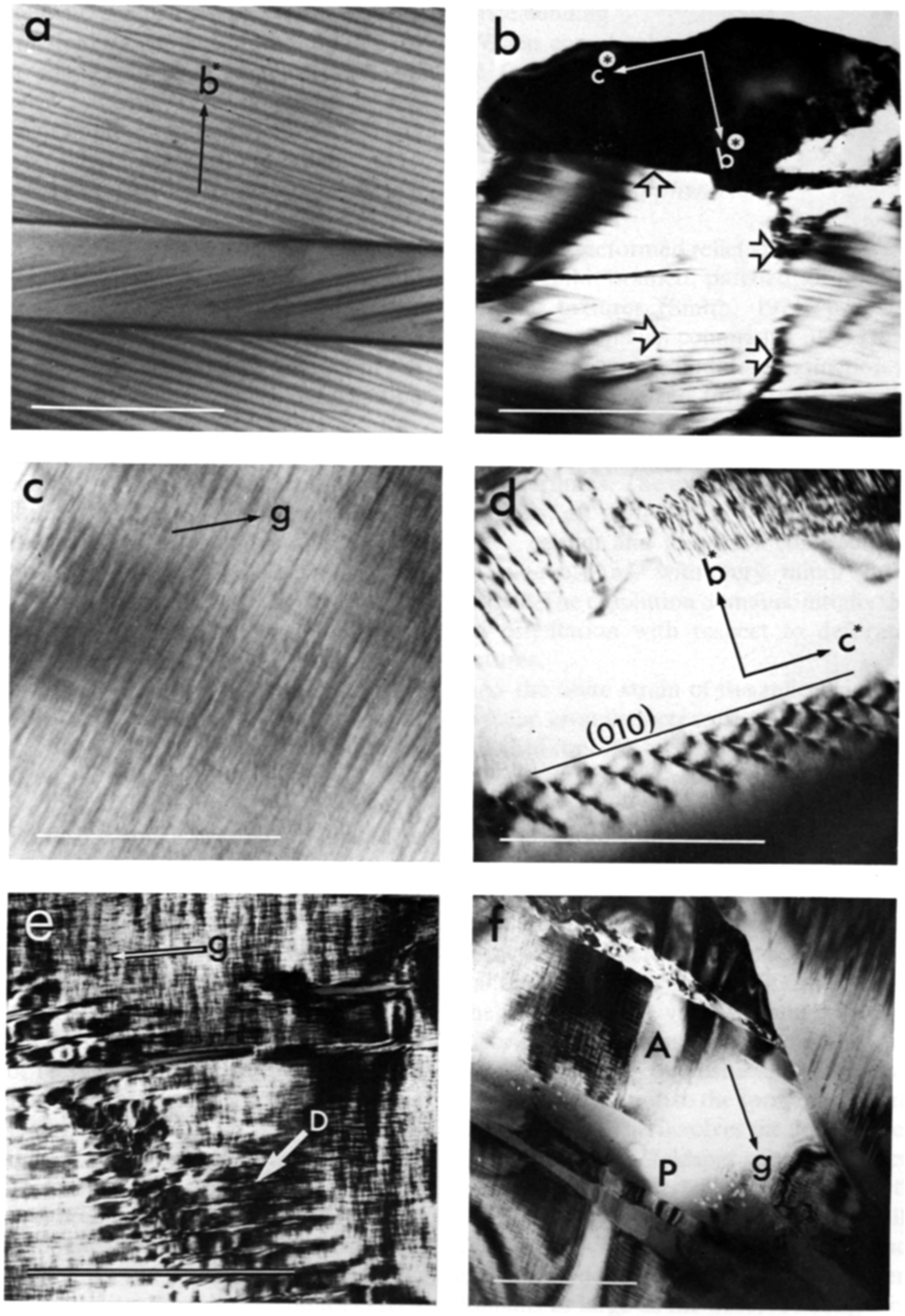

Fig. 4. (a) TEM micrograph of twinned peristerite from exsolved plagioclase domain in low-strain perthite 'porphyroclast'. Scale bar—250 nm. (b) TEM micrograph of peristerite from a deformed grain. Subgrain walls are developed throughout this material (arrowed). Scale bar—1 μm. (c) TEM micrograph of weakly-developed tweed texture in orthoclase from low-strain perthite; g = ⟨220⟩. Scale bar—500 nm. (d) Sub-grain wall development in K-feldspar domain from deformed grain. Walls are more regularly arrayed than in plagioclase domains and are commonly parallel to the trace of (010), which is also the direction of macroscopic grain elongation. Scale bar—500 nm. (e) Highly deformed K-feldspar domain with strongly developed tweed texture, incipient twins and abundant dislocations, D; g = ⟨021⟩. Scale bar—500 nm. (f) K-feldspar domain from highly deformed grain mantle showing development of twins on both albite, A, and pericline, P, laws in a matrix of strongly developed tweed and fine twins; g = ⟨110⟩. Edge of peristerite domain at right of micrograph. Scale bar—1 μm.

Detailed description of feldspar single-crystal deformation in this paper is restricted to the more-common alkali feldspar crystals, collected from the granite mylonite.

Following optical microscopical examination, selected areas of the feldspar crystals were prepared for transmission electron microscopy by standard ion-beam thinning techniques. Samples were examined with a Phillips EM 400 instrument operating at 120 kV. Using polished thin sections, compositional data were collected with a Tracor Northern energy dispersive analytical system attached to a Cambridge S4-10 scanning electron microscope.

Progressive increase in strain was defined within heterogeneously deformed single crystals, and among crystals from different parts of the host mylonite. Three main trends in the microstructural development of the alkali feldspar crystals are recognized as deformation becomes more intense:

(1) the accumulation of significant intracrystalline distortion, and recovery, prior to recrystallization;

(2) reorganization of exsolved plagioclase and K-feldspar domains within the microperthites and

(3) structural changes within the K-feldspar domains associated with development of Si/Al ordering features and polysynthetic twins.

OPTICAL MICROSCOPY

The mylonitic matrix

The deformed feldspar single crystals originated in pegmatite dykes, which intruded granite and leucogabbro mylonites in structural contact. Both mylonites are fine-grained, with an average grain size of 0.1 mm, though this is slightly variable depending on the strain intensity. With the exception of the dyke minerals, both mylonites are totally dynamically recrystallized. Foliation in both mylonites is defined by dimensional preferred orientation of recrystallized grains, polycrystalline quartz blades, mafic mineral aggregates, and aggregates of quartz or feldspar, or both.

Of the dyke minerals, plagioclase and alkali feldspars, quartz and amphibole show syntectonic recrystallization at their margins. Although sometimes recrystallized to grains of the same composition, amphibole in the granite mylonite more commonly has partially syntectonically recrystallized to yield biotite, ilmenite and minor carbonate. This implies the presence (and inhomogeneous distribution) during deformation of a minor amount of hydrous fluid.

Plagioclase 'porphyroclasts'

Compositions determined optically and by energy dispersive analysis cluster around An_{24-26} (oligoclase). All crystals exhibit broad, sweeping undulose extinction, and usually have well-developed subgrains and sub-boundaries. They generally show pronounced mechanical twinning. Using the twins as a marker, it is observed that many of the crystals are bent or folded, sometimes to a remarkable degree (Fig. 2b). Kink-like structures are not developed, except locally in areas of extreme lattice bending.

When completely recrystallized, the plagioclase has the form of a spindle-shaped aggregate. Individual grains of these aggregates show little internal strain, and are either untwinned or have several wide growth twins.

Alkali feldspar 'porphyroclasts'

The least-deformed relict alkali feldspar crystals commonly exhibit braided, patched, or interlocking microperthitic textures (Smith, 1974, pp. 403–417), with plagioclase domains comprising 35–45% of the crystal (Fig. 3a). Sweeping undulose extinction is ubiquitous, and there is localized formation of well-defined subgrains. Average bulk composition of the alkali feldspar crystals is $Or_{57}Ab_{40}An_3$, and they are therefore ternary microperthites. The exsolved phases have average compositions of: K-feldspar phase—$Or_{89}Ab_{11}$ with very minor celsian and anorthite components; plagioclase phase—$Ab_{87}An_{13}$ with very minor orthoclase component. The exsolution domains initially show no preferred orientation with respect to deformation-induced textures.

As the finite strain of the relict microperthitic alkali feldspar crystals increases, crystal–plastic deformation becomes concentrated in a narrow zone at the boundary between the parent grain and its recrystallized matrix. Both the exsolved domains and their albite-law twins serve as markers for crystal bending, and commonly are bent through more than 30° at the crystal edges (Fig. 3b) when compared to exsolved domains in the host crystal cores. Well-developed, optically visible subgrains occur in these more-deformed rims, producing a core-and-mantle structure (Fig. 3c, Gifkins 1976, White 1976). The subgrains have various amounts of crystallographic misorientation across their boundaries (between 2 and 10°). There is a compositional as well as a crystallographic contribution to the formation of subgrains in the grain mantles. This involves the development of discrete plagioclase and K-feldspar subgrains concurrently with progressively greater misorientation of the subgrains from host crystal core towards recrystallized matrix. This process involves a substantial readjustment of exsolution domain boundaries, in order to develop domains as large as the observed subgrains. Continued deformation leads to dynamic recrystallization by subgrain rotation, yielding new K-feldspar and plagioclase grains (Figs. 3c & d).

Strain-induced changes of exsolution domain geometry also occur within the cores of highly strained crystals. Initial changes involve elongation and boundary readjustment of the plagioclase domains, and their coalescence, causing them to become larger and more elongate (Fig. 3d). At high finite strains, as indicated by the degree of host crystal elongation, the amount of lattice bending and the intensity of subgrain formation, elongate plagioclase domains extend much of the length of the host grains (Fig. 3e). There is a repetitive parallelism between plagioclase domains, the trace of (010) host crystal planes, and the plane of foliation.

The K-feldspar phase of the least-deformed crystals is optically monoclinic orthoclase. With increasing strain, there is progressive development of polysynthetic twins associated with the symmetry transition to triclinic microcline. Microcline initially appears in the crystal mantle where the intensity of deformation is high (Fig. 3f). In very deformed crystals, it is developed heterogeneously throughout the grain. The mutual occurrence of microcline-twinned host grain with a mantle of subgrains, and adjacent microcline-twinned recrystallized grains, is consistent with progressive subgrain rotation being the recrystallization mechanism.

TRANSMISSION ELECTRON MICROSCOPY

Although the complexity of the alkali feldspar crystals is such that the TEM observations reported below are preliminary, these observations corroborate the degree of ductile deformation and crystal structure changes implied by the optical microstructures. In the least-strained crystals, plagioclase domains (Fig. 4a) consist of twinned peristerite characterized by exsolution into albite and oligoclase lamellae (McLaren 1974). Coexisting monoclinic orthoclase domains (Fig. 4c) have a weakly developed tweed or orthogonal distortion texture (McConnell 1971). Evidence of dislocation creep is abundant in the more deformed samples. Plagioclase domains show an increase in dislocation wall (subgrain boundary) frequency (Fig. 4b), but otherwise remain relatively unchanged. In K-feldspar domains, dislocations have generally become ordered into straight subgrain walls parallel to the trace of (010) crystal planes (Fig. 4d). The dislocation array frequency and the relative crystallographic misorientation across the arrays increase in areas of high macroscopic strain of the host. Free dislocation density is very low (generally too low to measure), and dislocations are straight. K-feldspar domains also exhibit a coarsening of the tweed texture (Fig. 4e) concurrent with this increase in dislocation wall frequency. In highly deformed crystals, intersecting albite-law and pericline-law twins occur in a matrix of coarse tweed and microtwins (Fig. 4f). Again, the frequency of twins is highest in the most deformed material. Development of these twins necessitates a change from monoclinic to triclinic symmetry, at least locally, in the crystal. Exsolution domain boundaries appear noncoherent (Yund & Tullis 1983) throughout the deformation sequence, although they are most complex in highly strained crystals. Rarely, adjacent domains have a common b^* axis orientation. Fine exsolution, complex dislocation arrays and crystal lattice bending all become concentrated in the narrow zones which separate exsolved plagioclase and K-feldspar domains, at states of high finite strain of the host crystals. These relationships are quite complicated, and after further study will be reported elsewhere.

DISCUSSION

Optical and TEM microstructures occurring in feldspar 'porphyroclasts' from the Parry Sound mylonites are evidence that deformation conditions exist in the earth's crust under which feldspars exhibit classical features of ductile deformation, features usually associated with such minerals as quartz and calcite. Two questions must be addressed: (1) what are the deformation mechanisms associated with these microstructures? and (2) what is peculiar about the deformation environment in which the mylonites form that would cause these deformation mechanisms to be active, in order to produce microstructures which contrast with almost all other reported observations of deformed feldspars?

Deformation mechanisms

Of immediate note in these feldspars is the apparent ease with which recovery has occurred, as shown by the production of subgrain structures typical of dislocation creep. Dislocation climb was, therefore, an important deformation mechanism at all stages of deformation of the feldspars.

The co-existence of recovery substructures, plagioclase/K-feldspar domain reorganization, and Si/Al ordering features (the coarsening of the tweed texture) emphasises the efficiency of diffusion during deformation, both in the accommodation of dislocation movement and in the migration of atomic species within the crystals. Reorganization of the exsolved domains is syntectonic. This is shown by the dynamic recrystallization of the microperthitic alkali feldspar crystals into two compositonally discrete populations of new feldspar grains, a process which requires the prior growth of individual feldspar domains to a size comparable with that of the recrystallized grains. This syntectonic domain reorganization is also shown by the progressive elongation and growth of exsolved plagioclase domains as host crystal strain increases. The striking change in shape of these exsolved plagioclase domains during growth may be due to a process closely analogous to Nabarro–Herring creep by intracrystalline diffusion (e.g. Ashby & Verrall 1977).

Deformation of the feldspars will be intrinsically linked to Si/Al interdiffusion, as Si diffusion is considered to be the most probable rate-controlling process for dislocation climb in feldspars (Tullis & Yund 1980). Observed variations in Si/Al ordering textures with degree of crystal strain in the studied specimens are consistent with this proposal, in that regions of the parent crystal with the most intense deformation show the coarsest tweed textures. Thus apparently, in these regions, Si/Al interdiffusion rates were higher than in less deformed parts of the crystals.

Different combinations of deformation mechanisms were important at different scales within the alkali feldspar crystals. Within individual plagioclase and K-feldspar domains, dislocation creep was active, in conjunction with (stress-controlled, or perhaps strain-controlled) intracrystalline diffusion. Along compositional domain boundaries, Na/K interdiffusion rates were probably enhanced (Yund 1983). This suggests that the microperthitic alkali feldspar crystals can be viewed in terms of deformation of a dispersed two-phase system where diffusion short-circuits along the domain boundaries, allowing accommodation of heterogeneous deformation by diffusion or dislocation climb, or both. This process is analogous to interface mechanism-controlled grain-boundary sliding (Ashby & Verrall 1973, Gifkins 1976), in which strain is concentrated at pre-existing heterogeneities (the grain boundaries) within a polycrystalline aggregate.

Deformation environment

Determination of deformation environments in natural systems is complicated by the fact that the microstructures used as evidence of the environment usually reflect some complex combination of metamorphic and deformational histories. Such determination is further hampered by the inherent difficulty of defining the syntectonic chemical parameters (activities and fugacities of chemical components, point defect chemistry, and so on) which affect deformation. This is especially true of the feldspars, with their complex chemical and structural properties.

The syntectonic metamorphic mineral assemblages within the mylonites place these feldspars at crustal depths in excess of 30 km during deformation, at temperatures in the vicinity of 750 °C (Thompson & Grundy 1984) and confining pressures around 900 MPa. These deep crustal conditions are thought to be the key to explaining the high single crystal strains observed in the feldspars. Temperature and pressure are directly related to dislocation creep strain rates through the diffusion coefficient D, where

$$D = D_0 \exp(-Q/kT) \exp(-P\Delta V^*/kT)$$

(after Lazarus & Nachtrieb 1963); Q is the activation energy, k is Boltzmann's constant, T is absolute temperature, P is pressure and ΔV^* is the activation volume. Hence, any diffusion-controlled process will proceed more rapidly at higher temperatures. Vacancy-controlled diffusion mechanisms should be slightly inhibited by high confining pressure. This results from the increase in the activation volume for vacancy self-diffusion with increasing pressure (e.g. Girifalco 1964). Note that the second bracketed term in the above equation is often much less than one, and is generally ignored.

Yund & Anderson (1978) measured oxygen diffusion rates in adularia in the presence of water, showing that diffusion rates were enhanced at higher pressures. Tullis & Yund (1980) experimentally deformed granite and polycrystalline albite rock, and showed a pressure dependence for hydrolytic weakening of the feldspars. Also, more rapid Al/Si disordering rates have been observed (Yund & Tullis 1980) in albite and microcline with increased pressure, water content and plastic strain. These authors also noted that mobile dislocations enhanced Al/Si interchange rates. Yund *et al.* (1981) measured oxygen diffusion rates in albite, showing that the presence of dislocations increased these rates.

As opposed to the direct effects of temperature and pressure on diffusion and strain rates, the influence of these parameters on point defect chemistry is probably of critical importance. The significance of electronic defects to the deformation of silicates has been discussed by several authors (Hobbs 1981, 1984, Kohlstedt & Hornack 1981, Jaoul *et al.* 1981, Jaoul 1984). Of particular interest is the work of Mackwell & Paterson (1985), who find that at temperatures of 800–1000 °C and pressures on the order of 1000 MPa, the incorporation into quartz of (OH) defects (which correlate with the hydrolytic weakening effect, Hobbs 1984) is strongly enhanced, and there is also a marked increase in the diffusion coefficient for this defect species. By analogy, similar behaviour may occur in the studied feldspars (though not necessarily involving the same defect species), allowing the very efficient climb of dislocations and diffusion implied by the observed microstructures. We favour the operation of a weakening effect which is activated by the interdependent action of a regionally extensive parameter, such as confining pressure, with a localized chemical parameter, such as the presence of trace amounts of 'water' (of whatever species). Evidence for this interdependence of regional and local weakening parameters is that very similar, though less intense, deformation effects are seen in feldspars of nearby, less hydrated, granulite facies gneisses (see General Geology section).

Exsolution must commence during the deformation for the feldspar microstructures to be syntectonic. Bulk compositions of the feldspar crystals are consistent with exsolution beginning at around 750 °C (Parsons & Brown 1983); this relatively high initial exsolution temperature is a result of the anorthite component of the alkali feldspars. Note however that the feldspars of Parsons & Brown (1983) exsolved at pressures of about 100 MPa. High confining pressure may likewise raise solvi such that exsolution can begin at high temperatures. Present compositions of the exsolved phases suggest that alkali diffusion continued during cooling to approximately 500 °C (Yund & Tullis 1983). Deformation during further cooling is thought to have been minimal, in that observed recovery structures are not common in reported examples deformed in this range of metamorphic temperatures, and dislocation movement is thought to cease totally by about 450 °C (Tullis & Yund 1980).

Sometime during the metamorphic/deformation history, grains, in whole and in part, transformed from orthoclase to microcline. On the TEM scale, there is the associated coarsening of the tweed texture. Both of these features are related to the transition from monoclinic to triclinic symmetry. Feldspar phase relations suggest that this should occur between 475 and 600 °C (Ribbe 1983b).

The changes in crystal symmetry and coarsening of the tweed texture in our samples are empirically linked to increasing intracrystalline strain. Similar observations have been made on perthites from other granulite facies terrains (Eskola 1952). Eggleton & Buseck (1980), in a study of alkali feldspars using high-resolution TEM, argue that Si/Al ordering during cooling can be halted by elastic strains caused by the formation of small triclinic domains which are forced to retain the original monoclinic crystal shape. Subsequent generation of dislocations released these elastic strains and allowed ordering to proceed. In support of this, Yund & Tullis (1980) show that order/disorder rates in albite and microcline are enhanced by mobile dislocations, whereas static dislocations have negligible effects on the rates. This apparent necessity for mobile dislocations to allow enhanced ordering rates (and thus the observed transformation of orthoclase to microcline) creates a dilemma with respect to the study samples, in that the significant deformation occurred well outside the expected stability field for microcline, at least at low pressures (Ribbe 1983b). Enhanced fluid-phase diffusion near grain boundaries during cooling has been used to explain preferential transformation of orthoclase to microcline (Raase 1976), but this does not explain the selective transformation of crystal cores that are intensely deformed; there still appears to be a direct link between the amount of host crystal strain and the tendency for microcline to develop.

The evolution of this microstructure and its implications to the deformation environment are as yet unclear, but the following possibilities are raised: (1) extreme intracrystalline deformation of K-feldspar under high pressure and temperature conditions, for which very few data exist, tends to allow more ordered and, subsequently, triclinic crystal volumes to form and be preserved, structures which are unstable or metastable at these conditions in the absence of such an externally-imposed strain (dynamic ordering); or (2) there is a fundamental change in the structure of highly deformed alkali feldspar crystals that is preserved during cooling, that allows significant Si/Al diffusion to continue at lower temperatures, eventually leading to development of microcline (static ordering). Such a change may involve a high frequency of dislocation walls that can act as high diffusivity paths (Cohen 1970), possibly in conjunction with a diffusion-enhancing point defect chemistry that is involved with these arrays of line defects (Hobbs 1981).

CONCLUSIONS

(1) Weakly-retrogressed mylonites from a deep-crustal shear zone contain alkali and plagioclase feldspars which have undergone, and preserve evidence of, extreme ductile deformation. Development of high finite strains in single crystals appears to be solely a function of deformation environment.

(2) Optical and transmission electron microstructures of the deformed alkali feldspar crystals show the co-existence of several syntectonic features. These include recovery substructures and recrystallization which are presumably linked to efficient dislocation climb, changes in Si/Al ordering textures (development and subsequent coarsening of tweed texture, and transition of K-feldspar from monoclinic to triclinic symmetry) and reorganization of exsolution domains involving Na/K and NaSi/CaAl interdiffusion. These features developed as the host crystals were accumulating significant ductile strain.

(3) The key to this anomalous (for feldspars) behaviour is thought to be the deformation environment, specifically the high temperatures and confining pressures involved and their possible effects on a deformation-enhancing point defect chemistry, similar to the well-known hydrolytic weakening effect in quartz. The presence of trace elements of 'water' during deformation is considered essential in allowing this behaviour.

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