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Deformation mechanisms in granitic rocks at shallow crustal levels

JAMES P. EVANS*

Department of Geology and Center for Tectonophysics, Texas A&M University, College Station, TX 77843, U.S.A.

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Abstract—Microstructural observations of naturally faulted granitic gneisses show that feldspar grains are weaker than quartz grains at temperatures below 325°C and at depths of less than 8–10 km. Feldspar grains sustained most of the deformation by grain-scale faulting, slip along cleavage-controlled fractures and cataclasis. Fracture of feldspar grains within fault zones promoted their alteration to kaolinite. Quartz grains also deformed by fracturing, and often healed to form quartz porphyroclasts and mosaics in a comminuted matrix of feldspar and kaolinite. Syntectonic alteration of the feldspar grains may have weakened the fault zones over time and resulted in foliated textures within the fault zones. This study of naturally deformed rocks confirms published experimental results on the behavior of granitic rocks at low temperatures and pressures and, taken together, these data show that the rheology of the upper 10 km of the crust is greatly influenced by cataclastic processes in feldspar.

INTRODUCTION

LITTLE work has focused on the deformation mechanisms in quartz and feldspar and the resulting textures in naturally deformed granitic rocks at low temperatures (<350°C) while, on the other hand, mechanisms and textures have been well documented in granitic rocks deformed at moderate to high temperatures and pressures. Quartz is weaker than feldspar under conditions of high pressure and temperature and controls the deformational fabrics of these rocks (Tullis & Yund 1977, Tullis 1983). Experimental work suggests that feldspars may be weaker than quartz at temperatures below 350°C, where crystal–plastic mechanisms are not activated (Tullis & Yund 1977, 1987). The microstructural observations and interpretations presented here provide insight into the processes of deformation in fault zones at shallow crustal levels.

Observation of fault-rocks in Precambrian gneisses of the Washakie Range, Wyoming, U.S.A., suggest that feldspars accommodated significant amounts of deformation during the formation of small- and large-displacement faults. The data presented here show that: (1) feldspar is weaker than quartz at low pressures and temperatures; (2) syntectonic alteration of the feldspar grains probably weakened the rocks over time; and (3) foliated fault rocks record brittle deformation of feldspar-rich rocks.

MACROSCOPIC DESCRIPTION OF THE FAULTS

The fault rocks discussed here formed in the Washakie thrust system of northwestern Wyoming (Love 1939, Winterfeld & Conard 1983). Faulted and folded Precambrian granitic gneisses in the cores of folds have been thrust 10–17 km to the southwest along thrust faults that dip 20–27° to the northeast (Evans 1986a). Reconstruction of cross-sections of the area suggests that fault zones now at the surface formed at a maximum depth of 8 km (Evans 1986b). All thrust and reverse faults and fault-related rocks described are demonstrably of Laramide (late Cretaceous to early Tertiary) age since the faults offset Paleozoic and Mesozoic strata. The faults were responsible for the emplacement of and deformation within the Washakie thrust sheets (Evans 1986b).

Two types of faults occur in the study area. Type 1 faults are narrow, small-displacement faults which accommodated internal deformation of the thrust sheets. Displacements along these faults range from the grain-scale to 30 cm. The faults are 1–10 cm wide and contain green, black or red fault gouge and light colored gneissic porphyroclasts. Gouge in these faults is well foliated and the boundaries between the fault zones and the protolith are sharp, often marked by slickenlines or polished fault surfaces.

Type 2 faults are wide, southwest-directed thrusts responsible for the emplacement and imbrication of the thrust sheets. Displacements along the thrust faults range from 0.1 to 4 km and individual fault zones are up to 250 m wide. Type 2 fault zones consist of discrete, anastomosing faults 10 cm to 6 m wide and lozenges of fractured and altered protolith. The faults are marked by highly comminuted, red fault gouge that is moderately to well foliated and contains rounded to elongate porphyroclasts of protolith gneiss. The boundaries between the fault zones and the fractured protolith lozenges range from sharp to gradational, and grooved, polished and slickenlined surfaces are common. The boundaries of the fault zones with the protolith are gradational and fracture intensity decreases away from the fault zones.

* Current address: Department of Geology, Utah State University, Logan, UT 84321-0705, U.S.A.

MICROSCOPIC OBSERVATIONS

Microscopic studies show that the type and abundance of deformation mechanisms and textures differ in: (1) the protolith gneiss; (2) the transition zone between the protolith and fault zones; (3) small-displacement (Type 1) faults; and (4) large-displacement (Type 2) faults.

Protolith

The protolith granitic gneisses contain approximately 38% quartz, 35% albite, 25% microcline and 2% kaolinite, by volume. Minor amounts of biotite, hornblende and opaque minerals also occur. There is little evidence for deformation in the protolith gneiss. Grain size ranges from 2 to 8 mm and the grains contain few cracks, subgrains, seams of recrystallized grains or undulose extinction. Feldspar grains have growth twins and very few cracks. The boundaries between the faults and the protolith are sharp, often cutting grains cleanly, and are marked by post-tectonic opaque minerals.

Transition zone

Deformation in the transition zone is concentrated in feldspar grains. The gradation from protolith to highly sheared fault rock occurs over a distance of 1–5 cm in the Type 1 faults and over 1–10 m in the Type 2 faults. Straight and stair-stepped inter- and intragranular fractures in feldspar grains appear along the (001) and (010) cleavages, at 30–60° angles to the cleavages or along twin planes (Fig. 1a). Intragranular fractures generally traverse one-quarter to one-half the width of a grain while intergranular fractures cut across several grains to an entire thin section. Intergranular fractures are sharp and straight, are filled by calcite, kaolinite and angular feldspar fragments, and are parallel and sub-parallel to the Type 1 faults.

Quartz grains are much less deformed than feldspar in the transition zone, exhibiting widely spaced fractures and mild undulose extinction. There are both open and healed fractures in the quartz grains; the latter are marked by bubble alignments (Fig. 1b). The fractures in the quartz grains rarely extend beyond grain boundaries (Fig. 1b) and are fewer in number relative to the feldspar (Fig. 3). In some cases fractures in feldspar grains terminate at quartz grain boundaries, healed fractures in the quartz grains appear to mark the continuation of the fracture.

Type 1 small-displacement faults

Feldspar grains experienced extreme cataclasis and alteration in the Type 1 faults, while the quartz grains exhibit less deformation than the feldspar grains. Angular fragments of plagioclase lie in the gouge while microcline grains have been almost completely altered to sericite or kaolinite (Fig. 1c). The altered microcline grains are lozenge-shaped and elongate, but the faint outlines of the parent grains and relict twinning patterns are in some places preserved. Kaolinite grains in the fault zones are kinked, folded and sheared (Fig. 1c). The gouge consists of 36% quartz, 31% plagioclase, 11% microcline, 16% kaolinite, 4% calcite and traces of biotite.

Quartz grains lie in elongate and irregularly-shaped porphyroclasts set in a matrix of fractured and altered feldspar grains in the small-displacement fault zones (Fig. 1c). Features that may indicate deformation mechanisms include open and healed fractures, undulose extinction and seams of small quartz grains near the edges of the larger grains. In some grains healed fractures mark the boundaries between grains with different optical orientation. The number of both open and healed fractures is much greater in the fault zone than in the protolith (Fig. 3) and quartz grain size is reduced by a factor of 4 in the Type 1 fault zones (Fig. 4). The undulose extinction and the seams of fine-grained quartz (<100 μm) may be evidence for crystal–plastic mechanisms and recrystallization or they more likely resulted from small-scale distributed fractures, micro-crush zones, pods of dissolved and subsequently re-precipitated quartz, or partially healed fractures. These alternatives cannot be distinguished at this scale of observation.

Type 2 large-displacement fault zones

Microstructures in samples from these faults are the same as those in the Type 1 faults, but all minerals

Fig. 1. (a) Photomicrograph taken in cross-polarized light of a fractured plagioclase grain. Fractures follow the (010) cleavage plane and albite twin planes (A), the (001) plane, or are at angles to these cleavages (B). Fractures within the grain are filled by very fine-grained plagioclase and phyllosilicates. Right half of the photo consists of angular fragments of plagioclase along the edge of a small fault. The scale bar in the upper left represents 0.25 mm. (b) Photomicrograph taken in cross-polarized light of fractured quartz in kaolinite cluster (K). Deformation in quartz consists of open cracks (OC) and healed cracks (HC), which cause the uneven extinction pattern in the quartz. The healed cracks are marked by bubble trains and are in some cases only partly healed, as shown by the lower HC. Highly fractured quartz along the left edge of the quartz grain lies in a matrix of kaolinite (K) and feldspar fragments. The scale bar in the upper right represents 0.25 mm. (c) Deformed kaolinite (K) cluster in a fault zone. Kaolinite grain extends between the white arrows. Kaolinite usually occurs as fine-grained clumps or strings in the fault zones. The amount and alignment of the kaolinite grains increases within larger displacement faults. Quartz (Q) occurs as large grains with healed microfractures (black arrows) or as small clusters of grains within the faults (denoted by the white Q on either side of the kaolinite grain). The scale bar in the upper left represents 0.25 mm. (d) Photo of an entire thin section with a narrow fault. This is a negative image, so that black regions are quartz (Q), grey regions are feldspars (F), and white material is fine-grained gouge or fracture fillings. Transgranular fracture (T) near the bottom of the thin section has subsidiary fractures which occur almost exclusively along cleavage planes in feldspars. The main fault in the thin section has sharp boundary (arrows) and a foliated texture defined by elongate quartz pods and faults.

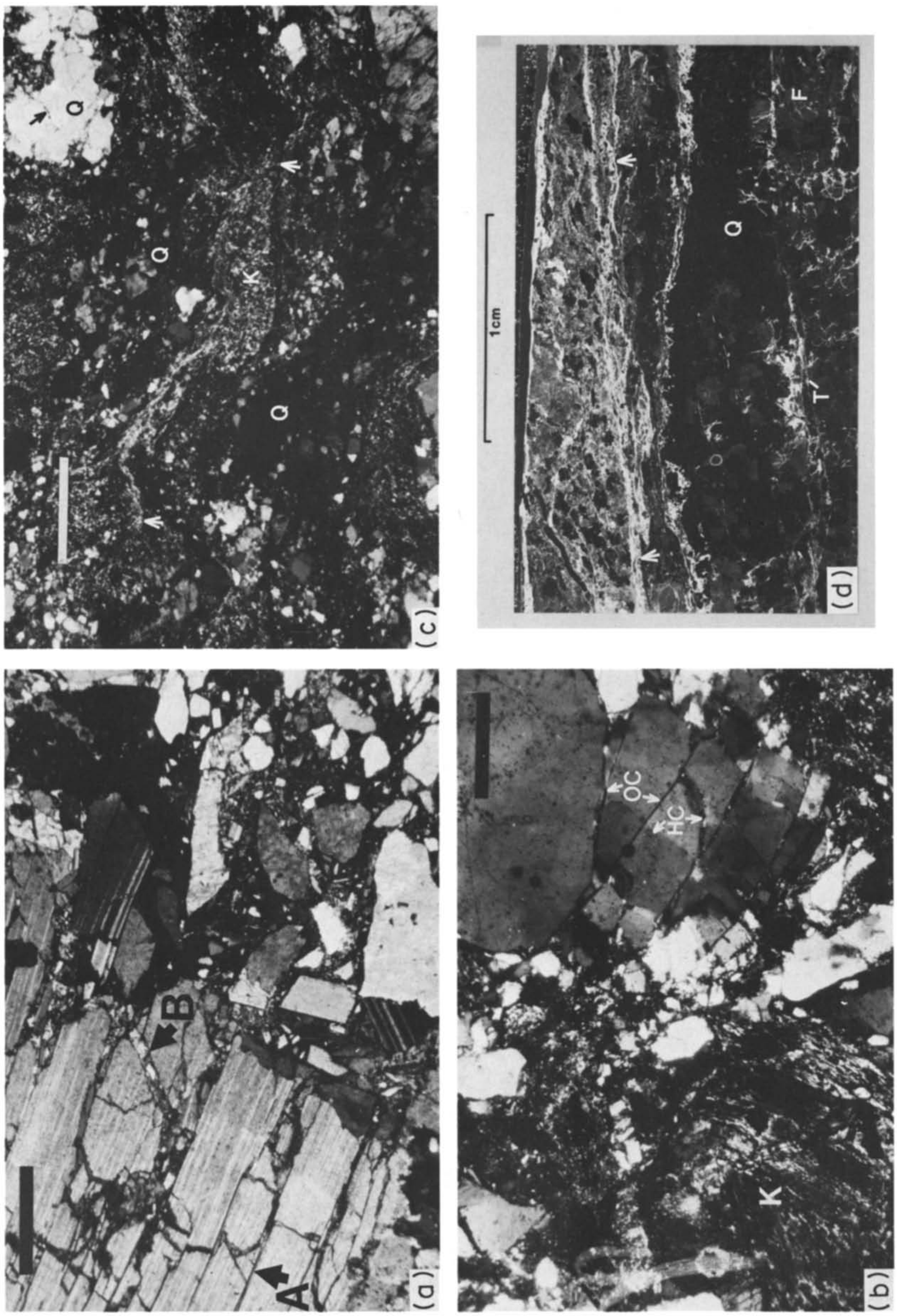

Fig. 1.

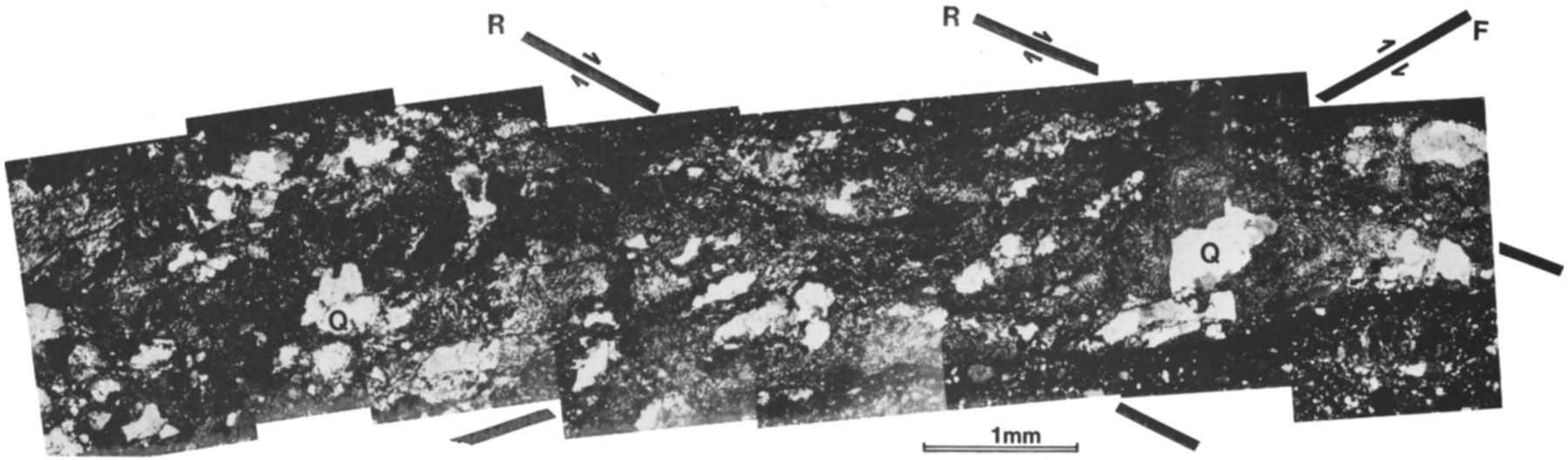

Fig. 2. Cross-polarized photomosaic of the top-right portion of the fault shown in Fig. 1(d). White elongate grains are quartz (Q) with healed microfractures and small zones of microcataclasite. These elongate regions are parallel and sub-parallel in the faults and define a foliated texture (*F*). The grey matrix around the quartz grains consists of sheared and altered feldspars. Top-to-the-right sense of shear is indicated by the development of an *R* shear plane developed at low angles to the shear zone boundary and foliation (*F*) in the fault zone (Petit 1987). This sense of shear agrees with the field relationships for offset along the fault.

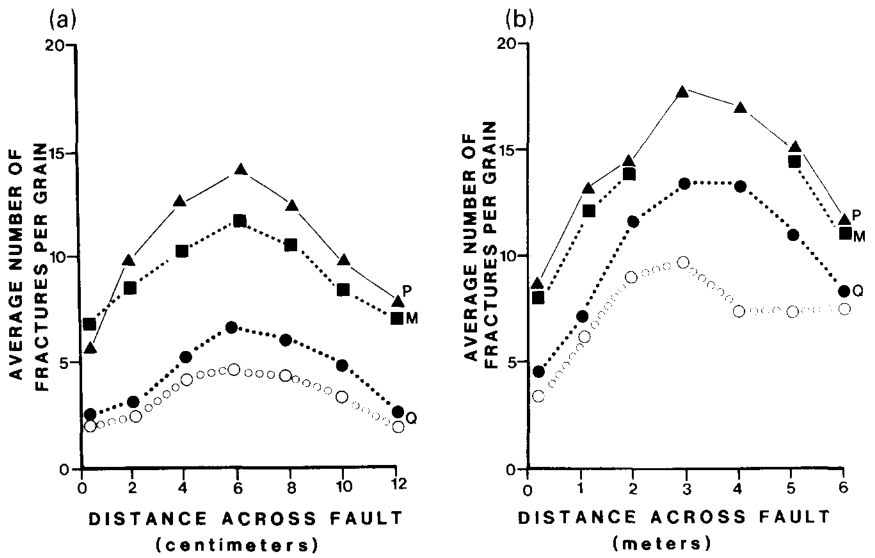

Fig. 3. Average fracture densities in feldspars and quartz across two faults. (a) Average number of fractures in plagioclase (P), microcline (M) and quartz (Q) for a fault 4-cm wide with a displacement of approximately 15 cm. Closed dots indicate all fractures (healed and open) in quartz, open dots indicate the open fractures in quartz. (b) Average number of fractures in plagioclase (P), microcline (M) and quartz (Q) for a fault 2.5 m wide with a displacement of 30 m. Number of fractures in feldspars in the fault could not be determined. In both faults the number of fractures in 50 grains of each mineral were measured in each of seven samples.

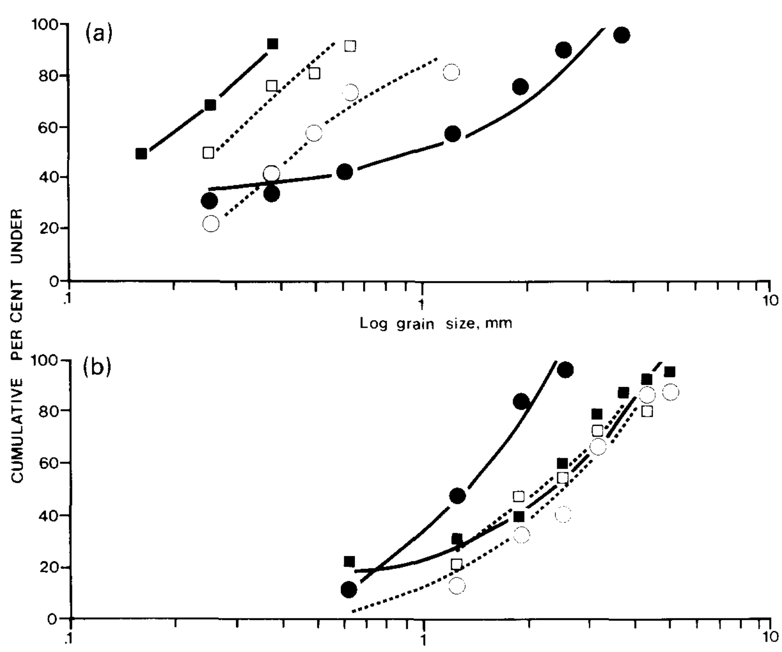

Fig. 4. Cumulative frequency curves of grain sizes from a 6 m wide fault zone. The long dimension of at least 50 grains of quartz and feldspar were measured with a petrographic microscope in each sample. Squares represent feldspar grain size, circles represent quartz grain sizes. Lines are least-squares best fit to the data. (a) Grain sizes in highly deformed gouge (solid symbols) and moderately deformed gouge rocks (open symbols). (b) Grain sizes in a sample along the edge of the fault zone (open symbols) and in the margin of the gradational transition from protolith to gouge zone (solid symbols). Feldspar decreases in grain size towards the center of the fault more than the quartz, indicating greater grain size reduction by comminution in the feldspar. Grain sizes may follow an approximately logarithmic normal distribution (see Sammis *et al.* 1986). A straight line would indicate a true logarithmic normal distribution.

involved show signs of greater deformation. Feldspar accommodated most of the deformation in these fault zones, exhibiting a large degree of grain size reduction (Fig. 4) via brittle fracture along with abundant chemical degradation. Semi-quantitative X-ray diffraction of samples from the large-displacement zones shows that the fault rocks consist of 38% quartz, 34% plagioclase, 19% kaolinite and 8% microcline, with traces of calcite and illite. Nearly a fifth of the fault-rock volume is occupied by kaolinite.

Deformation mechanisms in quartz grains include plastic deformation and fracturing. Evidence for both mechanisms are more abundant in the Type 2 than in the Type 1 fault zones, with quartz porphyroclasts composed of grains with optical mismatches, undulose extinction and fractures.

Plagioclase and quartz grains occur as angular fragments in a matrix of very fine-grained plagioclase and phyllosilicates. The mean grain size of all minerals is less in the large displacement faults than in the narrow faults, and very few microcline grains are identifiable at 400× magnification. Grain size distribution within a wide fault zone shows that, in general, feldspar experienced comminution to a finer grain size than did quartz (Fig. 4). The grain size data from the fault zone indicates that cataclasis resulted in a logarithmic normal grain size distribution within the fault zones for both quartz and feldspar (Fig. 4).

The foliation in the fault gouge is defined by alignment of phyllosilicates, segregation and elongation of minerals and clusters of minerals, fractures and faults which are nearly parallel to the fault boundaries, and seams of secondary and opaque minerals in the faults (Figs. 1d and 2). The opaque minerals and hornblende deformed by fracture, while biotite was sheared and altered to chlorite. This released iron and magnesium into the fault rocks to give the faults their characteristic reddish/black color. There is no evidence that the seams of opaques were the result of diffusive mass transfer. Cataclasis and subsequent syntectonic alteration of microcline produced the foliated gouge. The development of phyllosilicates was syntectonic, rather than pre- or post-tectonic, because: (1) there is an increase in the amount of phyllosilicates with increased feldspar deformation; (2) alignment of kaolinite grains increases with increased strain in the faults (Figs. 1c,d and 2); (3) little kaolinite or weathering rim on feldspar is observed in the protolith; and (4) phyllosilicates are kinked, folded and locally faulted. Kink bands and folds are present nowhere in deformed feldspar grains, and thus it is unlikely that feldspar has been replaced by kaolinite after deformation.

The most common alteration product is kaolinite, which occurs both in the fault zones and in fractures within deformed protolith. The kaolinite is primarily derived from the microcline, as it fills fractures in the microcline but is uncommon in other minerals. Garrels & Christ (1965) describe the reaction of the alteration of microcline to kaolinite as:

$$\underset{\text{microcline}}{2KAlSi_3O_8} + 2H^+ + 9H_2O = \underset{\text{kaolinite}}{Al_2Si_2O_5(OH)_4} + \underset{\text{dissolved silica}}{4H_4SiO_4}.$$

At higher temperatures (>100°C) microcline may first react with water to form pyrophyllite, which in turn reacts to form kaolinite (Hemley *et al.* 1980). In any case, kaolinite will not be stable above approximately 300°C and this further constrains the depth of fault development to less than approximately 10 km. These reactions consume water and produce excess silica. Independent evidence for fluids in the faults of the Washakie Range is provided by the fluid-filled bubble trains commonly found in the quartz grains. Excess silica may have been deposited in the small seams of quartz and/or deposited as veins near the faults. The presence of syntectonic kaolinite derived from the feldspar grains in the protolith suggests faulting took place at temperatures of less than 300–325°C (Montoya & Hemley 1975, Hemley *et al.* 1980).

DISCUSSION AND CONCLUSIONS

The microstructures of the fault-related rocks described here are a result of crystallographically-controlled fracture in feldspar grains followed by cataclasis and syntectonic alteration. Quartz grains deformed by fracture and possibly crystal–plastic mechanisms, but to a lesser extent than the feldspars. Water must have been present during deformation to allow the alteration of the feldspar grains and the healing of fractures in the quartz grains.

These observations suggest that the faults first developed by early cleavage-controlled fracture of feldspar which provided surface areas for alteration to phyllosilicates (Mitra 1978, Mitra & Frost 1981). Continued fracturing further reduced the grain size of the feldspar grains and promoted increased alteration of the feldspar grains to kaolinite. This probably weakened the fault zone since slip on phyllosilicates is relatively easy. The quartz grains in the faults were stronger than the feldspars and tended to fracture and re-heal within a matrix that, with progressive deformation, consisted more of phyllosilicates and less (in size and amount) of microcline and plagioclase. The cross-cutting healed fractures in the quartz grains show several episodes of fracturing and healing during the faulting process, similar to the situation described by White & White (1983). These processes took place at temperatures below 325°C in a hydrated environment. Alteration of feldspars to kaolinite, alignment and segregation of minerals and the cataclastic deformation of quartz grains produced a foliated cataclasite (Chester *et al.* 1985).

Borg & Handin (1966) showed that feldspars within gneisses and single feldspar crystals fractured along cleavage planes at a variety of pressures and temperatures. Through-going faults seemed to be unaffected by the presence of the cleavage cracks, but significant amounts of strain were accommodated in the samples by fracture of feldspar grains. Tullis & Yund (1977) suggest that below 250–350°C, where the dominant deformation mechanism is grain-scale fracture, feldspars sustain more deformation than quartz. Dislocation mobility in quartz grains and feldspar is low at low temperatures, and fracture along feldspar cleavage is easier than fracture in quartz (Tullis 1983). Thus, evidence from both experimentally and naturally deformed rocks suggests that feldspars are weaker than quartz at low temperatures where crystal–plastic mechanisms are not the dominant deformation mechanism. This indicates that the mechanical behavior of faults at shallow crustal levels is a function of the deformation mechanisms and strengths of feldspar and quartz, and is not solely dependent on deformation of quartz grains.

The data presented here document the deformation mechanisms in granitic rocks deformed at temperatures of no greater than 325°C and at maximum depths of 8–10 km. The initial stage of deformation in the fault zones was the cleavage-controlled fracture in feldspar. Quartz grains deformed by fracture and possibly minor crystal–plastic mechanisms. Feldspar was weaker than quartz grains in all samples examined regardless of the alteration state of the feldspar. Alteration of feldspar to kaolinite occurred after initial fracture, and as cataclasis increased, the alteration likewise increased. Continued fracture and cataclasis during fault zone evolution may have produced enough porosity and permeability to allow fluids to penetrate the feldspar grains and cause nearly complete alteration. Weakened feldspar grains and their alteration products weakened the fault zones, thereby making slip along the faults easier over time.

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