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Hydrolytic weakening of experimentally deformed Westerly granite and Hale albite rock

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Abstract—In order to determine the effect of water on deformation in the brittle-ductile transition region of crustal rocks, experiments have been conducted on Westerly granite and a polycrystalline albite rock, comparing samples dried at 160°C for 12 h ('dry') and samples with about 0.2 wt% water added ('wet'). The deformation mechanisms and style of deformation of the wet and dry samples, determined using optical and transmission electron microscopy, have been found to depend on temperature, pressure, strain rate, and strain. At 15 kb and 10^{-6}, the added water reduces the temperature of the transition between microcracking and dislocation glide and climb by about 150–200°C for both quartz and feldspar. However, the penetration of 'water' into the grains is slow compared with the time of the experiments and many of the wet samples show evidence of initial microcracking and later dislocation creep. Wet samples deformed at 10 kb show less hydrolytic weakening than wet samples deformed at 15 kb. Because the deformation mechanism and strength of silicates depend so sensitively on trace amounts of water, and because the water content of experimental samples varies with temperature and pressure and thus with time, flow laws for any samples are only meaningful if the water content has been carefully controlled or characterized.

INTRODUCTION

WATER is known to affect the deformation of crustal rocks in several ways. In the brittle regime, cracking and faulting are enhanced if there is enough water present so that the fluid pressure reduces the effective confining pressure (e.g. Terzaghi 1936). Trace amounts of water can also enhance brittle deformation by causing stress corrosion at crack tips, thus making crack propagation easier (e.g. Anderson & Grew 1977). Water apparently aids solution transfer processes ('pressure solution') (e.g. McClay 1977). Trace amounts of water can also cause hydrolytic weakening within the higher temperature and pressure regime where dislocation glide and climb are operative (e.g. Griggs 1967). Thus trace amounts of water can decrease the strength of a rock and increase the strain rate for a given stress, in both the brittle and ductile regimes.

The brittle–ductile transition for dry Westerly granite has been determined by Tullis & Yund (1977) (henceforth referred to as T & Y). In this paper, 'dry' will refer to samples dried overnight on a hot plate at 160°C and then mechanically sealed in a Pt tube. Over a wide range of temperatures and pressures, at a constant strain rate of 10^{-6}/s, T & Y found that both quartz and feldspars show a transition from dominantly microcracking at lower temperatures to dominantly dislocation glide and climb at higher temperatures. The transition is approximately 200°C lower for quartz than for feldspar. In the present study we have determined the effect of adding trace amounts of water on deformation in the brittle–ductile transition region, as a function of temperature, pressure, strain, and strain rate, for experimentally deformed Westerly granite and a polycrystalline albite rock. The results have important implications for the deformation of quartz and feldspar-bearing crustal rocks.

EXPERIMENTAL DETAILS

Westerly granite has been used in many previous studies and is well-described (e.g. Brace *et al.* 1965); it has a grain size of about 0.75 mm. The Hale albite rock is a pure, polycrystalline albite rock from the Hale pegmatite quarry near Middletown, Connecticut. It has a composition of $Ab_{96}An_3Or_1$ and an average grain size of about 0.2 mm. The sample assemblies and apparatus were the same as described previously for the dry Westerly granite experiments (T & Y). However, in this study the sample cores were vacuum impregnated with distilled water for two days; this should allow complete penetration of water along the pores of Westerly granite, given the permeability for this rock (Brace *et al.* 1965). The samples were allowed to air dry for a few hours until the net amount of water added was about 0.2 wt%, comparable to the amount of water in the structure of a 'wet' synthetic quartz crystal (Griggs 1967). The samples were then mechanically sealed in a Pt tube by fringing the ends of the tube which project about 0.5 in. beyond the ends of the sample, and folding these over $\frac{1}{4}$ in. Pt discs which were placed against the ends of the sample.

The experiments were done at a constant strain rate of 3×10^{-6}/s, except where otherwise noted. Most of the experiments were done at a confining pressure of 15 kb, at temperatures from 300–600°C (see Table 1 for experimental conditions). This temperature range spans the dry transition from microcracking to dislocation glide and climb for both quartz and feldspar (T & Y). Additional experiments to test the effect of pressure were done at 10 kb.

In order to maintain the water in the sample capsules, some pressure was applied while they were still at room temperature. Samples were taken to 5 kb confining press-

Table 1. Conditions of deformation experiments on wet Westerly granite and wet and dry Hale albite

Sample	Conf. pres. (kb)	Temp. (°C)	Weight % H_2O added	Strain rate (s^{-1})	$(\sigma_1 - \sigma_3)$ at 5% ε (kb	Axial strain (%)	Comments*
Wet Westerly granite							
W-121	15	300	0.23	3×10^{-6}	17	15	V, P
W-120	15	400	0.20	3×10^{-6}	9	28	V, P, F
W-34	15	500	0.17	3×10^{-6}	11	15	D, F
W-128	15	500	0.22	3×10^{-6}	12.5	15	V, P
W-119	15	600	0.27	3×10^{-6}	5.5	17	V, P
W-93	10	400	0.22	3×10^{-6}	11.5	20	D, P, F
W-69	10	500	0.23	3×10^{-6}	5	23	D, F
W-135	10	400	0.28	3×10^{-6}	8.5	27	V, P
W-68	10	700	0.12	3×10^{-6}	6.5	19	V, P
W-195	15	700	0.26	—	—	—	V, P
Wet Hale albite							
W-110	15	600	0.28	3×10^{-6}	15.5	11	D
W-111	15	600	0.24	3×10^{-6}	11.5	16	D
W-115	15	600	0.34	3×10^{-6}	8.5	40	D
W-64	15	700	0.09	3×10^{-6}	4	24	D
W-123	15	800	0.12	3×10^{-6}	4	24	V, P
W-125	15	800	0.22	3×10^{-5}	6	20	V, P
W-122	15	800	0.17	3×10^{-4}	6	40	V, P
Dry Hale albite							
W-26	15	600		3×10^{-6}	18.5	14	
W-255	15	600		3×10^{-6}	17	39	
W-23	15	700		3×10^{-6}	15	14	
W-29	15	700		3×10^{-6}	16	29	
W-37	15	700		3×10^{-6}	9.5	20	F
W-30	15	800		3×10^{-6}	13	18	
W-76	10	800		3×10^{-6}	10.5	24	
W-107	15	900		3×10^{-6}	4	21	
W-109	15	900		3×10^{-6}	3.5	45	
W-147	10	900		3×10^{-6}	4.5	20	

* V indicates sample was vacuum impregnated with about 0.2 wt% water.
D indicates 1–2 drops of water were placed inside Pt jacket with sample.
P indicates sample was preheated at 700°C for 24 h, at the pressure of subsequent deformation.
F indicates sample developed through-going fault.

ure, then to 300°C, then to 15 (or 10)kb, and then to 700°C where they were held for 24 h prior to deformation, in order to allow a better equilibration of the water, at least along grain boundaries. Preheating of the Westerly granite samples was not done at higher temperatures because partial melting should result. No evidence of partial melt was seen in any of the experimental samples.

The mechanism and rate of diffusion of the added water along grain boundaries and into the volumes of the grains is not known. Hydrogen diffusion appears to be much faster than oxygen diffusion, at least in quartz (Katz *et al.* 1962), but our experiments indicate that either hydrogen diffusion alone is not sufficient for 'water' penetration or its concentration in these experiments is very low. Several studies of oxygen isotope exchange in feldspars show that it is much faster for hydrothermal than for dry experiments (Yund & Anderson 1974), indicating that hydrogen or protons must be involved in the migration of oxygen, either diffusing with oxygen as OH^- or separately. For simplicity we will refer to 'water' diffusion and concentration in the grains, although we recognize that the diffusing species and its atomic mechanism are unknown. The data of Giletti *et al.* (1978) for oxygen isotope exchange between feldspar and water at 1 kb show that at 700°C and 24 h only a few percent isotopic equilibration will occur for a grain size of 0.7 mm. The slow diffusion of 'water' into the grains in these wet experiments appears to be consistent with the experimentally determined diffusion rates for 'oxygen' under hydrothermal conditions. Even allowing for increased 'oxygen' exchange at higher pressure (Yund & Anderson 1978) and an effective diffusion radius considerably smaller than the average grain size, due to cracking, it appears that only limited 'water' penetration into the grains would have occurred during the preheat. Thus the water must be inhomogeneously distributed within the sample at the beginning of the deformation.

Deformed samples were impregnated in epoxy and sawn in half along the axis of the sample cylinder. Standard petrographic thin sections were made from each half; one was used for optical observations and one for TEM observations. Samples were examined using a JEM-7 or a Siemens 101 instrument operating at 100 kV. The orientation of the TEM micrographs relative to the local or applied maximum stress is not known in most cases, and is not really pertinent to this study.

RESULTS

All of the wet samples have a lower yield strength and a lower modulus than those of their dry equivalents (Fig. 1). We have no direct measure of the fluid pressure in these experiments. The roughly 0.2 wt% water added only occupies one third the original pore space in the Westerly granite (Brace *et al.* 1968), and this rock has been shown to have the same porosity at 400°C and 5 kb as it does at room pressure and temperature (Sprunt & Brace 1973). Considering the isospecific volume curves for water (Burnham *et al.* 1969), it appears that the fluid pressure in these experiments must have been low. A few of the wet samples did develop through-going faults (Table 1), and perhaps for these samples the fluid pressure was higher. It is impossible to add exactly the same weight percent water to each sample, or to be sure that the entire amount weighed has remained in the capsule to high temperature and pressure; thus there may be variations in water content between samples. In comparison with experiments on dry samples (T & Y), the observation that the majority of wet samples did not develop faults suggests that the fluid pressure was generally less than 5 kb.

Wet samples deformed at the same conditions do not always show reproducible strengths; this is believed to be due to variations in the amount of water present. For example three samples of Hale albite rock were deformed wet at 600°C, and they had quite different strengths (Fig. 1c). Two of them had the same weight percent water added (Table 1), but one (W-110) had the temperature inadvertently raised before the pressure for a brief time, probably boiling off some of the water, and this sample is indeed stronger. The third sample had a greater weight percent water added and is weakest.

If the fluid pressure was low, then the lower strength shown by the wet samples must be due largely to the effect of water on the grain-scale deformation mechanisms, namely microcracking and dislocation glide and climb. Evidence for this comes from comparison of optical and especially TEM microstructures in the wet samples with those previously observed (T & Y) in dry samples deformed at the same conditions. T & Y observed that for both quartz and feldspar, the microstructures as a function of increasing temperature were: abundant microcracks; abundant microcracks with some dislocations inhomogeneously distributed in planar zones; higher but still inhomogeneous densities of tangled dislocations with fewer microcracks; a cellular substructure of dislocations with rare microcracks; a lower uniform density of straighter dislocations with subgrains and no microcracks; and a uniform density of straight dislocations with recrystallized grains. By comparing the number, character and distribution of the microcracks and dislocations in the wet and dry samples, for both the quartz and the feldspar, we have attempted to evaluate whether both are equally affected by the added water, or whether the temperatures for any or all of the above microstructural transitions are changed.

There are certain obvious differences in the optical microstructures between the wet and dry samples. The wet samples of both Westerly granite and Hale albite rock show a more inhomogeneous deformation. Even in the dry granite samples, the presence of three different minerals of contrasting rheology results in deformation which is inhomogeneous both within and between grains (T & Y), and this is amplified for samples deformed in the microcracking—dislocation creep transition region. However, in wet granite samples deformed at 400–600°C the deformation is even more inhomogeneous. In a wet sample deformed at 400°C, 15 kb, for example, some quartz grains appear relatively undeformed (Fig. 2a), the same as do all of the quartz grains in the equivalent dry

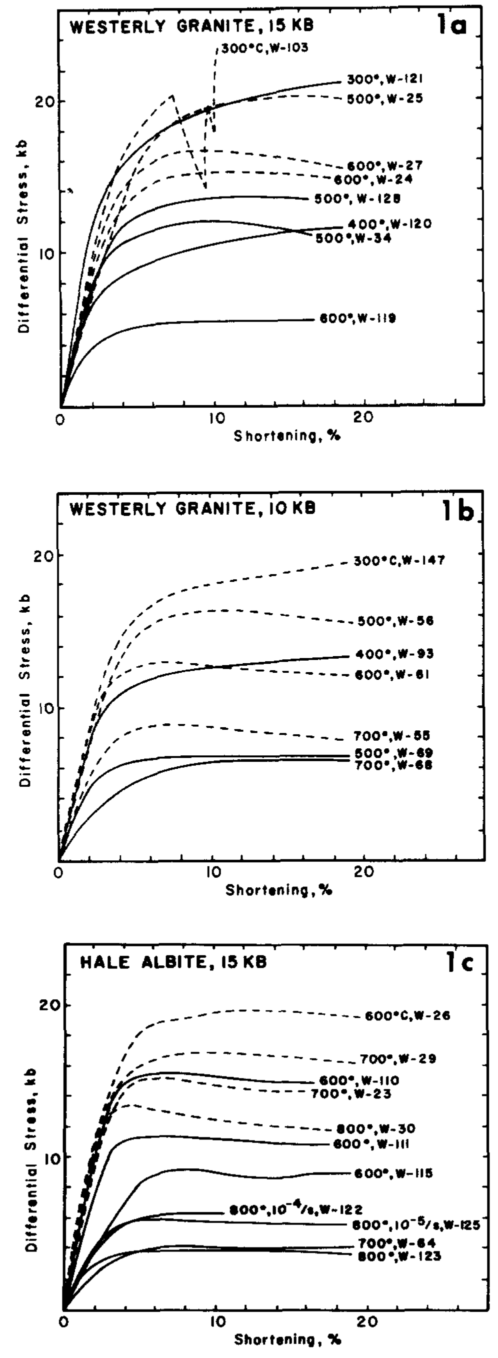


Fig. 1. Stress–strain curves for wet (solid lines) and dry (dashed lines) Westerly granite and Hale albite rock. All experiments were done at a constant strain rate of 3×10^{-6}/s, except where otherwise labelled. In all cases the wet samples have a lower strength than dry samples deformed at the same conditions. (a) Curves for Westerly granite deformed at a confining pressure of 15 kb. (b) Curves for Westerly granite deformed at a confining pressure of 10 kb (c) Curves for Hale albite rocks deformed at a confining pressure of 15 kb.

specimen. However, other grains show greater deformation with some evidence of recovery (Fig. 2b), and still others contain both regions with little or no deformation, and regions with greater deformation and recovery (Fig. 2c). The more deformed and recovered grains, which are inferred to reflect hydrolytic weakening, often occur at the ends of the sample or along fractures or faults extending all or part way through the sample. This suggests that inhomogeneous penetration of water has caused part of the inhomogeneous deformation in the wet samples.

The wet samples also show a wider range of deformation behaviour than is seen in equivalent dry samples; at some conditions they may show both grain-scale faulting and syntectonic recrystallization. In all of the wet samples there is some evidence of grain-scale faulting and cracking, more than is shown by equivalent dry samples. However, most of the wet samples show an additional and apparently later plastic deformation which appears to be 'higher temperature' in nature than that seen in equivalent dry samples. Gradual penetration of water into the grains is believed responsible for this deformation mechanism switch and for the resulting wider range of deformation behaviour in the wet samples.

We have made TEM observations on a number of grains from each wet sample, including those that optically show very little deformation and those that show extensive deformation and recovery. The deformation of the wet samples is very inhomogeneous on the TEM scale as well. In all of the wet samples, both quartz and feldspar show some crush zones and microcracked regions, but the dislocation substructure in the intervening regions varies regularly with temperature. It commonly appears that the brittle features were produced early in the deformation, and the dislocations were produced later. In the following summary of our observations, the TEM observations for wet samples represent the average behaviour of the given mineral in the regions between the relatively widely spaced crushed and cracked zones, and these are compared with the average behaviour in an equivalent dry sample.

Effect of temperature

At 15 kb and 10^{-6}/s we have done wet experiments at 300, 400, 500, and 600°C on Westerly granite (Table 1). This temperature interval encompasses the 'wet' microcracking—dislocation glide and climb transition for quartz but not for feldspar. Because wet experiments on granite at higher temperature would produce partial melt, we have done additional wet and dry experiments on Hale albite rock at 600, 700, and 800°C. The deformation microstructures observed in the wet experiments are briefly described below as a function of increasing temperature, and in each case are compared with the features seen in equivalent dry experiments.

At 300°C both the quartz and the feldspar in the wet granite sample appear optically similar to the equivalent dry sample; the quartz grains show sharp deformation bands and the feldspar grains show grain-scale faulting. TEM observations of the feldspar show the same microstructures (few dislocations, abundant microcracks and crush zones) as seen in the dry samples. However, the quartz in the wet sample has irregular areas of high dislocation density (Fig. 3b) in addition to abundant microcracks, whereas dry samples show only irregular, low dislocation densities (Fig. 3a), and dominantly cracks.

At 400°C the wet granite sample has a very sharp through-going fault (Fig. 2b). For dry samples at 5 kb, sharp faults are characteristic of temperatures $\geqslant 600$°C (T & Y), whereas at 400°C dry samples develop a much wider fault zone. Optically, a few quartz grains in the wet sample which lie along the fault appear to show a higher temperature style of deformation, with evidence of more homogeneous slip and even recovery (Fig. 2b), but the other quartz and feldspar grains appear essentially the same as in the dry sample (Fig. 2a). However, even quartz grains which optically do not appear to show any effect of water contain a relatively uniform and quite high density of tangled dislocations, characteristic of quartz from dry samples deformed at 500–600°C, in addition to some microcracks. Similarly, TEM shows that the feldspars have irregular areas of high dislocation density (Fig. 6a) in addition to abundant microcracks; in dry samples these are not seen at 400°C, but are characteristic at 500–600°C.

At 500°C, there is little optically detectable difference between the feldspars of the wet and dry samples although the former show somewhat more grain-scale faulting. A number of quartz grains in the wet sample show evidence of slip and recovery (Fig. 2c), whereas those in the dry sample do not. TEM of quartz in the wet sample shows higher and more uniform dislocation densities than are seen in equivalent dry samples. TEM of feldspar in the wet sample shows abundant although inhomogeneously distributed dislocation tangles in addition to common microcracks, whereas in equivalent dry samples there are abundant microcracks and only a few dislocations.

At 600°C both the quartz and the feldspar show evidence of enhanced slip and recovery. Optically the feldspars in the wet sample show some grain-scale faulting, but more deformation bands than those in dry samples. Almost all of the quartz grains in the wet sample are fairly homogeneously deformed and show abundant recovery (Fig. 2d) and even local recrystallization, whereas in dry samples the deformation is variable within and between grains, and there is little or no evidence of recovery. TEM shows that the feldspars from the wet sample have a high and fairly uniform dislocation density (Fig. 4a). In dry samples the dislocation density is much lower and less uniform (Fig. 4b), and there are abundant microcracks. TEM also shows that the quartz from the wet sample has a high and fairly uniform dislocation density with subgrains (Fig. 4c), whereas that from a dry sample has an irregular high density of tangled dislocations (Fig. 4d). Our results for the wet Hale albite rock deformed at this temperature are consistent with our observations of the feldspars in the wet granite samples.

At 700°C, the dry Hale albite sample shows extensive grain-scale faulting (Fig. 2e), whereas the wet sample is more inhomogeneously deformed, and shows evidence of both grain-scale faulting as well as slip and recovery (Fig.

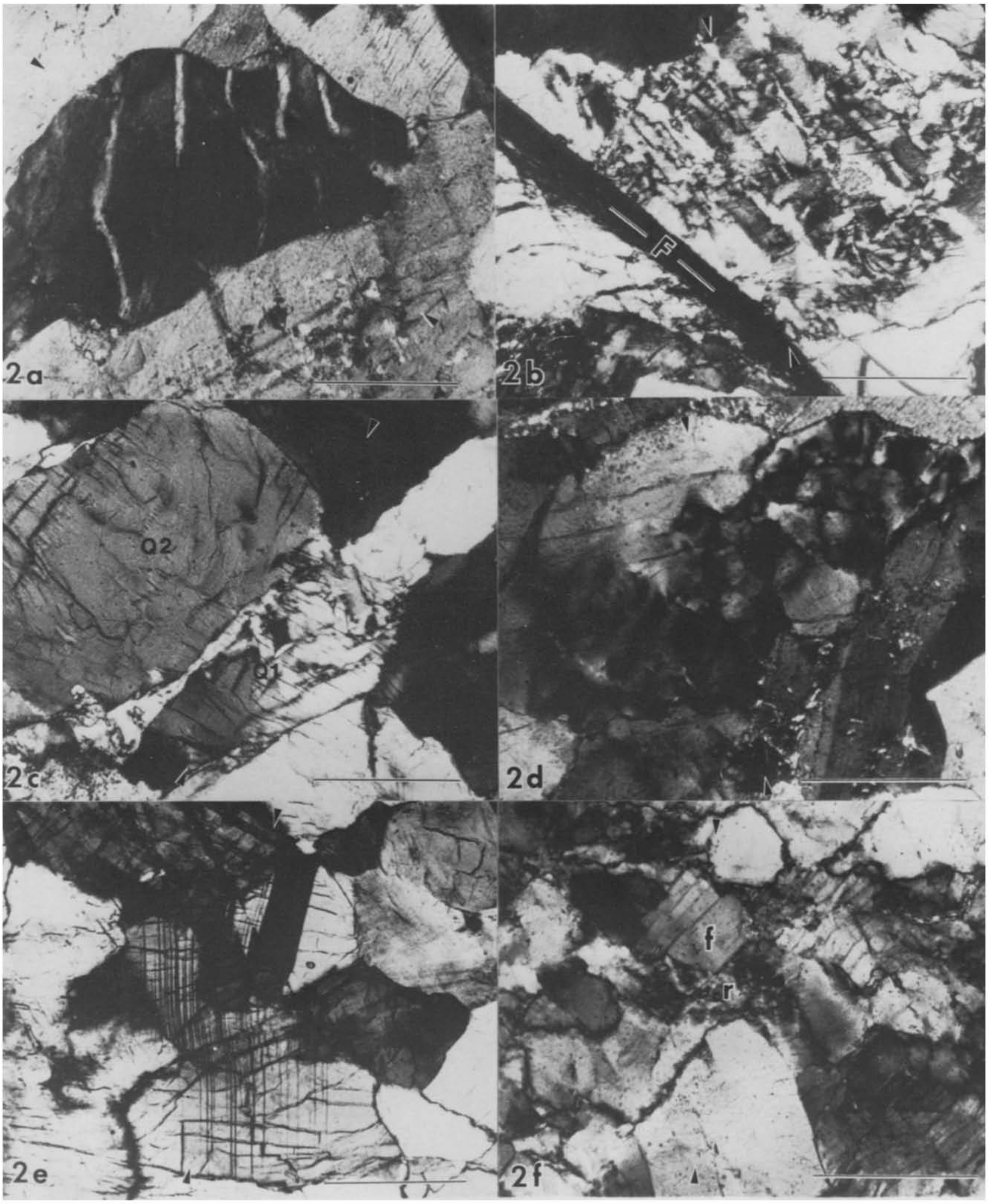
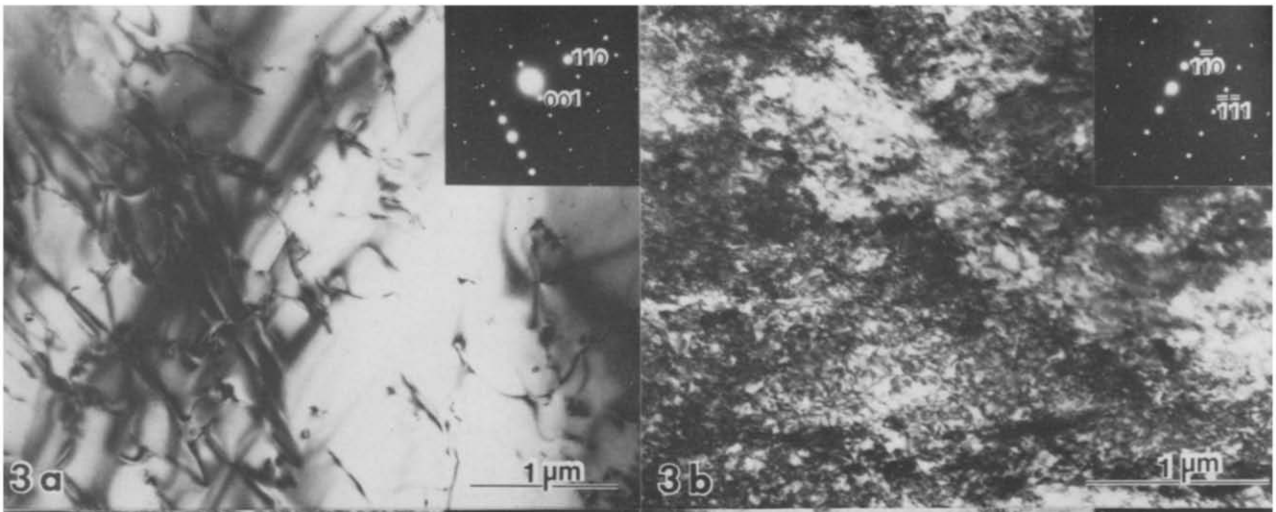


Fig. 2. Optical micrographs from samples of Westerly granite and Hale albite rock deformed at 15 kb and 3 × 10^{-6}/s. Scale bar is 0.2 mm. The direction of sample shortening is indicated by the black arrows. (a) Typical quartz grain from sample of Westerly granite deformed wet at 400°C; it shows a few thin deformation bands, but little evidence of recovery, and is similar to quartz in a sample deformed dry at the same conditions. (b) Quartz grain along a through-going fault (labelled F) in the same sample; it shows substantial deformation and recovery (note the relatively sharp internal boundaries). (c) Quartz grain from a sample of Westerly granite deformed wet at 500°C; the portion of the grain on the lower right (Q1) shows substantial deformation and recovery, but the larger portion on the upper left (Q2) shows none, perhaps reflecting inhomogeneous penetration of water into grains. (d) Quartz grain (occupying most of NW half of photo) from sample of Westerly granite deformed wet at 600°C, showing extensive subgrain development. (e) Hale albite rock deformed dry at 700°C; note grain-scale faulting shown by offset twins. (f) Hale albite rock deformed wet at 700°C; there is evidence of earlier grain-scale faulting (e.g. at f) and later plastic deformation, recovery, and recrystallization (fine-grained material along boundaries, e.g. at r).



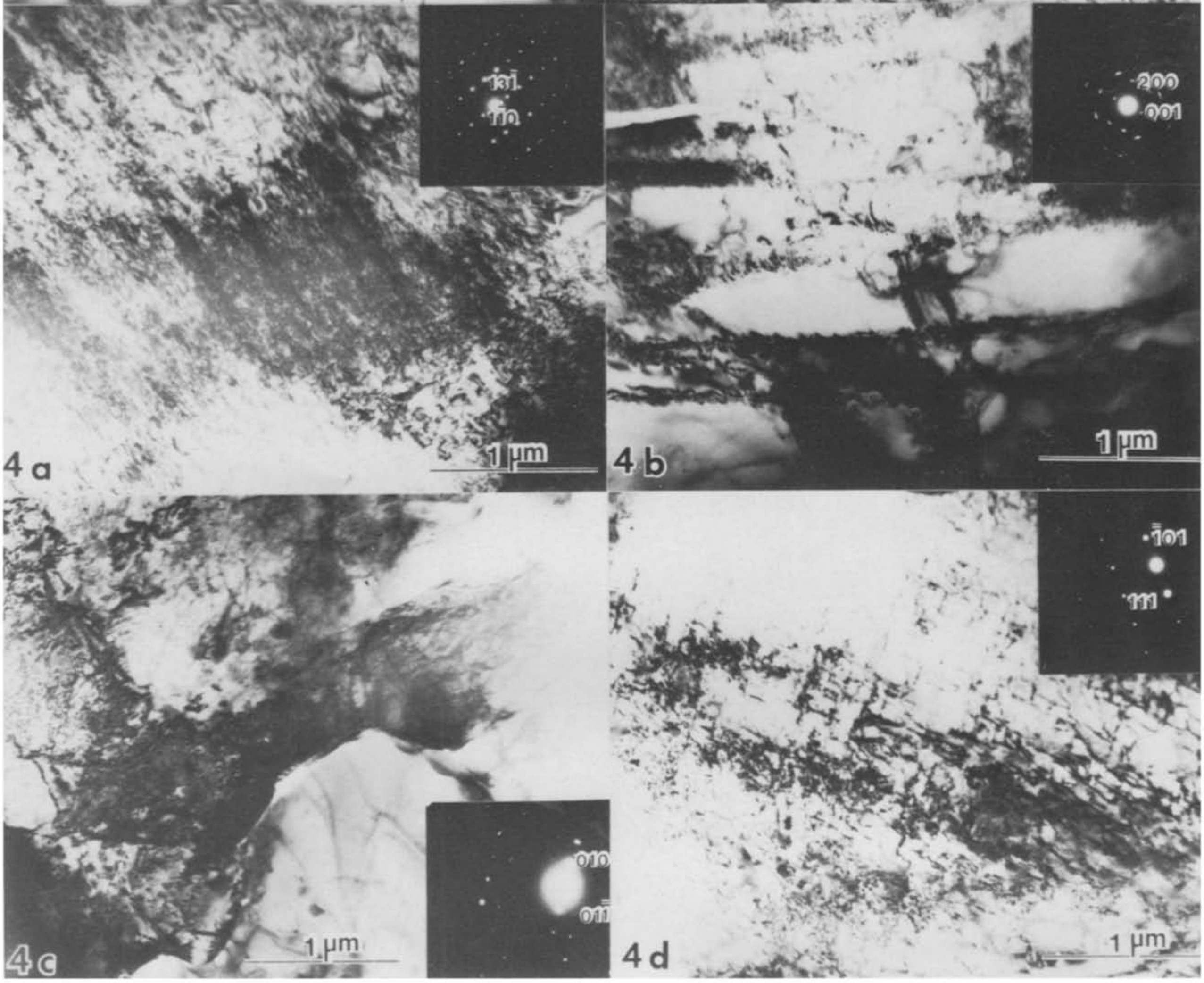


Fig. 3. TEM bright-field micrographs of quartz from Westerly granite deformed wet at 300°C, 15 kb, and 3×10^{-6}/s. The deformation in this sample is very inhomogeneous on a grain-scale. Quartz reflections are indexed on a hexagonal unit cell. (a) shows a region of low dislocation density which is about the highest density observed in a sample deformed dry at these conditions. (b) shows a region of much higher dislocation density, not uncommon in this wet sample, but never seen in an equivalent dry sample.

Fig. 4. TEM bright-field micrographs of feldspar and quartz deformed wet and dry at 600°C, 15 kb, and 3×10^{-6}/s. Both minerals in the wet sample show evidence of hydrolytic weakening. Quartz reflections are indexed on a hexagonal unit cell. (a) Typical feldspar grain from the wet sample, with a high and uniform dislocation density. (b) Typical feldspar grains from the dry sample, with a lower, non-uniform dislocation density. (c) Typical quartz from the wet sample, with subgrains indicating recovery. (d) Typical quartz from the dry sample, with a high dislocation density but not subgrains.

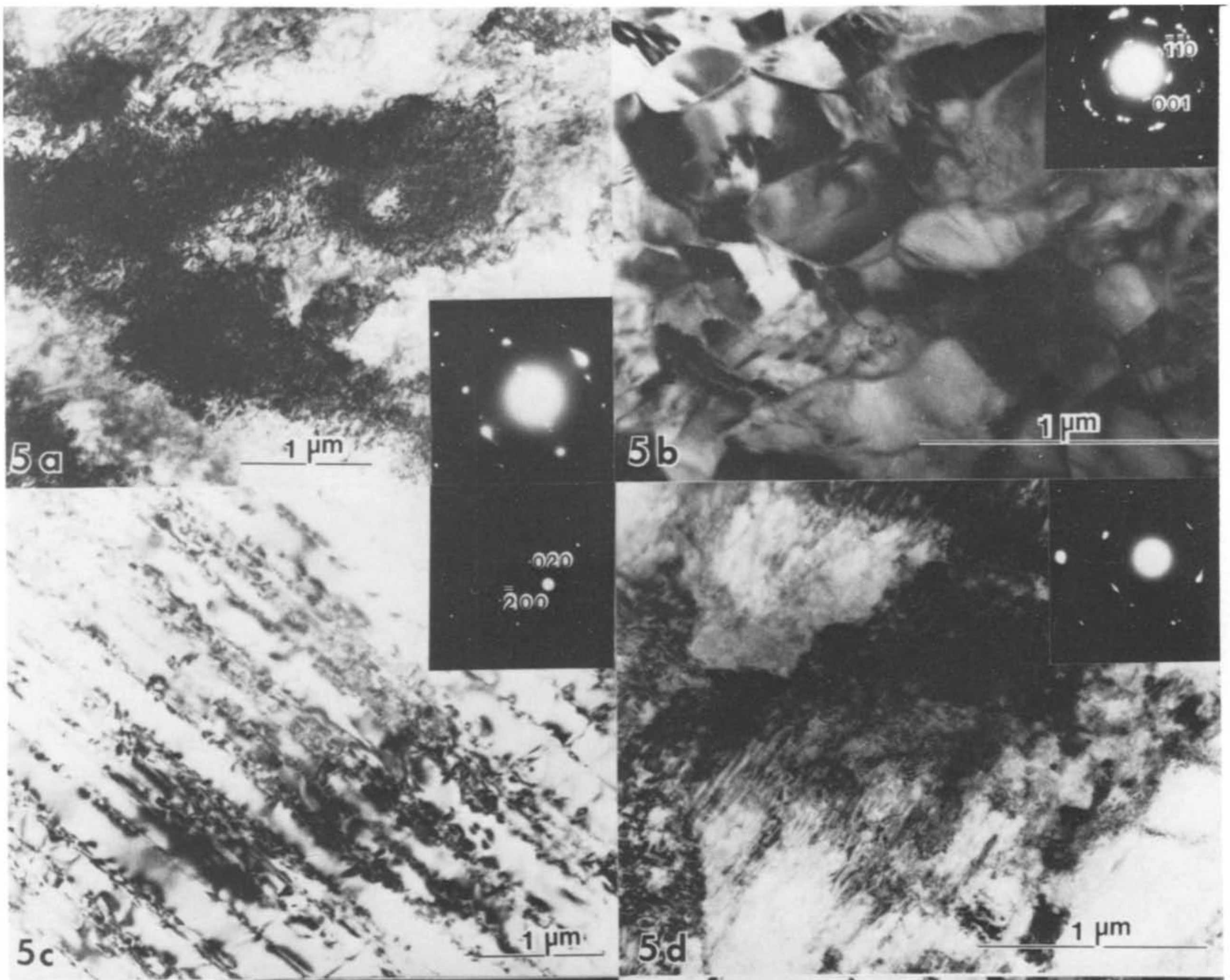


Fig. 5. TEM bright-field micrographs of Hale albite rock deformed both wet and dry at 800°C, 15 kb, and 3×10^{-6}/s. These micrographs illustrate the range of microstructures observed in each sample, and show that the wet sample, (a) and (b), has experienced more recovery than the dry sample, (c) and (d). (a) High dislocation density with cells, in the wet sample. (b) Recrystallized grains, wet sample. (c) Low dislocation density with dislocations aligned along (010), in the dry sample. (d) Higher density of tangled dislocations and cells in the dry sample.

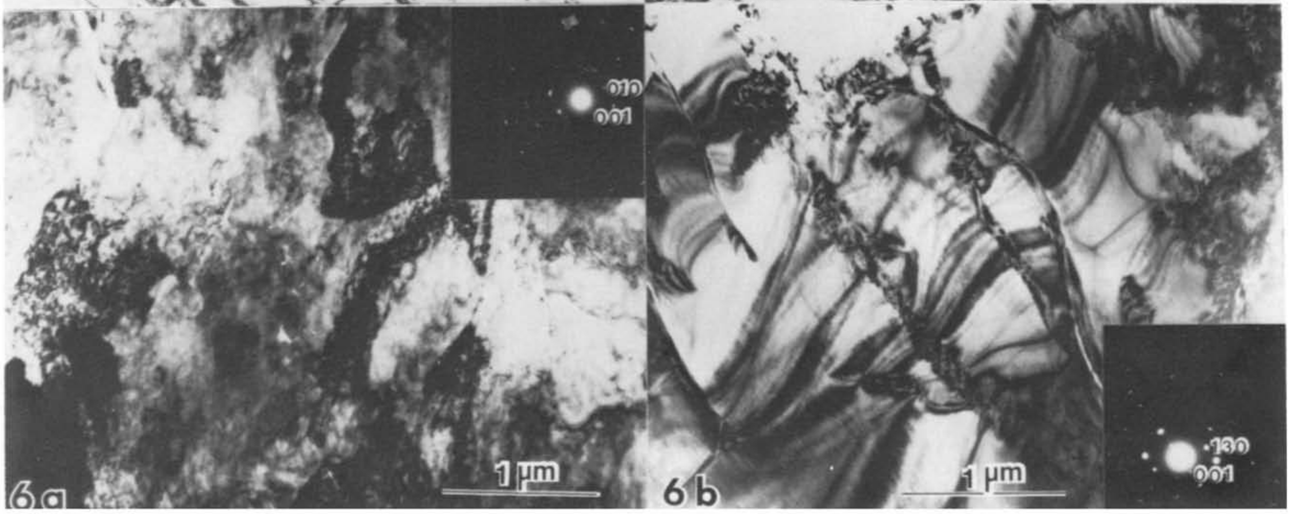


Fig. 6. TEM bright-field micrographs of feldspar from a sample of Westerly granite deformed wet at 400°C and 3×10^{-6}/s, illustrating more evidence of dislocation glide and climb at 15 kb (a) than at 10 kb (b). (a) Typical feldspar with a very high and fairly uniform density of dislocations forming a cellular microstructure, in the 15 kb sample. (b) Typical feldspar with a low density of irregularly distributed dislocations, and abundant microcracks, in the 10 kb sample.

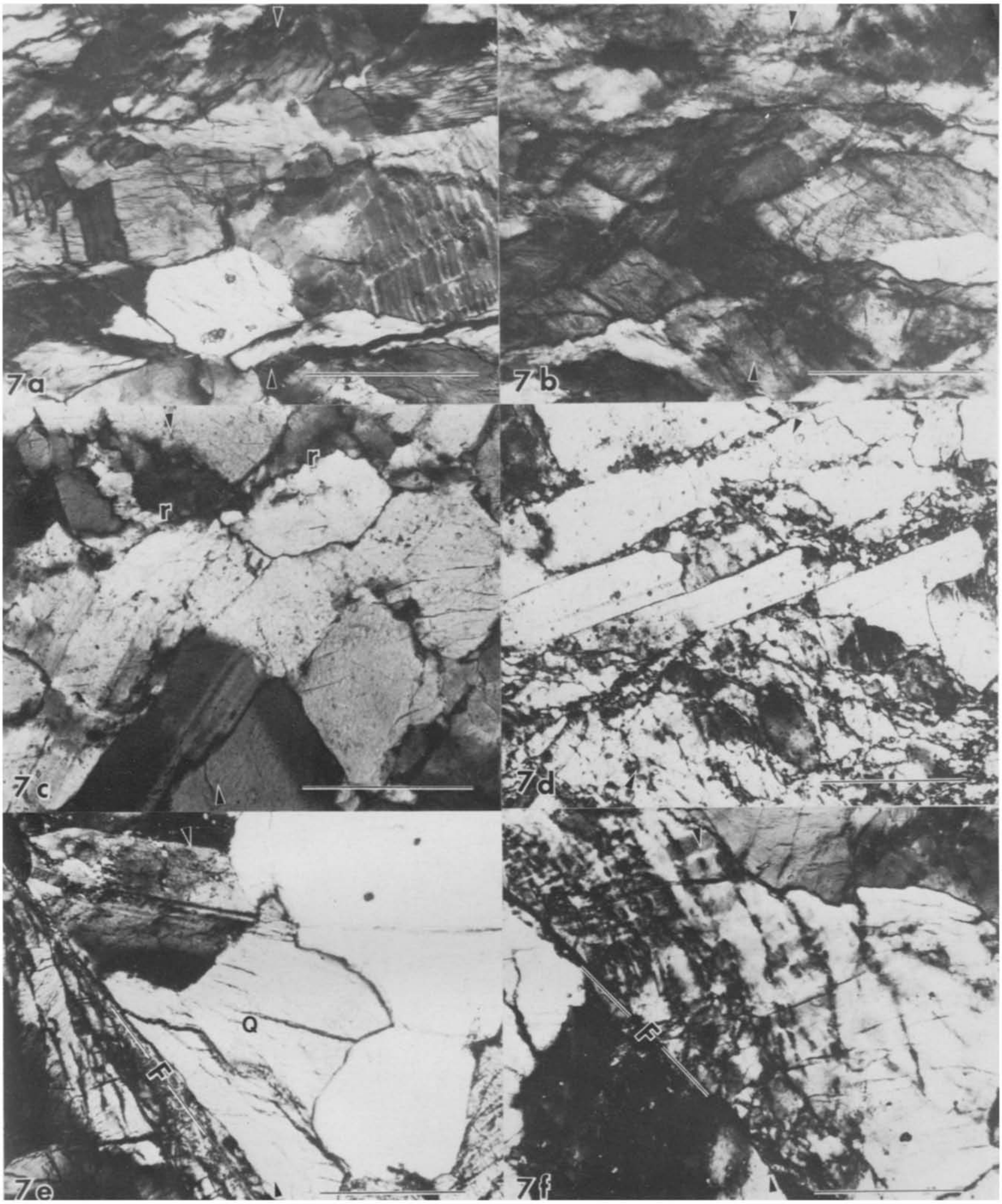


Fig. 7. Optical micrographs from samples of Westerly granite and Hale albite rock. Scale bar is 0.2 mm. The direction of sample shortening is indicated by the black arrows. (a) Hale albite rock deformed dry at 600°C and 15 kb to 39% shortening; there is abundant grain-scale faulting (note offset twins). (b) Hale albite rock deformed wet at the same conditions to 40% shortening; there is abundant plastic deformation (note undulatory extinction). (c) Hale albite rock deformed wet at 800°C, 15 kb, and 3×10^{-6}/s, showing plastic deformation and recovery (note subgrains, e.g. at r). (d) Hale albite rock deformed at the same conditions, but at 3×10^{-4}/s, and to a higher total strain. There has been grain-scale faulting (note extreme offset for light grain across the centre of the photo), and the finely crushed material has been sintered and partially recrystallised (e.g. lower portion of photo). (e) Quartz grain (Q) from Westerly granite deformed wet at 400°C, 3×10^{-6}/s, and 10 kb. This quartz grain lies along a through-going fault (F) but does not show plastic deformation and recovery, in contrast to the quartz grain along the fault in the 400°C, 15 kb wet sample shown in Fig. 2(b). (f) Quartz grain from Westerly granite deformed wet at 500°C, 3×10^{-6}/s, and 10 kb. This grain also lies along a through-going fault (F) and is the only grain in the section to show such extensive plastic deformation and recovery, whereas in the 500°C, 15 kb wet sample there are many such grains.

2f). TEM shows that the wet sample contains abundant regions of uniform high dislocation density with cells, whereas the dry sample contains a low and irregular dislocation density. (Cells are small irregular regions misoriented from each other by 1–2°, containing a high dislocation density and bounded by diffuse walls of dislocation tangles.)

At 800°C, the wet Hale albite samples show quite homogeneous deformation optically, with abundant recovered and even recrystallized zones both along grain boundaries and within grains. The dry sample shows no such recovered and recrystallized material. TEM of the wet sample shows variable microstructures ranging from cells to recrystallized grains (Figs. 5a & b). TEM of the dry sample shows a range from a moderate and inhomogeneous dislocation density (Fig. 5c) to poorly defined cells (Fig. 5d), with no recrystallization.

In summary, there is optical evidence for enhanced brittle behaviour early in the deformation history of all of the wet samples. However TEM observations in regions between the relatively widely spaced crush zones and cracked regions show a dislocation substructure which changes regularly with temperature and in all cases appears similar to that from dry samples deformed at a temperature about 150–200°C higher. This would not be expected if the only effect of the water in the samples was to reduce the effective confining pressure. Instead it appears that the immediate effect of the water is to enhance microcracking by stress corrosion, but that the net effect is one of hydrolytic weakening, and a lowering of the temperature of the transition from dominantly microcracking to dominantly dislocation glide and climb by about 150–200°C for both quartz and feldspar.

Effect of strain

Individual experiments on wet Westerly granite and Hale albite rock done at temperatures of 500–700°C show both grain-scale faulting as well as plastic deformation, recovery, and even recrystallization (Fig. 2f). Because some of the grain-scale faults contain recrystallized grains along them, whereas recrystallized regions are never themselves offset by faults, it is inferred that the faulting occurred earlier, and the plastic deformation and recovery later. Such combinations are never seen in the equivalent dry samples. These observations suggest that within a certain temperature interval, the presence of water causes the deformation mechanism to change progressively with strain (time), from dominantly microcracking to dominantly dislocation glide and climb.

In order to determine whether the microcracking and grain-scale faulting might be produced during loading and/or preheating, a wet sample of Westerly granite was loaded to 15 kb and 700°C and left for 24 h, and then unloaded. Both the quartz and feldspar grains showed extension fractures related to the unloading, as expected, but no distributed microcracking and/or grain-scale faulting.

We have done wet experiments on Hale albite rock at 600°C and 15 kb to 11, 16, and 40% strain. Optically, the two lower strain samples appear similar to the low-strain dry sample, with abundant grain-scale faults. TEM of the wet sample shows considerable variation from grain to grain, but there are some areas of high dislocation density, including cells. In contrast the dry sample shows fewer dislocations, irregularly distributed. The high strain wet sample shows fairly homogeneous grain flattening (Fig. 7a), with some evidence of earlier grain-scale faulting; an equivalent high strain dry sample shows that grain scale faulting and distributed microcracking remained the dominant deformation mechanism throughout the strain history (Fig. 7b).

One might expect to see, both optically and in TEM, more ductile deformation and recovery in the rims of grains than in their cores, due to progressive penetration of water into the grains from the grain boundaries. However, clear-cut examples of this have not been seen. This must be in part because in the granite the different phases with their different rheologies impose a very inhomogeneous loading on each grain, and in part because in both materials there is abundant cracking in the early stages of most of the experiments, and water can diffuse in from these cracks as well as from the grain boundaries.

Effect of strain rate

We have done experiments on wet Hale albite rock at 800°C and 15 kb at 10^{-4}/s, 10^{-5}/s, and 10^{-6}/s to test the effect of strain rate. As mentioned above, the 10^{-6}/s sample shows quite homogeneous deformation, with little evidence of grain-scale faulting but abundant recovery (Fig. 7c). The 10^{-5}/s sample shows less homogeneous deformation; there are zones of grain-scale fractures with regions of recovered material along them in places, but most of the volume of the sample appears to have deformed by microcracking with only limited dislocation glide. The 10^{-4}/s sample shows even more inhomogeneous deformation; there is one narrow zone of very intense deformation and most of the rest of the sample is little deformed. Within this zone are apparently rigid fragments of original grains which have separated and rotated within a finer-grained matrix (Fig. 7d). TEM shows this matrix to consist of a variety of fragments: some have cracks and pores along their boundaries, no dislocations, and large misorientations with their neighbours; others have no cracks or pores, high dislocation densities, and high misorientations; and others have no cracks and pores, few dislocations, and small misorientations with their neighbours. The latter we believe to be true recrystallized grains, but the former appear to have originated by crushing and subsequent sintering and plastic deformation. Thus it appears that in the fast strain rate experiment, water had time to diffuse into and weaken only a small volume of material. In the slower strain rate experiment, the diffusion of water into the grains was better able to keep pace with the imposed deformation.

Effect of pressure

We have done wet granite experiments at 400 and 500°C at 10 kb confining pressure (both the preheat and the deformation), for comparison with the 15 kb experiments. At 400°C and 10 kb the wet sample contains a through-going fault which is much sharper than that in an equivalent dry sample. Sharper faults are characteristic of the higher temperatures ($\geqslant 600$°C) for dry samples deformed at 5 kb (T & Y), hence the added water appears to have had the same effect as a higher temperature. However, this 10 kb wet sample does not show as much evidence for hydrolytic weakening as does the 15 kb wet sample. The 15 kb wet sample contains some quartz grains showing extensive strain with internal boundaries characteristic of recovery (Fig. 2b), but there are no such grains in the 10 kb wet sample, and even the quartz grains next to the fault appear unaffected by the water (Fig. 7e). TEM shows that compared with the 15 kb wet sample, the quartz in the 10 kb wet sample has a lower and less homogeneous dislocation density, and more abundant microcracks and crush zones; it is closer in character to the quartz in equivalent dry samples. TEM of the feldspar shows that compared with the 15 kb wet sample (Fig. 6a), the 10 kb wet sample shows fewer dislocations and more abundant microcracks (Fig. 6b).

At 500°C and 10 kb a wet sample deformed with no preheat shows a sharp through-going fault. Parts of several quartz grains along this fault do show relatively high strain with evidence of recovery (Fig. 7f), but there is a lesser volume of such material than in the 15 kb wet sample. TEM shows that the feldspar contains microstructures almost identical to those in dry samples, with fewer dislocations and more microcracks than in the wet, 15 kb sample.

Thus it appears that for wet experiments on Westerly granite at a given temperature, both quartz and feldspar show more microcracking and grain-scale faulting and less dislocation glide and climb at 10 kb than they do at 15 kb. The 10 kb wet samples are more similar to the dry samples.

DISCUSSION

Water content of experimentally deformed samples

Our evidence for hydrolytic weakening in the wet samples comes from comparison of the microstructures with those in equivalent dry samples. However, a consideration of the equilibrium water concentration is necessary for interpreting both 'wet' and 'dry' experiments. Assuming a sufficient supply of water and a sufficient time for volume diffusion, there is an equilibrium concentration of 'water' which will dissolve in the structure of any mineral. The exact form in which this 'water' diffuses into and resides within the crystal structure is unknown. The equilibrium concentration is a function of temperature, pressure, and the composition of the fluid phase. It appears to increase with increasing pressure (Paterson & Kekulawala 1979). The behaviour with increasing temperature is not well known; the experiments of Jones (1975) appear to show a decreasing concentration with increasing temperature, but water was probably diffusing from the quartz crystal into the drier surrounding materials, with faster diffusion at higher temperatures. The experiments of Paterson & Kekulawala (1979) show that the concentration of water in quartz at high temperatures and low pressure is exceedingly small (a few hundred molar p.p.m. OH at 900°C and 3 kb).

It is likely that many experimentally deformed samples never achieve an equilibrium water concentration during the short times of the experiments, because most deformation experiments are not done at the same temperature and pressure at which the starting material was originally equilibrated. At low pressure and high temperature the equilibrium concentration is presumably quite low, and many samples deformed at these conditions are observed to precipitate tiny water bubbles (e.g. Morrison-Smith *et al.* 1976). On the other hand, at high pressure and temperature the equilibrium concentration is apparently higher than that present in most natural samples used as starting materials. In this case equilibrium may not be achieved during the experiment if; (1) there is not enough water available (such as would be the case for a carefully dried single crystal deformed in an anhydrous medium), or (2) water which is available (from fluid inclusions or the grain boundaries of a polycrystalline aggregate, or from the sample assembly) does not have time to diffuse into the crystal during the experiment. Thus it seems likely that for many high pressure 'wet' experiments, the water concentration will increase during the course of the experiment, and depending on the time it may or may not reach the equilibrium value. Even for samples which are deformed 'dry' in the sense of no water added, the water concentration may increase during the course of the experiment, due to diffusion from fluid inclusions and grain boundaries.

Interpretation of the 'wet' Westerly granite and Hale albite rock experiments

In considering the effect of water on the transition from microcracking to dislocation glide and climb, it is useful to compare the hypothetical cases of 'wet' and 'dry' samples which have a different but unchanging water content. For such cases one can distinguish three temperature regimes. There is a lower temperature regime in which the deformation of the wet and the dry samples occurs dominantly by microcracking. In this regime the addition of water does not change the deformation mechanism, but it should result in a weakening due to stress corrosion at crack tips. There is an intermediate temperature regime where the deformation of dry samples occurs by a mixture of microcracking and dislocation glide but that of the wet samples occurs dominantly by dislocation glide and climb. In this regime the presence of the water changes the deformation mechanism and also causes a weakening (hydrolytic weakening). There is a higher temperature regime where deformation of dry samples occurs dominantly by dislocation glide and climb, and deformation of wet samples is by the same mechanism but involves more recovery. In this regime the presence of water does not change the deformation mechanism but it does result in hydrolytic weakening.

We have compared the microstructures of wet and dry samples of Westerly granite and Hale albite rock deformed at the same temperatures and pressures, but the interpretation is somewhat more complicated than the situation described above. The two sets of samples start out with the same amount of water in the crystal structure, but more water diffuses into the crystals in the wet samples during the course of the experiments.

For dry experiments on Westerly granite and Hale albite rock, the transition region from microcracking to dislocation glide and climb is quite broad. At 15 kb and 10^{-6}/s for quartz, dislocations are first seen at about 300°C and microcracks are last seen at about 700°C, and for feldspar these temperatures are higher, roughly 500 and 850°C (T & Y). Since the Westerly granite and Hale albite rock presumably formed at <5 kb, it is likely that their initial water contents were less than equilibrium for the conditions of many of the 15 kb dry experiments. There is some indirect evidence that the water concentration in the grains of the dry samples deformed at high pressures increased slightly during the experiments, and caused some hydrolytic weakening, because samples deformed at a higher pressure for a given temperature and strain rate are weaker than those deformed at a lower pressure, when the operative deformation mechanism is entirely dislocation creep (Tullis *et al.* 1979). However, the dry experiments used in this paper for comparison with the wet experiments generally do not show textural evidence for a change in deformation mechanism or style with increasing strain (to 20% shortening).

In most of the 15 kb wet experiments, in contrast, the samples show a lower strength and more obvious textural evidence for a change in deformation mechanism during the experiment, presumably reflecting a greater increase in water concentration. At low strains the deformation is similar to that of dry samples deformed at the same conditions, and for the temperatures of the wet granite experiments, 300–600°C, this predominantly involves microcracking. In fact, the microcracking in the wet samples appears to be somewhat enhanced by the presence of water. The cracks reduce the effective grain size and thus allow an increased rate of penetration of water into the grains. Depending on the temperature and the mineral, in the regions where water diffuses into the grains the dominant deformation mechanism may switch from microcracking to dislocation glide and climb. High dislocation densities are generated in these areas, which undoubtedly aid in the further penetration of water into the structure (Yund & Tullis 1980, Yund *et al.* in press). The effect of the added water after a certain time (strain) for diffusion of the water into the crystals is to lower the temperature of the transition from microcracking to dislocation glide and climb. This lowering of the transition temperature is greater after a greater strain at a given strain rate, or at a slower strain rate for a given strain.

The observation of more hydrolytic weakening at a given temperature for wet samples deformed at a higher pressure is consistent with other recent results showing that hydrolytic weakening depends strongly on pressure (Paterson & Kekulawala 1979, Tullis *et al.* 1979). Although the mechanism for this pressure dependence remains unclear, it appears to be related to an increased concentration of 'water' in the crystals at higher pressure, which may be associated with the increased diffusivity of 'oxygen' (Yund & Anderson 1978) and silicon and aluminum (Yund & Tullis 1980) observed at higher pressure when trace amounts of water are present.

The equilibrium water concentrations of quartz and feldspar at 15 kb and 300–800°C are unknown. However, the previous series of dry experiments (T & Y) showed that water from grain boundaries and fluid inclusions was apparently driven into the crystal structure of the grains at high pressure (10 and especially 15 kb) and accomplished some hydrolytic weakening (Tullis *et al.* 1979). From careful weighing after high temperature vacuum drying of these dry samples, it is known that the Westerly granite and Hale albite rock both contain about 0.08 wt% water. The present series of wet experiments has shown that at least some of the additional water supplied also goes into the crystal structure at high pressure, and accomplishes additional hydrolytic weakening. Thus the equilibrium water concentration must be >0.08 wt%, but we cannot place an upper limit on it.

Extrapolation to natural deformations

It is difficult to extrapolate the results of laboratory deformation experiments to nature in other than a qualitative way at present, because the water contents are not well known for either experimentally deformed samples or for most naturally deformed rocks. It is not sufficient to characterize a sample as 'wet' or 'dry' because the strength of silicates appears to vary continuously over a small range of water contents. In this study we have shown that samples with 0.1–0.2 wt% water added are weaker than samples which are hot plate dried (and which contain about 0.08 wt% water), and Shelton *et al.* (in press) have shown that samples which are vacuum dried at moderate to high temperature are much stronger than samples which are hot plate dried.

This significant and continuous variation in sample strength with trace amounts of water is an important consideration for flow laws determined experimentally. For both wet and dry high pressure experiments, samples deformed at different temperatures may have different water concentrations, due to varying rates of diffusion of 'water' into the structure. Thus one would fit data for materials of different properties (water content) to one flow law and this would result in faulty extrapolations. It is also likely that especially for 'wet' experiments, flow laws determined at higher pressure will be different from those determined at lower pressure, due to the higher water content of the former. This has important implications for attempts to measure the activation volume for creep (e.g. Ross *et al.* 1979). A third difficulty is that especially for high pressure 'wet' experiments, the water concentration will change during at least part of the experiment. It is thus questionable as to how many such experiments achieve steady state.

Even if experimental flow laws were determined for materials of known and constant water content, there are difficulties in applying these flow laws to nature. This is because of the lower pressures, and thus presumably lower equilibrium water concentrations, which are characteristic of crustal deformation. Samples experimentally deformed wet by dislocation creep at high pressure actually may be weaker than most equivalent materials deformed in the crust.

A further complication concerns whether natural deformations involve an equilibrium water concentration. Presumably for most crustal rocks there should be an equilibrium water concentration during the initial stages of a prograde metamorphism, assuming abundant hydrous phases to supply the water, and this amount will presumably be greater for higher pressures. Thus at a given temperature, rocks deformed at higher pressure should be weaker and show a greater proportion of dislocation glide and climb compared to microcracking, or a greater amount of recovery. At a given pressure, rocks deformed at higher temperatures should be weaker and show a greater proportion of dislocation glide and climb and/or recovery. However, the water concentration within grains will also depend on the degree to which the system is open, and there is abundant evidence that rocks of granulite facies are drier than those of lower grade. Rocks which have been dried out by a granulite facies metamorphism may not have water available with which to re-equilibrate during later lower temperature events. This may explain why some granitic gneisses show higher strain prior to recrystallization at granulite facies than at amphibolite facies (Bell & Etheridge 1976).

Our wet and dry experiments do provide the basis for making certain qualitative interpretations of relative strength and ductility from the textures of naturally deformed quartzo-feldspathic rocks. The onset of hydrolytic weakening is tied to that of substantial recovery (McLaren & Retchford 1969). If quartz exhibits sharp deformation bands and/or grain-scale faults, it has not experienced significant recovery and was relatively strong. However, if it exhibits subgrains and/or small new recrystallized grains, then it has experienced significant recovery and was presumably relatively weak. It appears that in natural deformations where water is available, quartz shows recovery at about 270°C and syntectonic recrystallization at about 300°C (Voll 1976, Kerrich *et al.* 1977).

Roughly the same criteria apply to feldspar, although it is somewhat more complicated. Weakness cannot be inferred from a few bent plagioclase twins, nor from all zones of undulatory extinction, as these may be caused by arrays of microcracks as well as dislocations (T & Y). Feldspars do not undergo significant weakening until they show actual recrystallization (White 1975), and for natural deformations this generally occurs at temperatures of about 450–500°C when water is available (Voll 1976). Naturally deformed feldspars show additional complications however, in that a chemical reaction may be involved in the recrystallization. Recrystallized grains of plagioclase may contain less An (Vernon 1975, White 1975), and potassium feldspar often recrystallizes to a fine-grained aggregate of quartz, albite, and muscovite (e.g. Potter 1976). In the latter case, the remaining potassium feldspar may be relatively strong, but the recrystallization products are generally observed to be quite weak (Allison *et al.* 1979). It is possible that some textures in anorthosites which have been interpreted as 'cataclastic', and the products of brittle crushing, may instead be syntectonic recrystallization, and the products of a high temperature, ductile deformation (Kehlenbeck 1972).

CONCLUSIONS

It is now clear that trace amounts of water have a profound effect on a variety of solid-state processes in minerals and rocks, including reaction rates (Goldsmith & Newton 1974), oxygen isotope exchange rates (Giletti *et al.* 1978), Al–Si interchange rates (Yund & Tullis 1980), and plastic deformation (Griggs 1967, and many others since; see Tullis 1979). Our study has shown that when the water in a 'wet' deformation experiment must diffuse into the grains during the course of the experiment, rather than the samples starting out saturated for the pressure and temperature conditions of the experiment, then the effect of the water on the deformation is a function of strain and strain rate as well as pressure and temperature. We have demonstrated that enough water enters the grains of quartz and feldspar after 15–20% strain in experiments at 15 kb, 10^{-6}/s, and 300–800°C to lower the transition from microcracking to dislocation glide and climb by about 150–200°C, compared to 'dry' experiments at the same conditions. We also demonstrated that there is substantially less hydrolytic weakening for samples deformed wet at 10 kb than there is at 15 kb. Thus it is not a simple matter to experimentally obtain a flow law for 'wet' material, nor to extrapolate experimental flow laws to naturally deformed rocks. It is important to conduct deformation experiments on material of known and unchanging water content, and to learn more about the water contents of minerals as a function of various metamorphic histories.

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