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MICROFRACTURING IN WESTERLY GRANITE
EXPERIMENTALLY EXTENDED WET AND DRY AT TEMPERATURES
TO 800°C AND PRESSURES TO 200 MPA

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ABSTRACT

Microfracturing in Westerly Granite

Experimentally Extended Wet and Dry at Temperatures
to 800°C and Pressures to 200 MPa. (May 1986)

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Chairman of Advisory Committee: Dr. Melvin Friedman

Microfracturing in Westerly granite specimens, extended wet and dry, at temperatures to 800°C and confining pressures to 200 MPa, is analyzed with a view toward understanding why, in the brittle field, rock strengths decrease with increasing temperature. Intragranular (IGC) and grain-boundary cracks (GBC) are mapped in two dimensions on either side of the tensile macrofracture, using optical microscopy, to determine, quantitatively, crack lengths and densities and, qualitatively, crack widths and orientations are visually examined to aid in interpretation.

Temperature and confining pressure tend to favor the development of different microfracture fabrics. Thermal stresses produce a random orientation of cracks while stresses resulting from the external differential loading of a specimen produce a preferred orientation of cracks parallel to the direction of σ_1 . In dry experiments, between 600° and 800°C, both GBC and IGC densities increase with increasing temperature. The increase in crack abundance is responsible for the thermal weakening of the rock. With increasing temperature, GBC play a greater role in the deformational history leading to rock failure.

In contrast to dry specimens, the IGC densities in wet tests decrease with increasing temperature. GBC densities tend to increase with increasing temperature, and GBC are qualitatively wider than their dry counterparts. The presence of water at elevated temperatures promotes weakening along grain boundaries and alters the conditions at grain boundaries, reducing their ability to transfer far-field stresses to the interior of the grains. The grain-boundary weakening is responsible for the decreased rock strength and increased ductility under wet conditions.

Specimens tested wet or dry, show a decrease in the average intragranular crack length with increasing temperature. This fact suggests that (a) longer IGC are not referred for coalescence to macroscopic failure where the grain-boundary cracks themselves are well developed, or (b) there may be some crystal-plastic mechanism operative at the higher temperatures producing crack tip blunting. The decreased stress concentrations at the crack tip inhibit propagation thereby increasing the relative number of short cracks.

Dedicated to
my parents, Fred and Bonna Hopkins
and my wife, Diane

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INTRODUCTION

A thorough understanding of the mechanical properties of rocks at confining pressure and high temperature is required for the solution of many engineering problems associated with energy-related activities, such as geothermal energy exploration and the safe disposal of toxic waste. Problems of concern include the drillability of rock, and borehole stability at high temperatures, and the likelihood of rock fracture, with subsequent loss of strength and increased fluid transmissivity, in environments of hot fluids and differential stress.

Mechanical and microstructural analysis of igneous rocks deformed in short-term triaxial-compressive tests or in constant stress creep tests at low effective confining pressure (less than 200 MPa) but high temperature (to partial melting) indicate that failure occurs predominantly by fracturing, and that fracture strengths appear to be temperature dependent (Friedman et al., 1979; Bauer et al., 1981; Handin et al., 1981; Friedman et al., 1982 and Bauer, 1982;1983). The principal purpose of this work is to gain a better understanding of why, in the brittle regime, rock strength decreases with increasing temperature.

An abundance of previous work demonstrates that macroscopic shear fractures or faults in nature and in laboratory compression tests arise from the coalescence of precursive microscopic extension or tensile fractures (e.g. Brace, 1971; Friedman, 1975; and Kranz, 1983).

This manuscript follows the style of Tectonophysics.

These precursive microfractures arise from local stress concentrations, which are mechanically or thermomechanically induced, and are oriented perpendicular to the local deviatoric tension (herein σ_3). The precursive fractures increase in abundance with increasing effective confining pressure. Macroscopic shear fracturing of brittle polycrystalline rocks begins with local tensile microfracturing, but the friction involved in shear failure is an extra complexity. This study investigates a simpler system involving tensile (or extensile) fractures induced in triaxial extension experiments under controlled conditions of temperature, effective pressure, and aqueous environment.

This research effort primarily involves microstructural analysis of Westerly granite samples that have been deformed in triaxial-extension tests. Jacketed, 2 by 4 cm., dog-bone-shaped cylindrical specimens, both dry and water-saturated, were deformed at a strain rate of 10^{-4} s^{-1} in a high temperature apparatus at a uniform temperature ranging between 25° and 900°C and a confining pressure between 20 and 200 MPa. An analysis of the stress field in the samples is presented in Appendix I. The apparatus and experimental methods are fully described in Friedman et al. (1979) and Bauer et al. (1981).

The objective is to study the development of tensile microfractures in Westerly granite in order to relate the grain-scale deformation to the macroscopic behavior of the rock. Specifically, observational analysis of the specimens is directed toward the characterization of the microfracturing (crack type, length, density,

and nature of coalescence) in order to understand the mechanisms by which the granite becomes progressively weaker with increasing temperature, especially when water-wet. This approach provides data on the nature and abundance of the precursive fractures upon which micromechanical models must be based.

PREVIOUS WORK

The deformation of igneous rock under the pressure and temperature conditions of this study occurs primarily by fracturing, which is initiated by local stress concentrations. At elevated temperatures, microfracturing results from two superposed stress states; one produced by the mechanical loads acting on the boundaries of the specimen and the other by differential thermal expansion of mineral grains induced by temperature changes (Friedman et al., 1982). Water acts in the fracturing process as well (Anderson and Grew, 1977), and degrades rock strength, particularly at high temperatures, as documented by many workers (e.g., Friedman et al., 1982).

Thermal stresses can cause microfracturing independent of any purely mechanical stresses arising from boundary loads. Sprunt and Brace (1974) observed extensive cracking in granites when cycled to 400°C, particularly along grain boundaries. In unconfined Westerly granite subjected to slow, uniform temperature change, significant microcracking initiates, as determined by acoustic emissions, once a threshold temperature of 70° - 75°C is reached, and the microcracking increases with increasing temperature (Johnson et al., 1978). Thermal stresses develop because of the mismatch of thermal expansions of neighboring grains and microcracking results. Johnson et al. (1978) found that microcracking occurs primarily along grain boundaries and secondarily within grains. In addition, they theoretically calculated the thermal stresses and the induced microcracks that would arise from a uniform change in temperature. Their experimental results were in

good agreement with the predicted behavior. Further work on thermal cracking in Westerly granite (Bauer and Johnson, 1979) yielded additional information on the microcracking behavior and its effects. Thermal cracking increases with temperature, and for temperatures above 450°, appreciable crack widening occurs. These microstructural changes result in progressive tensile strength degradation (as measured in unconfined brazilian tensile tests) for specimens cycled to temperatures above 150° - 200°C. When they distinguished grain-boundary from intragranular cracks the increase in abundance of the former levels off at 600°C, because all grain boundaries are cracked at this temperature.

It is known that confining pressure may inhibit thermal cracking or reduce its mechanical effect on rock. For example, Simmons and Copper (1978) found that most cracks in Westerly granite samples thermally cycled to 800°C closed at pressures below 50 MPa. Bauer and Johnson (1979) reported that Westerly granite samples subjected to confining pressures of 20 MPa, after thermal cycling, showed no reduction in compressive strengths for thermal cycle temperatures to as high as 800°C. Friedman et al. (1979) performed dry, triaxial compression tests on igneous rocks and observed a decrease in strength with an increase in temperature. The thermal cracking, however, was not the cause of strength reductions as rocks heated to temperatures between 750° and 1000°C and then deformed at room temperature and 50 MPa were no weaker than similarly deformed rocks without thermal treatment. They attributed the weakening to an inherent temperature effect on the load-induced fractures i.e., at the grain scale, the

fracture strength of the grains or grain boundaries decreases with increasing temperature. Finally, Wong (1982) tested whether thermal cracking was responsible for the weakening with increasing temperature by considering the temperature at which changes occur in the slope of the strength versus temperature curve. The break in slope, indicating an increased temperature dependence, occurred at lower temperatures for increased confining pressures. If thermal cracking was the cause of the weakening, and if pressure reduces the effect of thermal cracking, the opposite trend would be expected.

The number of precursive intragranular cracks increases with increasing effective confining pressure at room temperature as noted by Friedman (1975) and Hugman and Friedman (1979), among many others. Kranz (1980) observed, in static fatigue tests on Barre granite, that increasing confining pressure fosters larger total crack volumes and longer cracks prior to sample failure. Crack orientation may change as a function of pressure as well. With increased confining pressure cracks are oriented at greater angles to the maximum applied stress in compression tests (Wong, 1982 and Kranz, 1980). The increase in strength with confining pressure may be a result of increased friction along cracks at high angles to σ_1 as shearing becomes more prominent. That is, increased confining pressure increases the normal stress across cracks and within intact material and thus impedes crack propagation thereby decreasing coalescence and macroscopic failure (Friedman, 1976).

The importance of water, in regards to failure strength and microstructure, has been emphasized along with temperature and

confining pressure. Early work by Griggs and Blacic (1965) demonstrated that water weakens quartz and promotes ductile behavior at lower temperatures and stresses than for dry conditions. Water enhances crack growth by stress corrosion at crack tips (reviewed by Anderson and Grew, 1977), and water-weakening becomes more pronounced at higher temperatures (Griggs, 1967). Bauer et al. (1981) observed water-weakening in axially-shortened andesite and basalt specimens beginning at about 600°C, and Friedman et al. (1982) observed the same for granodiorite at effective pressures of 100 MPa above 800°C. In these studies, the average number of microfractures was the same for wet or dry conditions. They concluded that the water does not increase fracture abundance, but rather fosters microfracturing at lower differential stress.

The above are results from compression tests. In such tests, the coalescence of precursive cracks (mostly extension but possibly also of shear origin) to form the macroscopic shear failure zone is complex and not well known in detail. In contrast, failure in extension or tensile tests, also involves precursive cracks but their abundance and the complexities of their interactions appears much simpler (e.g., Bieniawski, 1967; Peng, 1975). Accordingly, study of specimens from such tests holds promise of providing greater insight into the fracture process and, specifically, the role of temperature.

EXPERIMENTAL METHODS

In this section, procedures associated with the analysis of the deformed samples are discussed. These include the experimental matrix, thin section preparation and observational methods. The rock deformation apparatus and specimen preparation procedure are described in Friedman et al. (1979) and Bauer et al. (1981). Special procedures for extension tests are discussed in Appendix II.

Experimental Matrix

All experiments were performed by Dr. S.J. Bauer while he was a graduate student in the Department of Geology at Texas A&M University and supported by DOE grant No. DE-FG-5-84ER13228. Experimental conditions for the triaxial-extension tests involve variations of temperature (25° to 900°C), confining pressure (20 to 200 MPa) and aqueous environmental (see Table I). All wet tests were performed at an effective confining pressure of 100 MPa. The tensile (extensile) stresses within the samples and the axial strains were calculated from force-displacement curves recorded for each experiment. Specimens studied microscopically are shown within the experimental matrix (Figure 1).

Very few microfractures accompany the macrofractures produced in samples deformed at room temperature. As the analysis in this study is based on statistics of precursive cracking, only the high temperature test specimens were studied in detail.

Table I. Results of Extension Experiments, Westerly Granite, at a Strain Rate of $3 \times 10^{-4}/s$

Exp. No.	T (C°)	$P_c = \sigma_1$ (MPa)	$\sigma_1 - \sigma_3$ # (MPa)	σ_3 (MPa)	Axial strain (%)	Fracture angle ## (°)	Fracture type ###	Micro-fracture Pattern*
E1	25	20	32.0	-12.0	0.4	?	?	UF
E2	25	50	61.1	-11.1	0.4	3	T	UF
E3	25	100	111.0	-11.0	0.5	3	T	UF
E4	25	150	156.8	-6.8	0.6	3-5	T	UF
E5	25	200	198.4	1.6	0.9	3-5	?	UF
E6	600	20	28.0	-8.0	0.4	3	T	B
E7	600	50	56.3	-6.3	1.0	3	T	B
E8	600	100	102.5	-2.5	1.2	3	T	A
E9	600	150	148.1	1.9	1.0	--	***	B
E10****	600	150	147.1	2.9	1.2	10	S	-
E11	600	200	183.4	16.6	1.2	--	***	A
E12	600	200**	93.6	6.4	1.8	2	T	A
E13	700	150	144.2	5.8	1.3	9	S	A/B
E14	700	200**	86.8	13.2	2.4	--	***	B
E15	800	20	22.8	-2.8	1.6	2	T	B
E16	800	50	50.0	0.0	1.5	3	T	B
E17	800	100	84.1	15.9	1.2	5	?	B
E18	800	150	87.0	63.0	1.5	--	***	B
E19	800	150	95.9	54.1	1.0	9	S	B
E20	800	200	148.2	51.8	1.6	9	S	A/B
E21	800	200**	44.0	56.8	5.3	--	***	B
E22	900	150	46.9	103.1	1.1	--	***	B

Differential stresses are not corrected for stress concentrations at fillets of "dog-bone-shaped specimens. Tensile strengths ($-\sigma_3$) could be 50% higher. Relative values are significant.

Angle between cylinder axis and normal to fracture surface.

T = tensile or extensile, S = shear, based on fracture angle.

* UF = few if any microfractures; A and B patterns (see text and Figures 7-12)

** $P_c = 200$ MPa, P_p (water) = 100 MPa, $P_e = 100$ MPa

*** Test terminated at peak stress but prior to macroscopic fracture

**** Specimen not available for observational study

EXPERIMENTAL MATRIX

	20	dry *	dry ✓		dry ✓
	50	dry	dry		dry
	100	dry * *	dry ✓ wet ✓	wet ✓	dry ✓ wet ✓
	150	dry * *	dry *	dry	dry •
	200	dry * *	dry ✓		dry ✓
		25	600	700	800
					900
EFFECTIVE CONFINING PRESSURE (MPa)					
					TEMPERATURE (°C)

Figure 1. Experimental matrix. ✓ signifies microfractures are mapped. * indicates experiment was terminated prior to macroscopic failure. ** indicates specimen is characterized by a single, throughgoing macrofracture. S indicates macroscopic fractures is a shear (Table I). In all other instances of macroscopic failure the fracture is tensile or an extensile.

Thin Section Preparation

Deformed specimens are oven dried and then vacuum and pressure impregnated with a low viscosity, room-temperature-setting, blue-stained epoxy. Immediately after vacuum impregnation, up to 6 MPa, N_2 -gas pressure is applied at a slow rate to a plastic sack containing the specimen and surrounding blue-stained epoxy. In this way, epoxy is forced into open microfractures formed during the experiment. After pressuring, each specimen is removed from its epoxy bath and the epoxy is allowed to harden at room temperature. Specimens are then cut in half longitudinally, parallel to the cylinder axis, i.e., parallel to the σ_3 direction, with an Isomet low-damage diamond saw. Specimens are successively hand ground with abrasive to $3\mu m$ and then polished with $0.3\mu m$ grit on a wheel. Specimens are then mounted on glass slides, polished side down, and trimmed to < 1.00 mm thickness with the low-damage saw. The sawed surfaces are then ground and polished as before with successively finer grits to $0.3\mu m$. A cover glass is added to complete each section.

Observational Methods

Thin sections are studied at 250x in plane- and cross-polarized light and only those microfractures containing the blue epoxy are examined in detail. This procedure eliminates counting microfractures induced during the sectioning process. Two types of microfractures, also called cracks, are of interest and will be described below. They are intragranular cracks (IGC) and grain-boundary cracks (GBC).

Microfracture linear densities (MLD) are calculated for all sections by counting the traces of microfractures intersected per millimeter in traverses oriented parallel to the σ_3 direction. The average value from four parallel traverses was used as the MLD value for each specimen. Separate MLD values were obtained for intragranular and grain-boundary cracks.

Microfracture maps are constructed by mapping the traces of microcracks on photographic enlargements while observing a given field of view with the microscope. As before intragranular and grain-boundary cracks are differentiated. The mapped area of each sample is kept consistent, and is determined by the width of the thin section and 4 mm to either side of the main macrofracture. For specimens that failed without a macroscopic fracture, a similar area, representative of the overall deformation was mapped. The maps aid in the visualization of microstructural differences and facilitate data collection.

From the microfracture maps, the number and lengths of fractures are recorded. A Numonic digitizer is used to determine area, because it varies slightly between maps. In this way, the areal density of the microfractures can be compared. The lengths of fractures also are measured using the Numonic digitizer. When tracing a curvilinear line segment (a fracture trace) length is displayed continuously. Frequently, IGC segments are connected by short GBC segments. If these appear as one continuous crack, the total crack length is measured and recorded as a single intragranular crack. Accordingly, data are obtained for plots of (a) microfracture linear density, (b)

GBC and IGC density and (c) IGC length versus temperature for wet/dry conditions, respectively.

EXPERIMENTAL RESULTS

Table I and Figure 2 summarizes the results of Bauer's extension tests and Figure 3 shows typical stress-strain curves for dry and water-saturated specimens. The results are straight forward and follow trends established in other studies. At room temperature and all confining pressures, stress-strain curves rise almost linearly until catastrophic failure occurs at strains of less than 1%. With increasing temperature, ductility increases slightly and ultimate strengths ($\sigma_1 - \sigma_3$) decrease, for a given confining pressure. The greatest strength reduction occurs between 600° and 800°C for most samples. Ultimate strength increases with increasing confining pressure, and at the higher confining pressures, failure occurs in shear under a compressive (positive) axial stress. The water-saturated specimens are more ductile and weaker than their dry counterparts, and none failed with a macrofracture, i.e., the test was stopped prior to macroscopic failure. Heating reduces both tensile and shear strengths, and wet specimens are water-weakened. The microstructural analysis provides possible explanations for these effects.

Figure 2. Variation of ultimate strength or maximum differential stress ($\sigma_1 - \sigma_3$) with temperature at different effective confining pressures for extension experiments on Westerly granite.

Figure 3. Sample stress/axial strain curves for specimens tested under wet and dry conditions. See corresponding data in Table I for specimens E3, E8, and E17, above, and E12, E14, and E21, below.

OBSERVATIONAL RESULTS

Nature of Macrofractures

Each dog-boned specimen contains fillets located approximately 0.5 cm from the ends of each specimen (see Appendix II, item 1). The dog-boned configuration reduces the diameter of the central 3-cm section of each specimen and allows the development of a macroscopic tensile stress during the extension experiment. None of the macrofractures produced in the experiments occur at the fillets. Instead, the macrofractures occur within the central neck region at distances of 1 to 10 mm from the fillets; most are 5 to 7 mm distant from the nearest fillet. Thus, the fracturing is initiated by stress concentrations inherent to the texture and fabric of the rock and not due to the man-induced fillets.

In four of the specimens, the macrofracture terminating the experiment is inclined to the longitudinal axis of the specimen at an angle of 9-10° and is considered to be a shear (S) fracture. Other fractures are essentially orthogonal to the longitudinal axis and are interpreted to be tensile or extension (T) fractures (Figure 1 and Table I, column 8). This point will be addressed again in the Discussion section after the microscopic observational results are given.

Nature of Microfractures

In this study, grain-boundary cracks (GBC) are distinguished from intragranular cracks (IGC) (Figures 4-6). GBC are coincident with grain boundaries, whereas IGC cut across grains or are contained

Figure 4. Photomicrographs showing the nature of microfracturing. (a) coalesced intragranular cracks (IGC) into strongly oriented transgranular network in specimen E12, and (b and c) grain-boundary cracks (GBC) in specimen E21. Plane polarized light. Scale line is 1.0 mm for (a and b) and 0.2 mm for (c).

Figure 5. SEM fractograph of specimen E17 ($P_c=100$ MPa, 800°C , dry). Fracture surface in quartz shows the separation and relative width of a grain-boundary crack (GBC) at (a), en passant growth of intragranular cracks (IGC) at (b), (IGC) propagated from a grain boundary (c), a partially healed crack or one that has not totally lost cohesion (d), and fine river markings with jagged fracture steps at (e). SEM work courtesy of Y. J. Choi.

Figure 6. SEM fractograph of specimen E12 ($P_e = 100$ MPa, 600°C , water-wet). In top photo (a) a grain-boundary crack (GBC) extends around a quartz grain from below the bold arrow on the left to beyond the open arrow at c. Details along this surface at the open arrows are shown in the views (b) and (c), respectively. In (b) striations on a quartz fracture surface seem to be curved or dragged at the grain boundary suggesting some shear displacement along that boundary. In (c) biotite is kinked or drag-folded adjacent to the same grain boundary. A left-lateral sense of shear (see arrows in b) would account for both the drag of the striations and the folding. Scale lines for (b and c) are the same. SEM work courtesy of Y.J. Choi.

a

b

c

within a single grain. A crack of either type cannot be specifically attributed to mechanical or thermal stresses. However, Simmons and Richter (1976) point out that most cracks produced by a mechanical differential stress are parallel or subparallel to the direction of the maximum principal stress and are likely to cross several grains. Heating Westerly granite at a slow rate predominantly results in GBC. Some GBC may be produced, however, from a purely mechanical stress because of the mismatch of elastic properties between pairs of grains that amplify the mechanical load across the boundaries of the sample. Bauer and Johnson (1979) reported both IGC and GBC produced in thermal cycling tests. The IGC produced from thermal stresses, however, are usually small cracks that are perpendicular to, and original from, grain boundaries (Friedman and Johnson, 1978). These cracks taper inward and tend to die out within a short distance from the grain boundary. Thus, IGC that continue across grain boundaries and are oriented parallel to σ_1 are most likely from mechanical stresses. These may have grown, however, from initial thermal IGC, if suitably oriented, with the application of mechanical loads. GBC are more likely the result of thermal stresses (Johnson et al., 1978; and Friedman and Johnson, 1978), but grain boundaries that lie parallel to σ_1 may link up mechanically-induced cracks because the grain boundary may provide less resistance to crack propagation than the interior of a grain.

Microfracture Maps

Maps of IGC and GBC (Figures 7 through 12 and pages 68 through 70

Figure 7. Microfracture maps of specimen E11 (P_e = 200 MPa, 600°C, dry). (a) strongly oriented IGC, and (b) moderately well oriented GBC. This microfracture development characterizes pattern A (see text). Maps here and on following Figures are oriented such that σ_3 is parallel to the short dimension of each map.

PATTERN A

a

2 mm

b

Figure 8. Microfracture maps of specimen E12 ($P_e = 100$ MPa, 600°C , water-wet). Pattern A shows strongly oriented IGC (a) coalescing across the center of the field of view to produce an incipient macrofracture. In (b) GBC are only weakly oriented. σ_3 is parallel to the short dimension of each map.

Figure 9. Microfracture maps of specimen E20 ($P_e = 200$ MPa, 800°C , dry) show a combination of pattern A and B characteristics. In (a) IGC are well developed adjacent to the macrofracture surface. In (b) GBC are only slightly oriented normal to σ_3 which is parallel to the short dimension of each map.

PATTERN B

a

2 mm

b

Figure 10. Microfracture maps of specimen E6 ($P_e = 20$ MPa, 600°C , dry) show the characteristic pattern B (see text). In both (a and b), the IGC and GBC, respectively, are diffusely oriented.

Figure 11. Microfracture maps of specimen E15 ($P_e = 20$ MPa, 800°C , dry). Pattern B characteristics are shown, except IGC (a) are nearly coalesced to produce a macrofracture across the center of the field of view. As in previous figures, GBC are shown in (b).

Figure 12. Microfracture maps of specimen E21 ($P_e = 100$ MPa, 800°C , water-wet). Maps show pattern - B assemblages of diffusely oriented IGC (a) and GBC (b).

in Appendix III) provide visualization of these features in specimens deformed at temperatures of 600° and 800°C and pressures of 20 MPa (dry), 100 MPa (wet), and 200 MPa (dry). Two distinct patterns are developed.

Pattern A (Figures 7-9) consists of well-developed IGC with a high degree of preferred orientation, perpendicular to the σ_3 direction. They often coalesce with nearby grain-boundary cracks of nearly the same orientation to produce an array of parallel microfractures, often extending several grain diameters in length. The grain-boundary cracks are developed less extensively and exhibit a weaker preferred orientation, compared to the intragranular cracks, but they too are weakly aligned sub-perpendicular to the σ_3 direction.

Pattern B (Figures 10-12) contains both types of microfractures, but exhibits only a weak preferred orientation. The grain-boundary cracks are well developed, existing along several or all sides of many of the grains to form a random pattern. Intragranular cracks show greater variation of orientation about the σ_3 direction than in pattern A.

All specimens, except those deformed at room temperature, exhibit either the type A or type B pattern (Table I). B-type patterns characterize the experiments at 800°C at all confining pressures and those at 600°C and low confining pressures. Room temperature specimen E1 is almost totally unfractured and specimens E2 through E5 each contain very few microfractures which were developed only adjacent to a single throughgoing macrofracture parallel to the σ_1 direction

(i.e., normal to σ_3). The remaining samples show wide zones of microfracturing, and either contain a macrofracture parallel to σ_1 or did not fail macroscopically.

Microfracture Linear Density

Microfracture linear densities (MLD) are used as one measure to characterize microfracture abundance. Similar changes in MLD occur for 600° and 800°C with increasing effective pressure for dry conditions (Figures 13 and 14). Intragranular microfractures (solid boxes) tend to increase with increasing confining pressure, while the abundance of grain-boundary cracks (open boxes) remains relatively constant for all confining pressures. Grain-boundary-crack densities show much less variation within a sample than do densities of intragranular cracks. The difference in GBC and IGC development bears out the preliminary assumption that the microfracture data should be analyzed as two separate populations with an eye toward separate controlling parameters and contributions from each. The MLD data from grain-boundary cracks suggest that all grain boundaries normal to σ_3 are cracked at 600°C, or confining pressure does not greatly affect the development of grain-boundary cracks.

The wet test data (Figure 15), show a marked decrease in intragranular microfracture abundance with increasing temperature. The GBC densities, however, measured normal to σ_3 , seem apparently independent of temperature.

Figure 13. Average microfracture linear density versus effective confining pressure for dry specimens at 600°C. IGC tend to increase with P_e while GBC are reasonably constant in development.

Figure 14. Average microfracture linear density versus effective confining pressure for dry specimens at 800°C. Data exhibit same trends as at 600°C, but the overall averages are somewhat higher (see Figure 13).

Figure 15. Average microfracture linear density versus temperature for wet tests at 100-MPa effective confining pressure. Note dramatic decrease in the abundance of IGC.

Areal Microfracture Density

Microfracture densities calculated from microfracture maps may be a more appropriate way of viewing crack density data. Less sampling bias is introduced than with densities calculated from parallel linear traverses. Areal crack densities can be calculated in two ways: (1) by dividing the total number of microfractures by the area in which the fractures occur, or (2) by dividing the summed lengths of microfractures by the same area. The latter method may be better, as the contribution of long cracks to the statistic is greater. A long crack has a greater potential to lead to macroscopic failure, and thus to the reduction of rock strength, than several short ones, and should be appropriately weighted.

Microfracture densities calculated in either way show contrasting results for the wet and dry specimens. Figure 16, based on summed lengths, shows that intragranular crack densities increase (or remain about the same) with increasing temperature for dry tests, but decrease with increasing temperature for wet tests. The relationship of areal IGC density to confining pressure is less consistent, and no consistent trends are apparent for GBC densities (Figure 17).

Crack Length

Intragranular crack lengths were measured directly from the fracture maps and the average length was calculated for each sample. With the exception of one test pair, the average intragranular crack length decreased with increasing temperature in both wet and dry tests (Figure 18). This also can be seen in histograms of the distribution

Figure 16. IGC density versus temperature for wet and dry specimens. Note the abundance of IGC in wet tests decreases while it increases in dry ones with increasing temperature.

Figure 17. GBC density versus temperature for wet and dry specimens. Under three of the four sets of conditions the GBC increase slightly in abundance with increasing temperature.

Figure 18. Average IGC length versus temperature for wet and dry specimens. Under three of the four sets of conditions the average crack length decreases with increasing temperature.

of microfracture lengths (Figure 19). With an increase in temperature, the percentage of fractures with lengths less than 0.5 mm increases and the crack length distribution is shifted toward shorter microfractures. The total length of grain-boundary cracks was measured, but there is no reliable way to count the number of GBC as they form an interconnected network. Therefore, an average crack length for GBC could not be determined.

Crack Width

No quantitative measure of crack width was undertaken for the study, but wet specimens examined optically appeared qualitatively to have very-wide grain-boundary cracks relative to those observed in dry samples. On the other hand, axial strain for all wet samples is much greater than for corresponding dry samples and the widening might reflect the greater strain.

Figure 19. Histograms showing the distribution of microfracture lengths for wet specimens. Specimens E21 (a), E14 (b) and E12 (c) were deformed at $P_e = 100$ MPa, water-wet and at temperatures of 800°, 700° and 600°C, respectively. The abundance of shorter microfractures increases with increasing temperature.

DISCUSSION

General Comments

The microstructure present in the Westerly granite specimens after triaxial extension is the result of superposed thermal and mechanical stresses. The changes in the state of stress that occur during the extension test is an important consideration when interpreting the microfracture data. Therefore, a short review of stress state changes and resulting microstructure follows.

Specimens are first subjected to a progressively increasing hydrostatic stress state ($\sigma_1 = \sigma_2 = \sigma_3$) until the desired confining pressure is reached. Cracks may open, close or lengthen because of the hydrostatic stress but, at the pressures of this study, these changes are likely to be relatively insignificant (Sprunt and Brace, 1974). Subsequent microstructural changes resulting from differential stresses across the boundaries of the specimen and from its thermal history are apt to be greater and more readily affect the fracture strength of the rock. The specimens are then heated until the desired temperature is attained and are allowed to equilibrate. Thermal stresses are sufficient to overcome the fracture-inhibiting effect of pressure, and thermal cracking occurs. For quartz-bearing igneous rocks, Kern (1978) determined that an increase in temperature of 100°C is necessary to overcome the fracture suppression effect of a 100-MPa increment of effective confining pressure. In regards to thermal cracking, the latter would have the effect of reducing the test temperature 100°C for every 100 MPa of effective pressure. Ignoring

any crystallographic anisotropy present in the rock, microfractures produced up to this point in the test should have a random orientation as the thermal and mechanical stress are reasonably isotropic on the scale of the whole specimen.

Once the desired confining pressure and temperature for the test has been reached, the axial piston is withdrawn at a constant rate, which results in a reduction of the axial force. The axial stress, corresponding to σ_3 , progressively decreases with continued piston retraction, while σ_1 and σ_2 are constant and equal to the confining pressure. As σ_3 decreases, the abundance of microfractures with orientations normal to σ_3 increases because the normal stress opposing the opening of these cracks is reduced. In contrast, the confining pressure (σ_1) continues to act on existing and potential cracks with orientations normal to σ_1 , inhibiting their development. The differential stress developed, thus, favors a preferred orientation of microcracks. This preferred orientation would be best developed for samples subjected to the higher confining pressures as a greater differential stress can occur.

Using the data of Kern (1978), allows one to consider the microcracking resulting from thermal and mechanical stresses as having been produced from thermal stresses alone. The "equivalent" temperature necessary to produce the latter is reduced from the actual test temperature 100°C for every 100-MPa increment of confining pressure. Accordingly, the microfractures produced from a specific temperature and confining pressure can be correlated to the unconfined thermal cracking data of Bauer and Johnson (1979).

Dry Effects

In dry tests, the intragranular crack densities (Figure 16) and the grain-boundary crack densities (Figure 17) tend to be greater at 800° than at 600°C (i.e. positive slopes exist along 4 of the 6 data lines in Figures 16 and 17). The relative increase, however, varies widely for different confining pressures. This variation in microfracturing with temperature can be explained, in part, through the work of Bauer and Johnson (1979) and Kern (1978).

Figure 20 from Bauer and Johnson (1979), shows IGC and GBC densities as a function of maximum thermal-cycle temperature for unconfined specimens. The abundance of both IGC and GBC increases with temperature until about 600°C. Between 600° and 800°C, the IGC density increases at a much smaller rate, while the GBC density remains constant. As described earlier, the work of Kern (1978) indicates that the pressure effect of thermal crack suppression can be compensated for by utilizing an "equivalent" temperature reduced 100°C for every 100-MPa increment of pressure. With this adoption, Bauer and Johnson's data on thermal cracking at unconfined conditions can be used to describe the fracture densities from this study provided "equivalent" temperatures are selected.

The IGC density at 600° and 800°C for three different confining pressures (Figures 16) could be represented by three different intervals of the IGC curve described by Bauer and Johnson's data (Figure 20). The intervals 400° to 600°C, 500° to 700°C and about 600° to 800°C should indicate the thermal crack abundance for the 200, 100 and 20 MPa data, respectively. As the slope of the curve is

Figure 20. Variation of linear crack density with maximum cycle temperature. The linear crack density (LCD) is the average number of microfractures intersected per millimeter traversed. The LCD is normalized with respect to the average grain boundary spacing (3 grain boundaries per millimeter) (modified from Bauer and Johnson, 1979).

greatest between 400° and 600°C, less steep between 500° and 700°C and very small between 600° and 800°C, the curve describes the relative changes with temperature of the data in Figure 16 fairly well. It must be kept in mind, however, that the reduced temperatures only apply in a direction parallel to the direction that the pressure is applied. The normal stresses acting in the σ_1 and σ_3 directions are not the same. In the σ_3 direction, the pressure at the termination of testing is either a small compressive stress or a tensile stress, so the thermal cracking, oriented normal to σ_3 , would develop as if the sample was essentially unconfined. This would modify the slopes somewhat, but Bauer and Johnson's data seem adequate to explain the relative variation of the increase in IGC density with temperature.

As we have seen, the slopes of the lines in Figure 16, showing changes in IGC density with temperature, are constant with Figure 20. However, the relative positions of these lines to each other are not in agreement with Bauer and Johnson's data. The 20-MPa data pair should have the greatest IGC density, based on the 600° to 800°C interval in Figure 20, because the confining pressure, which inhibits thermal cracking, is the lowest. Instead, the 20-MPa data pair has the lowest density of the three pairs. This difference is attributed to the effect of the initial confining pressure. As σ_1 promotes intragranular cracking parallel to the direction it is applied, the abundance of mechanically-induced microfractures would be greatest for the highest confining pressure (greatest value of σ_1) and least for the lowest confining pressure. If the cracking from both thermal and mechanical stresses are considered, the trends of IGC development

shown in Figure 16 seem reasonable, as the mechanically-induced microfractures do not affect the slopes of the lines, just their relative position. For the most part, the relative abundances of GBC for dry tests shown in Figure 17, can be explained in a similar fashion, by selecting appropriate intervals from the GBC curve in Figure 20.

The microfracture populations depicted by the fracture maps were categorized into an A- or B-type pattern. Differences between the two fracture patterns, in dry tests, can be attributed to differences in temperature and stress states. Pattern B develops in samples tested at low confining pressures at 600°C and for almost all values of confining pressure at 800°C (Table I). Pattern B (Figures 10 and 11) is characterized by a well developed GBC network and only a modest abundance of IGC relative to pattern A. The IGC show a slight preferred orientation parallel to σ_1 .

When σ_1 is equal to 20 MPa, its fracture-inhibiting effect is minimal and GBC develop similar to those in an unconfined test, completely surrounding a substantial number of grains (particularly quartz). As σ_1 is small, only a small differential stress can develop, so mechanically-induced IGC do not develop substantially and have a poor preferred orientation. At the higher test temperatures, thermal stresses can overcome greater values of σ_1 , and the extensive GBC development of pattern B is maintained.

Pattern A is characterized by abundant IGC with a strong preferred orientation parallel to σ_1 (Figures 7a and 9a). At the higher confining pressures, the GBC also exhibit a similar preferred

orientation (Figure 7b). Abundant IGC occur because σ_1 is large. With a higher initial confining pressure, a greater amount of mechanical energy is stored in the specimen, prior to the reduction of σ_3 , than at lower confining pressures. With a the reduction in σ_3 , IGC develop abundantly. The mechanical differential stress existing across the boundaries of the specimen results in the strong microfracture anisotropy as discussed earlier. Specimen E20 (Figure 9) shows both A and B characteristics. The IGC develop in an A pattern because of the large confining pressure and differential stress. The GBC, on the other hand, show a B-pattern because as before, we can assign an "equivalent" temperature of 600°C in the σ_1 direction and 800°C in the σ_3 direction. From Bauer and Johnson's data (Figure 20) there is no difference in GBC density between 600° and 800°C. Therefore, thermal cracks develop in specimen E20 equally in the σ_1 and σ_3 direction reflecting the B pattern.

The microfracture trends and microfracturing patterns have been examined in light of differences in temperature and pressure. If the microstructure controls the macroscopic behavior of the samples, then an important part of the study is to explain the strength behavior of the Westerly granite in terms of the variation in microfracturing development. Figure 2 shows the variation of ultimate strengths or maximum differential stress ($\sigma_1 - \sigma_3$) as a function of temperature and confining pressures. The maximum differential stress at failure decreases with increasing temperature and increases with increasing confining pressure. In extension tests, Handin et al. (1967) demonstrated that the tensile stress at failure (σ_3) for limestone is

independent of confining pressure (σ_1), and represents an inherent tensile strength dependent on rock type. If σ_3 is independent of σ_1 for all rock types, then it follows that ultimate strengths ($\sigma_1 - \sigma_3$) would increase with increasing confining pressure, as σ_1 increases and σ_3 remains constant. It may be best to examine how σ_3 varies as a function of σ_1 to see if this holds true.

For room temperature specimens, with σ_1 less than or equal to 100 MPa, the observed tensile stresses have a constant value (Figure 21) as might be expected from the work of Handin et al. (1967). However, the tensile stresses gradually decrease and approach zero as σ_1 approaches 200 MPa. Bauer and Johnson (1979) reported a uniaxial compressive strength (i.e. σ_3 is equal to zero) slightly greater than 200 MPa for Westerly granite at room temperature. As σ_1 approaches the uniaxial compressive strength, a smaller tensile stress is required for the specimen to reach a critical stress state because of the effect of σ_1 . For all values of σ_1 , the tensile stresses decrease with temperature, and for higher temperatures, the stresses become zero at lower values of σ_1 . This behavior could be expected as the uniaxial compressive strength of Westerly granite decreases with increasing temperature because of increased thermal cracking. When σ_1 is greater than the uniaxial compressive strength for a certain temperature, the samples fail with a positive value for σ_3 (the sample fails in compression).

The decrease in tensile stress with increasing values of σ_1 is accompanied by an increase in fracture angle as listed in Table I. Fractures with angles greater than 5° were classified as shear

Figure 21. Tensile stress (σ_3) as a function of maximum compressive stress (σ_1). Tensile strength decreases with increasing initial confining pressure (σ_1). The strength reduction is greater for higher temperatures.

fractures. Almost all specimens that failed in compression (σ_3 is positive) failed with a macroscopic shear fracture as would be expected in a standard compression test. An attempt was made to correlate microfracture pattern type (A or B), abundance and length with macrofracture type (S or T) (Table I, Figure 1). In no instance could an influence of macrofracture type be recognized. If an influence exists, it is smaller than the trends recognized for increasing temperature or effective confining pressure or those associated with wet versus dry conditions.

The maximum differential stress ($\sigma_1 - \sigma_3$) sustainable by the specimens, prior to failure, increases with increasing confining pressure. The value of $\sigma_1 - \sigma_3$ does not, however, increase at the same rate as σ_1 , as would be expected if the tensile stress is indeed independent of the value of σ_1 (compare values in Table I). The departure from a linear correspondence between maximum differential stress and confining pressure is because of the decrease in the critical value of σ_3 with an increase in σ_1 (Figure 21). The only consistent microstructural change to accompany an increase in σ_1 is the increase in abundance of intragranular cracks. This is crudely shown by the plots of MLD (Figures 13 and 14) and better depicted by the IGC densities (Figure 16). As microfracturing increases with increasing confining pressure, a smaller tensile stress is needed to effect macroscopic failure. Even though the ultimate strengths increase with increasing confining pressure, the amount of increase is less for greater values of σ_1 because of the reduction of σ_3 .

The crack densities of room temperature specimens were not measured because of the sparsity of microfractures adjacent to the macrofractures. As the interpretations of this study rely on statistics of precursive cracking, it may be inappropriate to base interpretations on so few microfractures. However, if precursive cracking does increase with increasing confining pressure at room temperature, perhaps a sufficient crack population is necessary before the inherent tensile strength is reduced. At temperatures greater than 600°C, an adequate crack population already exists, because of thermal cracks, and no inherent tensile strengths is manifested (i.e. there is no constant value of σ_3). Tensile strengths decrease for every incremental increase in confining pressure with no constant value of σ_3 . Investigations of a different nature may be necessary to better understand the room temperature behavior of rock.

A second observation from the dry experiments is that tensile stresses and ultimate strengths decrease with an increase in temperature at constant confining pressure. The microfracture statistics indicate that IGC and GBC increase from 600° to 800°C (Figures 16 and 17). In both cases, the increase is greater for higher confining pressures. The reduction in ultimate strengths and tensile stresses, between 600° and 800°C, is also greater for higher confining pressures (Figures 2 and 21, respectively). The correlation in data indicates that the increased abundance of microfractures with temperature, is responsible for the weakening. Further, the greater weakening at higher confining pressures suggests an interaction between thermal and mechanical effects which may be important to the strength of the rock.

The increase in total fracture length with increasing temperature (Figures 16 and 17) does not indicate the exact nature of the microstructural changes taking place. An increase in temperature may produce an increase in the number of cracks or alter the ability of a crack to propagate through the rock (resulting in longer cracks). Either mechanisms could produce an increase in total crack length. An examination of the crack length statistics may indicate the better alternative.

The average IGC length, for dry conditions, is smaller at 800° than at 600°C (Figure 18). If crack growth is favored by temperature, an increase in the average crack length could be expected. The data do not indicate this behavior. IGC are shorter for tests at higher temperature supporting the possibility that the strength reductions with temperature result from a greater number of cracks. A temperature effect on crack growth may still exist, but its importance may be secondary in regards to the strength of the rock.

Wet Effects

Water saturated specimens are weaker and more ductile than their dry counterparts (Figures 2 and 3). This difference in behavior is dramatically reflected in the microfracture statistics, particularly by the intragranular cracks. In marked contrast to dry specimens, the linear and areal densities of IGC (wet tests) decrease with increasing temperature (Figures 16 and 17). This is opposite to the trend in the dry tests. Not only are the IGC less abundant, but the average crack lengths decrease with increasing temperature as well (Figure 18). The

macroscopic behavior of specimens tested wet does not seem to result from the temperature effects on IGC. As the GBC tend to be somewhat better developed with increasing temperature (Figure 17), the key to the weakening may be the microstructural changes at the grain boundaries. In addition, at any given temperature the grain-boundary cracks in wet specimens are qualitatively wider than their dry counterparts (Figure 4, b and c). The increase in separation should result in greater de-coupling of grains and may be responsible for the increase in ductility.

The microfracture maps for wet specimens were categorized into the A- or B-pattern as were those of dry specimens. Though all wet tests were conducted at the same effective confining pressure ($P_e = 100$ MPa), an indirect confining-pressure effect can be shown from the way in which temperature and pressure interact and produce microcracks. At 600°C , an A-pattern results, while at 700° and 800°C , a B-pattern is produced (Figures 8, 12 and 24). At 600°C , the confining pressure is large enough to suppress cracking normal to σ_1 , and a strong microfracture anisotropy develops. At 700° and 800°C , thermal stresses are sufficient to overcome the suppression of cracking normal to σ_1 and the B-pattern results. The interaction between thermal and mechanical stresses is important in the microfracturing process with potentially significant implications for the macroscopic behavior of rock.

The fracture maps of the water-wet specimens tested at 700° and 800°C also show a conspicuous abundance of vertical IGC normal to σ_1 (Figures 12 and 24). The wide grain boundaries, vertical IGC and the

trend of IGC to decrease with increasing temperature, suggest that the water alters the conditions at the grain boundaries and reduces their ability to transfer the far-field stresses to the interior of the grains. This effect is more pronounced at higher temperatures.

Crack Lengths

The average intragranular crack length decreases with increasing temperature in both wet and dry tests (Figures 18 and 19). This result was not anticipated as temperature was expected to favor crack growth. The specimens weaken with increasing temperature, and it was envisioned that the average crack lengths would correspondingly lengthen. Clearly they do not. As the temperature increases, crack tips may be blunted by crystal plastic mechanisms. This blunting would decrease the stress concentration at the crack tip and inhibit propagation thereby increasing the relative number of short cracks.

Summary

In dry tests, any proposed model of precursive crack growth and coalescence to macroscopic failure must rationalize the following facts, namely;

- a. IGC and GBC increase in abundance with increasing temperature at constant confining pressure; and
- b. IGC increase in abundance with increasing confining pressure;
- c. IGC tend to be shorter with increasing temperature.

In the wet environment:

- d. IGC decrease with increasing temperature;
- e. GBC tend to be better developed with increasing temperature;
- f. see c (above).

The common thread is the enhanced development of grain-boundary cracks with increasing temperature. This trend suggests the grain boundaries must play an even greater role in the history leading to failure as temperature increases. For wet conditions, the GBC are best developed and consequently fewer and shorter IGC are required to achieve coalescence and failure. For dry conditions, the GBC are only slightly better developed with increasing temperature so that more IGC, even though short, are needed to effect macroscopic failure.

CONCLUSIONS

The microscopic observation and measurement of microfracture populations in specimens of Westerly granite, deformed in triaxial extension under selected pressure and temperature conditions, seems to warrant the following conclusions:

1. The ultimate strengths of the Westerly granite specimens deformed in extension increase with increasing effective confining pressure (20 to 200 MPa), decrease with increasing temperatures (25° to 800°C), and are lower in water-wet tests compared to their dry counterparts. Weakening with temperature (600° to 800°C) is much more dramatic in the wet environment. These trends are identical to the mechanical response of rock in compressive tests (e.g., Friedman, et al., 1982).
2. Intragranular (IGC) and grain-boundary (GBC) microfractures are conspicuous in all specimens. IGC strongly oriented normal to σ_3 occur at 600°C and effective pressures $\geq$ 100 MPa. At other conditions both IGC and GBC are more randomly oriented showing much less tendency to lie normal to σ_3 .
3. In dry experiments, the linear and areal densities (abundance) of IGC increase with increasing confining pressure and increase with increasing temperature at constant confining pressure. The GBC densities generally increase with increasing temperature.
4. In wet experiments ($P_e = 100$ MPa) the IGC areal density decreases by a factor of three with increasing temperature (600° to 800°C), while that of the GBC increases somewhat, but become conspicuously wider, with increasing temperature.

5. Increasing the confining pressure suppresses grain-boundary and intragranular crack development in a direction normal to the applied confining pressure and enhances cracking in a direction parallel to the confining pressure, resulting in a preferred orientation of microcracks. The effectiveness of the crack network to lead to macroscopic failure is diminished and ultimate strengths increase with increasing confining pressure.

6. The overall increase in IGC density with increasing confining pressure (σ_1) does result in a decrease in the tensile stress (σ_3) at failure with an increase in σ_1 . The decreasing tensile strength negatively affects the correspondence between increasing confining pressure and increasing ultimate strength (i.e., the increase in ultimate strength that occurs with an incremental increase in confining pressure is less for higher confining pressure).

7. Heating at a constant confining pressure in the dry environment negates a portion of the fracture-suppression effect of confining pressure and increases the abundance of IGC and GBC. The more abundant and more diffusely oriented IGC form an enhanced crack network that leads to the reduction in ultimate and tensile strengths with increasing temperature. A temperature effect on the ease of crack propagation through a rock mass subjected to a mechanical load may exist, but is secondary in importance to the weakening effect of the enhanced crack network.

8. The interaction between thermal and mechanical stresses may control microcrack development and so alter the macroscopic behavior of rock.

9. In the water-wet environment, IGC decrease in abundance while GBC tend to be better developed as temperature increases. In addition, at the higher temperatures, cracks coinciding with the grain boundaries attain significant width, and a conspicuous number of IGC cracks have orientations normal to the maximum compressive stress. These events correlate with dramatic strength reduction and increase in ductility and suggest that the presence of water alters the stress conditions at the grain boundaries. These trends emphasize the role of grain boundaries in the history of events leading to macroscopic failure.

10. Perhaps the most surprising result of this study is the evidence that the length of IGC decrease with increasing temperature, wet or dry.

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APPENDIX I: TRIAXIAL-EXTENSION TESTING

In the high temperature apparatus used by Bauer, triaxial-extension testing consists of superposing a uniaxial tensile (σ_t) on a hydrostatic confining pressure (P). The confining pressure is applied to the sides of the cylindrical samples and is prevented from acting on the ends of the samples by O-ring seals. An axial load is applied to the ends of the sample by the piston. The axial load and the confining pressure are simultaneously raised to achieve a hydrostatic stress state. The axial load is then reduced to produce a differential stress. The least principal stress $\sigma_3 = P - \sigma_t < \sigma_1 = \sigma_2 = P$. For wet tests, P is actually an effective confining pressure equal to the difference between the external confining pressure and the internal pore pressure.

The magnitude of σ_3 can be made tensile (negative) when there is a reduced diameter in the middle portion of the sample (dog-boned-shaped) (see Brace, 1964). If $A_{\max}$ and $A_{\min}$ are the cross-sectional areas of the specimen then the axial stress in the middle of the specimen is given by

$$\sigma_3 = F/A_{\min} - P(A_{\max} - A_{\min})/A_{\min}$$

When the axial force is reduced to zero, σ_3 reaches its maximum tensile value:

$$\sigma_3 = P - PA_{\max}/A_{\min}$$

APPENDIX II: EXPERIMENTAL PROCEDURE

Procedure is similar to that described in Friedman et al., 1979, with the following modifications necessary for triaxial extension.

1. To obtain true tensile stresses in extension tests, the diameter of the center 3-cm length of the 4-cm long cylinders was reduced about 2.0 mm. This procedure leaves fillets approximately 0.5 cm from the ends of each specimen.

2. The loading column is first subjected to a small axial load to seat all of the loading column members.

3. Axial force and confining pressure are raised simultaneously to the desired hydrostatic pressure. This is necessary as specimen assembly prevents confining pressure from acting on the specimen in the axial direction. For wet specimens, pore pressure and hydrostatic confining pressure are simultaneously raised to the desired value, resulting in 100 MPa effective confining pressure. Specimens are allowed to equilibrate.

4. Specimens are heated to the desired temperature at 2° to 3°C per minute. Axial load, confining pressure, and pore pressure (for wet tests) are manually adjusted to maintain the desired conditions during heating. Specimens are allowed to equilibrate overnight at temperature and pressure.

5. While keeping the effective confining pressure and , temperature constant, the axial load is reduced ($\epsilon = 3 \times 10^{-4}$) until fracture occurs or until appreciable strain has occurred.

6. At termination, the axial load is returned to the desired hydrostat. Temperature is then decreased at 5°C per minute to room temperature while effective confining pressures are maintained. Then pore pressure is released followed by confining pressure.

7. Specimens are then cut from the carbide spacers on a lathe and prepared for microstructural analysis.

APPENDIX III: SUPPLEMENTARY MICROFRACTURE MAPS

Additional microfracture maps that were not drafted follow. Grain-boundary cracks are in red and intragranular cracks are in blue. All scale lines are 2.0 mm and σ_1 is aligned parallel to the length of the page.

Figure 22. Microfracture map of E8 ($P_e = 100$ MPa, 600°C , dry).

Figure 23. Microfracture map of E17 ($P_e = 100$ MPa, 800°C , dry).

Figure 24. Microfracture map of E14 ($P_e = 100$ MPa, 700°C , water-wet).

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