MECHANICAL AND TRANSPORT PROPERTIES OF ROCKS AT HIGH TEMPERATURES AND PRESSURES

TASK I

THE PHYSICAL NATURE OF FRACTURING AT DEPTH

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'THE PHYSICAL NATURE OF FRACTURING AT DEPTH'

The primary goal of the research supported by contract DOE AS05-79ER10361-Task 1, has been to delineate experimentally, in P-T- σ - $\dot{\epsilon}$ space, the boundary separating elastic-brittle and transient-semibrittle behavior of granite and of its volcanic and metamorphic equivalents, rhyolite and granite gneiss. This choice of materials has been dictated by near-term geothermal energy and waste-isolation needs and effects of H₂O and moderately saline solutions on the mechanical behavior must be assessed in some detail. Especially important is the documentation of flow processes, to the atomic level, in the most important semibrittle regime as well as development of a macroscopic failure criterion which incorporates thermally-activated fracture and flow processes. Characterization of the flow processes in naturally deformed counterparts forms an integral part of the research program to ensure that the flow mechanisms and mechanical data obtained experimentally are applicable in field-scale experiments and in tectonic deformations.

As a major step toward this goal, we have completed a literature review of existing studies of creep of granitic rocks, have examined more than cursorily several suites of different granitic rocks, and have carried out preliminary experiments on Westerly granite deformed at intermediate to high-temperatures, primarily in a dry environment. The results of this work will be published in an article entitled "Creep and creep-rupture of granitic rocks", which should appear early in 1981 in A.G.U. Monograph 24 - The Handin Volume. The more important results of that study, as well as work in other areas pertinent to this project, is as summarized in context below.

Low-to-Moderate-Temperature Experiments on Barre Granite

Robert Kranz has succeeded in modifying our MTS deformation apparatus to accomodate 1-inch diameter cores of Barre granite to be deformed, along with Westerly granite (for comparison), in creep at 100 to 200 MPa confining pressure and temperatures to 400°C. Results are few to date and consist dominantly of comparing room temperature fracture strengths with those obtained at LaMont (Kranz, 1979a) and a few creep tests at 200°C. The room temperature fracture strengths at 100 MPa confining pressure are comparable and the

fracture strength at 200°C is 20 to 30 MPa less, as is expected. However, the times to fracture in tests at elevated temperature are both greater and less than those at comparable conditions at room temperature and the volumetric strain-rate differences are also erratic. This behavior is not understood at present and considerably more experimental work and analyses are required.

The specimens deformed at 200°C were also examined by scanning electron microscopy (SEM) for comparison, with Kranz's (1979b) work at room temperature. Again, the fracture characteristics at this low temperature are little different from those at room temperature. Figure 1A shows a low-magnification SEM photo of the Barre granite with a large feldspar grain surrounded by mica crystals (above) and quartz and one feldspar grain. The grain boundaries are well marked by ellipsoidal mounds, as are fractures which extend from grain boundaries into the large feldspar crystal. The several linking and interacting cracks in the quartz grains shown at higher magnification in Figure 1B are also typical of room temperature specimens. The most atypical feature observed is the occurrence of thin filaments across some open cracks in the elevated temperature runs (Fig. 1C). These filaments, of undetermined nature, bend sigmoidally in a sense such as to suggest a right-lateral component of shear but their character, as well as physical meaning, is unclear at present.

While these studies at low pressure and elevated temperature are, evidently, at the incipient stage, they are regarded as an essential link to the observations at high temperature and pressure to be discussed below. Stress and strain measurements under these modest conditions are much more accurate than those in solid-pressure medium equipment and hence the results obtained are crucial to interpretations of the latter. To this end, we plan to conclude the series at 200°C, 1 kb confining pressure during the present contract and propose to extend the series to 2 kb, 400°C in the MTS equipment during the next contract year. SEM will be used to determine fracture populations and configurations in these specimens, including depth-profiling or serial-sectioning of some grains and specimens of particular interest. Concomittantly, during the next contract year, Steve Bauer, a graduate student here, will begin a study of the effects of temperature on static fatigue of saturated and dry granite at low effective pressure (1 and 2 kb) and temperatures in the range 400 to 800°C. He is especially interested in evaluating effects of volume percent of mineral constituents, and grain-size and shape on bulk deformation properties and in determining rate controlling parameters. Both Bauer and Kranz are

currently working on a finite element simulation of deformational responses to be expected of polycrystalline aggregates whose constituents have different sizes, shapes, volume percentages and elastic and flow properties. The reasons for our interest in these topics will emerge clearly below; in any instance, it is essential to have a fundamental physical understanding of the effects of temperature on the deformational behavior of granitic rocks.

Experiments at moderate-to high-temperature

Somewhat more progress has been made at the more extreme conditions at high temperatures and pressures because equipment was available, though less accurate, to accommodate these conditions. In the initial experiments, Westerly granite cylinders were deformed dry in compression to low strains in a Griggs-type solid confining pressure medium apparatus (Green *et al.*, 1970). The cylindrical cores, 6.35 mm diameter by 17.8 mm long, were backed by Al_2O_3 -TiO end pieces and surrounded by 0.076 mm-thick platinum jackets, both to reduce the thermal gradient and to isolate the specimen chemically from the talc confining medium. All samples were dried overnight at 300°C in air and were then placed in a dessicator after cooling. Experiments were run at constant differential stresses of 0.6 to 1.2 GPa, temperatures in the range 470° to 765°C, and longitudinal strains from .002 to .02, all at a constant confining pressure of 1.0 GPa. Thus all experiments were carried out in the α -quartz stability field (Koch *et al.*, 1980).

The experiments were terminated at low creep strains because we are concerned here primarily with the high-temperature transient creep behavior of granite, although the steady-state was achieved in many of the runs. In conventional creep experiments, steady-state flow properties are generally the object and are assumed to be path independent, but in attempting to determine transient creep properties, it is the path towards a steady-state substructure that we wish to evaluate. This has required two modifications of the conventional loading procedure, in addition to more sensitive displacement measurements (a displacement of 5×10^{-4} " is recorded as 2 cm on the recorder, with a sensitivity of 5×10^{-5} "). The first modification was to raise the stress quickly, after equilibrating at the desired temperature and pressure, to minimize the time available for plastic strain and recovery to take place during loading. The specimens were loaded at about 140 MPa/sec. manually, typically reaching the desired stress difference in about 6 seconds. Giletti *et al.*, (1978) have determined oxygen diffusion parameters for adularia and albite in a hydrothermal environment; this should place approximate upper bounds on the

diffusion-controlled recovery in two dominant minerals in Westerly granite. The relation $x = 2(Dt)^{1/2}$ (Shewmon, 1963) gives x , the distance which oxygen will diffuse in time t for a given diffusion coefficient, D . Combined with the results of Giletti et al., (1978), diffusion distances at typical loading times for adularia and albite at 700°C are 135 and 93 Å, respectively, and hence should not allow significant recovery. The second modification is to control the drive motor speed manually at the beginning of the experiment to avoid oscillations due to insufficiently rapid damping of the creep servo. Using this procedure, differential stresses are maintained constant to about 10 MPa (ca. 1%); runs in which the stress level varied by more than 25 MPa were rejected.

Representative results for the dry creep experiments on Westerly granite are as shown in Figures 2A-C. As expected, creep resistance increases, at constant stress, with decreasing temperature (Fig. 2A) and at constant temperature, with decreasing stress (Fig. 2B). The data (dots) were fit to the presently favored general creep equation (Webster et al., 1969):

$$\epsilon = \epsilon_0 + \epsilon_T[1 - \exp(-t/\tau)] + \dot{\epsilon}_s t \quad (1)$$

where ϵ_0 is the "instantaneous" elastic and plastic strain during loading, ϵ_T is the total transient creep strain, τ is a relaxation time and $\dot{\epsilon}_s$ is the steady-state creep strain. Solid curves in Figures 2A and 2B are fits of the data to equation (1) and it is evident that the fit is quite satisfactory. Data shown in Figure 2C are more difficult to interpret and clearly do not fit the simple equation (1); curves in this Figure and the remaining curves in Figure 2 are merely eyeball fits to the data. Figure 2C shows creep curves in which two transient portions, with a steady-state region sandwiched between occur in three representative runs. This anomalous behavior may indicate that two or more competitive mechanisms are operative (Gangi, 1981) and is reminiscent of synthetic quartz crystals deformed at constant strain rate (e.g. Hobbs et al., 1972).

Figures 2D-E show the results of some preliminary experiments on "wet" Westerly granite, and dry Sioux quartzite and diorite (locality unknown) carried out merely for a comparison with the behavior of the dry granite. Following the Tullis and Yund (1978) procedure, wet granite specimens were prepared by vacuum impregnation of distilled H₂O (0.1 wt. percent added), were dried at room temperature and then encapsulated in platinum jackets. Wet granite samples were then soaked for 30 minutes at the ambient conditions of the experiment prior to deformation at the conditions shown in Figure 2D. Comparisons with curves of Figures 2A-C for the nominally dry granite indicate

that the wet granite deforms much more readily, under comparable conditions, as expected (Goetze, 1971; Tullis and Yund, 1978). The mechanical behavior of the quartzite (Fig. 2E) appears to lie between that of wet and dry granite and some of the peculiar behavior observed in Figure 2C also seems to be present in the quartzite. This appears to be true also of the diorite (Fig. 2F) but only at very low strains and times and thus may not be significant. The diorite, evidently, is much more creep resistant, under comparable conditions, than the other materials and deformed only in relatively low-temperature transient creep throughout the strain-time (to 8×10^3 seconds) range employed. More extensive experiments on quartzite and diorite will be discussed below.

As pointed out by Carter and Kirby (1978), most high-temperature transient creep data for rocks, primarily under uniaxial conditions, have been analyzed in terms of power-law transient creep. However, data for rocks deformed to high transient creep strains fit the physically more reasonable exponential decay law (second term in eqn. (1)) very satisfactorily. This is shown in Figure 3A which is a plot of $\log \Delta_\epsilon$ vs. t/t_s where Δ_ϵ is $\epsilon_T - \epsilon_t$ and t_s is the time required to reach the steady-state. These transient data should be linear on such a plot, with a slope equal to -1.74 and an intercept at $\log \epsilon_T$ (Carter and Kirby, 1978, p. 821). The data for other rocks are shown in the lower portion of the Figure and were taken from Carter and Kirby's Figure 2. Data for five of our experiments on high-temperature creep of Westerly granite are shown by the four curves with data points in the upper part of the diagram. Two other experiments (16 at 670°C, 1.0 GPa and 23 at 570°C, 1.0 GPa) could have been plotted on the Figure, but are so close to experiments 10 and 11 as to have cluttered the diagram. The slopes of the seven lines range from -1.2 to -2.0, with an average value of -1.72. Thus, the high-temperature transient creep data for Westerly granite, as well as other rock types for which comparable data are available, fit the transient part of equation (1) very well.

Our transient creep data have also been hand-fit to a power-law equation for comparison with similar data for granitic rocks, all of which have been cast in these terms. The best estimate of the power-law high-temperature transient creep equation is (Carter et al., 1981):

$$\epsilon_t = 7 \times 10^{-5} \sigma^{2.2} t^{0.5} \exp\left(-\frac{30.5}{RT \cdot 10^{-3}}\right). \quad (2)$$

The steady-state creep data were fit to the well-substantiated power law which adequately represents the high-temperature creep behavior of most

materials over a wide range of physical conditions:

$$\dot{\epsilon}_s = A \exp(-Q_c/RT) \sigma^n \quad (3)$$

where A is a nearly temperature-insensitive material constant, Q_c is the activation energy for creep and the remaining parameters have been specified previously. The least-squares fit of the data to this flow law is shown in Figure 4 and, although the data are few at present, they appear to fit (3) quite well. The resulting steady-state creep equation is (Carter *et al.*, 1981):

$$\dot{\epsilon}_s = 1.4 \times 10^{-9} (\pm 3.5 \times 10^{-9}) \exp\left(-\frac{25.3 \pm 2.2}{RT \cdot 10^{-3}}\right) \sigma^{2.9 \pm 0.3} \quad (4).$$

The activation energy, given here in kcal/mole, is slightly lower than that estimated above for power-law transient creep but the difference is well within estimated errors and is regarded as insignificant. The exponent on stress, 2.9, is also close to the 2.2 exponent found for the high-temperature transient estimate. Where they are comparable, these steady-state creep data are compatible with the constant strain-rate data of Tullis and Yund (1977). At a strain rate of 10^{-6} , they found that at 600° and 700°C, the steady-state flow stresses were about 1.2 and 0.8 GPa, respectively. Under comparable creep conditions, we find a steady-state strain rate of 1.1×10^{-6} /sec. at 570°C, 1.2 GPa and 1.3×10^{-6} /sec. at 670°C, 0.8 GPa.

In Figure 5, the power-law transient and steady-state creep behavior of Westerly granite deformed in our experiments are compared, arbitrarily, at 300° and 600°C and differential stresses of 50 and 500 MPa. The comparison is made in log strain - log time space by extrapolating equations (2) and (4) over the time range 10^7 seconds (0.32 year) to 10^{16} seconds (3.17×10^8 years) and a strain interval 10^{-6} to 10^4 . At any given set of conditions, steady-state creep gives the higher creep rate over the entire strain-time range shown and hence completely dominates the creep strain. The slopes of the lines representing the two creep regimes are such that they converge and intersect to the left and, in some instances, below the diagram. For example, at 600°C and 500 MPa, transient and steady-state curves intersect at $\log t = 3.5$ and $\log \epsilon = -4.0$; other intersections are at lower strains. These intersections (not shown) mark the time at which transient and steady-state creep contribute equally to the total creep strain and at which the creep strain-rates are identical. To the left of the intersections, transient creep dominates and to the right, steady-state creep dominates; over the strain-time range shown in Figure 5, the contribution due to transient creep is negligible.

We must now discuss briefly deformational processes observed in the experiments and in naturally deformed granitic rocks. Westerly granite is a relatively fine-grained (0.5 mm avg. grain diameter) granite consisting of 27.5% quartz, 42% k-spar, 31.4% plagioclase (An_{17}), 4.9% micas and accessories (Brace, 1965). The dominant deformational features in our experimentally deformed granite specimens are thin, irregular zones of intense rotations commonly associated with internal fractures. These features are believed to have resulted from semibrittle deformational behavior (thermally-activated processes are involved in fracture genesis, propagation and retardation) and have been observed previously in quartz (e.g. Heard and Carter, 1968; Tullis et al., 1973). Micas show the next most abundant deformation features and these occur as kink bands in grains oriented at high angles to the maximum principal compression stress axis. However, the volume percentage of such crystals is low and micas do not contribute appreciably to the general creep strain. The feldspars in our experiments show no hint of deformation at all, as deduced by optical studies and preliminary TEM analyses (Carter et al., 1981). This is contrary to the observations of Tullis and Yund (1977) who observed fairly extensive plastic flow of both quartz and feldspars in their constant strain rate experiments at rather extreme conditions but it must be remembered that their experiments were carried out to large creep strains. They did observe, however, that quartz deformed more readily than did feldspars under the conditions imposed in their experiments.

We have now examined several suites of naturally deformed granitic rocks, including an extensive suite of cores of granite obtained from various depths from the Illinois deep continental drilling project. In all instances (including the Westerly granite starting material), the granite shows small, but easily detectable (optically) creep strain as is evidenced primarily by undulatory extinction and well-developed polygonization in the quartz grains. Some of the micas are kinked and there is no optical evidence for deformation of the feldspars at all. Feldspars that have been deformed in experiments and in rare natural anorthosites show the same deformational features (kinks, undulatory extinction, polygonization, recrystallization) as does quartz and these, if present, could scarcely have gone undetected. We must conclude, on the basis of these preliminary observations, that quartz controls the creep rate of granitic rocks.

The foregoing conclusion is supported by available information on activation energies for creep of granite, quartz and feldspar. Goetze (1971) did a very careful study of high-temperature transient creep of Westerly granite at temperatures to melting, an external pressure of 500 MPa and an internal H₂O pressure of 100 MPa. He determined the activation energy to be 39 kcal/mol which is somewhat higher than the 30 kcal/mol determined in our transient creep experiments (eqn. (2)). This value is very close to the 38 kcal/mol observed by Koch et al., (1980) for quartzite deformed wet in the steady-state in constant strain rate experiments. Koch et al. (1980) obtained 36 kcal/mol for quartzite deformed dry and this value is not much higher than our dry values as given in equations (2) and (4). By contrast, activation energies for creep of albite rock and anorthosite, under conditions most favorable for low energies, are 55 and 60 kcal/mol, respectively (Tullis and Yund, 1979a,b). These observations, in conjunction with the preliminary analyses of naturally-and experimentally-induced microstructures, suggest that deformation of quartz may control the creep rate of granitic rocks (Carter et al., 1981).

Experiments on Quartzite and Diorite

When it was first realized that quartz, rather than the expected feldspar, might control the creep rate of granitic rocks, we felt that it was important to determine the creep properties of quartzite. At that time, we were unaware that such studies were in their advanced state at U.C.L.A. by Koch et al. (1980), although their experiments were run in the constant strain-rate mode. We began our creep work, in the same manner as described above for Westerly granite, on Sioux quartzite (Fig. 2E) but soon changed to Quadrant quartzite which is much more homogeneous both in constitution and in grainsize. Because of long delays experienced in obtaining ordered platinum jacketing materials, we began using inconel jackets with the result that the two jacketing materials, for some inexplicable reason, gave rise to substantial differences in the mechanical behavior of the quartzite. Upon receipt of the platinum tubing, we then abandoned the inconel and the steady-state results obtained to date for platinum-jacketed specimens are as shown in Figure 6. While the data are sparse, it is seen that the Sioux quartzite behaves similarly to the Quadrant in spite of the large differences in nature, grainsize and impurity content. This observation is encouraging in that it suggests that quartz, rather than other factors, dominates in controlling that creep rate and that other features are of secondary importance, an observation consistent with the mechanical

behavior of natural rocksalt (Hansen and Carter, 1980). All data were, therefore, fit by least squares to equation (3) and the isotherms and empirical constants thus obtained are shown in Figure 6.

In general, the fit to equation (3) is quite satisfactory, especially at the two higher temperatures. The activation energy obtained in these dry creep runs, about 28 kcal/mol, is similar to that found for our experiments on granite (eqn. 4) but about 8 kcal/mol lower than that obtained by Koch *et al.* (1980). The stress exponent obtained is lower than that observed either for the granite or the quartzite. It must be emphasized, however, that these results are few and preliminary and that these initial discrepancies are not intolerable. Furthermore, we have not evaluated the transient creep data for the quartzite and have not yet received thin sections of all of the deformed specimens. Thus, firm conclusions must await such studies as well as additional experiments and the results of Koch *et al.* (1980) must be regarded as much more reliable at present. Nonetheless, we feel that it is important to complete this study in order to: (1) compare the flow parameters for quartzite deformed at constant stress and at constant strain rate; (2) determine the mechanical transient creep response at high temperature; (3) determine and compare flow processes in quartz deformed to low strains in the transient and steady-state regimes. Such processes should be correlative with those in quartz in naturally-deformed granitic rocks if our contention that quartz controls the creep rate is correct.

Experiments on fine-grained, nearly equi-axial quartz diorite were carried out for contrast with the granite results because this material contains only three percent modal quartz and is composed dominantly of plagioclase. In this instance, it is inconceivable that quartz deformation might control the creep rate which should be dominated by either the feldspar or the pyroxene. In Figure 7 (left), the results of Figure 2F are expanded on the strain-time plot and nominal temperatures are indicated rather than the corrected temperatures of Figure 2F. The creep resistance decreases monotonically with increasing temperature at 0.9 GPa stress difference and also decreases still further with a larger constant stress difference of 1.2 GPa (Fig. 7, right; note change in scales), as expected. This latter behavior is shown more clearly in Figure 8 in which the strain, at constant nominal temperatures of 600°C (570°C) and 800°C (765°C), at various times is shown in the differential stress range 0.9 to 1.4 GPa.

Current data for diorite are incomplete and, because of the relatively high creep resistance (Fig. 2), are insufficient to estimate either high-temperature transient or steady state flow parameters. Higher temperatures and longer durations are required which, in turn, will necessitate a different sample assembly because of dehydration of talc at temperatures appreciably above 800°C. While the diorite provides only one possible material, low in quartz, and high in feldspar, for use as an end member, all similar rock-forming materials with these qualities are expected to be creep resistant and will require temperatures higher than those used to date. Therefore, in order to obtain the contrast desired, and to compare flow parameters with those of granite and feldspar rocks, a higher temperature dry assembly will be required and since we have a good start on diorite, we anticipate completion of tests on this material first.

The results available suggest that experimentally deformed granites in the low to moderate temperature range deform by brittle and semibrittle mechanisms and in the moderate to high-temperature regime, by semibrittle and ductile flow. Most of the creep strain appears to be accounted for by deformation of quartz rather than what would appear to be the feldspar structural framework. This appears to be true also of naturally deformed granites and that quartz deformation is controlling the creep rate is also indicated by comparisons of activation energies for high-temperature creep of granite, quartzite and feldspar-rich rocks. This conclusion, if borne out by a more complete analysis, is of extreme importance to considerations of the deformation of composite solids of all types, including rocks. It would appear that a minor phase could control the deformation only if either it forms a continuous matrix or if grain boundary sliding allows a stronger phase, such as feldspar, to act merely as pistons, deforming the weaker phase. The mosaic studies of Kranz, to date, suggest that the former explanation may be tenable for Westerly granite and, as noted above, Kranz and Bauer are investigating the matter using finite element models.

During the time remaining in the present contract, we shall continue to study deformation processes both in the experimentally and naturally deformed specimens. We should be able to complete experiments on both Barre and Westerly granites at 1 kb confining pressure and 200°C and have internally consistent, understandable and significant results both on mechanical behavior and deformation processes detectable by optical and SEM studies. Both the mosaic studies and finite element approximations should advance during this interval. Most of the experimental work on the quartzite should be completed

by the termination of the contract although proper analyses of the flow processes may take somewhat longer. We had not expected to work on quartzite for this contract but this additional task became necessary when we discovered that quartz apparently controls the creep rate of granite. This same discovery led to the work on diorite but, because of the high temperatures apparently required for steady-state creep of that material, we do not anticipate completion by the end of February. We shall be pleased if the advances contemplated can be made during this quarter as all are pertinent to both short-and long-range goals of the contract.

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CAPTIONS FOR FIGURES

1. Scanning electron microscope photographs of Barre granite deformed in creep under a differential stress of 510 MPa, confining pressure of 100 MPa at a temperature of 200°C.
 - A. Low magnification photograph showing a large feldspar grain surrounded by mica grains (above) and feldspar and quartz grains below. Note cracks extending into the large grain from boundaries.
 - B. Several linked and interacting microcracks in a quartz grain. Ellipsoidal mounds are an artifact of the ion-milling preparation technique.
 - C. Detail of a grain boundary in the specimen. The nature and significance of the sigmoidal filaments are not yet known.
2. A-C. Strain-time curves for representative creep experiments. Dry Westerly granite; dots are reduced data points. Curves in A and B are fits to equation (1). Curves in C are eyeball fits to the data points and emphasize the peculiar behavior discussed in the text.
D-F. "Wet" granite (D), dry Sioux quartzite (E) and dry diorite (F). Curves are all hand-fit to the data points and are not fit to any equation.
3. Test of fit of high-temperature transient creep data to equation (1). Slopes on $-\log \Delta \epsilon$ vs. t/t_s should equal -1.74 where $\Delta \epsilon = \epsilon_T - \epsilon_t$ and t_s is the time required to achieve steady-state creep (Carter and Kirby, 1978). Curves in the lower part of the diagram are from Carter and Kirby (1978, Fig. 2) with Twin Sisters dunite (T.S.) from data of Goetze and Brace (1972), halite polycrystals from Burke (1968), clinopyroxenite, from unpublished data by S.H. Kirby and Mt. Burnet dunite (M.B.) data from Post (1973). Data points and eyeball-fit lines in upper part of diagram are for five representative specimens of Westerly granite from this study.
4. Least-squares fit to steady-state creep data for dry Westerly granite using equation (4) in text.

5. Extrapolation in log strain -log time space of equations (2) and (4) for high-temperature transient and steady-state creep, respectively, of dry Westerly granite. Extrapolations are for 300° and 600°C and stress differences of 50 and 500 MPa. Steady-state creep gives the higher creep rate, at comparable stress-temperature conditions, swamping transient creep in the strain-time interval chosen.
6. Least-squares fit to steady state creep data for dry quartzite.
7. Creep data for dry diorite deformed at constant stress differences of 0.9 and 1.2 GPa in the nominal temperature interval 600° to 800°C (corrected temperature interval, 570° to 765°C).
8. Creep data for dry diorite deformed at constant nominal temperatures of 600°C (570°C) and 800°C (765°C) in the constant stress difference interval 0.9 to 1.2 GPa.

A

1mm

B

1μm

C

10μm

QUARTZITE

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MECHANICAL AND TRANSPORT PROPERTIES OF ROCKS AT HIGH TEMPERATURES AND PRESSURES

TASK II

FRACTURE PERMEABILITY OF CRYSTALLINE ROCKS AS A FUNCTION OF TEMPERATURE,
PRESSURE AND HYDROTHERMAL ALTERATION

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Technical Progress Report Number 1

1 March 1980 to 30 November 1980

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PREFACE

The long-term objective of Task II is to measure and understand the variation of fracture permeability in Sioux Quartzite, Westerly Granite and a fine-grained gabbro as a function of effective pressure and hydrothermal alterations. The first-year objectives of Task II are fourfold: (1) develop methods to characterize rough fracture surfaces, (2) determine the relationship between fracture-asperity characteristics and the variation of fracture permeability with changes of effective confining pressure (room temperature), (3) using closed-system, hydrostatic water/rock reaction experiments, characterize the hydrothermal alteration and the changes of fracture-surface asperity morphology and height distributions likely to occur in future permeability experiments at elevated temperature, and (4) design and build an experimental system for measurement of fracture permeability under hydrothermal conditions. Dr. Brann Johnson is the Principal Investigator (25% time) and is responsible with Dr. A. F. Gangi (8.3% time) for the work on fracture asperities and permeabilities. Johnson also is primarily responsible for the determination of fracture permeability under conditions of hydrothermal alteration. Dr. A. Hajash, Jr. (8.3% time) is primarily responsible for the hydrostatic water/rock reaction experiments. One graduate research assistant is currently assigned to this Task.

SUMMARY

We have been working on this project for 4 months.¹ The status of our progress to date briefly is as follows: (1) Methods of quantitatively

1. In contrast to Tasks I and III, which are continuations of on-going studies, Task II is a new project. The late emplacement of the research contract (mid-June, 1980), as a result of contract negotiations, prevented us from initiating our work on the "official" starting date (March 1, 1980). Furthermore, Drs. Johnson and Hajash had off-campus teaching commitments (Summer Field Camp) during the months of June and July.

characterizing asperity shape and height distributions and surface textures are being developed; (2) the room temperature permeability system is operational and we are measuring the permeability of "simulated" rock fractures as a function of effective pressure and pressure cycling; (3) the first series of hydrothermal alteration experiments for Westerly Granite in NaCl solutions and seawater have been completed and the results are being analyzed; (4) the design of the elevated temperature permeability system is nearing completion with construction to begin in approximately a month.

Fracture-Surface Characterization. We are developing a surface profilometer that will permit us to measure the shape and height distributions of surface roughness typical of rock fractures (commercial units are not applicable because of the extreme roughness). Replica techniques are being investigated as a means of obtaining a direct measure of the fracture aperture for various effective pressures.

Fracture Permeability Measurements. Our first experiments are for "simulated" fracture, which consist of a monolayer of small ($\sim 100\mu\text{m}$), spherical glass beads sandwiched between two halves of a steel split-cylinder. The glass beads represent the asperities on a rough fracture. Results indicate the permeability of the "simulated" fracture exhibits the same functional form with changes of effective pressure as do rock fractures. Permeability decreases with increasing pressure, with the greatest rate of decrease at the lower pressures. Upon unloading, permeability increases with decreasing pressure, but at a smaller rate as compared to the initial loading cycle. A significant component of the initial permeability decrease is irreversible as a result of inelastic deformation (breakage) of some of the load-carrying asperities. The

greatest rate of permeability change is at the lower pressures, as during the loading cycle. For subsequent loading/unloading cycles, the permeability vs pressure curves are nearly identical in form, with only a small hysteresis exhibited, provided the previous maximum pressure is not exceeded. This nearly reversible character suggests only elastic deformation of asperities is occurring. Asperity breakage is indicated during the first cycle loading by acoustic emissions. With distilled water as the fluid, we observe a time-dependent decrease of permeability at a constant pressure; this is related to continuing asperity breakage associated with hydrolytic weakening effects.

Hydrothermal Alteration Experiments. Westerly Granite was reacted for 4 months with 0.1 N and 0.5 N NaCl solutions and Copenhagen seawater at 300°C and 50 MPa. Preliminary study of these samples under the SEM indicates that significant dissolution and secondary mineral formation occurs. For all three solutions, the reactivity is quartz > microcline > biotite $\geq$ plagioclase. Quartz and microcline exhibit pronounced dissolution, which for the quartz is primarily along microfractures; the amount of dissolution increases with increasing Cl⁻ concentrations of the initial fluid. Secondary minerals consist of at least one, possibly two, clay minerals (vermiculite and smectite or illite?) and at least one framework silicate (zeolite?). X-ray analysis of alteration products has not been completed. The clay minerals exhibit both a honeycomb and an open spongy morphology, which results in a large effective volume to mass ratio. This may be an important way in which regions between load-carrying asperities on a fracture surface may be partially plugged by a small amount of clay minerals. Chemical compositions of the initial and final fluids indicate increases in Si and K and decreases in Na in the fluid.

Dissolution of quartz and microcline account for the increased Si and K, but the concentration of Si is significantly less than for a saturated quartz/water system (320 ppm vs 800 ppm). The quench pH is lowest for the seawater/granite experiment and is reflected by high metal (Fe, Mg, Mn) concentrations in solution; the high metal concentrations are not observed in the NaCl/granite experiment.

Goals for Remainder of Contract

(1) Continue "simulated" fracture permeability experiments and compare results with predictions of existing theoretical models (Gangi's "Bed of Nails" model and model of Greenwood and Williamson). Using experimental data, modify these models to incorporate asperity breakage.

(2) Measure fracture permeability of Sioux Quartzite and Westerly Granite (room temperature) both for saw-cuts roughened by sand blasting and tensile fractures. Attempt to correlate observed variations of permeability with pressure with theoretical models using asperity height distributions obtained from surface-characterization measurements and assess the changes in surface asperities (i.e., damage) due to effect of normal loads.

(3) Continue hydrothermal alteration experiments and study how hydrothermal alteration modifies the character of surface asperities by dissolution.

(4) Complete construction of elevated-temperature permeability system.

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MECHANICAL AND TRANSPORT PROPERTIES OF ROCKS AT HIGH TEMPERATURES AND PRESSURES

TASK III

MECHANICAL PROPERTIES OF ROCKS AT HIGH TEMPERATURES AND PRESSURES

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PREFACE

The objectives of this task (III), Mechanical Properties of Rocks at High Temperatures and Pressures, are (1) to determine in static triaxial experiments the short term strengths and ductilities of room dry and water-saturated, intact, pre-fractured and hollow cylinders of selected rocks at confining and pore pressures to 200 MPa, temperatures to 1000°C or partial melting, and strain rates of 10^{-4}s^{-1} to 10^{-7}s^{-1} , and (2) to extrapolate these data to the assessment of rock drillability and of borehole stability in the geothermal regime above buried magma chambers. This effort is essential to the evaluation of the scientific feasibility of geothermal energy extraction from buried magma chambers and from the overlying hydrothermal regime, safe underground isolation of toxic waste, and the seismic risk to nuclear power plants and other installations. Dr. J. Handin (12.5% time) is responsible for the experimental work, Dr. M. Friedman (16.6% time) is responsible for the observational work on the deformed specimens and for communicating the results to Sandia's Advisory Panel on Energy Extraction from Magma. Mr. S. J. Bauer, a doctoral candidate, devotes 50% of his time to the project.

SUMMARY

During the first 9 months of the initially proposed three-year effort we have (a) largely completed the evaluation of potential water-weakening effects at two effective confining pressures (0 and 50 MPa) at 10^{-4}s^{-1} , and at temperatures between 600° and 990°C for the Charcoal Granodiorite and Mt. Hood Andesite; (b) initiated study of the relative thermal expansion of these two rocks and the Cuerbio Basalt; and (c) designed and are having machined a new pressure vessel capable of testing

4 by 8 cm specimens at pressures to 300 MPa, temperatures to 1000°C, strain-rates of 10^{-4} s^{-1} to 10^{-8} s^{-1} , and with independently controlled pore pressures from 0 to 300 MPa. This vessel, which should be delivered in January, will be used interchangeably in the screw-driven press funded by DOE through the Office of Nuclear Waste Isolation for our studies of the creep of rock salt (recently renewed for three years). It is in this vessel that we plan to test pre-fractured and hollow cylinders.

Data from water-saturated specimens of the granodiorite and andesite, compared to room-dry counterparts (Friedman et al., 1980), indicate (1) the pore pressures are essentially communicated throughout each test specimen so that the pressures are truly effective, i.e., effective confining pressure (P_e) equals the confining pressure (P_c) minus the pore fluid pressure (P_p); (2) at $P_e = 0$ and 50 MPa [P_c and P_p of 50 MPa, and 100 and 50 MPa, respectively] the granodiorite does not water-weaken; (3) at these same effective pressures the more porous and finer-grained andesite begins to exhibit water-weakening at about 600°C; (4) at $P_e = 0$ and 870-900°C the andesite's strength averages 20 MPa while the strength of dry specimens at the same P and T exhibit a strength of 100 MPa, i.e., its strength is reduced by a factor of 5; (5) at $P_e = 50$ MPa and 920°C the andesite's wet strength is 45 MPa compared to 160 MPa dry; (6) ductility of the water-saturated specimens deformed at temperatures less than that of melting exhibit ultimate strengths at less than 3 percent shortening and then work-soften along faults, i.e., like their dry counterparts the rocks remain brittle up to the onset of melting; (7) again as in the dry rocks, the wet specimens deform primarily by microscopic fractures that coalesce into one or more macroscopic faults; (8) a specimen of the granodiorite held at effective pressure (50 MPa) and temperature (810°C) for 45 minutes before axially shortened, exhibits

the same strength and behavior as those held for our standard 15 minutes; (when a specimen was held at similar P_e and T for 3 hours the steel piston, rather than the rock, deformed upon application of differential stress); and (9) the temperature for incipient melting of the andesite is decreased $> 150^\circ\text{C}$ in the water-saturated tests.

Study of the relative thermal expansion of the three rocks at effective pressures of 0 and 50 MPa and over the temperature range $25\text{-}900^\circ\text{C}$ indicates (1) the granodiorite expands more at the lower P_e , as expected if thermal cracking is the mechanism of expansion; (2) the granodiorite also shows the greatest amount of expansion compared to the other two rocks; moreover its expansion is non-linear in the 550° to 600°C temperature range consistent with cracking associated with the α - β quartz-transition volume change (Bauer and Johnson, 1979); (3) the basalt shows the least amount of expansion of the three rocks and little differences as a function of effective pressure; these results are consistent with the fact that basalts do not undergo significant thermal cracking (Richter and Simmons, 1974; Simmons and Cooper, 1977); and (4) the andesite also shows little difference in the degree of expansion with pressure and less total expansion than the granodiorite even though its composition is similar to that of the coarser-grained granodiorite; these observations are consistent with the fact that thermal cracking decreases with decreasing grain size (Kuszyk and Bradt, 1973).

Extrapolation of strength and ductility data for both wet and dry specimens indicate: (1) crystalline rocks should be drillable because they remain brittle until partial melting occurs, and penetration rates should increase as temperatures increase because there is a corresponding

decrease in brittle fracture strength; (2) instantaneous failure strengths are apt to be more important to the assessment of borehole stability than transient creep of intact rock; (3) boreholes in "water-filled" holes will be stable to > 10 km at temperatures $< T_m$; (4) if temperatures are kept to $\leq 800^\circ\text{C}$, even unfilled (open) boreholes in granodiorite are apt to be stable to > 10 km; and (5) open boreholes in the andesite are apt to be much less stable, and at similar temperatures would fail at 2 to 5 km depth.

Work to date on intact specimens suggests it is scientifically feasible to drill to buried magma chambers at depths to 10 km. Engineering solutions to stabilize boreholes are to keep them cool as possible and with a borehole pressure comparable to that of a column of water at 25°C .

RESULTS

Water-Saturated Experiments

Initially, in work supported through Sandia National Laboratories, the experimental effort involved only room dry specimens of Charcoal Granodiorite (CG), Mt. Hood Andesite (MHA), and Cuerbio Basalt (CB). This was necessary because "dry-out" zones may exist immediately above buried magma and a data-base for dry rocks is needed for comparison with water-saturated experiments in order to evaluate the latter. At the end of our support through Sandia we reported results for water-saturated tests conducted at an effective confining pressure (P_e) of essentially zero, i.e., confining pressure (P_c) of 50 MPa and a pore pressure (P_p) of 45 to 50 MPa. Some of the work at $P_e = 0$ was done on the current contract in the transition between the switch in sponsors. Subsequently we have completed the work at $P_e = 0$, and added data at $P_e = 50$ MPa ($P_c = 100$ MPa and $P_p = 50$ MPa). All the water-saturated tests are listed in Table 1.

Methodology. The water-saturated experiments are performed as follows:

- 1) Each specimen is vacuum-impregnated with H_2O , and then kept in a beaker of H_2O until test time.
- 2) Specimens are jacketed into the loading column surrounded by the furnace, and secured inside the vessel.
- 3) An axial load of 10 MPa is applied to the specimen.
- 4) Bottle gas pressure is opened to the vessel.
- 5) Vessel is then degassed to about atmospheric pressure. This procedure effectively empties the vessel of volatiles which could lead to premature furnace degradation.

- 6) Bottle gas pressure is reapplied.
- 7) Confining pressure and axial load simultaneously are increased to maintain the hydrostatic condition (uniform confining pressure).
- 8) With as low as 10 MPa hydrostatic pressure, pore water pressure is applied to the specimen. To prevent flow around the spacers and out of the system through the bottom piston, P_p always is kept 5 MPa less than P_c . For experiments at $P_e = 0$, P_p is adjusted to equal P_c .
- 9) At the desired P_c and P_p , the furnace is turned on, and the system is heated to the temperature of interest (at $\approx 10^\circ\text{C}/\text{min}$). Pressures are adjusted for thermal expansion, and the specimen is permitted to soak and equilibrate at fixed P and T for 15 minutes. Then the axial load is increased (differential stress increased) until failure occurs.

Tests at $P_e = 0$. Twenty successful experiments have been conducted on water-saturated specimens of the three rocks at zero effective confining pressure, temperatures from 400° to 1015°C , and at a constant strain rate of 10^{-4} s^{-1} (Table 1). The stress-strain curves from these tests all show nearly linear rise to a peak differential stress (ultimate strength) at strains of ≤ 1.0 percent and then a work-softening phase to axial strains up to 4.5 percent (Figure 1). Displacements during work softening probably are along multiple macroscopic fractures (shattered specimens) or along discrete faults (Table 1). All tests were stopped prior to complete loss of cohesion.

Ultimate (fracture) strengths of the wet granodiorite show no water-weakening (Figure 2). In fact, between 400° and 1015°C the specimens are somewhat stronger than their dry counterparts. This suggests that the pore fluid probably is not in pressure equilibrium

Table 1. Experimental Data for Water-Saturated Charcoal Granodiorite, Cuerbio Basalt and Mt. Hood Andesite Shortened at 10^{-4} s^{-1} .

Rock Type and Specimen No.	Confining Pressure (MPa)	Pore Pressure (MPa)	Effective Pressure (MPa)	Temp. (°C)	Mean Stress (MPa)	Ultimate Strength (MPa)	Shortening at Failure (%)	
CHARCOAL GRANODIORITE								
280	100	100	0	400	50	150	0.7	Shattered, work-softened to 50 MPa at 1.9% shortening.
286	50	45	5	460	50	150	-	θ = 23°, } Heated at differential stress of 150 MPa until specimen failed. Shattered)
287	50	45	5	610	50	150	-	
289	50	50	0	740	35	100	1.0	Shattered, work-softened along multiple fractures to 45 MPa at 2.7% shortening.
291	50	50	0	835	25	75	1.0	θ = 34°, work-softened along fault to 15 MPa at 2.5% shortening.
294	50	50	0	945	20	55	0.9	θ = 34°, work-softened along fault to 15 MPa at 2.1% shortening, no melting.
308	50	50	0	1015	15	40	0.6	Shattered, work-softened along fault to 25 MPa at 3.2% shortening, partially melting.
311	50	50	0	990	15	40	0.4	Shattered.
320	100	50	50	615	210	485	1.3	θ = 27°.
314	100	50	50	800	170	360	1.7	Shattered, θ = 36° (best fault).
317	100	50	50	900	155	315	1.6	Shattered, θ = 34° (best fault).
324	100	50	50	810	174	372	1.5	Shattered, specimen held at T = 810°C 45 minutes prior to application of differential stress.
CUERBIO BASALT								
296	50	50	0	415	85	255	0.6	Shattered, work-softened along multiple fractures to 115 MPa at 1.7% shortening.
304	50	50	0	765	80	235	0.8	Shattered, work-softened with stick-slip to 135 MPa at 2.5% shortening.
307	50	50	0	916	30	90	0.9	Shattered, work-softened along multiple fractures to 60 MPa at 3.4% shortening.
309	50	50	0	850	45	135	0.3	Shattered.
310	50	50	0	945	20	60	0.1	Shattered, work softened along multiple fractures to 45 MPa at 2.7% shortening.
318	100	50	50	820	110	180	1.0	Shattered, θ = 35° (best fault)
MT. HOOD ANDESITE								
306	50	50	0	615	35	105	0.6	Shattered, work-softened along multiple fractures to 25 MPa at 1.8% shortening.
290	50	50	0	720	25	70	0.6	Shattered, work-softened along multiple fractures to 25 MPa at 2.0% shortening.
300	50	50	0	800	25	70	0.6	Shattered, work-softened along multiple fractures to 20 MPa at 3.5% shortening.
301	50	50	0	845	20	65	0.8	Shattered, work-softened along multiple fractures to 15 MPa at 4.0% shortening.
302	50	50	0	855	15	40	0.8	Shattered, work-softened along multiple fractures to 15 MPa at 4.3% shortening.
303	50	50	0	870	10	35	0.8	Shattered, work-softened along multiple fractures to 20 MPa at 3.1% shortening.
297	50	50	0	820	0	5	1.0	Ductile, no fracturing or faulting, total shortening 2.87 before test stopped.
305	50	50	0	880	10	25	0.7	Shattered, work-softened along multiple fractures to 10 MPa at 2.5% shortening, incipient melting (?)
327	100	50	50	600	120	205	1.5	Shattered, work-softened along multiple fractures to 195 MPa at 3.5% shortening.
319	100	50	50	610	125	225	2.0	Shattered, work-softened along multiple fractures to 215 MPa at 4.1% shortening.
324	100	50	50	610	115	190	3.2	Shattered, work-softened along multiple fractures to 190 MPa at 3.2% shortening.
312	100	50	50	745	85	110	3.4	Ductile, no faults to 3.5% shortening incipient melting.
325	100	50	50	920	65	45	3.1	Ductile, no faults to 3.3% shortening incipient melting.

H₂O-SATURATED TESTS, $P_e=0$

Figure 1. Stress-shortening curves for water-saturated specimens of the three crystalline rocks deformed at zero effective confining pressure (confining and pore pressures equal to 50 MPa) and at temperatures shown.

CHARCOAL GRANODIORITE

Figure 2. Ultimate strength versus temperature plot for Charcoal Granodiorite. Solid circles are data points at confining pressures of 0, 50, and 100 MPa for room-dry specimens. Solid stars and squares are data points for water-saturated specimens at P_e of 0 and 50 MPa, respectively. Triangles represent specimens heated dry to 1000 $^{\circ}$ C, then cooled and deformed at 25 $^{\circ}$ C, 50 MPa. Open square represents three dry, unconfined specimens heated to 900 $^{\circ}$ -1000 $^{\circ}$ C, cooled and deformed at 25 $^{\circ}$ C.

throughout the specimen so the effective pressure ($P_c - P_p$) is > 0 (but much less than 50 MPa). In contrast, the Mt. Hood Andesite (Figure 3) shows pronounced weakening between 850° and 880°C, at which point its fracture strength is between 5 and 25 MPa. In comparison, its dry strength is 75 MPa at 1000°C. The andesite has a higher porosity than the granodiorite so that pervasive water-pressure equilibration is more likely. Certainly the lower strength of wet andesite suggests P_e is small if not zero, and there does appear to be a water-weakening effect. Ultimate strengths are available for only five wet specimens of the basalt (Figure 4). Although sparse, the data suggest no weakening or apparent strengthening at temperatures to 763°C. There is, perhaps some weakening at $> 850^\circ\text{C}$. Clearly more data are needed for this rock, and conclusions made below are based primarily on the andesite and granodiorite.

Tests at $P_e = 50$ MPa. Ten successful experiments at an effective pressure of 50 MPa (P_c and P_p of 100 and 50 MPa, respectively) have been completed (Table 1). Most of these are for the CG and MHA. The basalt is too vesicular for these experiments. Numerous attempts on the basalt ended in jacket failures because the very weak copper jacket failed at vesicles exposed along the cylindrical surface of each specimen. Typical differential stress-shortening curves for the CG and MHA (Figure 5) show (1) the CG is significantly less ductile than the MHA with ultimate strengths between 1 and 2 percent shortening, and (2) while somewhat more ductile than the CG, the MHA fails at from 1 to 3.5 percent shortening with subsequent permanent shortening occurring by shear along one or more faults. Ductile flow occurs only when partial melting occurs (Figure 5, specimen at 920°C and see Table 1).

MT. HOOD ANDESITE

Figure 3. Ultimate strength versus temperature plot for Mt. Hood Andesite. Solid and open circles are data for room-dry specimens at confining pressures of 0, 50, and 100 MPa. Solid stars and squares are data for water-saturated specimens at P_e of 0 and 50 MPa, respectively. Triangles represent dry specimens heated to 930°-1000°C, cooled and deformed at 25°C, 50 MPa. The unconfined, strength of room-dry specimens at 25°C is virtually the same whether or not the specimen has been preheated and cooled.

Figure 4. Ultimate strength versus temperature plot for Cuerbio Basalt. Solid and open circles are data for room-dry specimens at confining pressures of 0, 50, and 100 MPa. Solid stars and squares are data for water-saturated specimens at $P_e = 0$ and 50 MPa, respectively. Triangle represents a dry specimen heated to 750°C, then cooled and deformed at 25°C, 50 MPa. Open squares are for unconfined, dry specimens heated to 905°-1000°C, cooled and deformed at 25°C.

Figure 5. Stress-shortening curves for water-saturated specimens of Charcoal Granodiorite (a) and Mt. Hood Andesite (b) at an effective pressure of 50 MPa, 10^{-4} s^{-1} , and at the temperatures ($^{\circ}\text{C}$) designated for each curve.

Ultimate strength of the CG at 50 MPa-effective confining pressure continues to show no water-weakening (Figure 2). The four data points are sufficiently close to those for dry specimens at 50 MPa to conclude that the P_p in the water-saturated specimens is equilibrated throughout the specimen, i.e., effective. The MHA, on the other hand, shows pronounced water-weakening (Figure 3). Its ultimate strength at 920° is only 45 MPa compared to 160 MPa dry, a strength reduction of about 4 times. Moreover, incipient partial melting occurs in specimens deformed at 745° and 920°C a reduction in the temperature of melting due to the presence of water of >150°C.

Mechanism of deformation. As noted in Table 1 most of the water-saturated rock specimens are macroscopically shattered, i.e., they failed along two or more shear fractures or faults. This often gives rise to an apparent steady-state or work-softening stress-shortening curve. True uniform ductile flow occurs only when incipient melting has occurred. In its very incipient stages this melting occurs at grain boundaries associated with biotite or hornblende or within feldspar and quartz grains as manifest by isolated patches of vesicles.

Aside from the incipient melting, microfracturing and the coalescence of microcracks into the macroscopic faults are the major mechanisms of deformation. Quantitative assessment of the abundance of these microfractures in wet tests shows that they are not more abundant than in dry counterparts (Figure 6).

Mechanisms for water-weakening. Water-weakening can occur due to (a) chemisorption or stress corrosion effects at crack tips that reduce fracture strengths (e.g., see review by Anderson and Grew, 1977), (b)

Figure 6. Microfracture abundance as functions of pressure and temperature in deformed, room dry Charcoal Granodiorite. Specimen 133 (▲) was heated to 1000°C, then cooled and deformed at 25°C, 50 MPa; the higher result includes gouge, and lower one does not.

lowered melting points, and (c) lowering of the critical resolved shear stresses for dislocation gliding, i.e., yield strengths for crystal-plastic mechanisms (e.g., Griggs and Blacic, 1965; Griggs, 1974; Balderman, 1974; Tullis, 1979). All three effects involve hydration of the silanol bonds in silicates. The higher is the temperature, the more significant is this phenomenon likely to be (Griggs, 1967). Without detailed thin section and perhaps TEM studies (scheduled for future work), it is not possible to say which of these mechanisms has produced the reduced strength of the andesite at elevated temperatures demonstrated above. But, it is generally recognized that H_2O must gain access to the crystal surfaces (item a, above) and then to their substructures (items b and c, above) to effect the hydrolytic weakening. It is not surprising therefore, that of the three rocks tested, the andesite shows the greatest weakening as its relatively large porosity (10-12 percent) permits greater access of the pore water to the solid surfaces.

In the ductile regime it has been recognized that there is a temperature effect on the water-weakening of quartz (Griggs, 1967; Balderman, 1974). Our temperatures are much in excess of these temperatures (300-500°C). More recently however, it has been shown that there also is a pressure effect, as water is driven from the surface of pores and cracks into the adjacent crystal structures with increased pressure (Tullis, 1979). Our pore pressures 50 and 100 MPa are small compared to those (1000 and 1500 MPa) needed in the laboratory to recognize this effect (Tullis and Yund, 1978). Thus, although our temperatures are more than sufficient, our pressures may be too low to foster the ductile aspect of water-weakening (item c, above). Coupling this view with the brittle

response and macroscopic appearance of the specimens, we tentatively conclude that the water-weakening of the andesite is a stress corrosion and/or reduced melting-temperature effect.

Column expansion analysis. During the procedure for the triaxial-compression testing to measure the strength and ductility of the rock specimens, it is quick and easy to measure fairly accurately linear thermal expansions (α) at confining pressures and temperatures before the rocks are deformed. Reliable values of α determined under appropriate conditions are required for predictive thermomechanical modeling of rock masses subject, for example, to the radiogenic heating of high-level nuclear waste.

During the heating phase of the water-saturated experiments, axial force is maintained so that the specimen is at confining pressure. As temperature is increased, the axial hydraulic pressure is regulated manually to a constant value. It is possible to measure the axial expansion of the loading column by recording the axial stress during heating alone. This expansion is that of the entire column and includes parts of the pistons, lucolux spacers, carbide spacers, and rock specimen. Since total expansion less that for a given rock specimen is the same for each experiment, we can gain insight into the relative axial, thermal expansion of our three rock types in separate experiments.

It is clear that for each temperature the CG expands more at lower effective pressure ($P_e \approx 5$ MPa) than at the higher pressure ($P_e = 50$ MPa, Figure 7), as expected if thermal cracking is the mechanism of expansion (Sprunt and Brace, 1974). The fact that we are able to measure this difference at the two pressures indicates itself that the pore fluid

Figure 7. Total column expansion for the Charcoal Granodiorite, Mt. Hood Andesite, and Cuerbio Basalt at $P_e = 5$ (•) and 50 MPa (x).

pressures must be effective. CB shows little difference in column expansion for the change in pressure. This is consistent with the findings of Richter and Simmons (1974) and Simmons and Cooper (1977) that basalts do not thermally crack a significant amount confined or unconfined. The MHA also shows little difference in expansion with pressure even though the andesite is similar mineralogically to the granodiorite. The behavior of both the andesite and basalt is explained by their fine-grain size. That is, fine-grained aggregates are less susceptible to thermal cracking than coarser-grained ones (Kuszyk and Bradt, 1973).

The thermal expansion of the three rocks are compared in Figure 8. The CG shows the largest amount of expansion (thermal cracking) and the CB the least, at both pressures. Also note the expansion of the CG accelerates between 550° and 600°C. This coincides with the α - β transition of quartz (573°C) and is consistent with the thermal cracking and volume change associated with that transition by Bauer and Johnson (1979).

BOREHOLE STABILITY

The rationale for our simplistic scheme to predict borehole stability or failure is given in detail in Friedman and others (1980). In brief: (1) Purely mechanical borehole stresses are calculated from elastic equations and certain assumptions dealing with the far field stresses (σ_h equal in all directions and $\sigma_h/\sigma_v = 2, 1, \text{ or } 0.5$), whether the borehole is open or filled with a material with the density of 1.0 g/cc, and whether the rock is dry or saturated (Table 2). (2) The borehole stresses as a function of depth are then drawn as straight lines (loci) on a plot of differential stress versus mean stress (e.g., Figure 9).

Figure 8. Comparison of the axial expansion of Charcoal Granodiorite (x), Cuerbio Basalt (•), and Mt. Hood Andesite (o) at effective pressures of 5 and 50 MPa.

TABLE 2. BOREHOLE STRESSES (MPa/km)

CONDITION		$\frac{\sigma_h}{\sigma_v}$	σ_1	σ_2	σ_3	$\sigma_1 - \sigma_3$	σ_m
DRY ROCK	OPEN HOLE	2	$\sigma_\theta = 108$	$\sigma_z = 27$	$\sigma_r = 0$	108	45
		1	$\sigma_\theta = 54$	$\sigma_z = 27$	$\sigma_r = 0$	54	27
		0.5	$\sigma_\theta = 27$	$\sigma_z = 27$	$\sigma_r = 0$	27	18
	FILLED HOLE	2	$\sigma_\theta = 98$	$\sigma_z = 27$	$\sigma_r = 10$	88	45
		1	$\sigma_\theta = 44$	$\sigma_z = 27$	$\sigma_r = 10$	34	27
		0.5	$\sigma_z = 27$	$\sigma_\theta = 17$	$\sigma_r = 10$	17	18
SATURATED ROCK	OPEN HOLE	2	$\bar{\sigma}_\theta = 88$	$\bar{\sigma}_z = 17$	$\bar{\sigma}_r = 0$	88	35
		1	$\bar{\sigma}_\theta = 34$	$\bar{\sigma}_z = 17$	$\bar{\sigma}_r = 0$	34	17
		0.5	$\bar{\sigma}_z = 17$	$\bar{\sigma}_\theta = 7$	$\bar{\sigma}_r = 0$	17	8
	FILLED HOLE	2	$\bar{\sigma}_\theta = 78$	$\bar{\sigma}_z = 17$	$\bar{\sigma}_r = 10$	68	35
		1	$\bar{\sigma}_\theta = 24$	$\bar{\sigma}_z = 17$	$\bar{\sigma}_r = 10$	14	17
		0.5	$\bar{\sigma}_z = 17$	$\bar{\sigma}_r = 10$	$\bar{\sigma}_\theta = -3$	20	8
$\sigma_z = \sigma_v = \rho_r g z = 27 \text{ MPa/km for } \rho_r = 2.7 \times 10^3 \text{ kg/m}^3.$							
$p = p_p = \rho_w g z = 10 \text{ MPa/km for } \rho_w = 10^3 \text{ kg/m}^3.$							

(3) The differential stress and mean stress at failure (ultimate strength) from our experiments are superimposed on the same diagram. (4) In order to use the laboratory data to predict failure of a borehole, we assume that ultimate strength ($\sigma_1 - \sigma_3$) at failure is a function only of the effective mean stress, $\sigma_m = (\sigma_1 + \sigma_2 + \sigma_3)/3$ and temperature. (5) If at a given mean pressure, say 50 MPa, the strengths for a given rock exceed the borehole differential stress, then the borehole will be stable. That is, it will not fail by shear fracturing in the short term. (6) Intersections of lines connecting rock strength data for a given temperature and the borehole stress loci mark the boundaries between the fields of stability, containing all points to the left of the loci of borehole stresses, and of instability, containing all points to the right-hand side. Predictions based on the dry strengths of all three rocks are given in Friedman and others (1980).

Here we concentrate on the likelihood of stable boreholes in water-saturated CG and MHA (Figures 9 and 10, respectively). The available data indicate (1) both rocks would afford stable boreholes to >10 km if σ_h/σ_v were 1.0 and the boreholes were filled with a material of density 1.0 gm/cc; (2) boreholes in CG would be stable to >10 km at all assumed conditions provided the temperatures did not exceed about 800°C; (3) boreholes are much less stable in the water-weakened MHA, and depending upon the assumptions would fail at 800°C at depths ranging from 2 to 5 km; and (4) boreholes even in the MHA would be stabilized appreciably if kept cool $\leq 700^\circ\text{C}$.

Above, we have addressed the matter of borehole stability from the short term failure viewpoint. That is, our predictions would hold as soon

Figure 9. Assessment of borehole stability in water-saturated Charcoal Granodiorite at $P_e = 0$ (solid dots) and 50 MPa (solid stars). Temperatures correspond to data points located to left. Four borehole stress loci and corresponding depth scales are given.

Figure 10. Assessment of borehole stability in water-saturated Mount Hood Andesite at $P_e = 0$ (solid circles) and 50 MPa (solid stars). Details of diagram are similar to those in Figure 9.

as the drill penetrated below a given depth. Shear failure at this stage could wedge out fragments of rock possibly large enough to stick a drill bit and cause a jammed or stuck drill-bit condition. Our predictions do not consider time effects, irregularities at the borehole wall that would concentrate the stresses and enhance failure, or existing natural fracture and fractures induced by drilling that could degrade rock strength. On the other hand, we also have not included superposed thermomechanical stresses arising from a cooled borehole in hotter country rock that would diminish the differential stresses at a borehole and promote stability. In Friedman and others (1980) we did discuss available data on transient creep of crystalline rocks, showing that the creep effects are very small under some conditions, and that the short term strengths seem more important at present. This is not to say however, that creep data are not needed at conditions similar to those expected in geothermal exploration and exploitation.

PROGNOSIS

In the remaining three months of the current contract we anticipate evaluating (1) the potential water-weakening of both rocks at $P_e = 100$ MPa, and (2) if soak-time at P and T is important in producing water-weakening. A specimen of the granodiorite held at $P_e = 50$ MPa and 810°C for 45 minutes before axially shortened, exhibited the same strength and ductility as when soaked for our standard 15 minutes. When a specimen was held at similar P and T for 3 hours, the steel piston, rather than the rock specimen, deformed upon application of differential stress.

In our proposal for renewal of this work we hope to proceed with our initial plan to determine the short term strength of pre-fractured cylinders, hollow cylinders, and rocks with strong planar anisotropy.

Intact specimens of a fine-grained gabbro will be studied, and further work on the Cuerbio Basalt discontinued because of its vesicular nature. New items proposed include static fatigue testing of specimens and numerical modeling with a view toward gaining a better understanding of time effects and of the influence of texture and composition on rock strength and ductility.

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