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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

DOE/ER/10361--T3

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FINAL REPORT

1 March 1980 to 29 February 1984

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ABSTRACT

This report summarizes the research performed under TASK III of D.O.E. Contract No. DE-AS05-79ER10361, 1 March 1980 to 29 February 1984. The overall objective of this work was to gain a fundamental understanding of the mechanical and transport properties of rocks under confining pressure and elevated temperature with a view toward assessing the scientific feasibility of certain energy-related activities. These include geothermal-energy exploration and exploitation, safe underground isolation of toxic wastes, seismic risk to nuclear power plants and other installations, and continental deep-drilling projects requiring stable boreholes in hot rocks. The work was divided into three tasks, each with its own Principal Investigators, personnel, and budgets, but all three operating under the single contract, as follows:

- I. Physical Nature of Fracturing at Depth
N.L. Carter, P.I.
- II. Fracture Permeability of Crystalline Rocks as a Function
of Temperature, Pressure, and Hydrothermal Alteration
Brann Johnson, P.I.

III. Mechanical Properties of Rocks at High Temperatures and Pressures

M. Friedman and J. Handin, Co-P.I.s.

This final report deals only with Task III.

Research conducted under Task III has led to the publication of five journal papers, four abstracts, and one Ph.D. dissertation. Herein, we give annual summaries, the abstract to each publication, and we append a copy of S.J. Bauer's recently completed dissertation. In detail there have been many contributions to our understanding of the mechanical behavior of rocks at high temperatures and pressures, but perhaps the three most outstanding contributions are the data which:

a) Have helped to demonstrate the scientific feasibility of energy extraction from buried magma by assessing the likelihood of the rock mass to support stable boreholes at the pressures, temperatures (to partial melting), and aqueous conditions apt to occur in crystalline rocks above buried magma chambers.

b) Have demonstrated that crystalline rocks deform primarily by brittle fracture when deformed at effective confining pressures to 200 MPa and temperatures to partial melting (to $> 1000^{\circ}\text{C}$), water-saturated or room-dry, and in constant strain rate tests ($\dot{\epsilon} = 10^{-4}$ - 10^{-7} /sec) or in creep tests.

c) Have shown that under these same conditions the time-dependent behavior of the rocks in the quasi-steady state regime is well described by the flow law: $\dot{\epsilon} = A\sigma^n \exp(-Q/RT)$ -- a formulation previously thought to be applicable to rocks deforming primarily by crystal plasticity. This result suggests that fracture is also a time-dependent, thermally-activated process.

INTRODUCTION

Several energy-related problem areas require a better understanding of the mechanical and transport properties of rocks under confining pressure at high temperature: geothermal-energy exploration and exploitation, safe underground isolation of toxic waste, siting of stable nuclear power plants, continental deep drilling, and earthquake hazards. Our objective is to learn more about these properties in the brittle and semibrittle regimes through experimental and observational studies, the results of which should be applicable to the prediction of the behaviors of rock masses in which heat has been stored naturally or artificially.

In previous years we have been concerned with the scientific feasibility of drilling through hot rocks above magma chambers. Our studies of the short-term strengths and ductilities of both dry and water-saturated igneous rocks, now complete (Bauer, 1982; Bauer et al., 1981; Bauer and Handin, 1981; 1983a, 1983b; Friedman et al., 1979, 1982; Handin et al., 1981) strongly suggest that up to temperatures of melting, these rocks could be drilled by conventional methods and that boreholes would be stable to at least 10-km depth, so long as the tools and rocks could be cooled and the boreholes could be pressurized by the drilling fluid.

The problem of deep drilling, as well as other mechanical problems associated with high-temperature crustal environments, cannot be fully resolved, however, without adequate knowledge of the (a) time-dependence of strength and ductility, (b) thermally-activated nature of the fracture process, and (c) frictional properties of crystalline rocks at high temperature (to 800°C) and low pressure (20 to 200 MPa). Our current work in these three areas should aid in assessing the scientific feasibility of (1) engineering projects in hot, fractured rock-masses and in other environments where the stability of

structures is essential, and (2) scientific projects such as continental deep-drilling where stable boreholes are needed at ambient stress and temperature conditions to permit the acquisition of scientific data.

Our work on the time-dependent deformations--creep rupture or static fatigue--of semi-brittle crystalline rock was completed for the time being with S.J. Bauer's (1984) Ph.D. dissertation (see Appendix I)*. Most of our current effort is devoted to two subtasks, the frictional strength and the tensile strength of Westerly Granite at confining pressures between 20 and 200 MPa and temperatures between 25° and 900°C.

Citations to publications emanating from work performed on this contract are listed chronologically in Table 1. The papers and abstracts are assembled in the same order in Appendix II.*

ANNUAL SUMMARIES

Work accomplished during each of the four years of this contract is listed below.

1980

We completed and published our petrofabric studies of dry and wet specimens of crystalline rocks deformed in short-time experiments at temperatures to partial melting (Friedman et al., 1982). Previously, we published the corresponding experimental data (Friedman et al., 1979) that was supported by DOE/OBES through the Sandia National Laboratory.

We were asked by Matt Salisbury of the NSF Deep Sea Drilling Project at Scripps Institution of Oceanography to test a few samples of basalt from a drillhole in crystalline rock. He was concerned about the marked decline in drilling rates with increasing depth subsea and wondered whether this parameter

* Removed and cycled separately.
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Table 1. Chronological List of Publications Resulting From Research
on Contract No. DE-AS05-79ER10361

- Friedman, M., J. Handin, N.G. Higgs, and J.R. Lantz, Strength and ductility of four dry igneous rocks at low pressures and temperatures to partial melting, Proc. 20th U.S. Symp. Rock Mech., Univ. Texas, Austin, 35-49, 1979.
- Bauer, S.J., M. Friedman, and J. Handin, Effects of water saturation on strength and ductility of three igneous rocks at effective pressures to 50 MPa and temperatures to partial melting, Proc. 22nd U.S. Symp. Rock Mech., MIT, 73-78, 1981.
- Bauer, S.J., and J. Handin, Thermal expansion of three water-saturated igneous rocks to 800°C at effective confining pressures of 5 and 50 MPa (Abstract), Am. Geophys. Union Trans., 62, 393, 1981.
- Bauer, S.J., N.L. Carter, and J.M. Logan, Effects of temperature and pore-water pressure on static fatigue of Westerly Granite (abstract): Trans. Am. Geophys. Union, v. 62, p. 1025, 1981.
- Handin, J., M. Friedman, and S.J. Bauer, Borehole stability and rock-drillability studies (Abstract), Am. Geophys. Union Trans., 62, 1057, 1981.
- Bauer, S.J., Brittle-ductile transition in dry and water-saturated Westerly Granite (Abstract), Am. Geophys. Union Trans., 63, 437, 1982.
- Friedman, M., J. Handin, and S.J. Bauer, Deformation mechanisms in granodiorite at effective pressures to 100 MPa and temperatures to partial melting, Proc. 23rd U.S. Symp. Rock Mech., Univ. California, Berkeley, 279-289, 1982.
- Bauer, S.J. and J. Handin, Thermal expansion and cracking of three, confined, water-saturated rocks to 800°C, Rock Mechanics and Rock Engineering, 16, 181-198, 1983.
- Bauer, S.J., Semibrittle Deformation of Granite at Upper Crustal Conditions, Ph.D. Dissertation, Texas A&M University, 1984.
- Bauer, S.J. and J. Handin, Mechanical properties of basalt cores from DSDP Hole 504B, Initial Reports of the Deep Sea Drilling Project, 83, in press.

might correlate with the triaxial compressive strength, expected to increase with increasing overburden pressure. Knowing of the interest of DOE/BES in continental deep-drilling and believing that results might be generally applicable to engineering problems of common interest, we tested 15 specimens. We did indeed find a good correlation between drilling rate and strength, and we understand that our data have been used in discussions with drillbit manufacturers on how to improve drilling rates in dense crystalline rocks like basalt (Bauer and Handin, in press. See Table 1 and Appendix II).

The bulk of our effort however, was devoted to the study of (1) the determination of the short-term strength and ductility of room-dry and water-saturated, intact, prefractured, and hollow cylinders of selected rocks at pressure to 200 MPa, temperatures to 1000°C, and strain rates of 10^{-4}s^{-1} to 10^{-7}s^{-1} , and (2) the extrapolation of these data to the assessment of rock drillability and of borehole stability in the geothermal regime above buried magma chambers.

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 ($P_e = 0$ 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.

Results of water-saturated tests show that (1) the granodiorite does not water-weaken at $P_e = 0$ and 50 MPa; (2) the more porous and finer-grained andesite begins to water-weaken at 600°C and between 870° and 920°C its

strength is reduced by factors of 5 and 4 at $P_e = 0$ and 50 MPa, respectively; (3) both rocks are at least as brittle when deformed wet as when dry, with the coalescence of microfractures into one or more faults the major mechanism of deformation; and (4) the melting temperature for the andesite is decreased $\approx 150^\circ\text{C}$ in the presence of water. Water-weakening is probably caused by the hydration of silanol bonds that lowers fracture strengths (stress corrosion) and melting temperatures.

Measurements of relative thermal expansion of the granodiorite, andesite, and basalt at $P_e = 0$ and 50 MPa and over the temperature range of 25 to 900°C indicate that the granodiorite undergoes more expansion at the lower P_e and more total expansion at both pressures than the finer-grained andesite and basalt. Moreover, the expansion in the granodiorite accelerates at the α - β transition of quartz (573°C). These results are consistent with a greater degree of thermal cracking in the granodiorite compared to that in the much finer-grained andesite and basalt.

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 $\leq 700^\circ\text{C}$, 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 1 to 3 km depth.

The deformation in these crystalline-rock specimens is multimechanistic; microfracturing of apparent extensile and shear origin, glide in quartz and biotite, microfracture healing, dissolution, and mineral alteration are mechanisms observed and evaluated as functions of temperature and strain. We attempt to partition the bulk specimen deformation into that contributed by the individual mineral species in the analysis. The systematic change in micro-mechanisms observed with increasing temperature is compatible with and the origin of the gradational succession of macroscopic deformation.

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 as cool as possible and with a borehole pressure comparable to that of a column of water at 25°C.

1981

During the report period, work has concentrated on determining (1) short-term strengths and ductilities of water-saturated Mt. Hood andesite and Charcoal Granodiorite at effective pressure of 100 MPa and temperatures to partial melting in order to assess the scientific feasibility of drilling stable boreholes associated with energy extraction from magma; (2) thermal expansions of these rocks and the Cuerbio Basalt at effective pressures of 5 and 50 MPa and temperatures to 800°C, in order to provide basic data for thermomechanical modeling; and (3) times to failure of wet and dry Westerly Granite at an effective confining pressure of 100 MPa and temperatures of 300°, 400°, 600°, and 800°C in order to assess the stability of boreholes and other underground openings for long periods of time.

Data from water-saturated specimens of the granodiorite and andesite compared to room-dry counterparts indicate that the pore pressures are

essentially communicated throughout each test specimen so that the pressures are effective. At effective confining pressures (P_e) of 0 and 50 MPa the granodiorite does not water-weaken; at these same effective pressures, the more porous and finer-grained andesite begins to exhibit water-weakening at about 600°C; at $P_e = 0$ and 870°C - 900°C, the andesite's strength averages 20 MPa whereas dry specimens at the same P and T exhibit a strength of 100 MPa; at $P_e = 50$ MPa and 920°C, the andesite wet strength is 45 MPa compared to 160 MPa dry. The ductility of the water-saturated specimens deformed at temperatures less than that of melting exhibit ultimate strengths at less than 3% shortening and then work-soften along faults; that is, like their dry counterparts the rocks remain brittle up to the onset of melting. Both dry and wet specimens deform primarily by microscopic fractures that coalesce into one or more macroscopic faults, and the temperature for incipient melting of the andesite is decreased ~150°C in the water-saturated state.

The extrapolations of these strength and ductility data for both wet and dry specimens indicate crystalline rocks should be drillable because they remain brittle until partial melting occurs; penetration rates should increase with temperature because there is a corresponding decrease in brittle fracture strength; boreholes in "water-filled" holes will be stable to >10 km at temperatures $< T_m$; if temperatures are kept to <700°C, even open boreholes in granodiorite are apt to be stable to 10 km; and open boreholes in the andesite are apt to be much less stable and at similar temperatures would fail at a 2 to 5 km depth. As a worse case, open boreholes in wet or dry andesite would fail shortly after drilling at ≤ 2 km if σ_h/σ_v were 2.0. Work to date on intact specimens suggests the scientific feasibility of drilling buried magma chambers at depths to 10 km. Boreholes can be stabilized by keeping them as cool as possible and with a borehole pressure equivalent to that of a column of water at 25°C.

Data are now available for the mean coefficient of linear thermal expansion (α) for these rocks. Differences between measured and calculated values are related to new crack porosity (ϕ) resulting from differential thermal expansions. For the granite a two or three order of magnitude increase in permeability (k) is predicted from the relation, $k \propto \phi^3$.

Westerly Granite is dramatically weaker and more ductile when deformed wet in creep tests than in our short-term experiments. Moreover, the weakening increases with increasing pore pressure at a given effective pressure. To determine if the assessment of borehole stability needs revision, we have extrapolated the times to failure for the most drastic case (800°C). Using the expected borehole stresses at 8 and 10 km and $\sigma_h/\sigma_v = 1$, we conclude that a borehole in granite would remain stable 10^4 and 1 years, respectively. Thus, our assessment does not change significantly.

1982

The problem of deep drilling, as well as other mechanical problems associated with high temperature crustal environments, cannot be fully resolved without adequate knowledge of short-term and time-dependent rock strength and ductility. Accordingly, during this report period we concentrated on (a) publishing our petrofabric studies of dry and wet specimens of crystalline rocks deformed in short-time experiments, (b) deforming a few samples of basalt acquired from the NSF Deep Sea Drilling Project in order to correlate rock strength with drilling rate, and (c) study of time-effects in room-dry and water-saturated Westerly Granite.

Since the bulk of our effort was devoted to (c), it is described briefly herein. It is an effort to characterize the rheology and flow processes (mechanisms of deformation) operative in Westerly Granite under semi-brittle

behavioral conditions in a series of drained constant-stress creep tests on 2 x 4-cm specimens, dry and water-saturated ($P_p = 100$ MPa at 100 MPa effective confining pressure) and temperatures of 300°C to in excess of T_m (1000°C). The deformation is multimechanistic; microfracture of extensile and shear origin, gliding in quartz and biotite, microfracture healing, dissolution, and mineral alteration are mechanisms observed and evaluated as functions of temperature and strain. The bulk specimen deformation is partitioned into that contributed by the individual mineral species in the analysis. The systematic change in micromechanisms with increasing temperature is compatible with the origin of the gradational succession of macroscopic deformation modes from a single fault ($T/T_m \leq .5$) to a shear zone ($T/T_m \approx .6$) to multiple faults ($T/T_m \approx .75$) to uniform flow ($T/T_m \leq .9$).

Flow data for 600°C and below (brittle field) are well fit by an equation of the form:

$$t_{\text{failure}} = t_0 P^{-\alpha} \exp (E/RT - K\sigma),$$

[where: t_0 , α , and K are experimental constants, P is the partial pressure of H_2O , E is the activation energy, σ is the differential creep stress, R the gas, and T the absolute temperature]. This equation has been shown to predict the static fatigue time for rock. Using this expression, we calculate apparent activation energies for the total fatigue process in the α -quartz field of 7.5 kcal/mole (300-400°C, dry) and 21.6 kcal/mole (400-600°C, wet).

Quasi-steady state flow occurs in the β -quartz field (700-800°C) and the flow behavior is well described by $\dot{\epsilon} = A \exp (-Q/RT) \sigma^n$, where the activation energy $Q = 68$ kcal/mole, $n = 2.7$, $\dot{\epsilon}$ is the strain rate, σ is the steady state stress and the constant $A = 25.2$. These results are significant because previously flow has not been so characterized where fracture is a major, if not the dominant, deformation mechanism. Our results suggests that fracture is a time-dependent, thermally activated process.

1983

To provide a sound physical basis for the above now empirical flow laws, it is necessary to investigate the thermal-activation and stress-corrosion aspects of fracture in wet and dry quartzite, granite, and basalt in extension tests, wherein true tensile fractures will be induced at a constant strain rate of 10^{-4} s^{-1} over a temperature range of 25° to 800°C , under effective confining pressures of 20 to 200 MPa and absolute pore-water pressures of 10 to 180 MPa. Time effects are studied by holding constant the tensile stress at different levels and recording times to failure.

Secondly, further to borehole stability problems of deep drilling in fractured rock, it is necessary to investigate the high-temperature ($300\text{--}900^\circ\text{C}$), low pressure (10-100 MPa) mechanical behavior of smooth, bare-rock surfaces in granite, granodiorite, andesite, and basalt to determine under what conditions of P and T does the frictional sliding strength of the rocks equal or exceed that of the unfractured, intact material. That is, under what conditions can it be modeled as a continuum.

Accordingly, we have studied the deformation of room-dry and water-saturated Westerly Granite and other rocks at confining pressures between 20 and 200 MPa and temperatures between 25 and 900°C , in order to evaluate:

- 1) time-dependent effects of strength and strain to failure,
- 2) frictional strength of bare-rock surfaces, and
- 3) effect of temperature on tensile strength, i.e., the possible thermal activation of the tensile fracture process.

With regard to our preliminary conclusions about borehole stability in crystalline rocks at low confining pressures but high temperatures, we note that:

a) The creep-rupture strength of granite is only about 20 percent below the short-time triaxial strength so that for geotechnical applications and failure in compression and effect of time may be ignored.

b) Results from twenty-four frictional sliding tests indicate that the frictional strength of smooth surfaces of granite is only about 50 percent of the intact strength.

c) Results from twenty-two triaxial-extension tests show that the tensile strength of granite drops from about 10 MPa at 25°C to sensibly zero at 800°C. This suggests that fracture is in fact a thermally activated process and it emphasizes the necessity to keep borehole pressures during drilling less than the least compressive principal stress in the rock mass to avoid hydraulic fracturing.

1984

The very next steps in this study are to:

1) study the textures and fabrics of tensile fracture surfaces and of precursive side cracking in Westerly Granite specimens to detect changes, if any, with increasing temperature (and decreasing strength),

2) extend our triaxial-extension testing to other rock types (e.g., basalt [without quartz] and pure quartzite) to further study tensile strength changes with temperature and the thermal activation of fracture;

3) extend our sliding friction work to these same rocks, and

4) look into the effects of water, surface roughness, and mineralization on the frictional properties of pre-existing fractures (joints).

With regard to (3) we would expect the strength reduction observed for smooth rock surfaces (about 50% over intact counterparts) to decrease, perhaps vanish, when rough and mineralized natural fracture surfaces are tested. If

so, can we then define pressure and temperature regimes where a jointed rock mass can be modeled solely as a continuum?

With regard to (2) it is important to deep drilling with pressured boreholes to know to what degree the tensile strength of other rock types is degraded with increasing temperature, and to understand the corresponding role of quartz (particularly at the α - β transition) in the tensile fracture process.

These expressions provide a means to predict flow and fracture of rock in engineering rock-mechanics problems at hand; however, they are empirical and lack a sound physical basis for extrapolation.

The deformation is multimechanistic with microfracturing of extensile and shear origins, glide in quartz and biotite, microfracture healing, dissolution, mineral alteration, incipient and partial melting, depending on temperature and strain. We attempt to partition the bulk deformation into that contributed by the individual mineral species in the analysis. The systematic change in micromechanisms observed with increasing temperature is compatible with the origin of the gradational succession of macroscopic deformation modes from a single narrow fault ($T/T_m \leq 0.5$) to a shear zone ($T/T_m \leq 0.6$), to multiple shear fractures ($T/T_m \leq 0.75$), to uniform flow ($T/T_m \leq 0.9$).

The creep-rupture strength of crystalline rocks is not dramatically lower than the short-time ultimate strength measured previously at the same confining pressure and temperature. Thus our previous conclusions about borehole stability (Handin et al., 1981) are probably valid even for loading durations of several weeks.

CURRENT WORK

TIME-DEPENDENT DEFORMATION OF WESTERLY GRANITE

This work, described in detail in S.J. Bauer's Ph.D. Dissertation (App. I) addresses the semibrittle deformation of crystalline rock under upper crustal conditions, characteristic of relatively high-temperature and low-pressure environments, that is by definition multimechanistic and therefore probably multirheologic. To enhance understanding of this deformation regime, our results are presented on: (1) finite-element models which simulate polyphase aggregate deformation; (2) deformation experiments appropriate to the environmental conditions; and (3) detailed petrofabric observations of deformed specimens.

In the finite-element models volume fractions of "weak" and "strong" elements are varied. Thirty percent (by volume) of a weak member will "control" the bulk deformation because (1) at least half of model strain is accommodated by the weak elements, and (2) model strength is less than half that of the stronger end-member. These results are consistent with numerous recent experimental studies of several rock types.

In an effort to characterize the rheology and flow processes (mechanisms of deformation) operative for semibrittle behavioral conditions, a series of drained, constant-stress, triaxial-creep tests was conducted on 2 by 4-cm specimens of dry and water-saturated Westerly granite at 100 MPa effective confining pressure and temperatures of 300°C to in excess of partial melting (~1000°C).

Available equations of flow and time to failure are used as response models to characterize the experimental data even though the multimechanistic deformation described above and the quasi-steady-state flow observed are not compatible with all the assumptions underlying the corresponding theories. Data for 600°C and below (the brittle field) are well fit by an equation of the form: $t_{failure} = t_0 P^{-\alpha} \exp(E/RT - K\sigma)$, which has been shown to predict the static fatigue time for several rocks. Using this expression, we calculate apparent activation energies (E) for the summed fatigue processes in the α -quartz field of 31 kJ/mole (300-400°C, dry), 69 kJ/mole (400-600°C, dry), and 90 kJ/mole (400-600°C, wet).

Quasi-steady state flow is observed in the β -quartz field (700-800°C), and the flow behavior is described by $\dot{\epsilon} = A \exp(-Q/RT) \sigma^n$, where $Q = 290$ kJ/mole, $n = 2.7$, and $A = 25.2$.

FRICTIONAL PROPERTIES OF GRANITE

Few rock masses are free of macrofractures (joints), the pertinent frictional strengths of which, in comparison with the strengths of the intact rock, must be known for predictive modeling. Accordingly, we have mapped, in temperature and confining-pressure space, the frictional-sliding strengths of bare-rock surfaces in Westerly granite.

The specimens, 2 by 4-cm, right-circular-cylinders, are cut at 35° to the cylinder axis. The precut is then hand-polished with 400 grit. Thus far 24 experiments have been done at temperatures of 200° , 400° , 600° , 700° , 800° , and 900°C , and confining pressures (P_c) of 25, 50, 100, 150, and 200 MPa (Table 1). Because the experimental matrix is large, we can evaluate the effects of both confining pressure and temperature at constant axial strain-rate.

At both 200° and 400°C , frictional strength increases with increasing confining pressure. At 600°C , increasing confining pressure from 25 to 100 MPa increases the frictional strength from 125 MPa to 400 MPa. However further increases in confining pressure to 200 MPa, do not cause further changes. At 700°C , our measurements are poorly reproducible and range from 300 to 500 MPa for 100 to 200-MPa confining pressure. This behavior is probably associated with a brittle - ductile transition. At 800°C , strength increases from 185 MPa ($P_c = 25$ MPa) to 250 MPa ($P_c = 50$ MPa) to 310 MPa ($P_c = 100$ MPa), then decreases to 280 MPa ($P_c = 150$ MPa) to 230 MPa ($P_c = 200$ MPa). The apparent lack of pressure dependence on frictional strength at 800°C may be signaling a predominance of ductile deformation mechanisms. Frictional resistance may well increase with temperature because asperities flow, and real area of contact grows (cf. Logan, 1975; Logan and Teufel, 1976).

At each of the five confining pressures, increasing the temperature from 200° to 400°C causes an increase in frictional strength. For $P_c = 25$ MPa, further increases to 600° and 800°C result in systematic increases in strength, whereas at $P_c = 50$ MPa, although the strength increases from 400°C to 600°C , a decrease is observed from 600° to 900°C . Frictional strengths at 100 MPa display a slight systematic weakening from 400° to 800°C . At 150 MPa the strength hovers around 450 MPa for tests at 400° , 600° , and 700°C , whereas the strength at 800° drops to 290 MPa. Finally, at $P_c = 200$ MPa, the strength at 400°C (520 MPa) drops to 370 MPa at 600° to 700°C and 230 MPa at 800°C .

Table 1. Results of Friction Experiments on Bare-Rock Surfaces in Dry Westerly Granite at Different Temperatures (T) and Confining Pressures (P_c) at a Constant Axial Strain-Rate of 10^{-4} s^{-1}

Exp. No.	T (°C)	$P_c = \sigma_3$ (MPa)	At slip	At termination		At slip
			$\sigma_1 - \sigma_3$ (MPa)	$\sigma_1 - \sigma_3$ (MPa)	Strain (%)	τ/σ
F1	200	25	40	115	1.4	0.49
F2	200	50	130	220	2.0	0.66
F3	200	100	355	395	1.5	0.77
F4	200	200	465	500	1.7	0.62
F5	400	25	75	120	0.8	0.71
F6*	400	50	180	190	0.6	0.77
F7	400	100	325	425	0.8	0.74
F8	400	150	465	465	0.6	0.72
F9	400	200	525	525	0.4	0.66
F10*	600	25	145	145	1.0	0.94
F11*	600	50	230	200	0.7	0.86
F12	600	100	325	400	1.5	0.74
F13	600	150	445	450	2.0	0.71
F14	600	200	390	330	1.5	0.56
F15	600	200	355	325	1.5	0.53
F16	700	100	260	350	1.6	0.66
F17	700	150	495	490	1.7	0.74
F18	700	200	370	325	1.7	0.54
F19	800	25	160	185	0.9	0.97
F20	800	50	240	255	1.2	0.87
F21	800	100	320	320	1.3	0.73
F22	800	150	280	215	1.2	0.54
F23	800	200	235	165	1.7	0.40
F24	900	50	120	130	0.9	0.63

*Stick-slip was observed in these three specimens only.

These changes in frictional strength relative to the imposed environments of deformation probably reflect changes in the operative mechanisms. During the remainder of this contract-year we shall be examining the sliding surfaces microscopically to identify these mechanisms, the better to explain the effects of normal stress and temperature on frictional strength.

Finally, one of our main purposes for determining frictional strengths under these high-temperature and low-pressure conditions is to complement our previous work on strengths and ductilities of intact rock under similar experimental conditions. Comparison of the data with those of Friedman et al. (1979) and Bauer et al. (1981) reveals that the frictional strength of precut specimens is always less than the strength of intact specimens at $P_c = 50$ and 100 MPa. The difference in strengths does decrease as temperature is increased. For example, at 400°C the frictional strengths are 30 to 40 percent of intact strengths, whereas at 800°C they are 60 to 70 percent. Thus, we have not yet found a regime where slip along pre-existing fractures is not potentially important, i.e., where the fractures can be ignored as passive relative to assessment of borehole stability in jointed rock-masses. However, the effects of surface roughness, water, and joint filling remain to be evaluated.

TENSILE STRENGTH OF GRANITE

Because we have recognized that macroscopic shear fracturing of brittle and semi-brittle rocks begins with local tensile microfracturing, we have begun measurement of the mechanical behavior of granite in extension as a function of temperature, effective confining pressure and absolute pore-water pressure. The data, combined with detailed petrofabric work, should enable us better to understand the phenomena of tensile fracturing and its thermal activation.

In a triaxial-extension test, $\sigma_3 < \sigma_1 = \sigma_2 = P_c$, where σ_i are principal stresses and P_c is confining pressure, compressive stresses counted positive. To date we have done 19 experiments on dry Westerly granite at confining pressures between 20 and 200 MPa and temperatures between 25° and 900°C, and 3 experiments on water-saturated specimens at an effective confining pressure of 100 MPa and 600°, 700°, and 800°C (Table 2). At all confining pressures except possibly 200 MPa, the axial stress is tensile (negative) at room temperature, and the specimens fail by tensile fracturing at close to 90° to $-\sigma_3$. At 600°C, tensile fracturing occurs at confining pressures between 20 and 50 MPa, and only at 20 MPa at 800°C. Under all other conditions σ_3 at failure is positive, and shear fracturing occurs as the Coulomb-Mohr criterion would predict (e.g., Handin, 1969). The effect of pore water is to reduce shear strength and increase ductility.

During the remainder of this contract-year we shall do more tests at low effective confining pressures (20 to 50 MPa) to achieve tensile fracturing and assess the reproducibility of tensile-strength measurements. We shall observe the fracture surfaces microscopically to help determine why tensile strength is temperature-sensitive and how the presence of water may affect the processes of fracturing. We shall also compare the failure surfaces in differential stress/mean stress/temperature space, developed for triaxial compression ($\sigma_1 < \sigma_2 = \sigma_3$) and extension ($\sigma_3 < \sigma_1 = \sigma_2$) states. We can then decide whether our previous conclusions about borehole stability, based solely on compression tests, are valid for a state of extension under otherwise similar conditions.

Table 2. Results of Extension Tests on Westerly Granite at Different Temperatures (T) and Confining Pressures (P_c) at a Constant Axial Strain-Rate of $3 \times 10^{-4} \text{ s}^{-1}$

Exp. No.	T (°C)	$P_c = \sigma_1$ (MPa)	$\sigma_1 - \sigma_3$ (MPa)	σ_3 (MPa)	Axial strain (%)	Fracture angle (°)	Fracture type
E1	25	20	32.0	-12.0	0.7	?	?
E2	25	50	66.1	-11.1	0.6	3	T
E3	25	100	111.0	-11.0	0.7	3	T
E4	25	150	156.8	-6.8	0.8	3-5	T
E5	25	200	198.4	1.6	1.3	3-5	?
E6	600	20	28.0	-8.0	0.5	3	T
E7	600	50	56.3	-6.3	1.5	3	T
E8	600	100	102.5	-2.5	1.8	3	T
E9	600	150	148.1	1.9	1.4	3	?
E10	600	150	147.1	2.9	1.5	10	S
E11	600	200	183.4	16.6	1.8	--	**
E12	600	200*	93.6	6.4	2.6	--	**
E13	700	150	144.2	5.8	2.0	9	S
E14	700	200*	86.8	13.2	3.6	--	**
E15	800	20	22.8	-2.8	2.3	2	T
E16	800	50	50.0	0.0	2.2	3	T
E17	800	100	84.1	15.9	2.0	11	S
E18	800	150	87.0	63.0	2.2	--	**
E19	800	150	95.9	54.1	1.4	9	S
E20	800	200	148.2	51.8	2.4	15	S
E21	800	200*	44.0	56.8	5.3	--	**
E22	900	150	46.9	103.1	1.1	--	**

*Confining pressure, $P_c = 200$ MPa; pore pressure, $P_p = 100$ MPa; effective pressure, $P_e = 100$ MPa.

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

PROGNOSIS

By the end of this contract-year we shall have largely completed our work on the frictional properties of bare-rock surfaces and the tensile strength of Westerly granite, including selected petrofabric observations of the deformed specimens. To follow up this work logically, we have submitted a proposal for a renewal of our grant for 1984-1985. Should the renewal be awarded, we shall (1) extend our triaxial-extension testing to other rock types, probably basalt (without quartz) and pure quartzite; (2) extend our sliding-friction study to these same rocks; and (3) look into the effects of water, surface roughness, and filling on the frictional properties of pre-existing fractures (joints).

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