**ANISOTROPIC YIELDING OF ROCKS AT
HIGH TEMPERATURES AND PRESSURES**

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SUMMARY SHEET

Anisotropic Yielding of Rocks at High Temperatures and Pressures

DE --FG05 -- 87ER13711

A. K. Kronenberg (P.I.) and J. E. Russell (P.I.)

Accomplishments During Period 15 April, 1987 to 15 December, 1987

Significant progress has been made within the first eight months of the project period, April 15, 1987 to December 15, 1987, towards the experimental determination of anisotropic yielding of foliated rocks, the theoretical treatment of the results, and characterization of foliations in and surrounding buried magma bodies.

Results to date are as follows:

1. All of the starting materials for the three year project have been collected. Included in our collection are relatively fine-grained, fresh, oriented blocks of schist, gneiss, and micaceous quartzite with well-defined foliations and lineations, as well as granite blocks oriented with respect to the principal quarrying orientations, the rift, grain, and hardway.
2. A suite of samples has also been collected from an exposed granite stock and surrounding country rocks in order to evaluate the strengths and distribution of fabrics which may be encountered while drilling. These fabrics appear to be directly related to the forceful emplacement of the pluton.
3. The literature on the mechanics of intrusion has been reviewed with regard to strain gradients and foliation development associated with diapiric flow. This information will be used to evaluate the effect of varying fabrics on yield criteria within and surrounding magma chambers.
4. Twenty three successful experiments have been performed on samples of gneiss cored along six different orientations at temperatures ranging from 25° to 700°C. These experiments include extension tests, unconfined compression tests, and compression tests performed at $P_c = 100$ MPa.
5. Theoretical yield conditions for anisotropic materials have been reviewed and the assumptions upon which they are based probed. These yield conditions will ultimately be used to fit our data on gneiss, and the other foliated rocks under investigation.
6. Two abstracts have been published and oral presentations made at the 1987 Fall Meeting of the American Geophysical Union, based upon our previous DOE-sponsored work on tensile fracturing of quartzite (DOE Contract No. DE-FG05-84ER13228) and related work on semi-brittle deformation of granitic rocks.

Continued Research Support

Continued support for the three year project period, April 15, 1987 to April 14, 1990, should result in a comprehensive data set for the deformation of foliated rocks, providing the first complete determinations of anisotropic yield criteria for geologic materials, and ultimately provide the means of predicting borehole stability within foliated rocks surrounding deeply-buried magma chambers. Over the next four months, we plan to complete the determination of the pressure effect on deformation of gneiss and continue to determine yield strengths in six orientations at temperatures ranging from 25° to 700°C. In the following year, we expect to complete the experimental program on Four mile gneiss and fit the experimental data with an anisotropic yield criterion. Work on the strongly foliated Partridge schist and more nearly isotropic Westerly granite will proceed following completion of the gneiss experiments.

TECHNICAL PROGRESS REPORT

INTRODUCTION

Significant progress has been made within the first eight months of the project period, April 15, 1987 to December 15, 1987 (DOE sponsored DE-FG05-87ER13711), towards the determination of anisotropic yield conditions for foliated rocks and application of these criteria to deep drilling to buried magma chambers. We have completed our collection of starting materials which now includes relatively fine-grained, fresh, oriented blocks of schist, gneiss, and micaceous quartzite with well-defined foliations and lineations, and granite blocks oriented with respect to the principal quarrying orientations, the rift, grain, and hardway. In addition, we have collected samples from an exposed granite stock and surrounding country rocks to evaluate the strengths and distribution of fabrics which may be encountered while drilling, resulting from the emplacement of an igneous pluton. We have reviewed the literature on the mechanics of intrusion with regard to strain gradients and foliation development and plan to evaluate the effect of varying fabrics on yield criteria within and surrounding magma chambers. Samples of gneiss cored along six different orientations have been prepared and twenty three successful experiments performed at conditions spanning temperatures of 25° to 700°C, confining pressures of 0.1 to 100 MPa, in extension and in compression. We have reviewed the theoretical yield conditions for anisotropic materials and studied their form, the assumptions upon which they are based, and their implications for the deformation of foliated rocks. Two abstracts have been published and oral presentations made at the 1987 Fall Meeting of the American Geophysical Union, based upon our previous DOE-sponsored work on tensile fracturing of quartzite (DOE Contract No. DE-FG05-84ER13228) and related work on semi-brittle deformation of granitic rocks.

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providing the first complete determinations of anisotropic yield criteria for geologic materials, and ultimately provide the means of predicting borehole stability within foliated rocks surrounding deeply-buried magma chambers.

PUBLICATIONS

Two abstracts have been published within the funding period April 15, 1987 to December 15, 1987, based upon our previous DOE-sponsored work on tensile fracturing of quartzite (DOE Contract No. DE-FG05-84ER13228) and related work on semi-brittle deformation of granitic rocks:

Mardon, D., A. K. Kronenberg, J. Handin, M. Friedman, and J. E. Russell, Effect of temperature on fracture strength and morphology in experimentally extended Sioux quartzite, Trans. Am. Geophys. Union, **68**, 1464, 1987.

Notched samples of Sioux quartzite have been extended to failure at temperatures T from 25° to 700°C, strain rates $\dot{\epsilon}$, from $5.2 \times 10^{-6} \text{s}^{-1}$ to $6.7 \times 10^{-4} \text{s}^{-1}$ at a confining pressure $P_c = 100 \text{ MPa}$ and fracture morphologies investigated. Tensile strengths (e.g. 11 MPa at 25°C to 4.5 MPa at 500°) are insensitive to variations in T and $\dot{\epsilon}$ and are comparable to previously reported values for unconfined, room T tests (Krech et al., 1974). Force-displacement records for tests at $T = 25^\circ - 412^\circ \text{C}$ exhibit nearly perfect linear elastic behavior prior to failure whereas those for $T \geq 500^\circ \text{C}$ tests exhibit significant inelastic yielding. The inelastic work done in extension at 500°C is $\sim 1.2 \text{ J}$, approximately 5 times the room T value. Features common to test specimens at all T are: (1) fractures consist of intragranular cracks (IGC), oriented sub-parallel to the fracture, linked by grain boundary crack (GBC) of all orientations, (2) all IGC visible in thin section occur within a narrow zone ~ 2 grain diameters $\bar{d}$ wide ($\bar{d} = 160 \mu\text{m}$) centered on the fracture, (3) GBC comprise at most a few percent of the total fracture surface area, (4) well developed river pattern and sets of concentric steps on IGC surfaces, demonstrating that cleavage cracking on r and z is the dominant grain-scale deformation mechanism. Local crack propagation directions

directions within the fracture plane. IGC in $T \geq 500^{\circ}\text{C}$ test specimens show a broader range of orientations than in $25^{\circ} - 412^{\circ}\text{C}$ samples. Inelastic yielding prior to failure at high T is attributed to extensive formation of GBC in a widening zone about the main fracture.

Kronenberg, A. K., and P. Segall, Fluid inclusions along healed microcracks and dislocations within a ductile shear zone: implications for fluid access and hydrolytic weakening, Trans. Am. Geophys. Union, **68**, 1471, 1987.

Two distinct populations of fluid inclusions decorating healed microcracks and dislocations within a ductile, granodiorite shear zone of the central Sierra Nevada have been observed by transmission electron microscopy which record interactions between fluids and processes of brittle failure and ductile flow during two deformation events. Fluid inclusions associated with an initial phase of tensile fracturing and dilatancy are relatively large ($\sim 0.4 - 1.0 \mu\text{m}$ in diameter), irregular in shape and form planar arrays along the traces of healed microcracks both within quartz and feldspar grains. A second set of fluid inclusions, however, appears to be associated with later ductile shearing, consisting of extremely fine ($20 - 150 \text{ nm}$ in diameter), more nearly spherical inclusions which consistently lie along free dislocations and dislocation nodes, and exhibit relationships with dislocations similar to those observed in hydrolytically-weakened synthetic quartz. Previous investigations of the field relationships, finite strains, and intragranular water contents of this ductile shear zone (Segall and Simpson, 1986; Kronenberg et al., 1984) have suggested a mechanism of ductile strain localization on a pre-existing healed fracture by fluid infiltration and hydrolytic weakening. Intracrystalline diffusion rates of water in quartz have been shown to be sluggish, however, and fluid access along microcracks followed by pipe diffusion along mobile dislocations appears to have been essential to the hydrolytic weakening of these rocks.

PROJECT DESCRIPTION AND GOALS

The exploration and development of sources of geothermal energy associated with buried magma chambers and regions of high heat flow require drilling to depths of up to 10 km at temperatures ranging from ambient surface temperatures to those of partial melting. Successful drilling to these depths within steepened geothermal gradients depends upon rock strengths sufficient to support the stress fields generated around the borehole at depth. Previous experimental studies, directed towards determining the strengths and ductilities of rocks under conditions appropriate to the borehole environment, have provided useful constraints on the conditions for which borehole failure may be anticipated for massive, relatively isotropic rocks. However, predictions of borehole stability in such strongly foliated rocks as slates, schists, and gneisses cannot be made using isotropic failure envelopes.

One of the outstanding problems remaining in the prediction of borehole stability in crystalline rocks is the influence of fabric anisotropy on yielding. Our study of the mechanical behavior of foliated rocks using anisotropic yield criteria has been initiated with the view to predicting their behavior in the stress field surrounding a borehole at temperatures and pressures representative of the borehole environment. Our approach is to perform a suite of experiments designed to determine the full anisotropy of yielding for granite (presumed to be nearly isotropic), a layered gneiss, and a strongly foliated quartz-mica schist, followed by modeling their behavior in the vicinity of a borehole.

The results of these studies will be used to establish the means of predicting the mechanical response of schists, slates (using published results), and gneisses to the stress fields surrounding boreholes over a wide range of temperatures and pressures that may be encountered in geothermal source regions. Below are detailed statements of our progress through the first eight months of this contract.

STARTING MATERIALS

All of the starting materials for the three year project have been collected, including a schist and two gneisses with well-developed foliations and lineations, a micaceous quartzite, and several oriented blocks of Westerly granite, purchased from Bonner Monument Co., Ashaway, R.I. The samples of schist, gneisses, and micaceous quartzite were procured during a collecting trip to northern Massachusetts in late May and early June of 1987. This area was selected as the best locale for sample collection because metamorphic rocks of a variety of compositions are exposed here, and areal mapping has been completed in great detail. Dr. Peter Robinson of Amherst University accompanied us on our field forays; with his intimate knowledge of the metamorphic geology of New England, we were able to collect large amounts of excellent material for the entire three year project period. Rock-types collected include two quartz-feldspar-biotite-muscovite gneisses (the Four Mile gneiss and the Monson gneiss), a quartz-biotite-muscovite schist (the Partridge schist) and a micaceous tectonite quartzite (the Pelham quartzite). Descriptive details of samples and collecting localities are given in Table 1.

Selection of suitable experimental materials was based on a number of criteria. To assure relative freshness of the materials, samples were collected from roadcuts (the Monson gneiss, Partridge schist and Pelham quartzite), or in the case of the Four-Mile gneiss, a quarry which was operative in the 1800's. All rocks were closely inspected in the field to avoid weathered material or secondary fractures. Materials collected are rocks having well-defined foliations and lineations with no superposed folds. Simple planar and linear fabrics negate the effect of irregularities such as folds on the mechanical behavior of the material, and have the additional benefit of allowing the preparation of precisely oriented cores for experiments. All samples are unimodal in grain size, with few quartz or feldspar segregations. Since the foliation and lineation are the sole mesoscopic-scale inhomogeneities in all samples, their effects on the mechanical behavior and mode of deformation of the material are effectively singled-out. Both the Four-Mile gneiss and the Monson gneiss are granitic orthogneisses, comparable in grain-size and mineralogy to the Westerly granite; comparison of the foliated granitic materials to the relatively homogeneous Westerly granite will provide

additional information on the effects of metamorphic fabrics on the mechanical behavior of materials.

Blocks of Westerly granite were purchased from Bonner Monument Company, Ashaway, Rhode Island. A wide variety of physical and mechanical properties of Westerly granite have already been measured and it may serve as both a standard, and as an end-member in anisotropy; its yielding is expected to be isotropic, relative to the deformation of schist and gneiss. Nevertheless, even for this starting material, fracture strengths of samples cored in differing orientations to the rift, grain, and hardway may differ according to an anisotropic yield function. The blocks of Westerly granite we acquired were carefully oriented with respect to these quarrying orientations.

Finally, as part of our sampling of foliated rocks, we have collected samples from a relatively small granite stock. These include strongly foliated samples along its margin and more homogeneous samples from its interior. Several lines of evidence suggest that their fabrics developed by the forceful emplacement of the stock into the surrounding country rock.

During the course of deep drilling to buried magma chambers, rocks may be encountered with foliations associated either with prior tectonic events, or with the intrusion of the pluton. Application of the experimental results for anisotropic yielding of foliated rocks will require a knowledge of the orientations and magnitudes of foliations and lineations. Thus, our sampling has partly been directed towards characterizing the strengths and distribution of these fabric elements in and surrounding the granite stock. The details of this suite of samples and a review of the literature on the mechanics of intrusion and fabrics associated with these deformations are elaborated upon in later sections.

Table 1. Field data for experimental materials.

Samples FMG-1 and FMG-2 - Precambrian Four-Mile Gneiss, collected from quarry on Roman T hill, near Miller's Falls, Massachusetts. Latitude 42° 39' 06", Longitude 72° 26' 09", Northfield 7.5' quadrangle. Quartz-feldspar-biotite-muscovite gneiss from Pelham Dome.

Samples OPS-1, OPS-2 and OPS-3 - Ordovician Partridge Schist, collected from roadcut along Massachusetts Rte. 2, near Orange, Massachusetts. Latitude 42° 35' 08", Longitude = 72° 19' 36", Orange 7.5' quadrangle. Quartz-biotite-muscovite schist, with accessory fibrolitic sillimanite, graphite and pyrrhotite.

Sample MO-1 - Precambrian Monson Gneiss, collected from roadcut along exit ramp, intersection of Massachusetts Rtes. 2 and 122. Latitude 42° 33' 27", Longitude 72° 19' 46", Orange 7.5' quadrangle. Quartz-biotite-feldspar-muscovite gneiss from Monson Dome.

Sample PO-1 - Precambrian Pelham Quartzite, collected from roadcut along U.S. Highway 202. Latitude 42° 24' 15", Longitude 72° 24' 03", Shutesbury 7.5' quadrangle. Tectonite quartzite with sparse muscovite, from interior of Pelham Dome.

Samples WG-1, WG-2, and WG-3 - Late Pennsylvanian or Permian Westerly Granite, purchased from Bonner Monument Company, Ashaway, Rhode Island. 12 inch cubic blocks oriented with respect to the principal quarrying orientations, the rift, grain, and hardway. Massive, fine-grained, and equigranular, Westerly granite consists of 43% plagioclase, 22% microcline, 25% quartz, 7% biotite, and 2% muscovite.

SAMPLE PREPARATION AND EXPERIMENTAL IMPROVEMENTS

To date, all sample preparation and experimental work has focused on the Four-Mile gneiss. The samples used in experiments are cores 0.725 inches in diameter, drilled at six different orientations with respect to the foliation and lineation (Fig. 1). Drilling was facilitated by carefully cutting the original sample into oriented blocks, as shown in Figure 2. Once cores were removed from oriented blocks, they were finished in two different configurations: Cores used in compression tests are simple right cylinders, but those used in extension tests are notched cylinders with a "dogbone" configuration (Figs. 3 and 4). A one-inch diameter diamond impregnated drill-bit was used to grind the notches, assuring precise and reproducible notch dimensions. In both configurations, ends were lapped so that they are mutually parallel, and perpendicular to the cylindrical axis; this allows the pistons to sit flush against the ends of the sample, preventing stress concentrations which may produce erroneous results. Cores used in extension tests have been prepared in the orientations parallel and perpendicular to the foliation (orientations X, Y, and Z) and those used in compression tests have been prepared in all six orientations.

Several improvements in experimental design have been made, principally in furnace design, aimed at improving the temperature distribution within samples and furnace lifetime. These include substitution of ceramic insulating materials, coil spacing and radius, and furnace connectors. We have recently acquired Mo wire and plan to substitute the furnace windings currently used with this less-costly material. Finally, we have added TECO digital temperature controllers (using other available funds) to both apparatus used for this project.

Extension experiments were performed using the same apparatus as was used for our previous work on Sioux quartzite and Westerly granite (Friedman et al., 1987; Mardon et al., 1987) incorporating free travel of the load piston prior to loading the sample. Thus, friction corrections may be made for each individual experiment. Compression experiments were performed in the same apparatus, again with free travel of the load piston so that friction corrections could be made.

Figure 1. Orientations of the principal axes of fabric symmetry e_1 , e_2 , and e_3 may be defined (A) using cleavage and lineation orientations for the schist starting material, or (b) from quarrying plane (rift, grain, and hardway) orientations for granite. (C) Measurements of deviatoric stresses (X, Y, Z, R, S, and T, respectively) are required for uniaxial compression tests on samples cored along the symmetry axes e_1 , e_2 , and e_3 of the rock and along their bisectors (e_1 and e_2), (e_1 and e_3), and (e_2 and e_3):

Figure 2. Exploded view of Sample FMG-1, showing oriented blocks.

Figure 3. Photograph of samples used in compression experiments, orientations X, Y, Z, R, S, and T, from left to right.

Figure 4. Notched samples ("dogbones") used in extension experiments, orientations X, Y, and Z, from left to right.

Several new parts to the apparatus have been designed and sent out for machining to replace existing parts which have been in use for the last twenty years. These include a pressure vessel, endplugs, glands and pistons. Several of these new parts have been purchased using other available funds, but several have been charged to this project.

Finally, a pressure servo control system has been installed on one of the apparatus, capable of controlling to within ± 2 MPa at a confining pressure of 400 MPa, allowing for close pressure control over extended periods of time. We plan to install a similar unit to the second apparatus used for this project.

EXTENSION TESTS

Extension experiments on Four-Mile gneiss have been completed using an internally heated triaxial gas apparatus, in the manner described previously for Sioux quartzite and Westerly granite (Friedman et al., 1987; Mardon et al., 1987).

Samples were jacketed in annealed copper tubing 0.010" thick, collapsed into the notch under pressure. Copper jacket strengths were determined at confining pressures of 50 MPa and temperatures of 25°C and 500°C using a pre-cut steel "dogbone" (Fig. 5). The experimental conditions and sample column configuration used in tests on copper jacketing material were identical to those used in experiments on rock samples; force-displacement data for the copper jackets were thus subtracted directly from experimental results to correct for the behavior of the jacketing material.

Furnaces used in tests run at elevated temperatures were calibrated at experimental pressures to measure temperature gradients. During experiments, furnaces were positioned such that the thermal gradients at the notch were minimized, allowing accurate determination of temperatures at the notch center. Fluctuations in temperature due to thermal convection within the pressure vessel were minimized by packing the furnace with boron nitride powder.

Results of Experiments

Extension tests have been completed on samples of the Four-Mile gneiss in orientations parallel to the foliation, with the core axis both parallel and perpendicular to the lineation (orientations X and Z, respectively), as well as perpendicular to the foliation (orientation Y). Experiments were carried out at confining pressures of 50 MPa, temperatures of 25°C, 500°C, and 700°C, and strain rates of 1×10^{-5} /sec; results of experiments are summarized in Table 2.

Experiments run at room temperature conditions (25°C) indicate that strengths of this material in extension are quite small, ranging from 2.6 to 3.5 MPa. Although different strengths were determined for each orientation (Fig. 6), the variations are probably within the experimental errors involved and do not reflect accurately the anisotropic behavior. At elevated temperatures, samples tended to fail immediately upon entry into the tensile field, or at tensile strengths that reflect the strength of the copper jacket alone. Thus, samples in all orientations at 500°C and 700°C have no measurable tensile strength using this method.

These data indicate that the tensile strength of Four-Mile Gneiss is not measurably affected by material anisotropy. Since micas are not the dominant foliation forming mineral, this behavior probably reflects that of the less mechanically anisotropic quartz and feldspar. We will examine the roles of micas versus quartz and feldspar by examining deformed samples in thin section. In addition, we plan to test this idea by carrying out experiments on the Partridge schist, which contains a much larger modal proportion of mica. If our hypothesis is correct, the Partridge schist should exhibit significant anisotropic mechanical behavior in extension.

Figure 5. Results of copper jacket strength experiments in extension, at 25°C and 500°C, $P_c = 50$ MPa, $\dot{\epsilon} = 1 \times 10^{-5} \text{ cm}^{-1}$.

Figure 6. Stress-displacement curves for Four-Mile gneiss in extension at $T = 25^\circ\text{C}$, $P_c = 50\text{ MPa}$, $\dot{\epsilon} = 1 \times 10^{-5}\text{ cm}^{-1}$, orientations, X, Y and Z. Stress measurements assume that failure is instantaneous, and that the cross-sectional area upon which force is acting is the cross-sectional area of the undeformed sample at the notch.

COMPRESSION TESTS

To date, compression tests have been completed on samples in all orientations at conditions of 25°C and 0.1 MPa, and in orientations parallel and perpendicular to foliation at 25°C and 100 MPa. Strain rates used in all experiments were $1 \times 10^{-5} \text{ sec}^{-1}$. Experimental conditions and results are summarized in Table 2. The data presented are corrected for the effect of copper jacketing material using the experimental results of Handin and Hager (1958). Results clearly indicate that anisotropy plays an important role in the mechanical behavior of Four-Mile gneiss in compression. Differences in strength and behavior are particularly pronounced under ambient pressure conditions (0.1 MPa). As observed by other workers (for example Donath, 1964) the strongest orientation of an anisotropic material under uniaxial compression corresponds to the compression axis perpendicular to the foliation (orientation Y). Experimental results show predominantly elastic behavior followed by failure, with little inelastic strain (Fig. 7). In contrast, samples oriented with the compression axis parallel to the foliation are weaker, and, particularly in the case of orientation X, exhibit a more pronounced inelastic behavior prior to brittle failure (Fig. 8).

Our results deviate markedly from the yield conditions proposed for transversely isotropic shales and slates (Donath, 1961, 1964; Chenevert and Gatlin, 1965; McLamore and Gray, 1967; Nova, 1980; Smith and Cheatham, 1980). Although samples whose foliation plane is in the orientation of maximum resolved shear stress, (i.e 45° from the compression axis, orientations R and T) are relatively weak, orientation R, in which both the foliation and lineation are inclined at 45° to the compression axis, is clearly the weakest orientation. The stress-strain curve generated on a sample of orientation R shows typical elastic behavior, followed by inelastic strain, and failure (Fig. 9). In contrast, the strength in orientation T (compression axis 45° from foliation and orthogonal to lineation) is significantly greater than R, and more comparable to those which lie in the foliation plane (X and Z). Stress-strain records from samples deformed in orientation T show chiefly elastic behavior, followed quickly by brittle failure (Fig. 10), contrasting the larger inelastic strain accommodated by orientation R. These experiments indicate that the linear, as well as planar

DIFFERENTIAL STRESS VERSUS AXIAL STRAIN

HTR GAS RIG

200

Differential Stress

Pconf= .1
 Temperature (C)= 25
 Strain Rate 1.E-5
 DOE #14 10/11/87
 Orientation Y

AXIAL STRAIN

.02

Figure 7. Stress-strain record for Four-Mile gneiss, $T = 25^{\circ}\text{C}$, $P_c = 0.1 \text{ MPa}$, $\dot{\epsilon} = 1 \times 10^{-5} \text{ cm}^{-1}$, orientation Y. Uncorrected for copper jacket strength.

DIFFERENTIAL STRESS VERSUS AXIAL STRAIN

HTR GAS RIG

Figure 8. Stress-strain record for Four-Mile gneiss, $T = 25^{\circ}\text{C}$, $P_c = 0.1 \text{ MPa}$, $\dot{\epsilon} = 1 \times 10^{-5} \text{ cm}^{-1}$, orientation X. Uncorrected for copper jacket strength.

DIFFERENTIAL STRESS VERSUS AXIAL STRAIN

HTR GAS RIG

Figure 9. Stress-strain record for Four-Mile gneiss, $T = 25^{\circ}\text{C}$, $P_c = 0.1 \text{ MPa}$, $\dot{\epsilon} = 1 \times 10^{-5} \text{ cm}^{-1}$, orientation R. Uncorrected for copper jacket strength.

DIFFERENTIAL STRESS VERSUS AXIAL STRAIN

HTR GAS RIG

Figure 10. Stress-strain record for Four-Mile gneiss, T = 25°C, P_c = 0.1 MPa, $\dot{\epsilon}$ = 1 x 10⁻⁵ cm⁻¹, orientation T. Uncorrected for copper jacket strength.

fabric elements (defined by lineations and foliations, respectively) play an important role in the mechanical behavior of gneissic material.

The effect of linear fabric elements is further elucidated by experiments on samples at various orientations within the foliation plane. Orientations parallel and perpendicular (X and Z, respectively) to the lineation exhibit similar strengths, but orientation X accommodates more inelastic strain before brittle failure. Orientation S, which is inclined at 45° to the lineation is markedly stronger than either X or Z, approaching the strength of the orientation perpendicular to foliation (orientation Y).

To date, compression experiments carried out at confining pressure are limited to orientations parallel and perpendicular to the foliation. Confining pressures of 100 MPa have the effect of dramatically increasing the strengths of the materials (Table 2), and limiting the differences in mechanical behavior. Stress-strain curves for orientations X, Y and Z are nearly identical, exhibiting elastic behavior to about 400 MPa, followed by inelastic deformation, and eventual brittle failure at over 600 MPa and 1% strain (Fig. 11). Stress drops at failure are dramatic, and result in a loud report from the experimental apparatus. As with experiments at atmospheric pressure, samples oriented with the compression axis perpendicular to the foliation (orientation Y) are strongest, with those in the foliation plane somewhat weaker and of approximately equal strength.

DIFFERENTIAL STRESS VERSUS AXIAL STRAIN

HTR GAS RIG

Figure 11. Stress-strain record for Four-Mile gneiss, $T = 25^{\circ}\text{C}$, $P_c = 100\text{ MPa}$, $\dot{\epsilon} = 1 \times 10^{-5}\text{ cm}^{-1}$, orientation Y.

Table 2. - Summary of experimental results.

Experiment number	Sample orientation	Experiment type	Temperature	Confining pressure	Strain Rate (cm ⁻¹)	Yield strength	Ultimate strength
DOE #1	Y	extension	700 ± 5°C	50 MPa	1 x 10 ⁻⁵	0 MPa	0 Mpa
DOE #2	X	extension	700 ± 10°C	50 MPa	1 x 10 ⁻⁵	0 MPa	0 MPa
DOE #3	Z	extension	700 ± 10°C	50 MPa	1 x 10 ⁻⁵	-	-
DOE #4	Z	extension	700 ± 10°C	50 MPa	1 x 10 ⁻⁵	-	-
DOE #5	Y	extension	500 ± 5°C	50 MPa	1 x 10 ⁻⁵	0 MPa	0 MPa
DOE #6	Y	extension	25°C	50 MPa	1 x 10 ⁻⁵	-	3.0 MPa
DOE #7	X	extension	25°C	50 MPa	1 x 10 ⁻⁵	-	2.6 MPa
DOE #8	Z	extension	25°C	50 MPa	1 x 10 ⁻⁵	-	3.5 MPa
DOE #9	Z	extension	700 ± 10°C	50 MPa	1 x 10 ⁻⁵	0 MPa	0 MPa
DOE #10	X	extension	500 ± 15°C	50 MPa	1 x 10 ⁻⁵	0 MPa	0 MPa
DOE #11	Z	extension	500 ± 10°C	50 MPa	1 x 10 ⁻⁵	0 MPa	0 MPa
DOE #13	X	compression	25°C	0.1 MPa	1 x 10 ⁻⁵	66.8 MPa	81.4 MPa
DOE #14	Y	compression	25°C	0.1 MPa	1 x 10 ⁻⁵	104.0 MPa	109.5 MPa
DOE #15	Z	compression	25°C	0.1 MPa	1 x 10 ⁻⁵	72.8 Mpa	86.5 MPa
DOE #16	R	compression	25°C	0.1 MPa	1 x 10 ⁻⁵	-	-
DOE #17	S	compression	25°C	0.1 MPa	1 x 10 ⁻⁵	88.6 MPa	100.4 MPa
DOE #18	T	compression	25°C	0.1 MPa	1 x 10 ⁻⁵	76.4 MPa	85.6 MPa
DOE #19	R	compression	25°C	0.1 MPa	1 x 10 ⁻⁵	50.0 MPa	68.9 MPa
DOE #20	X	compression	25°C	100 MPa	1 x 10 ⁻⁵	-	-
DOE #21	Y	compression	25°C	100 MPa	1 x 10 ⁻⁵	400 MPa	658 MPa
DOE #22	X	compression	25°C	100 MPa	1 x 10 ⁻⁵	440 MPa	613 MPa
DOE #23	Z	compression	25°C	100 MPa	1 x 10 ⁻⁵	380 MPa	607 MPa

ANISOTROPIC ELASTIC-PLASTIC THEORY

We expect that the behavior of the anisotropic rocks that we are studying will be adequately described by an anisotropic elastic - plastic - temperature dependent material model. The elastic portion of the response will be assumed to be adequately described by an orthotropic - linear elastic model which describes the behavior of the material for stress states that do not satisfy the yield criterion, i.e., points in stress space that are inside the yield surface. As the stress state moves onto the yield surface, the stress state is restricted to stay on the yield surface but the yield surface may expand uniformly through isotropic hardening, or warp toward a particular direction in the case of kinematic hardening. For stress states on the yield surface, increments of deformation are described by the flow rule which may be associative (directed normal to the yield surface) or non-associative. Unloading from the yield surface is expected to be on a linear elastic path with a modulus equal to the linear elastic load up.

In summary, the elastic - plastic theory consists of several component parts, not all of which may be necessary to describe the behavior of the class of materials in which we are interested. The choices that need to be made in developing an adequate constitutive model must be based on experimental data collected primarily from the laboratory. The elastic portion of the response will probably require nine independent elastic moduli as discussed below. The yield function for anisotropic materials is not nearly as well understood as the elastic response. Some candidate yield functions are discussed below, and one of our principal objectives in this project is to experimentally determine the yield functions for the class of anisotropic rocks being considered and determine the relationship between the fabrics observed and the yield functions. The other component parts of the total constitutive model: the flow rule (associative or non-associative) and the hardening rule will be assumed, consistent with our observations and those of others, when modeling the stability of wellbores in hot anisotropic rocks. A very preliminary assumption, based on the stress-strain curves in this report, Fig. 8 for example, is that we may be able to neglect

strain hardening and use an elastic - perfectly plastic model (no hardening). Detailed experimental studies on different load paths are needed to determine the nature of hardening and whether the flow rule should be associative or non-associative. These path dependent studies are beyond the scope of our current work but we may be able to determine the relative importance of these parts of plasticity theory to the questions at hand.

Orthotropic Linear Elasticity

At isothermal conditions, the stress-strain law, generally known as the generalized Hooke's law, takes the form

$$[\epsilon] = [c] [\sigma] \quad (1)$$

where $[\epsilon]$ is the small strain tensor, $[\sigma]$ is the Cauchy stress tensor, and $[c]$ is the compliance tensor of rank four. The generalized Hooke's law provides the simplest linear relationship between 9 components of strain and 9 components of stress, which implies that $[c]$ could have a maximum of 81 components. However, kinematic considerations indicate that the strain tensor is symmetric, while angular momentum considerations show the stress tensor to be generally symmetric. Consequently, we can write Eq. (1) as

$$\{\epsilon\} = [C] \{\sigma\} \quad (2)$$

where $\{\epsilon\}$ is a 6 x 1 strain vector with components subscripts xx yy zz xy yz zx , $\{\sigma\}$ is a 6 x 1 stress vector with components subscripts corresponding to those of the strain vector, and $[C]$ is a 6 x 6 matrix of compliances.

The compliance matrix $[C]$ is symmetrical provided that the strain energy density function U exists and has the property that stress components may be found by differentiation of the U with respect to the corresponding strain components. Thus

$$U = 1/2 \sum C_{ij} \epsilon_i \epsilon_j \geq 0 \quad (3)$$

which is a quadratic form in the components of strain and the components of stress are

$$\partial U / \partial \epsilon_i = \sum C_{ij} \epsilon_j = \sigma_i \quad (4)$$

(Sokolnikoff, 1956).

The symmetry of the compliance matrix reduces the possible number of independent elastic constants from 36 to 21. If we further require elastic symmetry on the x-y plane and the y-z plane, the number of independent elastic constants drops from 21 to 9. This type of symmetry is referred to as orthotropic (or orthorhombic) symmetry in the elasticity literature. The non-zero components of $[C]$ are the 6 diagonal components, C_{kk} , and components (1,2), (1,3), and (2,3) where 1, 2, and 3 are associated with x, y, and z directions.

In terms of moduli of elasticity, the components of $[C]$ are $C_{kk}=1/E_k$ where $k = 1, 2, 3$; $C_{44}=1/(2G_{xy})$; $C_{55}=1/(2G_{yz})$; $C_{66}=1/(2G_{zx})$; $C_{12}=-\nu_{yx}/E_y$; $C_{13}=-\nu_{zx}/E_z$; and $C_{23}=-\nu_{zy}/E_z$. The remaining non-zero components of $[C]$ are determined by invoking the symmetry condition that $C_{ij}=C_{ji}$. In these equations E represents a modulus of elasticity in the direction of the subscript, G represents a shear modulus in the plane defined by the subscripts, and the terms of the form $-\nu_{ij}/E_i$ represent the contribution to strain in the "j" direction due to the component of stress in the "i" direction. Thus the ν 's are analogous to the Poisson's ratio of isotropic elasticity. The 9 independent components of $[C]$ reduce to 5 for the higher order symmetry associated with planar isotropy, and finally to 2 for the isotropic case.

Several important observations can be made for an orthotropic material that make it different from an isotropic material. First consider a stress path along the hydrostat where

the 6 components of stress are $(1 \ 1 \ 1 \ 0 \ 0 \ 0)\sigma_m$ where $\sigma_m = I_1/3$ and I_1 is the trace (sum of the diagonal terms) of the stress tensor. The three normal components of strain will now be of the form

$$\epsilon_{xx} = (1/E_x - \nu_{yx}/E_y - \nu_{zx}/E_z)\sigma_m \quad (5)$$

where the bracketed scalar term changes with the direction indicated by the subscript on the normal strain component. Therefore, the components of normal strain will be different even though the normal stress components in each direction are the same, which implies that the strain tensor will have distinct principal directions while every direction is a principal direction for the stress tensor, consequently the principal directions of stress and strain do not coincide for a general orthotropic material.

The volumetric strain is found by the trace of the strain tensor based on purely kinematic reasoning, which remains valid for an orthotropic material. The volumetric strain has the form

$$\partial V/V = [1/E_x + 1/E_y + 1/E_z - 2(\nu_{xz}/E_x + \nu_{yx}/E_y + \nu_{zy}/E_z)]\sigma_m \quad (6)$$

which reduces to $[3(1-2\nu)/E]\sigma_m = \sigma_m/B$ where B is the bulk modulus for an isotropic material.

If we now require that the volumetric compressibility (bracketed term in Eq. (6)) be greater than or equal to zero (which must be true to satisfy the second law of thermodynamics), we must place two restrictions on the values of the anisotropic moduli:

$$1/E_x + 1/E_y + 1/E_z > 0 \quad (7)$$

and

$$w_x v_{xz} + w_y v_{yx} + w_z v_{zy} \leq 1/2 \quad (8)$$

where $w_x = (1/E_x)/(1/E_x + 1/E_y + 1/E_z)$, etc. so that the sum of the weights equals unity. Eq. (8) indicates that not all values of μ are admissible and is equivalent to stating that Poisson's Ratio for an isotropic material must be less than or equal to $1/2$. If the three values of v in Eq. (8) are equal to $1/2$, we note that the deformation will apparently take place at constant volume.

ANISOTROPIC YIELDING

Anisotropic yield criteria describing the deformation of foliated rocks can be generalized from well known relationships describing the flow and fracture of isotropic materials. These anisotropic yield functions depend upon the mechanisms of deformation, just as do their isotropic counterparts, giving rise either to strengths which are independent of, or critically dependent upon the hydrostatic stress. The deformation mechanisms most commonly leading to ductile flow, such as dislocation glide and climb, and mechanical twinning are activated under the influence of shear stresses, showing negligible dependencies upon hydrostatic stress. Microcrack nucleation and growth, on the other hand, depend upon the presence of local states of tension, leading to cataclastic flow and fracture strengths which are strongly affected by the hydrostatic stress.

The anisotropic deformation of rocks which flow by pressure-insensitive plastic mechanisms will be investigated using a modified von Mises yield criterion, whereas rocks which deform by pressure dependent brittle mechanisms will be studied using a modified Mohr-Coulomb envelope.

Modified von Mises Criterion

The plastic flow of isotropic materials which exhibit pressure-insensitive strengths may be expressed by the von Mises (1928) yield criterion, which is based upon the second invariant of the deviatoric stress J_2 and thus incorporates the influence of the intermediate principal stress (Hill, 1950; Handin et al., 1967) to the distortional strain energy and the state of yielding. Yielding occurs when

$$J_2 = k^2 \quad (9)$$

where k is a constant, derivable from the deviatoric yield stress measured in uniaxial compression ($\sigma_1 - \sigma_3 = \sqrt{3} k$) and

$$J_2 = \frac{1}{6} [(\sigma_{22} - \sigma_{33})^2 + (\sigma_{33} - \sigma_{11})^2 + (\sigma_{11} - \sigma_{22})^2] + \sigma_{23}^2 + \sigma_{13}^2 + \sigma_{12}^2 \quad (10)$$

Hill (1950) generalized the isotropic von Mises yield criterion to anisotropic materials with orthorhombic or higher symmetries. Expressed in quadratic terms of stress components, similar to the isotropic von Mises criterion, yielding occurs when

$$F(\sigma_{22} - \sigma_{33})^2 + G(\sigma_{33} - \sigma_{11})^2 + H(\sigma_{11} - \sigma_{22})^2 + 2L\sigma_{23}^2 + 2M\sigma_{13}^2 + 2N\sigma_{12}^2 = 1 \quad (11)$$

Six independent parameters, F , G , H , L , M , and N need to be determined for rocks of orthorhombic symmetry, whereas the number of independent terms is reduced as symmetry is increased; in the limit of isotropic yielding, $L = M = N = 3F = 3G = 3H$ (and $2L = 1/k^2$). Unlike the von Mises yield criterion, which is invariant upon transformation, however, the form of the anisotropic yield function depends upon the choice of reference frame; the simplest form (11) corresponds to Cartesian coordinates which coincide with the principal symmetry axes of the rock fabric.

Modified Mohr-Coulomb Criterion

Both cataclastic flow and fracture of isotropic rocks can be described by nonlinear forms of Mohr-Coulomb envelopes

$$|\tau| = \mu \sigma_n + s_0 \quad (12)$$

where τ and σ_n are the shear stress and normal stress, respectively, on a particular plane, μ , s_0 and n are constants. Rewriting (12) to incorporate the influence of the intermediate principal stress

$$|J_2|^{n/2} = \mu I_1 + s_0 \quad (13)$$

where

$$I_1 = \sigma_{11} + \sigma_{22} + \sigma_{33} \quad (14)$$

Pariseau (1972) generalized this expression, assuming orthorhombic symmetry, to

$$\begin{aligned} & [F(\sigma_{22}-\sigma_{33})^2 + G(\sigma_{33}-\sigma_{11})^2 + H(\sigma_{11}-\sigma_{22})^2 + 2L\sigma_{23}^2 + 2M\sigma_{13}^2 + 2N\sigma_{12}^2]^{n/2} \\ & - (U\sigma_{11} + V\sigma_{22} + W\sigma_{33}) = 1 \end{aligned} \quad (15)$$

where the nine parameters F , G , H , L , M , N , U , V , and W characterize the full anisotropy of inelastic deformation. Just as for the case of the anisotropic von Mises yield function, the form of (15) is specific to the reference frame, defined by the symmetry of the rock fabric. For fabrics of higher symmetry than orthorhombic, the number of parameters required to characterize the deformation is reduced.

The yield strength of Four-Mile gneiss is clearly pressure-dependent, and once the suite of gneiss experiments has been completed, we will apply these yield relationships to determine the parameters F , G , H , L , M , N , U , V , W , and n . At present, the fabric and mechanical properties of Four-Mile gneiss do not appear to be transversely isotropic; rather the results of compression tests currently in hand suggest a fully orthorhombic yield

criterion related to both the planar and linear fabric elements (foliation and lineation, respectively).

FOLIATIONS ASSOCIATED WITH IGNEOUS INTRUSIONS

Both the Four Mile gneiss and Partridge schist are representative of regionally metamorphosed rocks with a fairly consistent penetrative foliation. We have emphasized the need to determine their anisotropic yield envelopes in order to predict borehole stability in foliated crystalline basement surrounding buried magma chambers. Around many intrusive bodies, geologic evidence (Buddington, 1959; Sylvester et.al., 1978) and theoretical studies (Marsh, 1982; Daly and Raefsky, 1985) predict the occurrence of a more localized foliation near the country rock/magma interface, even in cases where the country rock was undeformed prior to magma intrusion. This localized foliation results from ductile strains generated as hot magma diapirs ascend through and transfer heat to the surrounding, plastically deforming wall rock. Due to the strongly temperature-dependent rheology of these wall rocks, foliation intensity within this zone of ductile strain can vary markedly. It is generally most strongly developed near the intrusive contact, and commonly persists for some distance both into the pluton interior and out into the surrounding country rock.

Since such an inhomogeneous fabric might be encountered during drilling of a buried magma chamber, it seems important to determine the extent to which foliation strength influences mechanical anisotropy. Towards this end we have collected and plan to deform a suite of granitic rocks of similar composition which possess a variably developed foliation. Samples were collected along the deformed margin of an eroded Tertiary pluton in East-central Nevada, and the foliation has been interpreted as resulting from forceful magma emplacement. During the collection process, we have assessed the relative style, intensity, and extent of foliation development within both granite and country rock, with the hope of improving our understanding of this particular mechanism of foliation development.

A Natural Example

We selected the Kern Mountains plutonic complex (Fig. 12) for our study, since mapping studies by Best et. al. (1974) and Ahlborn (1977) indicate that it satisfies two useful criteria: (1) The granite pluton was emplaced at a relatively shallow level into a previously undeformed carbonate sequence. (2) A strain-induced foliation, generally parallel to the igneous contact, develops in both the country rock and granite and decays to a homogeneous fabric in both directions. More recently, Gans (pers. comm., 1987) has collected extensive thermal data from the contact aureole, which can be combined with our foliation study to provide useful constraints on country rock rheology.

Figure 12) Kern Mountains plutonic complex

Guided by the objectives outlined above, the following work has been completed to date:

1. A suite of variably foliated granites has been collected from the localities shown in figure 12. From this suite, we have selected strong, moderate, and weakly foliated blocks of similar composition, which we plan to deform at comparable conditions to those of the Four-Mile gneiss and Westerly granite.
2. The intrusive contact separating early Tertiary (~70 my) Tungstonia granite from a package of Paleozoic sediments and their metamorphic equivalents has been mapped at a scale of 1:12000. From this contact traverses were carried out both toward and away from the pluton interior, in order to assess the nature of foliation development around the intrusive stock. These observations have been used to assess the case for forceful emplacement, as discussed below.

Geologic Description

General features of the Kern Mountains plutonic complex have been discussed previously by Best et. al. (1974) and Ahlborn (1977). Here we summarize a few important aspects:

1. The Kern Mountains range consists of a granite core surrounded by a complex package of predominantly carbonate country rock. The core is a composite pluton, and we have focused our study on the 70 my Tungstonia granite, which occupies the north-west corner of the range. The smaller and younger (35 my) Skinner Canyon granite is exposed to the southeast.
2. The country rock contains contact metamorphosed marbles and hornfelses, as well as their unmetamorphosed Paleozoic equivalents.

Commonly, the sedimentary rocks structurally overlie the metamorphic package in low angle fault contact. In locations where the transition from metamorphosed to unmetamorphosed country rock is clearly gradational, the metamorphic envelope surrounding the Tungstonia granite is quite thin. Bleached marbles are restricted to a zone a few tens of meters from the contact, and unpublished geothermometry using conodont color indices (Gans, pers. comm. 1987) locates the 200°C isotherm at a distance of less than a few hundred meters from the intrusive contact. Skarn deposits are rare, and the lack of aplite and pegmatite dikes cross-cutting the intrusive contact apparently attest to relatively low hydrothermal circulation during the late stages of pluton emplacement.

Foliated Granites

The interior of the Tungstonia pluton contains coarse-grained muscovite- and biotite-bearing granites with an isotropic igneous fabric and no discernible foliation. Aplite dikes up to a meter thick are abundant and occur in subparallel arrays or, less commonly, as more randomly oriented swarms. Closer to the intrusive contact a weak foliation develops, that dips consistently away from the pluton interior at a moderate (localities 1-3 and 7-10) to steep (localities 4-6) angle. This foliation is defined by the grain-shape preferred orientation of flattened quartz grains and alignment of mica minerals. In some locations (localities 1-3) this foliation can be traced a few hundred meters into the pluton interior, but more commonly it is restricted to a zone less than 100 meters from the intrusive contact. As the fabric strengthens, the rock weathers out in ledges along definite foliation planes and, where it is most intensely developed, the foliation is defined by a pronounced mylonitic banding. In hand specimen the banding consists of augen gneiss containing coarse feldspar porphyroclasts and a distinct schistosity, alternating with finer-grained, more leucocratic layers that appear to be the strongly thinned equivalents of the aplite dikes found within the

granite interior. Where the foliation plane has been freshly exposed along fracture surfaces, a weak lineation defined by stretched and elongated mineral grains can be identified within the mylonitic granite.

Foliated Country Rock

Foliation development within the meta-carbonate country rock sequence is less consistent than within the granite, and in some units is difficult to distinguish from primary sedimentary bedding. Thickly bedded to massive, buff colored marbles display little foliation, even within meters of the intrusive contact. Darker, more strongly layered marbles commonly show a strong foliation which persists for several hundred meters from the intrusive contact. In places, the foliation appears to represent an enhancement of original bedding features. Evidence for this conclusion comes from outcrops near the contact, which contain tight-to-isoclinally folded marble layers in which an axial planar foliation has developed parallel to layering. Pinch-and-swell features indicating extension parallel to the foliation also developed within the layered marbles, and can also be observed in calcite veins developed within more massive marble units.

The metamorphic sequence is often overlain by brecciated but unfoliated sequences of Paleozoic carbonates emplaced on top of the meta-carbonates along low angle normal faults. Where the contact between metamorphic and undeformed carbonates is gradational, the foliation also appears to weaken and disappear into the unmetamorphosed rocks.

Evidence for Forceful Emplacement

Several lines of field evidence strongly support the conclusion that foliation development within both the Tungstonia granite and surrounding meta-carbonate sequence occurred during intrusion of the granite body, and not during later extensional events which affected the Eastern Great Basin. (1) Although the contact between mylonitic granite and foliated marbles is generally buried, its orientation can be determined graphically from mapped outcrop patterns. The boundary orientation coincides with foliation attitudes in both

granite and country rock, and wraps around the pluton boundary. (2) Foliation development is everywhere restricted to a few hundred meters into the granite interior. Within the country rock, foliation is strongest in rocks showing the most pronounced metamorphic effects. Such a relationship is to be expected in rocks deforming by crystal-plastic mechanisms, since rock strength decreases with increasing temperature.

Intrusion accommodated by magmatic stopping is also tentatively ruled out, for the following reasons. (1) Xenoliths of country rock are absent within the granite mass. (2) Widespread fracturing of the surrounding wall rock does not occur, and the intrusive contact is everywhere smooth and sharp. Where the contact is offset, it is usually along high angle Basin and Range normal faults.

In conclusion, field evidence is consistent with a mechanism of forceful emplacement of a rising granitic diapir into previously undeformed carbonate rocks. Foliation within the granite may have resulted from late stage deformation of an early-formed solid rind surrounding the magma diapir, as the still-liquid interior continued to rise.

Ultimately, predictions of borehole stability in regions of high heat flow and in the vicinity of buried magma chambers will depend on the anisotropic yield envelopes of foliated rocks, and the fabric development resulting from their tectonic and intrusion histories. As we determine anisotropic yield envelopes for schist, gneiss, and granite, and develop an understanding of the distribution, strengths, and orientations of fabrics associated with this natural example of a diapiric igneous intrusion, we may provide a more reliable means of assessing mechanical properties and borehole stability within and surrounding hot magma chambers.

CONTINUED RESEARCH

We are well on the way to determining the anisotropic yield function for gneiss and will concentrate our efforts during the remainder of the first contract year on the gneiss experiments and fitting of the data with theoretical yield functions. In continuation of our work on Four-Mile gneiss, we plan the following:

1. Completion of compression experiments at $P_c = 100$ MPa, and extending the results to higher pressures (200 and 300 MPa) to determine the nonlinear pressure-dependence of strength in differing orientations.
2. Completion of a suite of compression tests on Four-Mile gneiss samples cored in six orientations at a single temperature, strain rate, and pressure in order to define the anisotropic yield condition under a single set of external variables.
3. Extension of the anisotropic yield condition to temperatures ranging from 25° to 700°C and strain rates of 10^{-4} to $10^{-6}/\text{s}$ using compression tests on selected sample orientations.

These experiments will be used to determine apparent activation energies and stress dependencies of the yield envelope.

During the second year of this contract, we propose to work on the following:

- A) Analysis of fabric elements giving rise to the three-dimensional yield envelope. We will make use of a combination of optical microscopy, and SEM and TEM in order to determine the dominant mechanisms of deformation in the Four-Mile gneiss.
- B) We plan to develop a physically-based model of the grain-scale deformation of Four-Mile gneiss on the basis of our microstructural observations. This model is anticipated to take the form of an inclusion-in-host model, in which an isotropic host material will include an array of

inclusions; each inclusion will have a preferred slip direction with slip governed by an elastic-perfectly-plastic law.

C) Continued study of the strengths and distribution of fabrics within and surrounding igneous intrusions and application to those which may be encountered while drilling to buried magma chambers.

D) Initiate experimental studies of Partridge schist and Westerly granite by an experimental approach similar to that of the Four-Mile gneiss experiments. The initial step will be to define their pressure-dependencies of yielding using extension and compression tests.

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