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ANISOTROPIC YIELDING OF ROCKS AT HIGH TEMPERATURES AND PRESSURES

FINAL REPORT

By

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1. INTRODUCTION

This is the final report for the three-year, DOE/OBES Grant No. DE-FG05-87ER13711, "The anisotropy of failure and yielding of rocks at high temperatures and pressures." It contains the results of research accomplished since the original starting date April 1[illegible], 1987 of this grant until its conclusion on September 14, 1990 at the Center for Tectonophysics under the direction of Drs. Andreas Kronenberg and James E. Russell. In addition, results are presented from our investigation of rocksalt constitutive relations, work that was initiated under a subcontract No. E512-11900 with the Battelle Project Management Division of the Office of Nuclear Waste Isolation and completed under a supplement to this grant in its final year. Much of our work has been presented at national meetings of the American Geophysical Union and the Geological Society of America, and has been assembled in refereed journals and monographs that are either in print or have been accepted for print and should be available to the public shortly. In the following, we summarize the results of our research very briefly, followed by more detailed accounts of the research in the form of published abstracts, journal papers, and chapters describing results that have yet to be published. Publications resulting from the research funded in full, or in part, by the Department of Energy under this grant include eight abstracts in *Transactions of the American Geophysical Union* and *Geological Society of America Abstracts with Programs* and six papers in the *Journal of Geophysical Research*, *AGU Geophysical Monograph 56*, a *Geological Society of London Monograph* (Special Issue 9190), and *Tectonophysics*.

The anisotropic deformation of foliated and lineated rocks has been investigated, primarily to predict the mechanical response of rocks surrounding buried magma chambers to the stress fields generated by deep drilling. The principal application in this regard has been to evaluate the scientific feasibility of extracting geothermal energy from buried magma chambers. Our approach has been to perform triaxial extension and compression tests at temperatures and pressures representative of the borehole environment on samples cored along six selected orientations and to fit the data to an orthohombric yield criterion. We have investigated Four-Mile gneiss (a strongly layered gneiss with well defined lineation), a biotite-rich schist, and Westerly granite (using a block oriented with respect to the granite's rift, grain, and hardway). Progress has been made in three areas: the experimental determination of strength anisotropies for the three starting materials, theoretical treatment and modeling of the results, and characterization of fabrics surrounding magma bodies resulting from their diaperic emplacement into shallow portions of the Earth's crust.

In addition, results have been obtained for the tensile fracture of quartzite, basal slip and anisotropy of biotite single crystals, and anisotropic flow of bedded rocksalt. Under our new DOE grant (Mechanical Properties and Modeling of Seal-Forming Lithologies), we will continue our work on schist; we already have data for several starting materials with variable mica contents, preferred orientations, and spatial distributions and we plan to investigate the roles of these fabric elements in the mechanical behavior of mica-rich, foliated rocks. Under the new grant, we will take new directions in the investigation of shales of va: ying clay content, mineralogy, preferred orientations, and distributions, hydration states, and partial pore pressures. We will initiate a modeling program directed at simulating the growth of salt nappes off the shores of Louisiana and Texas using finite element and material modeling codes, continuing in this way our investigations of rocksalt rheology.

Summary of Work Completed

Gneiss

Extension and compression experiments defining the inelastic behavior of Four-mile gneiss have been completed; nearly 80 oriented samples have been tested at temperatures ranging from 25° to 800°C, confining pressures of 0 to 400 MPa and strain rates of 10^{-4} to $10^{-6}s^{-1}$. A rate-independent constitutive relationship for Four-mile gneiss may be justified by negligible variations in strength with strain rate and weak dependencies upon temperature.

Differential stresses measured both at the onset of yielding and at failure vary with specimen orientation, with maximum compressive strengths exhibited by samples cored perpendicular to S and minimum strengths exhibited by samples cored at 45° to both *S* and *L*. While failure strengths are influenced most strongly by the orientation of *S*, they appear to depend upon the orientation of *L* as well. An orthorhombic failure criterion, generalized from a nonlinear Mohr-Coulomb relation, has been considered with quadratic and linear stress terms resembling those of invariants J_2 and I_1, respectively, and material parameters estimated by nonlinear regression methods.

Mechanisms of deformation and sources of anisotropy have been identified by examining microstructures developed in deformed specimens and observing their relationships to those fabric elements initially present in the starting material. Throughgoing shear fractures developed in samples shortened in all orientations with respect to *S* and *L* by the coalescence of microcracks in feldspar and quartz grains, as reported for isotropic granites. However, inelastic strains within mica grains were accommodated by slip, frictional sliding, and kinking, and deformation of favorably oriented micas appears to have led to local stress concentrations in neighboring phases that result in nucleation of tensile microcracks. Based upon these results, the following conclusions can be drawn:

1. Fracture strengths of Four-mile gneiss display significant anisotropy with orthorhombic symmetry defined by the orientations of foliation *S* and lineation *L*. Samples shortened in directions perpendicular and parallel to *S* are consistently strong while samples shortened at 45° to *S* are consistently weak. The influence of *L* is more subtle than that of *S*; however, it is revealed by compressive strengths which are greater parallel than measured perpendicular to *L*.

2. A failure criterion of the form

$$|F(\sigma_{22}-\sigma_{33})^2 + G(\sigma_{33}-\sigma_{11})^2 + H(\sigma_{11}-\sigma_{22})^2 + 2L\sigma_{23}^2 + 2M\sigma_{13}^2 + 2N\sigma_{12}^2|^{m/2} - (U\sigma_{11} + V\sigma_{22} + W\sigma_3) = 1$$

provides a satisfactory description of compressive fracture strengths measured in 13 orientations with respect to S and L with material parameters $F > G > H, L \cong M > N, U < V < W$ and $m =$ 1.313 ($\pm$ 0.002) at $T = 25°C$ and $\dot{\varepsilon} = 10^{-5}\ s^{-1}$.

3. Four-mile gneiss exhibits only small reductions in strength with increasing temperature over the range of conditions tested ($25° \leq T \leq 800°C, 0 \leq P_c \leq 400$ MPa, $\dot{\varepsilon} = 10^{-5}\ s^{-1}$), presumably as a result of thermal cracking. Values of F, G, H, L, M, and N determined at $T = 700°C$ are somewhat greater than determined at $T = 25°C$ whereas values of U, V, W, and m appear to be unchanged. The mechanical anisotropy at $T = 700°C$ is remarkably similar to that determined at $T =$ 25°C.

4. The observed mechanical anisotropy may be explained by a simple model involving tensile crack nucleation within the brittle framework silicates ahead of and between biotite grains oriented favorably for internal slip and frictional sliding on {001}. The orthorhombic character of deformation may therefore be linked to the orthorhombic symmetry of the biotite {001} preferred orientation.

Schist

Compressive strengths of biotite schist exhibit dependencies upon confining pressure as well as upon temperature and strain rate over the experimental conditions tested, $0 \leq P_c \leq 500$ MPa, $25° \leq T \leq 400°C$, $10^{-7}s^{-1} \leq \dot{\varepsilon} \leq 10^{-4}s^{-1}$, a result we may expect if deformation is accommodated both by brittle and by ductile processes. Remarkably, the schist chosen exhibits very weak anisotropy as compared with the gneiss and previous results for phyllite. The temperature dependence of strength resembles that of biotite single crystals, reflecting the predominance of basal dislocation glide; however, biotite schist strengths exhibit a weak, though measurable, dependence upon confining pressure, suggesting that dilatant brittle mechanisms are operative as well.

Associated with this mechanical behavior, deformed schist samples exhibit shear zones along which strains have become localized. Shear zones which cross-cut biotite segregations in samples loaded perpendicular to foliation appear wider than those which utilize pre-existing segregation seams in samples loaded at 45° to foliation. However, in all samples, biotite grains deform by a combination of kinking, dislocation glide, dilatant microcracking, and frictional sliding on (001). The near-isotropic mechanical response can apparently be explained by the wide distribution of biotite orientations within the matrix, outside of the biotite-rich segregation seams.

The transitional brittle-ductile deformation of schist appears to be subject to history- and path-dependencies and rheologies must incorporate these effects. Schists with different mica contents, preferred orientations, and spatial distributions exhibit yield strengths with similar temperature, pressure, and rate dependencies; however, they exhibit dramatic differences in anisotropy associated primarily with the contiguity of mica-rich seams through the samples and with mica contents. Two manuscripts are currently under preparation, one on the original, isotropic schist, and the other on the roles of those fabric elements that influence anisotropy.

Biotite

The basal slip systems of biotite and their mechanical expressions have been investigated by shortening single crystals oriented to maximize and minimize shear stresses on (001). Samples loaded at 45° to (001) exhibit gentle external rotations associated with dislocation glide. High-angle kink bands in these samples, unlike those developed in micas loaded parallel to (001), are limited to sample corners. Samples shortened perpendicular to (001) show no evidence of nonbasal slip and fail by fracture over all conditions tested.

The mechanical response of biotite shortened at 45° to (001) is nearly perfectly elastic-plastic; stress-strain curves are characterized by a steep elastic slope, a sharply defined yield point, and continued deformation at low (mostly < 100 MPa), relatively constant stresses at strains >1%. Stresses measured beyond the yield point are insensitive to confining pressure over the range 200 to 500 MPa and exhibit weak dependencies upon strain rate and temperature. Empirical fits to the data yield values of $\alpha = 0.41 \pm 0.08$ MPa^{-1} and $Q = 82 \pm 13$ kJ/mol assuming an exponential relationship between stress and strain rate or $n = 18 \pm 4$ and $Q = 51 \pm 9$ kJ/mol assuming a power law. Samples oriented favorably for slip in directions [100] and [110] are measurably weaker than those shortened at 45° to [010] and [310], consistent with the reported Burgers vectors <100>, 1/2 <110>, and 1/2 $<\bar{1}10>$ and with observed dislocation interactions within the basal plane. The anisotropy of biotite is further revealed by contrasting these plastic strengths with results of samples deformed parallel and perpendicular to (001). Previous studies have shown that biotite loaded in the (001) plane is strong prior to the nucleation of kink bands. The strength of biotite shortened perpendicular to (001) exceeds that measured parallel to (001) and is pressure dependent.

Granite

Room temper .ure compression experiments were performed on samples of W.:sterly granite cored in six orientations with respect to the quarrying planes, the rift, grain, and hardway, and their mechanical responses compared. Westerly granite resembles Four-mile gneiss in com,position and grain size. However, in contrast to Four-mile gneiss, Westerly granite shows no meas.rable strength anisotropy. Petrographic examination of Westerly granite reveals preferred o.ientations of microcracks but negligible mica preferred orientations. We conclude that the anisotropy of quartzo-feldspathic rocks depends most strongly upon mica preferred orientations, even under conditions favoring fracture as the predominant deformation mechanism. Strengths of Westerly granite at failure are comparable to those measured for gneiss samples in the strongest orientation.

Foliations Surrounding Magma Chambers

The foliation development within the metamorphic and deformation aureoles of a granite stock exposed in the Kern Mountains of Nevada has been investigated and compared with models of forceful magma emplacement. The deformation aureole surrounding this granite body is narrow relative to the pluton's size with foliations extending ~400 m into the country rocks, compared with a mean pluton radius of 5 km. In addition to foliations in the country rock, the granite exhibits a foliation around its margins. In some locations 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 contact. Several lines of evidence support the conclusion that foliation development within both the granite and surrounding country rock occurred during intrusion of the granite body, and not during later extensional events that affected the eastern Great Basin. Our study of this granite stock continues, including X-ray goniometer measurements of texture, strain analysis and geothermometry. Consistent with the theoretical intrusion models, deformation and resultant foliations are localized in those regions that experienced high temperature subsolidus conditions over extended times. Ultimately, these results will aid in determining those regions where fabric development associated with intrusion are most pronounced, so that appropriate anisotropic yield envelopes may be applied.

Experimental Extension of Quartzite

Notched samples of Sioux quartzite have been extended to failure at temperatures T between 25° and 710°C, strain rates $\dot{\varepsilon}$ from 5.2×10^{-6} to $6.7\times10^{-4}s^{-1}$, and 100 MPa confining pressure, and fracture morphologies examined by optical and scanning electron microscopy. In all the extension tests performed, sample failure occurred by the formation of a tensile fracture in or near the notch mid-plane. Differential stress magnitudes at failure are insensitive to variations in T and $\dot{\varepsilon}$ and calculated tensile strengths are comparable to previously reported values for unconfined tests at room temperature. Force-displacement records show a change in mechanical response, from linear elastic behavior at temperatures between 25° and 412°C to significant yielding in compression prior to failure in the 500° to 710°C tests. In all cases, fractures consist almost entirely of intragranular cracks (IGC) which exhibit characteristic surface features which can be used to infer local crack propagation directions. In one test in which fracturing was initiated at an edge flaw, IGC propagation directions show no overall trend. The observations indicate that the mechanism of fracture propagation involves nucleation, growth and coalescence of IGC which are themselves propagating in all directions in the plane of the main fracture. The onset of inelastic yielding prior to failure at elevated temperatures is attributed to the formation of thermally induced GBC which act as nucleation sites for IGC during extension.

Material Modeling of Rocksalt

A new isothermal, isovolumetric model has been developed to describe the deformation of Avery Island rocksalt. It postulates the existence of internal variables that evolve during deformation and whose sum is the measured stress difference. The rate of change of each internal variable depends on the difference between hardening and recovery terms. As steady state is approached, these terms come into balance, and the rate of change of the internal variables approaches zero. This model is based on two hypotheses:

(1) the same steady state is approached regardless of the load path; and

(2) the constitutive model should be evolutionary in nature to be capable of predicting the response of the material on different load paths.

Microstructural analyses of specimens deformed in creep, constant-strain-rate, and strain-rate-decrement tests support hypothesis (1), and comparisons of predictions with data for three load paths support the validity of hypothesis (2). Although the subgrain size resulting from strain-rate-controlled deformation falls somewhat below that from the stress-controlled creep deformation, the overlap of deviations of data leads us to question the physical significance of these differences.

Creep data for Avery Island rocksalt have been extended using screw-driven machines with exceptionally reliable data-acquisition and confining-pressure systems and an uninterruptible power-supply. Avery Island rocksalt specimens have been shortened at constant strain-rates down to 10^{-9}/s. Two experiments performed at $\dot{\varepsilon} = 10^{-9}$/s, one at T = 50°C, and the other at T = 100°C, have functioned continuously over 800 days and continue at present (shortening strains are currently ~

6.9%). The results are remarkably consistent with the material model that has been based upon higher strain-rate data.

Deformation of Bedded Rocksalt

Based upon diff·rential stress measurements of bedded rocksalt samples cored parallel to bedding, perpendicular to bedding, and at 45° to bedding, anisotropy is difficult to detect. However, differing strain rates in directions normal to the imposed shortening direction of individual samples are indicated by distinctly elliptical cross-sections following deformation. Due to the power law relationship between differential stress and strain rate, finite strains are a more sensitive measure of anisotropy, given that the material flows ductilly, and finite strain components of the polycrystalline bedded salt samples resemble strains measured for NaCl single crystals.

Abstracts to Conference Presentations

Gottschalk, R. R. and A. K. Kronenberg, Anisotropic yielding of gneiss: influence of foliation and lineation, EOS Trans. AGU, 69, 474, 1988a.

The mechanical anisotropy of Four-Mile Gneiss (a feldspar-quartz-biotite gneiss from Pelham Dome, Mass.) has been investigated in a series of compression and extension tests carried out in a triaxial gas apparatus at 25°C to 700°C, confining pressures of 0.1 to 200 MPa and a strain rate of $10^{-5}sec^{-1}$, on samples cored in 6 orientations with respect to the foliation (S) and the lineation (L). Differential strengths vary by up to a factor of 2, with the maximum strength contrast exhibited by cores with sample axes (S.A.) ⊥ S, and samples with S.A. 45° to both S and L. The results cannot be fit by transversely isotropic yield envelopes, but rather, yielding is fully orthorhombic with symmetry axes corresponding to the metamorphic fabric elements. At T = 25°C, all samples failed by brittle fracture; failure strength for each orientation at T = 25°C may be described by a non-linear envelope of the form $|\tau|^n = \mu\, \sigma_n + S_o$, where n = 1.3, and:

$\mu = 6.1$	$S_o = 15.9$ MPa	S.A. ⊥ S
5.7	20.0 MPa	S.A. ∥ S and ∥ L
5.2	18.2 MPa	S.A. ∥ S and ⊥ L
5.8	17.4 MPa	S.A. ∥ S and S.A. ∧ L = 45°
4.3	12.9 MPa	S.A. ∧ S = 45° and S.A. ∧ L = 45°
4.5	13.5 MPa	S.A. ∧ S = 45° and S.A. ⊥ L

These results can be condensed into a single, generalized yield envelope for anisotropic solids (Pariseau, 1972) involving 9 temperature-dependent parameters; the effect of temperature on these parameters is currently under investigation.

Gottschalk, R. R., and A. K. Kronenberg, Experimental deformation of gneiss: influence of phyllosilicates on fracture mechanisms and anisotropic yielding, Geol. Soc. Am. Abstracts with Programs, 20, A213, 1988b.

Samples of Four-Mile Gneiss (plag - 46.1%, qtz - 29.0%, kfs - 14.8%, biot - 9.0%, musc - 1.0%, from Pelham Dome, MA), cored at six different orientations with respect to foliation (S) and lineation (L), have been experimentally deformed and examined by optical microscopy. Experiments were carried out in a triaxial gas apparatus at confining pressures of 0.1 to 400 MPa, and temperatures of 25°C to 800°C, at a strain rate of $1 \times 10^{-5} s^{-1}$. Results indicate significant anisotropy in compressive yield strength, with the maximum strength contrast exhibited by cores with sample axes (S.A.) perpendicular to S, and S.A. inclined at 45° to both S and L. Yield strengths in samples with S.A. $\perp$ S (σ_{max}) are comparable to those of Westerly Granite deformed under similar experimental conditions, but samples in other orientations, particularly those with S.A. $\wedge$ S = 45° are significantly weaker, with strengths differing by a factor of as much as 0.5 times σ_{max}.

Samples in all orientations failed by macroscopic brittle fracture under all experimental conditions. At the grain scale, throughgoing fractures developed by the coalescence of brittle microcracks in feldspar and quartz grains, whereas inelastic strains within mica grains were accommodated by slip and kinking. In samples with S.A. parallel or perpendicular to S (in which micas are not favorably oriented for slip), microcrack nucleation proceeds by mechanisms similar to those observed in isotropic granites. However, microstructural relations in samples with S.A. $\wedge$ S = 45° indicate that dislocation slip and/or frictional sliding in micas produce local stress concentrations within the surrounding feldspar and quartz grains, promoting the nucleation of tensile microcracks. Thus, comparison of our experimental results with microstructural observations suggests that inelastic deformation at relatively low differential stresses in samples with S.A.$\wedge$ S = 45° results, in large part, from microcrack nucleation enhanced by slip on favorably oriented mica grains. Propagation of microcracks along mica flakes inclined to the compression axis may also help to promote unstable fracture propagation and ultimate failure at relatively low differential stresses. A similar influence of micas as material flaws is suspected at elevated confining pressures ($P \geq 200$ MPa, but microstructural relations are complicated by the development of shear zones, characterized by cataclasis.

Shea, W. T., and A. K. Kronenberg, Experimental deformation of biotite schist, EOS Trans. AGU, 70, 477, 1989a.

Biotite-rich schist samples cored perpendicular and at 45° to foliation (and lineation) have been shortened at a strain rate of 1 x 1(·'s^{-1}, temperatures from 25°C to 400°C, and confining pressures from 50 to 300 MPa using a triaxial gas apparatus. Although the rock possesses a strong foliation defined by alternating mm-wide mica-rich (>90% bt) and mica-poor (50-75% bt) seams, the mechanical anisotropy is weaker than the stress resolution of these experiments. Shear zones develop in samples deformed in both orientations, they are characterized by optically discontinuous biotite containing dense kinkbands and cleavage cracks, as well as microcracks within the stronger phases (epidote, feldspar). Permanent strains decay away from shear zone centers in both orientations, to distances of 0.2-1 mm in 45° samples and up to 3 mm in samples shortened perpendicular to foliation.

The corresponding mechanical response of all samples may be characterized by a linear elastic slope and sharply defined yield point followed by nearly constant differential stress. Yield strengths (σ_{diff}= 250 MPa and 150 MPa at 25°C and 400°C respectively, for P_c = 200 MPa), are only a factor of 2-3 greater than previous measurements of biotite single crystals that deformed by basal slip (Kronenberg et al., 1985), but are weakly dependent on pressure. Effective friction coefficients determined from strengths at 2% strain (μ = .15-.20) are lower than those reported for frictional sliding of biotite (μ = .3; Horn and Deere, 1962). In addition, the yield strengths are temperature dependent, and may be described by σ_{diff} = Bexp (Ψ/RT). At P_c = 300 MPa, B = 96 MPa and Ψ = 685 cal/mol. This temperature dependence Ψ is, within experimental error, identical to that exhibited by biotite single crystals (Ψ = 678 cal/mol). While localized displacements and faulting occur by purely brittle mechanisms in almost all other polycrystalline silicates deformed under these conditions, the combined microstructural and mechanical results for biotite schist suggest that both brittle and ductile mechanisms contribute to the deformation.

Shea, W. T., and A. K. Kronenberg, Path-dependent, brittle-plastic flow of biotite schist, EOS Trans. AGU, 70, 1364-1365, 1989b.

The transitional brittle-plastic deformation of a foliated but mechanically isotropic biotite schist has been investigated at strain rates from 10^{-5} to $10^{-7}s^{-1}$, temperatures from 25° to 400°C, and confining pressures from 0.1 to 300 MPa. At all conditions, deformation is strongly localized within mm-wide shear zones, with inelastic strains accommodated by microcracking, frictional sliding, intense kinking, and dislocation glide within biotite grains.

Corresponding yield strengths are sensitive to confining pressure over all tested conditions, but the Mohr envelope they define shows pronounced curvature (with μ > 0.4 at P_c < 100 MPa to μ < 0.1 at P_c > 200 MPa). Temperature and strain rate dependencies of strength determined in stepping tests at P_c =200 MPa reveal a strong history dependence to flow. Plots of $(\sigma_1-\sigma_3)$ vs (1/T) yield slopes of 65 GPa°K when temperature is sequentially increased from 25° to 400°C during an experiment, whereas slopes are lower by a factor of 3-4 when the path of temper .ure steps is reversed. Similarly, a 15% reduction in strength is obtained when strain rates are systematically decreased from 10^{-5} to 10^{-7} s^{-1}, whereas increases in strength are not resolvable for the reversed path.

Microstructural observations of samples deformed to low strains (of 0.5 - 3.0%) at 25° and 400°C reveal that the same mechanisms of nucleation occur independent of temperature, and the degree of localization correlates with strain alone. Samples taken to their yield point exhibit distributed patches of grains with undulatory extinction. Discontinuous, sub-planar arrays of closely-spaced grain scale kink bands transect samples shortly thereafter, but before the ultimate strength is achieved. Kink band arrays coalesce into narrow shear zones with increasing strain, and continue to widen. Only differences in kink band geometry are apparent in samples deformed at 25° and 400°C; we therefore believe that microstructures leading to history-dependence occur at the scale of the finely-spaced kink bands (or smaller), but not at the shear zone scale. If we assume a constant activation energy for flow, Q, then a flow law of the form $\dot{\varepsilon} = B\exp(\alpha\sigma)\exp(-Q/RT)$ cannot describe the observed path-dependent behavior unless α differs by a factor of ~4 over the temperature interval 25°-400°C.

Russell, J. E., and R. R. Gottschalk, Anisotropic yielding of Gneiss: modeling of room temperature results, EOS Trans. AGU, 70, 477, 1989.

The anisotropy of the mechanical response of Four-Mile Gneiss (a feldspar-quartz-biotite gneiss from Pelham Dome, Mass.) has been determined experimentally in triaxial compression and extension tests to confining pressures of 200 MPa and temperatures to 700°C at a strain rate of $10^{-5}s^{-1}$. Specimens have been cored at various orientations to foliation (S) and lineation (L). Room-temperature stress-differences at failure vary up to a factor of 2 with maximum perpendicular to foliation and minimum at 45° to lineation and foliation (Gottschalk and Kronenberg, 1988).

A nonlinear yield model, proposed by Pariseau, 1972, for materials with orthorhombic symmetry has been selected as the first candidate model for describing the material response. This model is a generalization of a vonMises-type model for metals proposed by Hill, 1950. The generalized form accounts for nonlinear mean stress effects and requires the estimation of 10 parameters. Results for stress-difference versus confining pressure for 6 orientations appear to be quite good considering the relatively large number of parameters. For each value of confining pressure, model values of stress-difference are also plotted versus angle between the direction of the maximum principal stress and material axes, similar to plots presented for rocks exhibiting transverse isotropy (Donath, 1964). Again the model fits to the data appear to be quite reasonable. Future work will include testing the model with previously published data on both transversely isotropic and orthotropic rocks.

Shea, W. T., The experimental deformation of mica-rich schists: roles of fabric and mica concentration, Geol. Soc. Am. Abstracts with Programs, 1990, in press.

Five schists with varying mica contents and crystallographic fabrics have been experimentally shortened both perpendicular and at 45° to foliation, and their mechanical properties compared. At the conditions tested (air dry, $P_c \leq 400$ MPa; $T \leq 400°C$; $10^{-5} \leq \dot{\varepsilon} \leq 10^{-7}s^{-1}$), deformation of these rocks is complicated by strong anisotropy and restricted, basal slip of the micas, and lack of crystal-plasticity within the other silicates present. This results in macroscopic brittle-plastic flow, which is influenced by the concentration, contiguity, and preferred orientations of mica in the starting material.

The influence of fabric on strength is most pronounced at low mica contents. Schists with the highest percentage of mica (> 75%) are weakest ($\sigma_{diff} \leq 350$ MPa for all P_c, T, ε conditions) and mechanically isotropic. In all orientations their steady-strength deformation is restricted to one or more narrow, discrete shear zones, which localize through the coalescence of grain-scale micro-kinks at extremely low axial strains ($\varepsilon \leq 1\%$). At the optical scale, individual grains are seen to contain several tens of few-mm-wide micro-kinks, while TEM microstructures are characterized by extremely high dislocation densities and patches of dense, sub-micron-wide kink bands.

Schists of lower mica content (<30%) can be strongly anisotropic. When shortened at 45° to foliation, both the strength and deformation mechanisms of these mica-depleted samples are similar to those of the most mica-rich schists. Samples shortened perpendicular to foliation can be up to 3 times stronger, and typically fail in brittle fashion along discrete cataclastic faults. Mechanical anisotropy appears to be associated with a domainal fabric, in which thin, mica-rich segregation seams are interlayered in a quartzo-feldspathic matrix which lacks interconnected micas.

Shea, W. T., A. K. Kronenberg, and B. G. Erskine, Diapiric emplacement of granitic magma: a natural example, Geol. Soc. Am. Abstracts with Programs, 20, A272, 1988.

Ascent of granitoid bodies through continental crust requires the displacement of overlying country rock. Deformed rocks associated with these displacements within and surrounding a small, late Cretaceous granite stock in the Kern Mountains, eastern Nevada are used to test diapiric models of intrusion. Observations which suggest that the mechanism of intrusion was diapirism (rather than stoping, ballooning, or zone melting) include the following: (1) The granite is encircled by a sequence of metamorphosed Paleozoic carbonates, and the intrusive contact is everywhere sharp and generally undisrupted by faults, fractures, or offshooting dikes; (2) A strong penetrative foliation wraps around the granitic stock, and is localized near and strikes parallel to the trace of the igneous contact; foliation attitudes coincide in granite and country rock, and foliation intensity decays away from the contact in both directions; (3) Xenoliths of country rock are distinctly absent within the granite; (4) Near the intrusive contact, there is clear microstructural evidence for simple shear (rotation of feldspar augen, asymmetric deformation of micas) in both mylonitized granites and associated aplite dikes which have been sheared into parallelism with the penetrative foliation.

Recent models (Marsh, 1982; Mahon et al., 1988) of hot spherical diapirs rising through a colder medium of temperature-dependent viscosity have shown that deformation of country rock is confined to a narrow channel at the diapir surface. Consistent with these models, the zone of intense deformation within meta-carbonates is restricted to a 200 m width, but strains appear to decay continuously away. In addition, strong gneissic foliations develop within the granite to a distance of 100 m from the contact, although microstructures formed by high-temperature crystal-plastic flow of quartz and mica minerals persist into the center of the stock. Since the ratio of deformation zone width to pluton radius is inversely proportional to the strength of viscosity temperature-dependence, the value obtained in this study (with pluton radius = 5km) suggests that activation energies for creep of both limestone and granite are large.

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 $\dot{\varepsilon}$, from $5.2 \times 10^{-6} s^{-1}$ to $6.7 \times 10^{-4} s^{-1}$ at a confining pressure $P_c = 100$ 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 $\dot{\varepsilon}$ and are comparable to previously reported values for unconfined, room T tests (Krech et al., 1974). Force-displacement records for tests at T = 25° - 412°C exhibit nearly perfect linear elastic behavior prior to failure whereas those for $T \geq 500$°C tests exhibit significant inelastic yielding. The inelastic work done in extension at 500°C is ~ 1.2 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 ($\bar{d} \approx 160$ μm) 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 inferred from these surface features show no preferred orientation, even in one test where fracturing was initiated at an edge flow. Thus, the advance of a fracture front occurs by coalescence of microcracks propagating in all directions within the fracture plane. IGC in T ≥ 500°C test specimens show a broader range of orientations than in 25° - 412°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.

Students Supported

Three students in the Center for Tectonophysics have received support from this grant in the form of research assistantships. William Shea has been involved in the work on biotite schist and is expected to complete his Ph.D. thesis on "The Roles of Micas and Fabric in the Deformation of Foliated Rock: An Experimental Study" by June, 1991. Peng Lin performed the granite experiments and completed and defended her M.S. thesis on "The Interaction of Two Closely Spaced Cracks—Rock Models and Computer Simulations" in May, 1990. Michael Tsenn was involved in the work on salt deformation and defended his Ph.D. thesis on " Strengthening Effect of Dislocation Networks in Halite" in June, 1990.

Richard Gottschalk received support from this grant in the form of a postdoctoral fellowship. In addition to completing a thorough investigation of Four-Mile gneiss, Rick effectively extended his education in structural geology and tectonics to include a solid background in mechanics.

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