Temperature and pore pressure effects on the shear strength of granite in the brittle-plastic transition regime

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Abstract. Currently published lithospheric strength profiles lack constraints from experimental data for shear failure of typical crustal materials in the brittle-plastic transition regime in wet environments. Conventional triaxial shear fracture experiments were conducted to determine temperature and pore pressure effects on shear fracture strength of wet and dry Tsukuba granite. Experimental conditions were 70MPa < P_c < 480MPa, 10MPa < P_p < 300MPa, 25°C < T < 480°C, at a constant strain rate of $10^{-5}s^{-1}$. An empirical relation is proposed which can predict the shear strength of Tsukuba granite, within the range of experimental conditions. Mechanical pore pressure effects are incorporated in the effective stress law. Chemical effects are enhanced at temperatures above 300°C. Below 300°C wet and dry granite strengths are temperature insensitive and wholly within the brittle regime. Above 400°C, semi-brittle effects and ductility are observed.

1. Introduction

The brittle shear failure strength of rocks under ambient crustal conditions provides the upper limit to their frictional strength [Brace and Kohlstedt, 1980; Kirby, 1980; Strehlau, 1986; Kohlstedt et al, 1995]. Although mechanical failure, such as faulting, usually occurs on a plane of weakness, at some stage, the rupture will be resisted by patches of high rupture growth resistance, such as asperities and barriers along the fault. The highest rupture growth resistance of the fault zone depends on the shear fracture properties required to shear the largest asperity. Furthermore, at high pressures and temperatures close to the base of the brittle crust, frictional strength will begin to conform to intact rock strength. It is therefore crucial to determine the strength of intact rock, as a first approximation to estimating the upper bound for frictional strength.

Simple models for lithospheric strength show that the shear frictional resistance acting on faults increases linearly with depth according to Byerlee's Law [Byerlee, 1978] in the brittle regime, below which the resistance falls off exponentially according to a plastic flow law [Kirby, 1980; Carter and Tsenn, 1987]. This leads to a sharp brittle-plastic transition where extrapolations of the two laws intersect. More recent models remove this sharp transition by incorporating a broad zone of brittle-plastic transition between the brittle and plastic zones [Scholz, 1988; Ranalli, 1995]. However, the strength profile in this transition zone is poorly understood due to a lack of experimental observations at the environmental conditions prevalent in this zone.

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The important deformation variables influencing shear resistance of wet lithospheric materials are pressure, temperature, strain rate, and interstitial pore fluid pressure (including mechanical and chemical effects). In particular, it is essential to have a clear understanding of the effects of both pressure and temperature on shear strength. In the purely brittle regime, mechanical properties of rock are highly pressure sensitive, but approximately temperature insensitive, and vice versa for the purely plastic regime. On the other hand, within the brittle-plastic transition zone, rock fracture is both temperature and pressure sensitive and as such both effects must be quantified separately. Although all the variables above are important, this study concentrates on the effects of effective normal stress and temperature on shear strength.

The paper discusses a failure relation that is based on a series of wet shear fracture experiments on Tsukuba granite and compares this to a previously published relation based on dry experiments in Westerly granite [Ohnaka 1992, 1995]. The effects of effective normal stress and temperature on the shear resistance of wet granite in the brittle to upper brittle-plastic transition regimes have been quantitatively evaluated and an equation for shear failure in a wet granitic crust has been empirically determined. Fixed experimental conditions ranged from confining pressures of 70-480 MPa, pore pressures between 10 and 300 MPa, temperatures from room to 480°C, and a constant strain rate of $10^{-5}s^{-1}$.

2. Experimental procedure

Granite is one of the major constituents of the crust, and is therefore selected as a representative rock type. Tsukuba granite (from the Ibaraki Prefecture, Central Honshu, Japan) was used in this study, because it is fine grained (0.5-1mm diameter), isotropic and homogenous, similar to Westerly granite. Approximate modal compositions are: quartz 30%, alkali feldspar 30%, plagioclase feldspar 30%, biotite 5%, chlorite 5%, muscovite <1%, magnetite and accessory minerals <1%. Porosity is estimated to be 0.58-0.79%. There was no pervasive fabric observed in the blocks, even so, samples were cored and deformed in the same orientation. Sample dimensions were cylindrical, 40mm length, 16mm diameter, with <0.02mm axial parallelism. Samples were air dried for over 1 week, and wet samples were fully submerged in water after 2 episodes of boiling to drive air out of pore spaces in order to achieve saturation. Full saturation was reached after 2 weeks of submerging. The sample is placed inside a graphite sleeve (also water saturated for wet tests). The graphite has a higher porosity than granite, and is also much weaker. It serves to aid even pore fluid distribution and also to buffer the jacket from rupturing during large amounts of slip. The sample and graphite sleeve are then placed inside a clean silver jacket.

Conventional triaxial fracture experiments were performed using the triaxial pressure vessel at the Earthquake Research Institute, University of Tokyo, which has been described in detail by Ohnaka et al, [1997]. Both confining pressure (silicon oil) and pore pressure (water) were servo-controlled to be held constant during deformation. Computer controlled actuators applied a constant strain rate to the two vertical tungsten carbide pistons. Corrections were made for seal friction and elastic deformation of the pistons. An internal furnace supplied up to 500°C and temperature was measured by 3 chromel-alumel thermocouples spaced along the sample.

Measurement errors are as follows: temperature (T) ±5%, confining pressure (P_c) ±2.5%, pore pressure (P_p) ±1%, angle of failure (θ) ±3%.

3. Results

3.1 Testing the data to the effective stress law.

Observations by Brace and Martin [1968] suggest that the effective stress law is compromised at strain rates faster than $10^{-7}s^{-1}$ in low porosity crystalline rocks. Since Tsukuba granite is a relatively tight rock, it is important to show that the samples were not deformed too quickly, in order to maintain pore fluid pressure equilibrium in the developing fracture network. The effective stress law is frequently expressed as [Paterson, 1978]:

$$\sigma_i^{eff} = \sigma_i - \alpha P_p \qquad (1)$$

where α is a constant, generally treated as unity when the effective stress law has been strictly maintained. For simplicity, the wet, 25°C data can be described by the following linear failure criterion:

$$\sigma_1 - \sigma_3 = a + b\ \sigma_3^{eff} \qquad (2)$$

Substituting (1) into (2) and rearranging gives:

$$\sigma_1 = a + \sigma_3(b+1) - \alpha b P_p \qquad (3)$$

and by carrying out a multiple linear regression on:

$$\sigma_1 = c_0 + c_1\sigma_3 + c_2 P_p \qquad (4)$$

where a = c_0 ; b = c_1 -1 ; α = $-c_2/(c_1 - 1)$. Multiple linear regression fits to the wet and dry data show that α is 1.05 for wet tests and 1.26 for wet and dry tests This study therefore

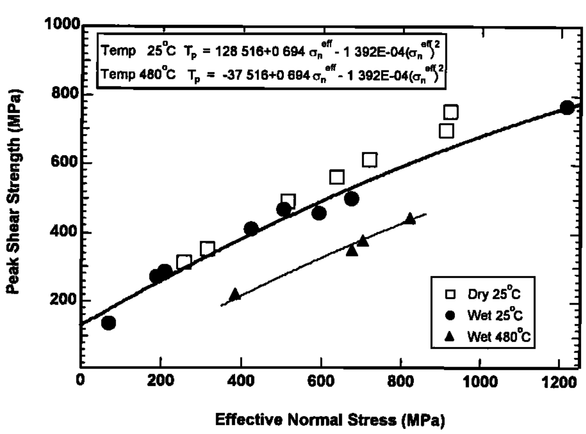

Figure 1. Relation between peak shear strength [$\tau_{p0} = \tau_p(\sigma_n, T, \dot{\varepsilon}_0)$] and σ_n^{eff} at various temperatures for Tsukuba granite. Upper line represents polynomial fit to wet and dry room temperature data. Lower curve represents parallel curve fit to high temperature data.

demonstrates that the effective stress law has not been unduly compromised for Tsukuba granite at a strain rate of $10^{-5}s^{-1}$.

3.2 Quantitative effects of effective normal stress and temperature on shear strength

The failure strength of rock under confining pressure is traditionally represented in terms of the differential stress at failure as a function of confining pressure. To quantitatively evaluate the shear rupture process specifically it is more appropriate to express shear strength in terms of the peak shear stress (τ_p, along the fault surfaces) as a function of the normal stress (σ_n, across the fault surfaces) since both factors are directly pertinent to the eventual fracture. Stresses are defined as positive when acting in compression. The differential axial stress (σ_1-σ_3) can easily be determined and applied in the following formulae to obtain τ_p and σ_n acting on the fracture surfaces at failure, aligned at an angle θ (angle of failure) from σ_1, [Jaeger and Cook, 1976].

$$\tau_p = [(\sigma_1 - \sigma_3)/2](\sin 2\theta) \qquad (5)$$

$$\sigma_n = \sigma_3 + [(\sigma_1 - \sigma_3)/2](1 - \cos 2\theta) \qquad (6)$$

Following Ohnaka [1992, 1995], the peak shear stress, τ_p, is a function of the normal stress, σ_n, temperature, T, and strain rate, $\dot{\varepsilon}$. Assuming these parameters are linearly independent we can write:

$$\tau_p(\sigma_n, T, \dot{\varepsilon}) = f(\sigma_n) g(T) h(\dot{\varepsilon}) \qquad (7)$$

where $f(\sigma_n)$, $g(T)$ and $h(\dot{\varepsilon})$ are functions of σ_n, T and $\dot{\varepsilon}$ respectively. When T = T_0 (room temperature) and $\dot{\varepsilon} = \dot{\varepsilon}_0$ ($10^{-5}s^{-1}$), τ_p is a function of σ_n alone, and under the assumption that $f(\sigma_n)$ is expanded in a series of σ_n, the relationship between shear stress and normal stress is well approximated by the following polynomial function, which reduces to the linear Coulomb relation in its simplest form

$$\tau_p(\sigma_n, T_0, \dot{\varepsilon}_0) = f(\sigma_n) = c_0 + c_1\sigma_n + c_2\sigma_n^2 + ... + c_x\sigma_n^x \qquad (8)$$

For wet data, we can replace σ_n with σ_n^{eff} (= σ_n - P_p), since the effective stress law is obeyed. When the strain rate is held constant ($\dot{\varepsilon} = \dot{\varepsilon}_0$), the shear strength relative to that at T = T_0 is a function of T alone, since [from Ohnaka 1992,1995]:

$$\frac{\tau_p(\sigma_n, T, \dot{\varepsilon}_0)}{\tau_p(\sigma_n, T_0, \dot{\varepsilon}_0)} = \frac{g(T)}{g(T_0)} = g(T) \qquad (9)$$

Figure 1 shows a plot of the peak shear strength against the effective normal stress data for our experimental data. The open squares represent dry room temperature data, and the solid circles represent wet room temperature data. We found that the relationship between τ_p and σ_n^{eff} is well described by the second order polynomial fit:

$$\tau_{p0} = 128.516 + 0.694\ \sigma_n^{eff} - 1.392 \times 10^{-4} (\sigma_n^{eff})^2 \qquad (10)$$

where τ_{p0} represents the peak shear strength at room temperature. Equation (10) has a good correlation to the experimental data in wet environments (polynomial regression fit = 0.980) since it incorporates the concave down portion of the data at lower normal stresses (Figure 1). The solid triangles represent wet experiments at temperatures between 450°C and 480°C, and these data can also be fitted by a second order polynomial. The intermediate temperature experiments are not shown in Figure 1 for purposes of clarity.

We notice from Figure 1 that dry granite shear strength data lie slightly higher than the shear fracture envelope of wet room temperature data (solid line fitting data points),

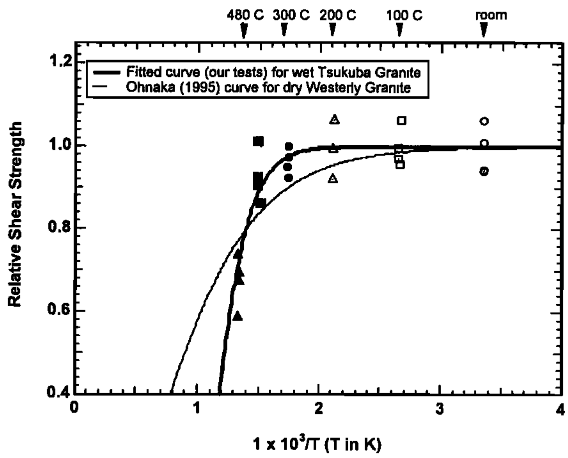

Figure 2. Relation between the relative shear strength and absolute temperature for wet Tsukuba granite (shown by solid line). A curve obtained from dry Westerly granite (Ohnaka, 1995) is also shown for comparison.

although the difference between wet and dry strength decreases with decreasing stress. We suggest that this may be due to the chemical effect of water (the mechanical effect is incorporated in the calculation for effective normal stress), and that the chemical effect is enhanced at higher stresses.

The relative shear strength at any temperature can be defined by normalizing the peak shear strength at elevated temperature to the peak shear strength at room temperature. The normalized function $\tau_p(\sigma_n, T, \dot{\varepsilon}_0)/\tau_p(\sigma_n, T_0, \dot{\varepsilon}_0)$ may be written as τ_p/τ_{p0}. Figure 2 shows a plot of the relative shear strength against 1/T for the test results of wet Tsukuba granite. We find from Figure 2 that the effect of temperature on the shear strength of wet Tsukuba granite follows a similar trend to the dry Westerly granite data curve obtained by Ohnaka [1995]; who compiled shear fracture data of dry Westerly granite from Griggs et al, [1960]; Stesky et al, [1974] and Wong [1982a,b] and showed that the shear strength of dry Westerly granite is empirically well fitted by:

$$g(T) = \tanh\left[\frac{Q}{R}\left(\frac{1}{T} - \frac{1}{T_1}\right)\right] \qquad (11)$$

where Q/R = 1100K and T_1 = 2500K (R being the gas constant). We find that the present data set of wet Tsukuba granite can also be fitted to equation (11) but with different parameters (Q/R = 3200K and T_1 = 950K). These values are significantly different from those for the dry Westerly granite, and show the presence of water greatly influences the fracture strength of initially intact granite. The mechanical effect of the pore fluid is incorporated within the σ_n^{eff} effect (Figure 1) and differences between wet and dry curves may be due to the chemical effect of the pore fluid and the different origin and evolution histories of Tsukuba and Westerly granites.

3.3 Description of deformed samples

A detailed description of our test results and observations can be found in a companion paper (in preparation), so only a summary is provided here. Microscopy revealed that low temperature tests (≤200°C) have a highly localised fault plane (approximate widths of 0.25-0.5mm) containing along- plane fracture porosity. Cracking is localised in and around the fault, whereas grains further from the fault plane remain fairly intact. High temperature tests (≥300°C) have a more diffuse fault zone (approximate widths of 1.0-1.5mm) containing highly crushed grains. The samples are extensively cracked, including grains further from the fault plane. Fault gouge becomes finer grained at higher temperatures; e.g. at room temperature, typical gouge diameters are approximately 0.5-1mm, whereas at 480°C the diameters are <0.5mm. Higher temperature tests also showed some bulging in the central part of the sample. One high temperature test showed macroscopic welding after removal from the pressure vessel.

4. Discussion

Both wet and dry Tsukuba granite data confirm work on dry granite by Tullis and Yund [1977] and Wong [1982a] who observed that the effect of temperature is insignificant below 300°C for dry granite. Lockner [1998] commenting on Wong's [1982a,b] and Tullis and Yund's [1977] dry granite data suggests that above 300°C, dislocation mechanisms are activated and samples have moved into a different deformation regime. The experiments reported here for wet granite are consistent with these ideas, within the experimental time scale. More specifically, Figure 2 suggests that up to 300°C, data from both wet and dry tests lie within the purely brittle regime since there is no temperature dependence on strength. Above 300°C, curves for wet and dry tests deviate from the horizontal showing that strength now depends on temperature. The decrease in strength for wet rock is more rapid than dry rock. As suggested in the previous section, this may be chiefly ascribed to the enhanced chemical effect of the pore fluid at higher temperatures. It could also be inferred that the presence of water significantly lowers the temperature where deformation of quartz and feldspar minerals switches from microcracking to dislocation glide and climb [e.g. Tullis and Yund, 1977]. Our observation that the fault zones widen and gouge diameter decreases with temperature suggest that microcracking becomes more pervasive with temperature. Stress corrosion in granite is enhanced by temperature [Meredith and Atkinson, 1987]. As temperature increases, there are a greater number of crack tips for any thermally activated chemical effect to work on, causing a decrease in strength. This feedback process may be responsible for the critical temperature dependence on strength observed in wet Tsukuba granite in this study.

One test at 480°C showed "welding" after fracture. Stesky [1978] observed that welding over the entire fault surface occurred at 500°C in frictional sliding experiments. He showed that frictional shear strength of granite will conform to the shear failure strength of initially intact granite above a critical temperature (≈500°C). Crystal plastic deformation near the fault surfaces is required to make the real area of contact equal to the nominal area, which will lead to welding of the surfaces, allowing the frictional strength to approach the failure strength of intact rock. Stesky [1978] optically observed plasticity in quartz above 500°C and with a transmission electron microscope he was able to find a marked increase in dislocation density at 700°C. Griggs et al [1960] also found evidence of plastic deformation of quartz above 500°C. In our tests, a thicker fault zone was observed at higher temperatures, which supports Wong [1982a] who inferred plasticity facilitated a thicker fault zone. We suggest that welding and a wide fault zone are evidence for plastic deformation in our tests.

Keeping all these observations in mind, we infer that the operative deformation mechanism ≥400°C is mixed between chiefly brittle and marginally ductile (possibly plastic) processes. Biotite semi-brittleness/ductility is seen in the form of kink bands even at dry room temperature conditions, which suggest that biotite is not responsible for the transition at 400°C. Feldspar does not deform plastically until far greater temperatures, above 700°C [Tullis and Yund, 1980]. Therefore, we suggest that ductile, possibly plastic, quartz deformation is initiated at >400°C, below which quartz deformation is purely brittle, hence suggesting that quartz is responsible for the observed transition.

5. Conclusions and Future Work

We have found that the shear failure strength at a constant strain rate of $10^{-5}s^{-1}$ in the brittle to brittle-ductile transition obeys an empirical relation expressed by equation 12:

$$\tau_p(\sigma_n^{eff},T,\dot{\varepsilon}) = \{h(\dot{\varepsilon})\}\{c_0 + c_1\sigma_n^{eff} + c_2(\sigma_n^{eff})^2\}\left\{\tanh\left[\frac{Q}{R}\left(\frac{1}{T}-\frac{1}{T_1}\right)\right]\right\}$$

More wet tests are required at high temperatures (>480°C) to check the fit of the lower part of the wet curve presented in Figure 2, to establish Q and T_1 over a wider range of temperatures. The strain rate effect has not been quantified in our experiments, which were all performed at a constant rate of $10^{-5}s^{-1}$. In summary:

1. Temperature and pore fluid pressure effects greatly influence the strength of granite at a constant strain rate in the brittle transitional regime.
2. Pore fluid pressure effects may be separated into mechanical and chemical effects. Mechanical effects are incorporated in the effective stress law. Chemical effects are greatly enhanced at temperatures above 300°C, below which wet and dry rock strengths are temperature insensitive and wholly within the brittle regime. More rapid reduction in strength is observed in wet tests.
3. Strength of wet and dry granite is insensitive to temperatures up to 300°C. Above 400°C, semi-brittle effects and ductility (including inferred plasticity) are observed, and temperature and pressure effects can be distinguished separately.
4. Shear failure strength can be described by equation 12, which separates pressure, temperature and strain rate effects.
5. Realistic models of lithospheric strength in wet environments will be presented in a companion paper (in preparation) on the basis of the results herein.

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