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# Effects of Elevated Temperature and Pore Pressure on the Mechanical Behavior of Bullfrog Tuff

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Effects of Elevated Temperature and Pore Pressure on  
the Mechanical Behavior of Bullfrog Tuff\*

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ABSTRACT

Samples of the Bullfrog Member of the Crater Flat Tuff from the depth interval 758.9 to 759.2 m in hole USW-G1 on the Nevada Test Site were tested in triaxial compression. Test conditions were: 1) effective confining pressure to 20 MPa; 2) temperature of 200°C; 3) both dry and with pore water pressures from 3.4 to 5 MPa; and 4) a strain-rate of  $10^{-4}$ /s. The results suggest that the presence of water causes the strength to decrease. In addition, the brittle-ductile transition pressure for this rock was found to be about 15 MPa, regardless of saturation. Below this pressure deformation is characterized by unstable stress drops and the development of a single fracture, and above this pressure deformation is stable and distributed more uniformly throughout the sample.

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INTRODUCTION

The Nevada Nuclear Waste Storage Investigations (NNWSI) project which is administered by the Nevada Operations Office of the U. S. Department of Energy is assessing the feasibility of emplacing nuclear waste in silicic tuffs at Yucca Mountain, on and near the Nevada Test Site. Part of this program consists of design calculations for an underground nuclear-waste repository which require extensive mechanical-property data. A preliminary testing program (Olsson and Jones, 1980) concentrated on nominally dry samples at room temperature. The rock near a proposed repository at depths below the water table is wet, and will be subjected to both thermal and mechanical loading, so it is necessary to determine the effects of these variables on matrix mechanical properties. Accordingly, samples of the Bullfrog Member of the Crater Flat Tuff from the depth interval 758.9 to 759.2 in hole USW-G1 on the NTS were tested in triaxial compression at test conditions of: 1) effective confining pressure to 20 MPa; 2) temperature of 200°C; 3) sample state both dry and with pore water pressures from 3.4 to 5 MPa; and 4) a strain-rate of  $10^{-4}$ /s.

Because sample availability was limited, it was necessary to recore test specimens 2.54 cm in diameter and 5.08 cm long from a 6.3 cm-diameter sample core. Seven specimens were recovered. The small size of the specimens precluded specimen volume measurement during the triaxial tests because the sensitivity of the dilatometric volume-measuring system is not sufficient. Thus, only axial load-deformation data were measured.

Specimens were jacketed with sleeves of silicone rubber sealant. Constant pore pressure was applied to both ends of the samples. The calculated porosity of tuff at a depth of 759.9 m is 0.27; this is probably representative of the rock tested.

### RESULTS

Four of the seven samples were tested dry and vented at 200°C. Effective confining pressures were 5, 10, and 20 MPa. Stress-strain curves for these tests are shown in Figure 1. Curves obtained at the two lower confining pressures exhibit maximums in the stress difference, followed by intervals of decreasing stress; eventually the stress becomes essentially constant. The peak stress is taken to indicate the fracture stress, and the lower value of stress at high strain is a measure of the frictional resistance to sliding on shear fractures formed during the falling part of the stress-strain curves. The 10-MPa test illustrates this shape best; the 5-MPa test had not yet reached a constant value of stress. The two tests run at 20 MPa show little or no stress-drop after peak stress, although the curve for sample number 5 shows a sudden decrease in stress at 2.8% strain, which was caused by a leak in the jacket.

Posttest examination of the specimens show that, at 5 MPa effective confining pressure, this tuff develops a well-defined but irregular shear fracture at about 25° to the axis of maximum compression. At 20 MPa,

deformation is distributed over numerous intersecting shear fractures, causing the specimen to take on a bulging appearance. At 10 MPa, the macroscopic mode of deformation is intermediate between those at higher and lower confining pressures. The strength of the dry specimens increases from 87 MPa at 5 MPa confining pressure to an average of 134 MPa at 20.7 MPa confining pressure (Table 1).

The results for the three tests run with constant pore pressure are exhibited in Figure 2. A trend similar to that for the dry specimens is seen with regard to the shape of the stress-strain curve as a function of confining pressure. That is, at 5 MPa effective confining pressure, there is a well-defined stress maximum which is followed by a stress drop and a subsequent interval of constant stress. At 12.5 MPa, the stress drop is more gradual, and occurs at a higher strain. There is no stress drop at 20 MPa. The macroscopic modes of deformation are the same as for the dry specimens. The strength of the wet specimens (Table 1) increases from 70 MPa at an effective confining pressure of 5 MPa to 86 MPa at an effective confining pressure of 20.7 MPa.

#### DISCUSSION

Orowan (1960) suggested that the gradual disappearance of post-fracture stress drops with increased confining pressure can be explained in terms of the relative values of the frictional resistance to sliding and the shear strength of intact rock. At lower pressures, the frictional resistance to sliding is less than the matrix shear-fracture stress, so that when the shear fracture forms, stress drops to an equilibrium value dictated by the sliding resistance (e.g., the 5 MPa and 10 MPa curves in Figure 1). Because frictional resistance to sliding increases more rapidly with confining pressure than does intact rock strength (e.g., Olsson, 1973), there comes a point when the fracture stress and frictional

stress are equal. Deformation will then be distributed more uniformly throughout the specimen, and it may occur as either distinct shear fractures or as a more ductile mode of deformation characterized by crystal plasticity.

The pressure at which the disappearance of post-fracture stress drops is essentially complete has been referred to as the brittle-ductile transition pressure (Heard, 1960; Byerlee, 1968). Examples comparing friction stress as a function of confining pressure to intact rock shear strength as a function of confining pressure for different rock types may be found in Byerlee (1968) and Olsson (1973).

It is clear from the macroscopic modes of deformation and shapes of the stress-strain curves that Bullfrog tuff (0.27 porosity) deformed at 200°C, wet or dry, is characterized by a brittle-ductile transition at the relatively low effective confining pressure of about 15 MPa. There are at least two implications of this behavior: the first is related to excavation stability and the second concerns altered permeability. With regard to the first point the specimens were tested in a displacement-controlled machine, so that no increase in strain-rate occurred during fracturing. In loading systems that have higher effective compliances, such as the in-situ loading system which is comprised of the surrounding rock plus discontinuities and voids, such stress drops can take place much more rapidly. In fact, seismic energy can be released, or structural integrity lost. Thus, the higher the effective confining pressure, the less likely structural instability is to occur as a result of postfracture stress drops.

As to the second implication of altered permeability, at low confining pressure where failure occurs along one well-defined fracture, permeability will be enhanced due to the presence of the fracture. However, at a pressure at which many fractures are formed throughout the specimen, permeability may be enhanced even more. Alternatively, permeability may



change little if the multiple fractures are not interconnected. Extrapolation to the field, however, also requires consideration of the competing process of decreased fracture permeability due to increased pressure.

The effect of the presence of water on the strength of the Bullfrog samples studied here is shown in Figure 3 as a plot of  $\sqrt{J_2} = (\sigma_1 - \sigma_3)/\sqrt{3}$  against  $I_1/3 - P_p$ .  $J_2$  is the second invariant of the stress deviator,  $I_1$  is the first stress invariant, and  $P_p$  is the pore pressure. A straight-line fit, calculated by the method of least squares, is drawn through the dry data points as a reference. There are insufficient data from saturated tests to establish an accurate relationship between shear strength and mean effective pressure, but the trend is clear: the presence of water has a significant weakening effect. This is consistent with earlier findings at room temperature on welded samples from the Grouse Canyon Member of the Belted Range Tuff (Olsson and Jones, 1980).

#### CONCLUSIONS

The seven tests reported here are consistent with the following conclusions:

1. The presence of water causes the strength of welded tuff to decrease, at least at a temperature of 200°C.
2. The brittle-ductile transition pressure for Bullfrog tuff with a porosity near 0.27 is about 15 MPa, regardless of saturation state; the dependence of this pressure upon strain rate remains undefined.
3. Below the brittle-ductile transition pressure, postfracture deformation is characterized by unstable stress drops; at higher pressures, postfracture deformation is stable.

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Table 1. Triaxial Test Data for Bullfrog Tuff at 200°C

<u>Sample Number</u>	<u>Confining Pressure (MPa)</u>	<u>Pore Pressure (MPa)</u>	<u>Maximum Differential Stress (MPa)</u>	<u>Young's Modulus (GPa)</u>
3	5	0	87	16.5
4	10	0	93	15.7
2	20.7	0	119	17.6
5	20.7	0	148	20.5
7	10	5	70	13.1
6	17.5	5	83	17.8
1	24.1	3.4	86	13.8

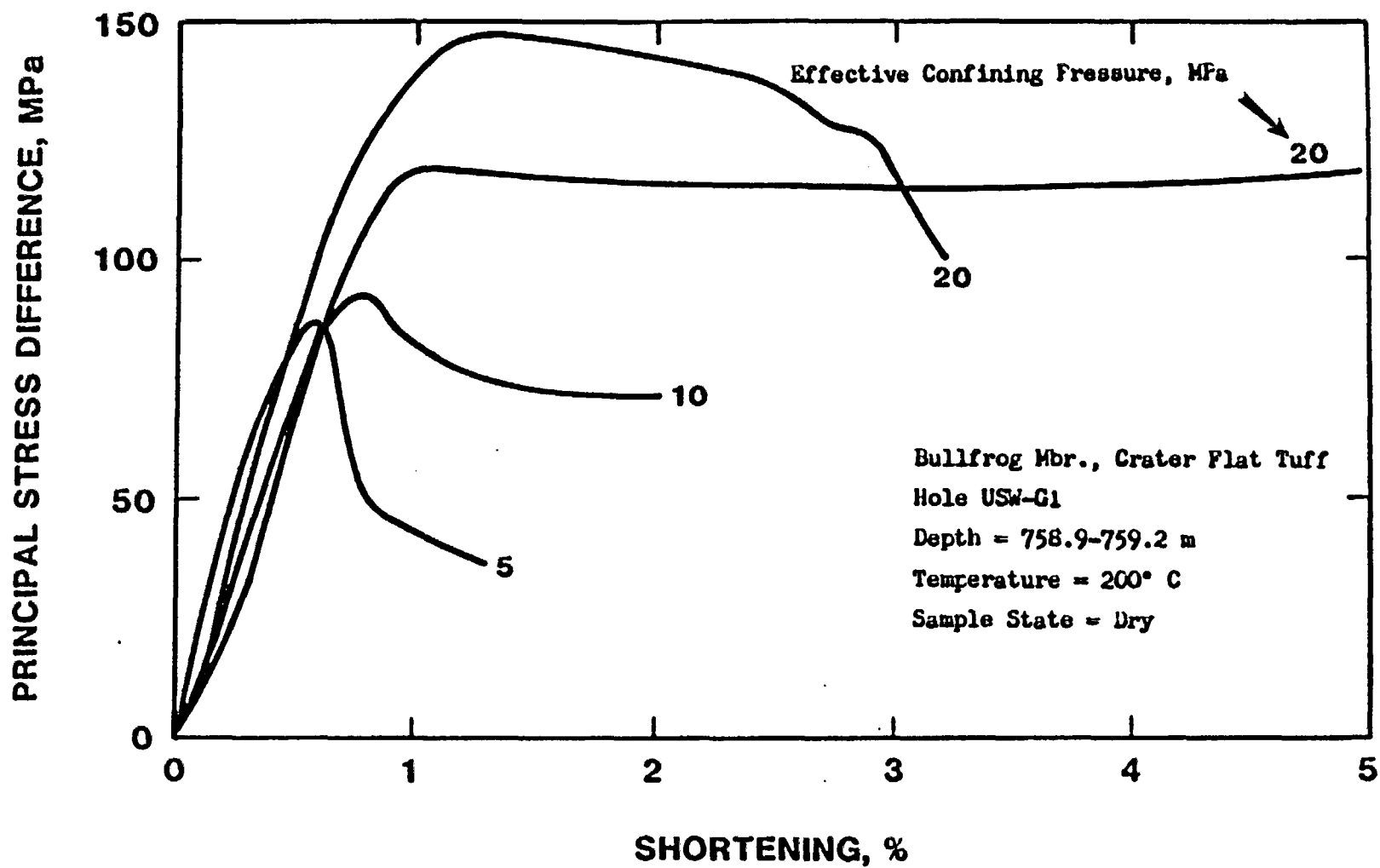


Figure 1: Stress-strain curves for Bullfrog tuff obtained on dry samples at 200°C.

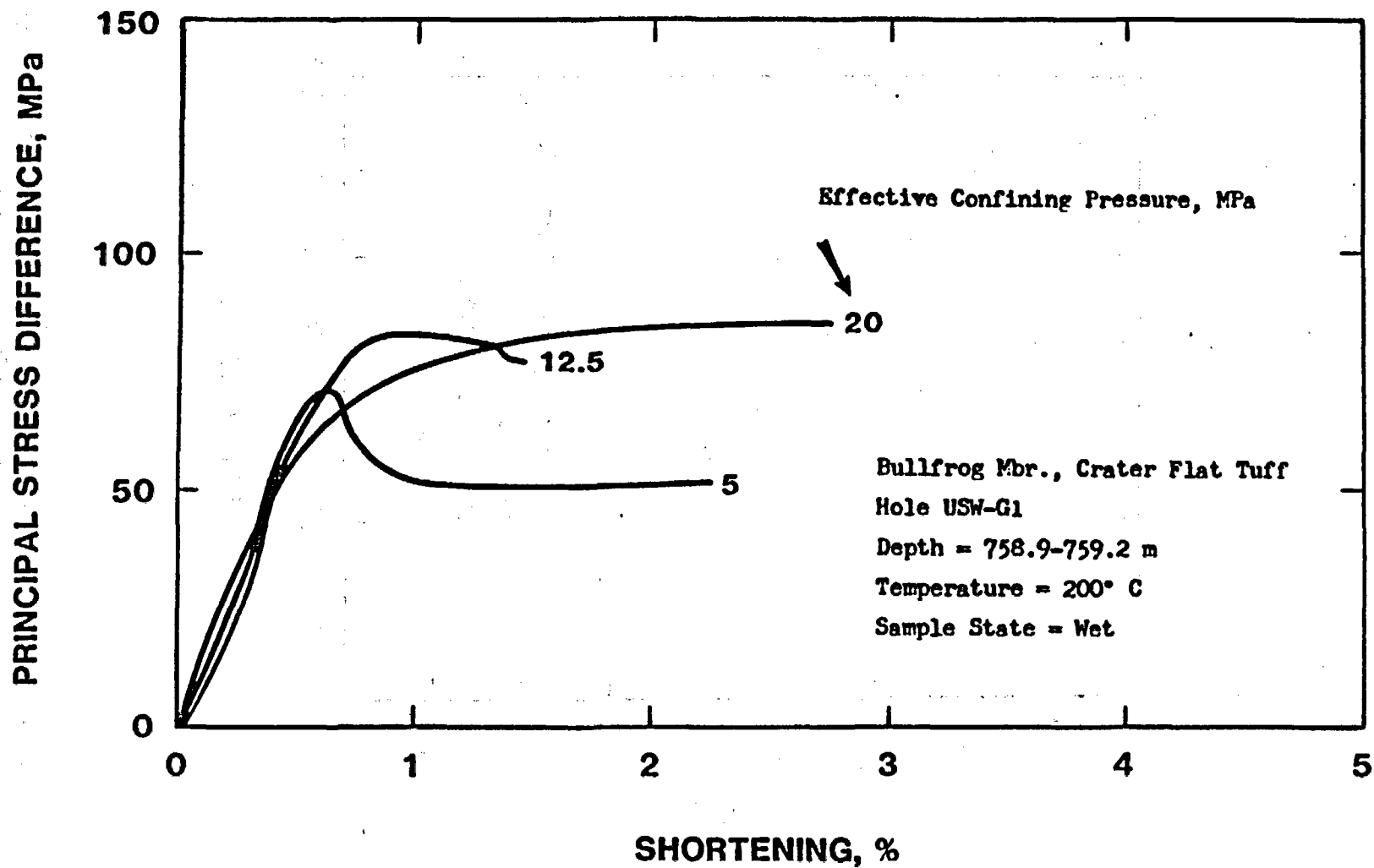


Figure 2: Stress-strain curves for Bullfrog tuff obtained on wet samples with constant pore pressure at 200°C.

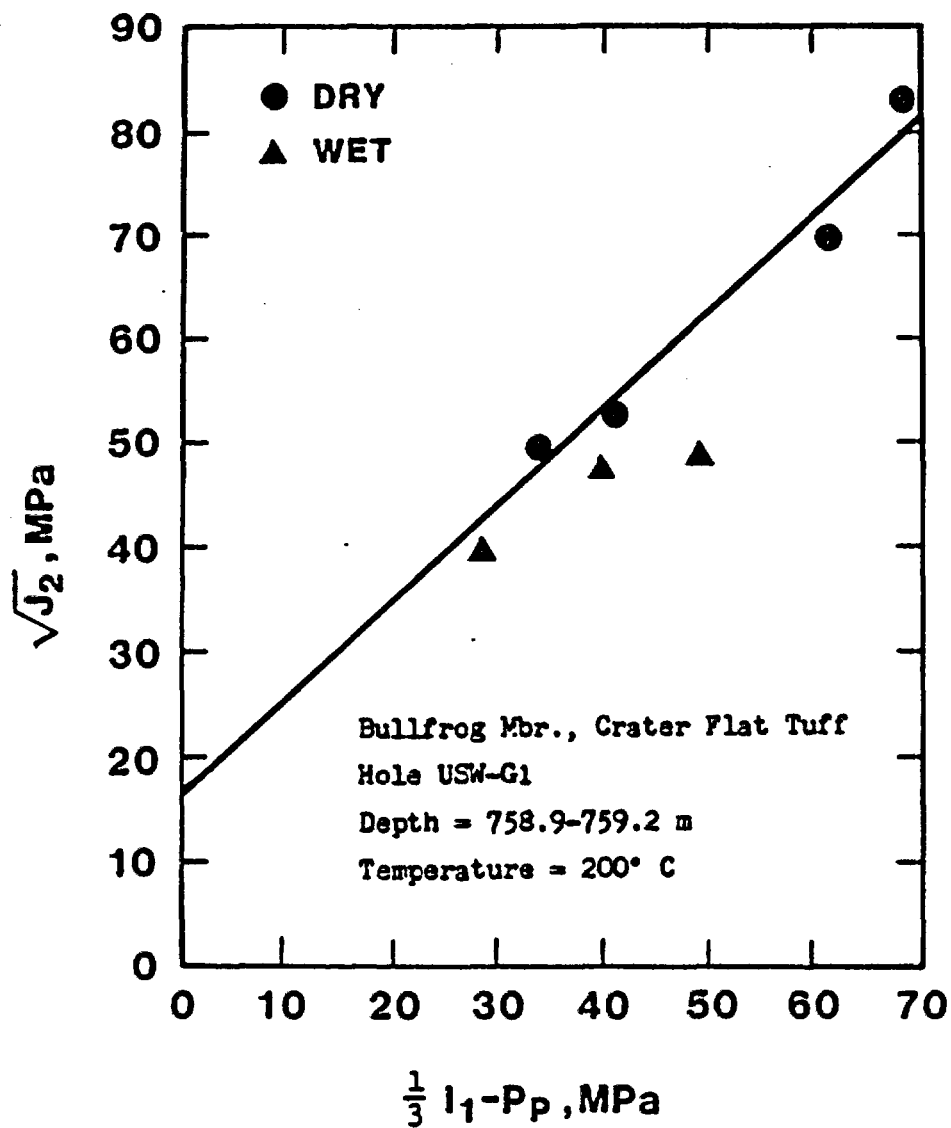


Figure 3: Shear strength-mean effective pressure relationship for Bullfrog tuff at 200°C, both wet and dry.

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