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DRILL-BACK STUDIES EXAMINE FRACTURED, HEATED ROCK

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ABSTRACT

To investigate the effects of heating on the mineralogical, geochemical, and mechanical properties of rock by high-level radioactive waste, cores are being examined from holes penetrating locations where electric heaters simulated the presence of a waste canister, and from holes penetrating natural hydrothermal systems. Results to date indicate the localized mobility and deposition of uranium in an open fracture in heated granitic rock, the mobility of U in a breccia zone in an active hydrothermal system in tuff, and the presence of U in relatively high concentration in fracture-lining material in tuff. Mechanical - property studies indicate that differences in compressional- and shear-wave parameters between heated and less heated rock can be attributed to differences in the density of microcracks. Emphasis has shifted from initial studies of granitic rock at Stripa, Sweden to current investigations of welded tuff at the Nevada Test Site.

INTRODUCTION

The local geochemical - hydrological regime will be affected by high temperatures over long periods of time in the near field of a nuclear waste canister. These hydro-geochemical processes must be understood if the transport of radionuclides away from a breached canister is to be modeled and predicted. The objective of our investigations is to develop an undersanding of the interaction, under long exposure to elevated temperatures, of radionuclides in the fluids with material lining fractures in the rock, and to understand the mechanical response of the fractured rock to the elevated temperatures. To accomplish this, samples of core from holes that penetrate high-temperature zones and holes cored through heater-test zones are examined petrologically, geochemically, and geomechanically.

Initial emphasis was on core samples of quartz monzonite, obtained by drilling back into rock previously subjected to a year-long heater experiment simulating high-level radioactive waste, conducted at Stripa, Sweden. As interest in tuff as a repository medium became apparent, we examined core from a hole penetrating a fractured hydrothermal system in rhyolitic tuff, and most recently we are investigating heated and unheated, unsaturated tuff from the Nevada Test Site. Our examinations compare properties of rock in elevated temperature zones with those of lower and near-ambient temperature.

GRANITIC ROCK

Studies of the quartz monzonite at Stripa, Sweden [1,2] incorporated core from zones affected by a year-long heater test (Fig.1). In this test, peak temperatures reached 375°C in rock next to the heater and 100°C in rock ~1.7 m from the heater.[3] Mineralogical alterations in the rock adjacent to the heater were most pronounced in chlorite, which showed a marked change in color and a decrease in the dimensions of the unit cell.[4] An open fracture was observed near the heater, but elsewhere in the core fractures were filled. In the Stripa quartz monzonite, U and Th, each at 30-40 ppm, are concentrated considerably higher than in most granitic rocks, and their abundances are nearly equal. Uranium is strongly associated with fracture-filling chlorite, and in some cases with epidote and sphene. Alpha- and fission-track radiography were used to investigate the distribution and abundance of uranium in material lining and filling fractures in the heated rock. Based on fission-track exposures of thin sections and standards, the U concentration in the epidote-sphene-rich lining of the open fracture within 5 to 7 cm of the heater (Fig. 2) is 1.2 to 1.8%, then decreases to ~0.2% about 1 mm away from the fracture's edge (Fig. 3). This contrasts with fairly even U distributions of ~0.1% over epidote-sphene and chloritic material that completely fills nearby fractures. The presence of Bi in portions of the 1mm zone adjacent to the fracture was indicated by x-ray fluorescence measurements and x-ray and electron microprobe scans. At present, we are not able to explain this occurrence of Bi in close association with U.

Comparison of alpha- and fission-track densities indicates disequilibirum in the U-decay series in the open fracture lining. We calculated the alpha-track densities that would result from the U contributions observed from the fission-track data, and compared these calculated track densities with observed alpha-track densities. The ratio of observed to calculated track densities is plotted with distance from the fracture edge in Fig. 4. A ratio of 1 represents secular equilibrium and a ratio less than 1 indicates the absence of some alpha-emitting daughters in

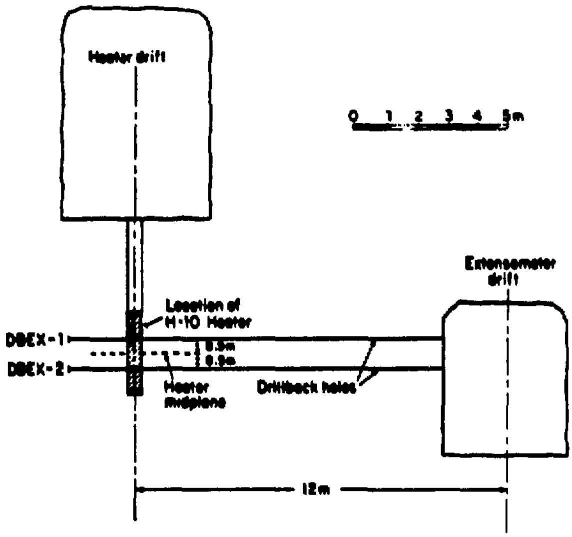

Figure 1. Cross section through Stripa heater hole and adjacent drifts, showing location of drillback holes.

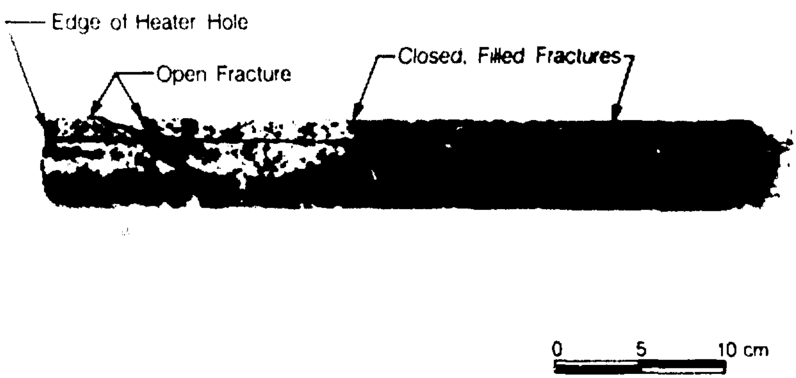

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Figure 2. Stripa drillback core closest to heater, showing locations of fractures examined for radioelements.

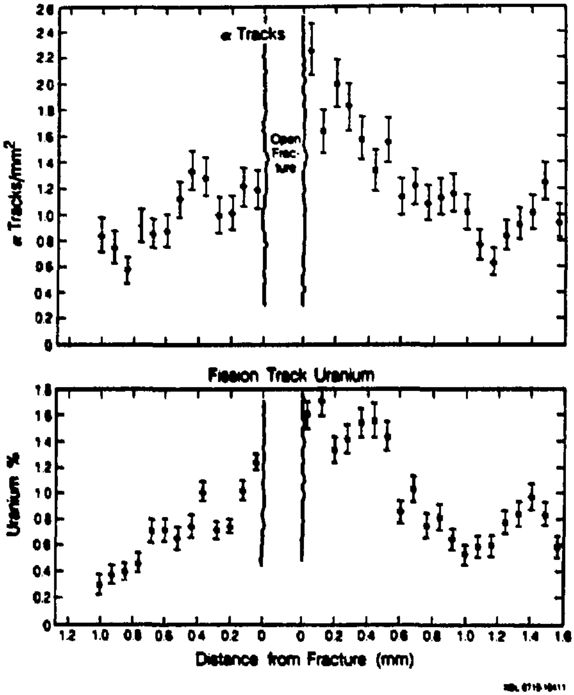

Figure 3. Alpha-track densities and U concentrations (by fission tracks) in material lining an open fracture in core near Stripa heater hole. Error bars reflect counting statistics.

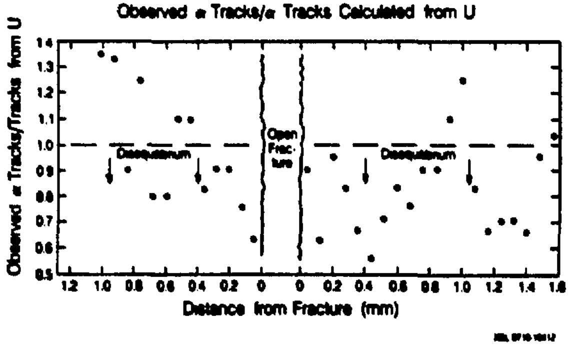

Figure 4. Ratios of observed alpha-track densities to those calculated from U concentrations; same coverage as shown in Fig. 3.

the U decay series. Uncertainties in the ratios are 10 to 20%, but there is strong evidence of disequilibrium in that there are several values less than 0.8. These could represent the recent addition of U to the fracture lining material, or the removal of one or more U daughter elements. At sites of relatively low U concentration where the ratio is well above 1 the excess alpha tracks might be due to the presence of Th and its daughters in significant abundance. This may also be the case in a filled fracture ~15 cm from the heater where U averages 0.17%, there is no gradient in U concentration, and the ratio of observed to calculated alpha tracks is 3. The U distribution pattern and evidence of U-series disequilibrium in the vicinity of the open fracture then suggest that U was mobilized and deposited in a localized hydrothermal system in open fractures near the heater. Alternatively, but less likely, it is possible that the fracture was open prior to heating and U was mobile over a much longer time under ambient conditions.

The evidence of U mobility implies that in the near-field repository environment, mineral - filled fractures might reopen in response to construction activities and/or to the thermally induced stress caused by introduction and long - term presence of the waste. Uranium leaking from a canister might be mobilized in a near - field hydrothermal system in the open fractures, and depending on fracture-lining mineralogy, a significant portion of the U could be deposited on fracture-lining minerals.

Mechanical Response

The seismic velocity and attenuation characteristics of heated rock, as well as the distribution and abundance of microcracks were also investigated in the Stripa drillback core. Samples examined were located 6, 15, and 80 cm from the edge of the heater hole. Maximum temperatures were calculated to have reached 375^{o} C at the 6 cm site, 325^{o} at 15 cm, and 200^{o} at 80 cm.[3] Compressional (P) and shear-wave (S) velocities, amplitudes and seismic quality factors (Q) were measured under axial loads from 4.1 to 62 MPa. The maximun stress was less than one-half the unconfined compressive strength of the rock. Values of Q were calculated by the spectral ratio method, using reference signals from an aluminum standard.

The effect of the long term heating was to lower seismic velocities and increase attenuation in the ~6 cm of rock nearest the heater. Effects on attenuation are illustrated by the P- and S-wave amplitude responses, shown in Fig. 5. Some correlation exists between P-wave amplitudes and distance (temperature) from the heater hole (Fig. 5a), i.e.,the lowest amplitudes occur with the hottest sample. P-wave amplitudes for the two cooler samples were similar. As shown in Fig. 5b, the S-wave amplitudes of both the hottest and intermediate - temperature samples were lower than those of the coolest sample. The increase in amplitude of the P- and S-waves with axial load is commonly observed and is attributed to the closure of microcracks. At the lowest axial load, values of Q_p ranged from 10 in the sample nearest the heater to 16 in the farthest sample. Corresponding values of Q_s at the lowest load were 18 and 32. The increased attenuation near the heater is attributed to microcracking in response to the long term heating.

Results of P-wave velocity measurements were consistent with the attenuation measurements, in that the hottest sample exhibited the lowest velocities. S-wave velocities of the hottest sample were low compared to the sample at intermediate temperature. However, in contrast to the P-wave measurements, the S-wave velocities of the coolest sample were about equal to those of the hottest sample. Since the seismic transducers produced polarized shear waves, an explanation for the difference between P- and S-wave behavior is anisotropy in the rock. A source of anisotropy could be microcracks with a preferred orientation parallel to the axis of the core. Drilling of the heater hole and subsequent heating would produce cracks parallel to the hole surface and perpendicular to the core axis. Microcracking with orientation parallel to the axis of the core had not been anticipated.

The intensity and orientation of microcracks were investigated by examination of sections, cut both parallel and perpendicular to the core axis, by scanning-electron microscopy. To date, cores at 20 and 80 cm (Fig. 6) from the heater hole have been examined. In core at 20 cm, there are more open microcracks, their direction of opening is subparallel to the core axis, and their orientation is distinct from those of closed cracks. In contrast, core at 80 cm has fewer open cracks and their orientations are not distinct from those of closed or healed cracks. We are examining core closer to the heater to determine the number of microcracks and their orientations. At this time we can state that the greater number and more consistent orientation of microcracks at 20 cm than at 80 cm can be attributed to thermally-induced stresses and/or stress redistribution caused by creation of the heater cavity.

TUFF

Hydrothermal Systems

Samples of core from a 730m - deep hole drilled by the Department of Energy in rhyolite of the Long Valley caldera were examined.[5] This hole penetrates a thermal regime from near ambient temperature to over 200^{o} C, primarily in moderately to strongly welded tuff (Fig. 7). Examination of the gamma-ray log of the hole and gamma-spectral measurements of the core indicated an anomalous zone in calcite-cemented breccia at 165^{o} C (asterisks in Fig. 7), where U is the predominant radioelement. In this zone, temperature rapidly increases with depth, and oxygen-isotope ratios concomitantly decrease from +3 to -2. Fission-track radiography showed that U is concentrated in the range 20 to 70 ppm, against a background of ~6 ppm in unbrecciated tuff, and is associated with sulfide-mineral-rich zones in the breccia. High-resolution gamma spectrometry indicated that the U in the breccia zone is not in secular equilibrium with its daughter elements, suggesting mobilization/deposition of parent U and/or its daughters in the hydrothermal environment. There is evidence then for mobility of U in an

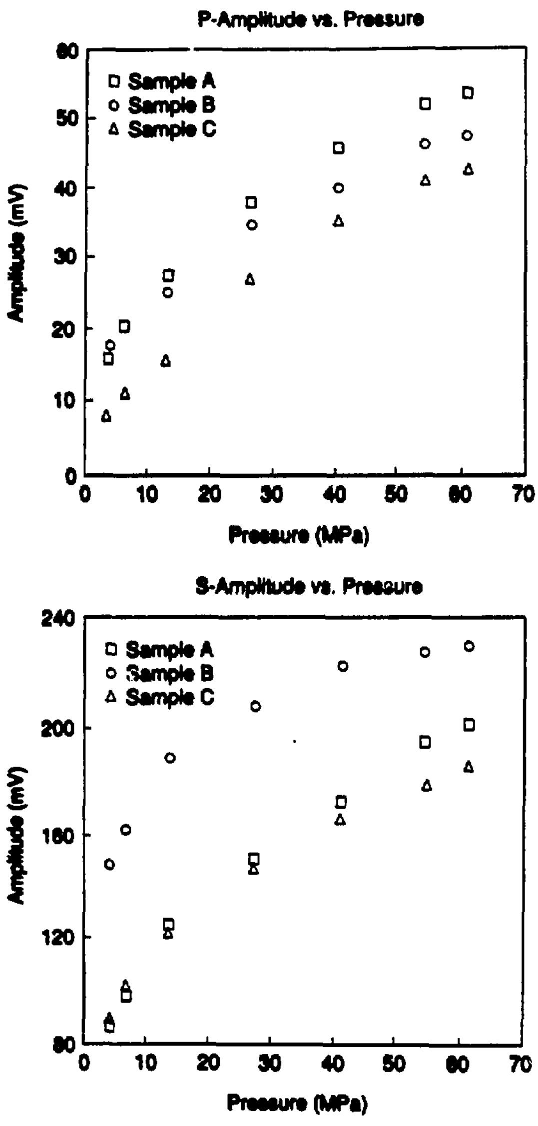

Figure 5. Variation of peak-to-peak amplitude of P- and S- wave signals through core samples as a function of pressure. Sample C is nearest the heater, sample B the farthest.

a

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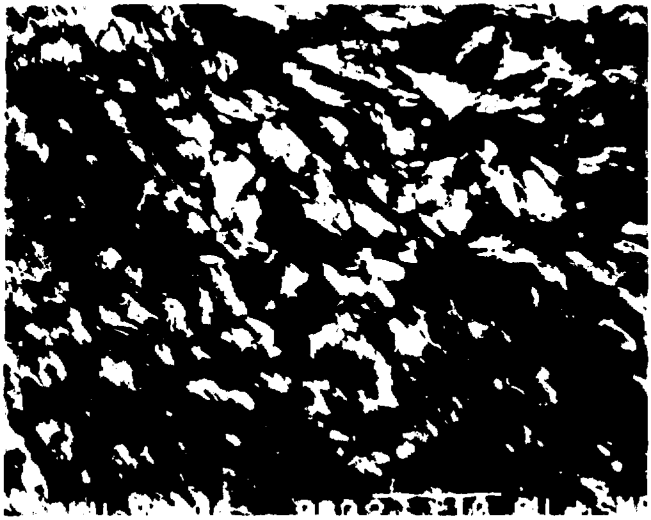

b

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Figure 6. a) S.E.M. photograph of step-like crack formed by reactivation of sealed grain - boundary cracks in quartz, at a location 20 cm from the heater. Bar is 1 micron.

b) Crack in chlorite, showing effect of cleavage foliation on crack direction; location 80 cm from heater. Bar is 10 microns.

active hydrothermal system in tuff, at temperatures comparable to those expected in a repository environment. Similar studies will be conducted on core samples from a vapor-dominated sector of a scientific drill hole in the Valles caldera, New Mexico.[6]

Nevada Test Site

At the G-tunnel test facility, Nevada Test Site, drillback core has been obtained for mineralogical, geochemical and geomechanical studies of welded tuff, in the unsaturated zone, that has been heated to repository temperature. The mineralogical and physical properties of this tuff, the Grouse Canyon, are similar to those of the densely welded Topopah Springs tuff, the candidate repository medium.[7] In an experiment conducted by Lawrence Livermore National Laboratory, an electric heater simulated the localized thermal field caused by introduction of high-level waste. The heater was at full power for 4 months, with a temperature of 240° C at the heater edge and 120° C in rock at a distance of 0.7m (A. Ramirez, LLNL, private comm., 1989).

For future comparison with drillback core, we selected core from a hole that passes within 1 m of the electric heater (Fig. 8). The distribution of radioelements in this core was investigated by gamma spectrometry, and results showed a relatively even distribution of U (~3.5 ppm) and Th (~16 ppm) over the length of the core. Radioelement comparisons indicate a strong linear correlation of Th with K (r^2=0.96) while correlations of U with Th and K are relatively weak (r^2=0.43 and 0.28, respectively). This apparently independent behavior of U was investigated by more detailed gamma spectrometric and fission-track measurements. In this respect, gamma spectrometry indicated high concentrations of U and Th associated with an open fracture, coated partially with amorphous silica. This occurrence was examined by fission-track radiography, disclosing that U, at ~20 ppm, is concentrated 5 times higher in the silica coating than in the tuff matrix. This U-rich coating could have been associated with the hydrothermal system that developed soon after deposition of the tuff, or with a cooler, fracture-controlled groundwater system that subsequently developed.

We shall investigate similar occurrences in core obtained from drillback through the heater hole, where localized heating may have affected fracture-lining constituents. The mechanical properties of core from the heated and unheated zones will also be investigated in a similar fashion to the Stripa core studies, for comparison of pre- and post-heating effects on welded tuff. This will serve as a prototype investigation for those expected to be conducted in the Exploratory Shaft Test Facility, once it is excavated in the Topopah Springs tuff.

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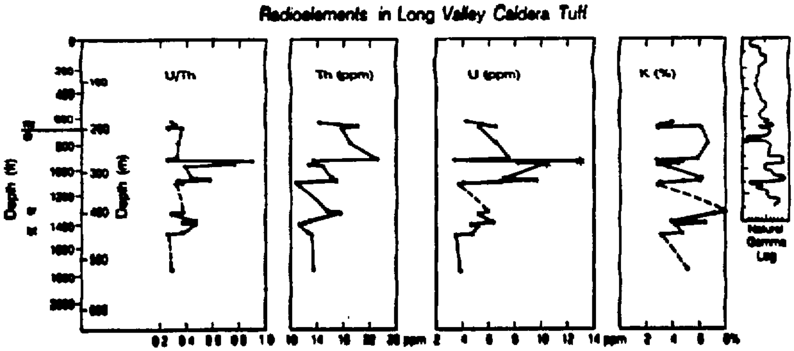

Figure 7. Distribution of radioelements over a temperature range from 80 to 200°C in tuff of Long Valley caldera. Asterisks indicate sites of U-series disequilibrium and detailed fission-track examinations.

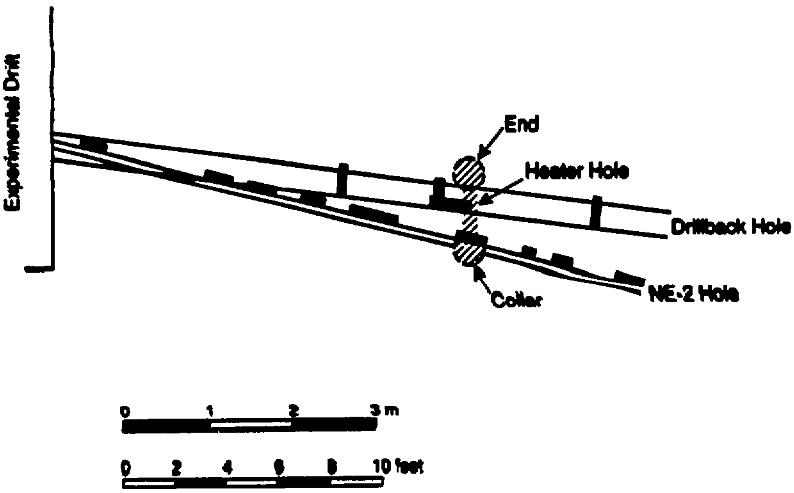

Figure 8. Section perpendicular to heater hole in G-tunnel, Nevada Test Site, showing sampled intervals in core from the initial (NE-2) hole and the drillback hole.