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LBL/GRP Studies of Fractured Rocks: Summary FY 1986–1990

Geologic Repository Project Group

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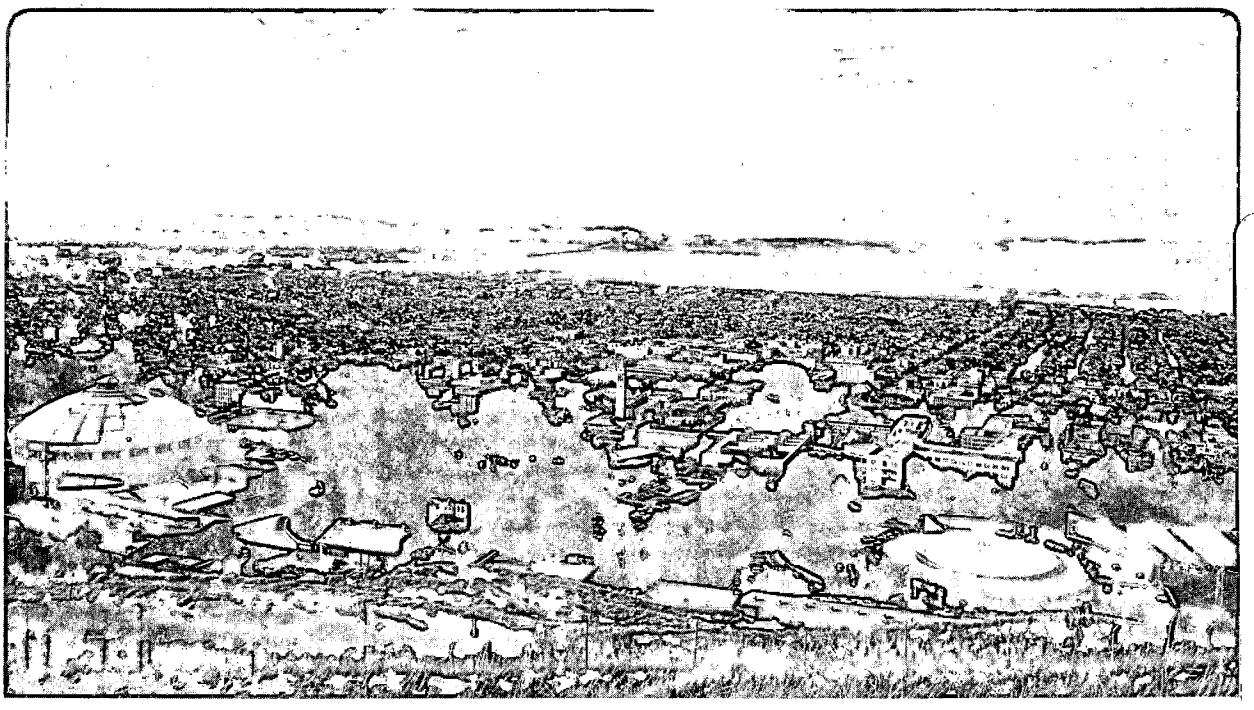

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LBL Studies of Fractured Rocks: Summary FY 1986–1990

Intact pieces of many rocks have extremely low values of fluid permeability and high (relative to, say, concrete) values of mechanical strength. If the properties of rock masses were the same as those of the intact rock there would be few, if any, questions concerning the effectiveness of nuclear waste isolation by deep geologic repositories. However, rock masses are heterogeneous structures comprising different compositions and textures separated and intersected by discontinuities on all scales; from microcracks through bedding planes, joints and fractures to faults. This heterogeneity significantly complicates the evaluation of transport of potentially contaminated groundwater away from a repository. Extensive discontinuities may allow significant quantities of groundwater to flow at much greater velocities than could occur in a porous rock medium. Therefore, the development of a successful geologic repository requires the ability to detect and characterize discontinuities and to evaluate fluid flow through them as a function of changes resulting from repository construction, waste emplacement, tectonic activity, and/or a different climate.

Recent interest in site characterization and performance assessment of rock masses for the design and construction of nuclear waste repositories provided the motivation for the LBL studies of the hydraulic, mechanical, geophysical, and geochemical properties of discontinuities. These studies are presented schematically in Figure 1, where the different focal points of these investigations are depicted and identified for reference. They are grouped into eight topics: (1) The study of the

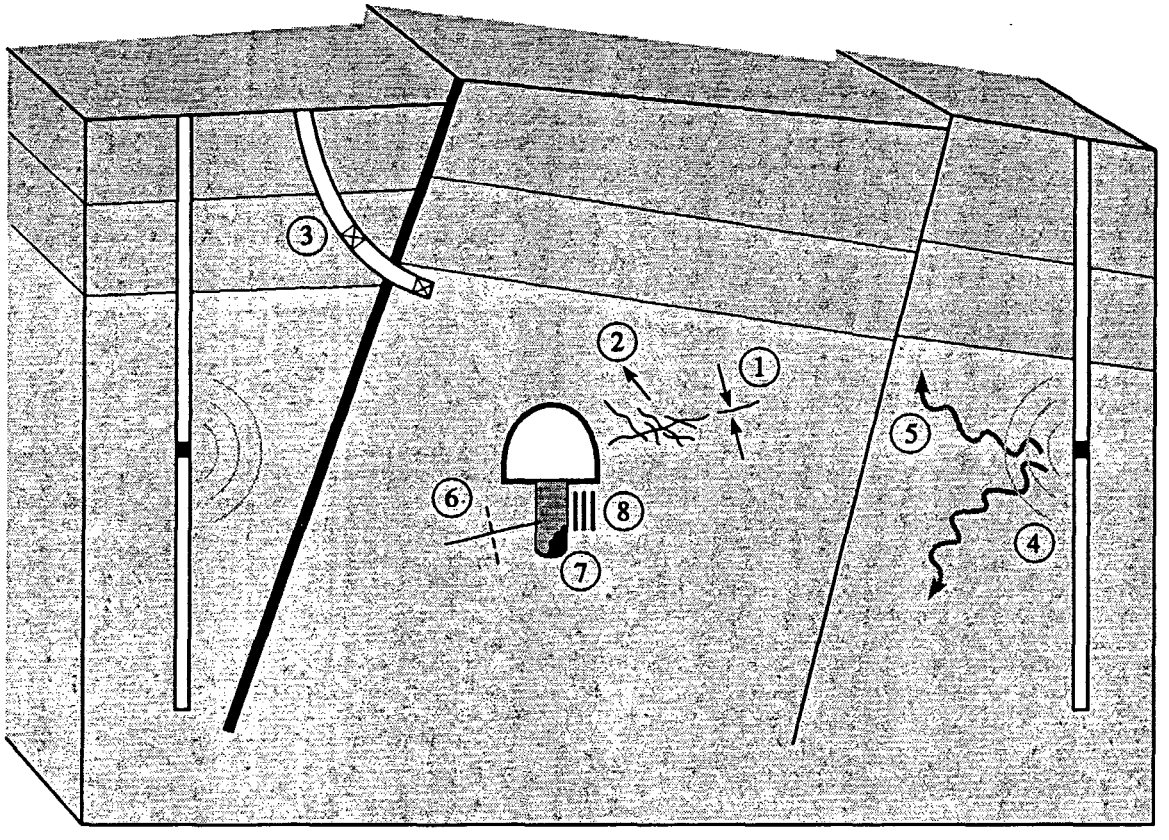

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Figure 1. Schematic depiction of the eight main focal points of the LBL/GRP studies of fractured rocks:

(1) Studies of the hydromechanical and geophysical properties of individual fractures.

(2) Studies of flow channeling in fractures.

(3) Development of hydrologic characterization methods for near-vertical faults and other potentially highly conductive features.

(4) Modeling studies associated with Vertical Seismic Profiling and other seismic techniques for characterizing fracture systems and fault zones.

(5) Modeling studies of electrical and electromagnetic geophysical techniques for the detection of fractures and their subsequent characterization using borehole data.

(6) Studies of the geochemical-hydrological regime of radionuclides in the material lining fractures.

(7) Studies of the effects of a varying thermal field on the precipitation of minerals and the possible reduction of mass diffusivity and fluid flow.

(8) Studies of canister borehole degradation under thermomechanical stress changes and the mechanical response of fractures to elevated temperatures.

correlation between the mechanical properties of a fracture, its hydraulic conductivity, and the amount of seismic attenuation it causes; (2) the phenomenon of flow channeling through preferred pathways in the fractures, which has important implications for radionuclide transport; (3) on a larger scale, the hydrologic characterization of near-vertical faults and other potentially highly conductive features with a view to analyzing the flow of water and air in an unsaturated fault-rock system; (4) also on a larger scale, the use of Vertical Seismic Profiling (VSP) and cross-hole seismic tomography to map elastic properties indicative of fracture density and structure, and to detect and characterize fractures and fault zones away from subsurface workings; (5) as a complement to seismic methods, studies of the use of electrical resistivity properties of the subsurface to detect the presence of fractures and their geometric orientation away from boreholes; (6) on a smaller scale near the waste canisters, investigations of the geochemical-hydrological interaction of radionuclides in the fluids with the material lining fractures in the rock; (7) also at this scale, numerical modeling studies to examine the effects of a varying thermal field on the precipitation of otherwise soluble minerals and the resulting decrease of porosity that could reduce the migration of solutes by diminishing mass diffusivity and fluid flow; (8) investigation of the mechanical degradation of the walls of the waste canister boreholes due to thermomechanical stress changes, and to understand the mechanical response of the fractured rock to elevated temperatures. The major findings in each of these areas are summarized briefly below.

Heterogeneous Flow in Fractures

Measurements of fluid flow through natural fractures in low permeability rocks have shown that, at low effective stresses, flow through a fracture diminishes much more rapidly with increasing stress than the cube of the apparent fracture aperture, but at high stresses it is asymptotic to a constant, stress-independent, irreducible flow

(Pyrak-Nolte *et al.*, 1987b). Important progress in understanding the real nature of the hydraulic and mechanical properties of natural fractures in low permeability rock has come from images of the fracture void space using Wood's metal porosimetry and a fractal construction for the correlated aperture distribution (Pyrak-Nolte *et al.*, 1988; Nolte *et al.*, 1989; Pyrak-Nolte *et al.* 1990a).

One result of the above studies showed that in a single fracture the void structure is a very heterogeneous two-dimensional system. This indicated that fluid flow through a fracture may be very non-uniform, and that the majority of the flow might be concentrated in a few preferred paths. A study of the heterogeneous nature of flow in a single fracture led to the concept of flow channeling to characterize mass transport in a system of realistic fractures having variable apertures. In the presence of flow channeling, the conventional methods of analyzing fluid flow and solute transport are generally not suitable since they have been formulated for relatively uniform flow in porous media.

Since it is impractical to obtain detailed data on fracture geometries in the field, our approach was to construct a conceptual model where the rock mass properties such as permeability to flow and dispersivity in tracer transport are correlated directly to a few basic geometric parameters. In our model these are the mean aperture value, its standard deviation, and the correlation length of the spatial distribution of fracture apertures. Because the heterogeneous nature of flow channeling implies that data from point measurements depend sensitively on the location of measurement, interpretation of data from a point measurement may not yield flow and transport parameters that are representative of the rock mass. We have used a statistical approach to analyze multiple-point measurements in order to calculate representative geometric parameters which characterize the flow and transport properties of the medium. Based on this framework we carried out a series of theoretical studies as well as applications to the analysis of field data.

The conceptual model of channeled flow and transport was first defined after a review of experimental evidence (Tsang and Tsang, 1987). Then the theoretical basis of the model was studied (Moreno *et al.*, 1988; Tsang and Tsang, 1989), and properties of the channel model were investigated (Tsang *et al.*, 1988). Implications of the model on experimental measurements of tracer transport in fractured rock were then explored and correlated with observations (Moreno *et al.*, 1990; Moreno and Tsang, 1990). Finally, we applied our approach to the substantial set of tracer data on fractured rocks from the three-dimensional experiments at Stripa, Sweden, by Neretnieks and coworkers. Our analysis of these results succeeded in obtaining not only estimates of the mean and standard deviation of fracture apertures, but also of Peclet numbers, dispersivity, and the number of channels involved in the tracer transport (Tsang *et al.*, 1990). An interesting and surprising observation is that dispersivity decreased with mean travel time, i.e., the Peclet number increased with the mean travel time. This is contrary to the traditional concept in hydrogeology. We have shown that this trend is a consequence of the strong heterogeneity of the flow system in fractured rocks.

A tentative conclusion that emerges from these investigations is that the conventionally defined dispersivity may not be an appropriate characterizing parameter of the flow system and that the mean and standard deviation of fracture apertures may be the more relevant parameters to be determined by flow and tracer measurements. This conclusion may have significant impact on the interpretation of tracer test data that will be part of site characterization activities at Yucca Mountain in the coming years.

Hydrologic Characterization of Faults

The capability of characterizing near-vertical faults and other potentially highly conductive geologic features in the vicinity of a high-level waste repository is also of great importance. The existence of faults near a repository may provide a fast flow path from the disturbed zone to the accessible environment. Thus, part of our work

was devoted to the development of mathematical solutions describing the hydrologic behavior of faults.

We studied the flow of water in a faulted multiple aquifer system and the flow of air in unsaturated faulted rock masses. These studies showed that if a permeable fault zone intercepts two horizontal aquifers, hydrologic characterization of the fault can be achieved by pumping water from one of the aquifers and monitoring drawdowns in nearby observation wells (Shan, 1990).

It has been proposed that the hydrologic properties of a fault crossing an unsaturated zone may be estimated by measuring subsurface air pressure changes. Analytical solutions were developed to calculate the pressure response of the faulted rock mass to atmospheric pressure variations (Javandel and Shan, 1990). Numerical methods were used to study multi-layered unsaturated systems like the Ghost Dance and Solitario Canyon faults at Yucca Mountain.

These studies suggest that when the fault permeability is at least an order of magnitude larger than that of the surrounding rocks, air pressure changes measured in isolated intervals of a horizontal or inclined borehole drilled through the fault zone, could be used to estimate the fault/rock mass permeability ratio.

Seismic Properties of Fractured Rocks

One of the most crucial needs in the design and implementation of an underground waste isolation facility is a reliable method for the detection and characterization of fractures in zones away from boreholes or subsurface workings. Within underground workings we are able to examine fractures directly; however, a major problem exists in trying to extrapolate this information to unexposed regions. The techniques of Vertical Seismic Profiling (VSP) and cross-hole seismic imaging may be applicable to characterizing fractured media because of the anomalous behavior of fractures, faults, and joints relative to the propagation of seismic energy.

Previously, it was assumed that the ratio between the aperture of a fracture and seismic wavelengths was so small that individual fractures could not be located seismically. However, the combined effect of a number of fractures could be detected by seismic velocity anisotropy. A displacement- and velocity-discontinuity theory showed that single natural fractures do affect propagation of seismic waves at all wavelengths. This was confirmed by laboratory measurements (Pyrak-Nolte *et al.*, 1990b). The approach was extended by Pyrak-Nolte *et al.* (1987a, 1990c) to investigate the effect of multiple fractures arranged in sets. The combined theoretical and laboratory results show that for such a system the expected variation in shear-wave velocity with propagation direction is significantly different from that expected for a conventional representation of a fractured rock mass as an anisotropic elastic medium. The displacement-discontinuity theory shows that a group time-delay and changes in seismic wave amplitude occur when a seismic wave encounters a fracture so that, in principle, the location and stiffness of fractures can be detected seismically even for a single fracture. Thus the techniques of VSP and crosshole tomography may be applicable in locating and characterizing fractures.

It is now necessary to relate the measured seismic properties to the overall hydrologic and geomechanical characteristics and predicted performance of the rock mass. There have been some attempts to relate geophysical anomalies to hydrologic or geomechanical parameters of geologic materials and to interpret the data for a better overall understanding of the rock properties, but there have been few reliable data sets available for such a study. Myer *et al.* (1990) showed that a relationship exists between the mechanical stiffness of a fracture, its hydraulic conductivity, and the amount of seismic attenuation it causes. The relationships between the topography of fracture surfaces, mechanical stiffness, and hydraulic conductivity at different effective stresses have been examined using numerical models by Hopkins *et al.* (1987) and Hopkins (1990). These results confirm the inverse relationship between mechanical

stiffness and hydraulic conductivity, as well as the rapid decrease in hydraulic conductivity with decreasing fracture aperture.

Modeling Seismic Wave Propagation through Fractured Rock Masses

Whereas several numerical techniques are available for predicting fluid flow through fracture networks, the corresponding computational tools for determining how a seismic wave is affected as it propagates through a network of arbitrarily located and oriented finite fractures was not available at the onset of this study. One-dimensional and two-dimensional ray tracing and synthetic seismogram models that originally relied on conventional welded boundary theory were modified to admit compliant fracture surfaces with arbitrary orientation by including the displacement-discontinuity boundary conditions in the solution for the propagation of the seismic wavelet. This allows us to vary fracture geometry, density and orientation in a medium and measure the seismic response. Parameter studies were carried out to determine the degree to which VSP is sensitive to interconnection, orientation, and other geometric properties of the fractures in the rock mass. Assuming that the displacement-discontinuity theory will hold at large scale, we now can model fracture density, geometry, and orientation (Lee *et al.*, 1990).

Due to the complex geometry of fractures and the complexity involved in ray tracing through many fractures, we soon realized that while the fracture displacement-discontinuity approach greatly enhances our understanding of the mechanisms that affect the propagation of seismic energy, it is impracticable to model each individual fracture. Therefore, we maintained and improved our synthetic seismogram capability by integrating a more complete anisotropy theory into our numerical codes that trace rays through equivalent fractured media (Flueh *et al.*, 1989; Flueh and Okaya, 1989; Gajewski and Psencik, 1990). Simultaneously, data from actual VSP field studies in crystalline, tuffaceous, and metamorphic fractured rocks were modeled to match the

observed seismic wave behavior.

Electrical Methods to Characterize Fractured Rock Masses

Another aspect of our geophysical research was to investigate the relationship between the fluid saturation and the electrical conductivity of fractured rock masses. This relationship is needed to develop quantitative electrical and electromagnetic (em) imaging of fractures, fluid saturation, and to complement seismic imaging used in monitoring changes in the rock mass around the repository.

The electrical conductivity of rocks is controlled by pore fluids and their conductivity. Fluid saturation, in particular, has a dramatic effect on this parameter. As water is withdrawn from a saturated rock, the large pores and fractures desaturate first, but the bulk resistivity increases rather slowly since it is mainly controlled by the small interconnected water-filled pores and fractures. At this point the rock resistivity is roughly proportional to the inverse of saturation squared. As desaturation progresses, a critical saturation is reached at which point there is no longer any water to conduct along some pores and fractures. This breaking of the conduction paths leads to a much more rapid increase in resistivity, roughly proportional to the inverse of saturation to the fourth power. The critical saturation depends on the rock type (the nature of the porosity) and may also depend strongly on the fracture network pattern.

So far, our studies have emphasized the dc resistivity method, where current is injected through electrode pairs and the resulting voltage drops are measured in the vicinity with other pairs of electrodes. The measured voltage drops are then used to infer the distribution of electrical resistivity. Using a difference scheme in the dc method, a two-dimensional modeling study was carried out to simulate repository environments (Asch and Morrison, 1989). It was shown that resistivity measurements, using electrodes in boreholes located well away from the repository and on the surface, are sensitive to resistivity changes in the repository that could not be practically

observed from surface measurements alone.

Another important practical problem addressed was the detection of any major fracture zone near, but not intersected by, boreholes. However, these boreholes still allow the use of subsurface em techniques to detect and characterize these nearby fractures. Using the integral equation modeling technique, Lee *et al.* (1990) showed that a fracture can be identified and subsequently characterized from data collected in a crosshole environment. A diffusion tomography technique was also developed (Zhou, 1989) for analyzing crosshole audio-frequency em data which is similar to diffraction tomography in seismic applications. Studies using synthetic two-dimensional models showed that this approach is very promising for detecting individual fractures and their dips in the region between boreholes. Other calculations indicated that two fractures could be resolved when the separation is as close as about one-tenth of the wave length. This is the first quantitative assessment of the resolution of fracture networks with em methods.

Radionuclide Transport in Fractured Rock Masses

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 hydrogeochemical processes must be understood if the transport of radionuclides away from a breached canister is to be modeled and predicted. The objectives of these investigations were to develop an understanding of the interaction, under long exposure to elevated temperatures, of radionuclides in the fluids with the materials lining the 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 penetrated high-temperature hydrothermal zones and holes cored through heater-test zones were examined petrologically, geochemically, and geomechanically.

Initial emphasis was on core samples of quartz monzonite, obtained from rock previously subjected to a year-long heater experiment simulating high-level radioactive waste, conducted at Stripa, Sweden (Wollenberg and Flexser, 1986). Results indicated localized mobilization and deposition of uranium in an open fracture in the heated rock, and that differences in compressional- and shear-wave parameters between heated and less-heated rock can be attributed to differences in the density of microcracks (Wollenberg *et al.*, 1990a).

As interest in tuff as a repository medium became apparent, we examined core from holes penetrating fractured hydrothermal systems in rhyolitic tuff of the Long Valley and Valles calderas, and are investigating heated and unheated, unsaturated tuff from experiments at G-tunnel, Nevada Test Site. The Long Valley and Valles studies indicate the localized mobilization of uranium and its daughter elements associated with iron-rich minerals in tuff and with carbonaceous minerals in underlying sedimentary rocks, at temperatures comparable to those expected in a repository environment. Investigations of welded tuff in cores from the G-tunnel heater experiment show that U is concentrated 4 to 10 times above whole-rock values in Fe-Ti-Mn-oxide minerals, with an apparent depletion in U observed in these minerals over the 10 cm of tuff adjacent to the heater. Scanning-electron microscopy and mechanical properties studies of this heated core continue (Wollenberg *et al.*, 1990b). Observations to date suggest that U is mobile in hydrothermal systems, but that localized reducing environments provided by Fe-rich minerals and/or carbonaceous material concentrate U and thus attenuate its migration.

An aspect of geochemical behavior that can have important consequences in performance assessment is the effect of a variable thermal field on (1) the movement of major solution components and dissolved waste radionuclides, and (2) the stabilities of minerals exposed to the changing thermohydrochemical environment. Variable thermal fields can arise in the near vicinity of nuclear waste canisters and from mixing of

fluids having different temperatures. Such fields imposed on previously stable or metastable fracture minerals can induce dissolution of existing minerals, transport of dissolved chemical species, and precipitation of new solid phases. Redistribution of materials within fractures by chemical reactions and transport can produce changes of physical properties of the rock mass such as porosity, mass diffusivity, and permeability. Changes of these parameters can affect transport of both radionuclides and major components of subsurface fluids. In particular, precipitation of minerals at or near the fracture-matrix boundary can reduce diffusive transport of radionuclides into the matrix, thus decreasing the effective retardation of the radionuclides. On the other hand, alteration of some mineral species may enhance their ability to retard radionuclides.

Modeling studies (Carnahan, 1990a,b) showed that a varying thermal field could induce precipitation of otherwise unstable (soluble) minerals, and that the resulting decrease of porosity could reduce migration of solutes by decreasing mass diffusion and fluid flow. The extent to which these mechanisms are effective in particular settings depends on the magnitudes of temperature changes, compositions and solubilities of existing minerals, and composition of the fluid phase.

Mechanical Degradation in Rock

Heat flow and solute transport near the waste canisters may also be affected by mechanical degradation of the walls of boreholes within which the canisters will be placed. This could adversely affect heat transfer, impose mechanical loads on waste canisters, and provide paths for groundwater flow to and from the canisters. A series of laboratory experiments on borehole breakout using Wood's metal porosimetry has shown how this phenomenon occurs by the subcritical growth of extensile cracks driven by the tangential compressive stress around the hole, (Ewy *et al.*, 1988; Ewy and Cook, 1990a,b). This study showed that time-dependent borehole degradation is

likely to occur, but that it can be avoided easily by lowering rock temperatures or by installing appropriate borehole liners.

Summary

These brief summaries of the LBL fracture studies, supported by the cited references, show that significant advances have been made in our understanding of basic phenomena and material properties affecting the hydrologic, mechanical, geophysical, and geochemical characteristics of fractured rock masses. Along with this increased understanding, new techniques were developed for detecting and characterizing fractures and fault zones in the subsurface, predicting the response of fractures to hydraulic, mechanical, and thermal stresses, and evaluating the main processes that control fluid flow and solute transport in fractured rock masses. This improved understanding and the analytical and practical methods developed in the past four years constitute part of LBL's contribution to the present state-of-the-art in site characterization and performance assessment of rock masses that will be needed in the design and construction of nuclear waste repositories.

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