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Method Development and Strategy for the Characterization of Complexly Faulted and Fractured Rhyolitic Tuffs, Yucca Mountain, Nevada, USA

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ABSTRACT

Field experimental and analytical methods development is underway to define the hydraulic and transport properties of a thick saturated zone that underlies the planned high-level nuclear waste repository at Yucca Mountain, Nevada. The characterization strategy for the highly heterogeneous hydrology is that of hypothesis testing and confidence building. Three test wells, the UE-25c-holes, have been drilled and preliminary data have been collected. Hydro-mechanical analyses indicate formation fluid at depth is hydraulically connected to the water table. Preliminary hydraulic tests indicate highly localized, fracture-controlled transmissivity. Cross-hole seismic tomography is planned to assess the inter-borehole structure of fractures and faults. Multi-level cross-hole hydraulic interference and tracer tests are planned using up to 5 packed-off zones in each of the c-holes to assess the hydraulic conductivity and transport structure in a crude tomographic fashion. An equivalent discontinuum model conditioned with the observed hydraulic measurements will be applied to interpret the hydraulic test responses. As an approach to the scale problem the tests will be designed and analyzed to examine the hypothesis that the flow system may be represented by fractal geometry.

INTRODUCTION

The planned high level nuclear waste repository at Yucca Mountain, Nevada, USA (Figure 1a), would exist in unsaturated, fractured welded tuff. One possible contaminant pathway to the accessible environment is transport by ground-water infiltrating to the water table and flowing through the saturated zone. Therefore, the characterization effort of the saturated zone hydrology is being undertaken in parallel with that of the unsaturated zone. As a part of the saturated zone investigation, three wells; UE-25c#1, UE-25c#2, and UE-25c#3 (hereafter called the c-holes), were drilled to study hydraulic and transport properties of rock formations underlying the planned waste repository. The location of the c-holes is such that the formations penetrated in the unsaturated zone occur at similar depths and with similar thicknesses as at the planned repository site. The c-holes penetrate to a depth of approximately 914 m with separation among the wells of 30–75 m (Figure 1b). Geophysical [1] and geologic logs [Richard W. Spengler, U.S. Geological Survey, written commun., 1989] with information on the degree of welding of the tuffs and formation stratigraphy are available for the c-holes. The surface geology has also been mapped [2].

In characterizing a highly heterogeneous flow system several issues emerge: (1) The characterization strategy should allow for the fact that it is virtually impossible to enumerate and characterize all heterogeneities. (2) The methodology to characterize the heterogeneous flow system at the scale of the well tests needs to be established. (3) The tools for scaling-up the information obtained at the well test scale to the larger site scale are needed. In the present paper, the characterization strategy and the methods under development are discussed with the focus on the design and analysis of the field experiments at the c-holes.

YUCCA MOUNTAIN

Geology

Yucca Mountain is in the Great Basin section of the Basin and Range physiographic province of North America. Basin and Range faulting and volcanism during the Tertiary Period have resulted in predominately north-south oriented mountain ranges, separated by broad basins filled with Tertiary and Quaternary sediments. During the Miocene Epoch, a large volcano field developed near Yucca Mountain and covered the area with rhyolitic ash-flow and air-fall tuffs [3].

Yucca Mountain is a north-south trending ridge bounded on the west by Solitario Canyon and Crater Flat, and on the east by Fortymile Canyon and Jackass Flats (Figure 1a). The west face of Yucca Mountain is a scarp defined by the Solitario Canyon Fault. The eastern flank slopes toward Fortymile Canyon and smaller intervening ridges and valleys. From the crest of Yucca Mountain eastward to Fortymile Wash, many other smaller north-south trending faults bound individual blocks of mostly rhyolitic tuffs. The larger of these include the Paintbrush Canyon, Ghost Dance, and Abandoned Wash Faults. These are high angle normal faults bounding blocks that dip eastward 5 to 20°. The tuffs, intercalated with thin beds of lava and bedded tuffs, were deposited unconformably upon Paleozoic bedrock between 15 and 11 million years ago. The thickness of the tuffs exceeds 1200 m on the eastern flank of Yucca Mountain where test well UE-25p#1 penetrated the Timber Mountain Tuff, the Paintbrush Tuff, the tuffaceous beds of Calico Hills, the Crater Flat Tuff, the Lithic Ridge Tuff, the Older Tuffs, and 500 m of Paleozoic carbonate rocks (Figure 2). Bedded tuffs were encountered between each of the major tuffs.

These tuffs have a wide range of physical properties varying from nonwelded to welded, devitrified to vitrified, and nonzeolitized to zeolitized. The welded tuffs are characterized by relatively small matrix hydraulic conductivities, and a tendency to fracture easily. Bulk permeability values are relatively large. The nonwelded and bedded tuffs characteristically have larger porosities, are generally less fractured, and, unless the rock is altered and contains clays and zeolites, have larger matrix hydraulic conductivities than the welded tuffs [4]. Fracture density, orientation, aperture, and interconnectivity determine the magnitude and direction of flow under a given hydraulic gradient. Information on fracture densities and orientations from outcrop transects, pavement mapping, and boreholes indicate that two sets of fractures are present. The first set strikes N15-40°W and the second strikes N5-35°E, both dip steeply (60-90°) to the west. At Yucca Mountain the least horizontal principal stress is oriented N60-65°W, which is coincident with the regional direction of tectonic extension. In an otherwise homogeneous stress field, fractures perpendicular to this axis would be under tensional stress and tend to be more conductive.

Hydrogeology

Yucca Mountain is located within the most arid region of the United States. Average annual precipitation at Yucca Mountain is estimated to be about 100 to 150 mm. Ground-water recharge rates for the alluvium in nearby Yucca Flat were estimated at about 0.5 mm/yr [4], but rates for the exposed welded tuffs of Yucca Mountain are not known. Here, localized inflow through fracture openings is the probable recharge mechanism based on two lines of evidence, 1) tritium in rock moisture at depth, and 2) ground-water accumulation in some shallow (15 m deep) unsaturated zone boreholes following snowmelts on Yucca Mountain. Ground-water flowing beneath Yucca Mountain is recharged predominately at Pahute Mesa, and discharged principally as evapotranspiration in Alkali Flat.

In the saturated zone, aquifer boundaries may not coincide with stratigraphic boundaries. Results from borehole geophysical surveys and well hydraulic tests suggest that a strict hydrostratigraphic categorization based on lithology and laboratory derived hydraulic properties inadequately represents ground-water flow at the scale of the well tests [4]. While fractures are the principal conduit for ground-water flow in the saturated zone, borehole flow-production surveys show that the majority of fractures mapped in boreholes do not contribute to flow. Flow is typically dominated by only a few fractures or groups of fractures.

Most well hydraulic tests conducted at Yucca Mountain have been single-well tests conducted in thick composite sections of borehole, and most of these have been falling-head injection tests. The pressure-transient responses for most of the tests conducted in fractured intervals of boreholes cannot be explained by linear or radial flow models. Spherical flow models [5], and another model based on a noninteger-dimension flow field [6] can explain many of the pressure-transient responses. These models indicate that the flow geometry has a fractional dimension somewhere between 2 (radial) and 3 (spherical). Several tests conducted in unfractured sections of boreholes were indicative of poorly conductive units and displayed ideal radial flow behavior for the duration of the tests. Similarly mixed pressure-transient responses have been measured in single-well tests conducted in tuffs elsewhere at the Nevada Test Site [Charles Savard, U.S. Geological Survey, oral commun., 1990].

Several preliminary multiple-well tests were conducted at the c-holes. Two tests conducted in UE-25c#3 showed markedly different drawdowns in the pumping well despite similar pumping rates. The only difference in the test configurations was the position of the packers in the two observation wells. This is likely a result of discontinuous flow paths that are short circuited by one of the boreholes. It is also an indication that a porous medium approximation of the saturated zone at the scale of the well tests may be inappropriate. These preliminary tests did establish that a hydraulic connection exists among the wells at the c-hole complex. The analyses and interpretation of these tests are providing part of the basic hydraulic information necessary to design and conduct multiple-packer cross-hole interference tests.

Earth Tide and Atmospheric Loading Analyses

Additional information about the hydraulic characteristics of the tuffs comes from the hydro-mechanical analysis of fluid-pressure responses to periodic strain waves measured in the c-holes and other wells in the vicinity of Yucca Mountain [7]. Many of the records show aquifer fluid-pressure responses to earth tides and atmospheric loading. Measured responses to seismic waves generated by earthquakes and underground nuclear explosions have also been recorded in several wells. The time series of aquifer fluid-pressure changes, measured as water level fluctuations in a well, the imposed atmospheric load, measured as barometric pressure at land surface, and the imposed earth tide, calculated on the basis of the theoretical strain tide, can be analyzed to estimate aquifer hydraulic properties. Atmospheric loading and earth tides influence a larger aquifer volume than can be influenced by smaller scale well tests and provide independent estimates of the larger scale aquifer hydraulic parameters. This is desirable because such parameters are very difficult to estimate and are usually extrapolated from small-scale hydraulic test measurements or computed by parametric studies to fit head-level measurements.

The frequency dependent fluid-pressure responses measured in the c-holes can be explained by water-table drainage, indicating that the monitored intervals are in hydraulic connection with the water table. For the response measured below the packer in UE-25c#3 this means that the hydraulic connection between the lower Bullfrog Member of Crater Flat Tuff and the water table near the top of the tuffaceous beds of Calico Hills is realized over the 350 m thickness of saturated tuffs (Figure 2). Estimates of vertical hydraulic conductivity made on the basis of the frequency dependent responses in the c-holes, are on the same order of magnitude as those measured in cores from nonwelded units, and about two to three orders of magnitude larger than measurements made on cores from moderately-to-densely welded units [7]. If conductive fractures alone provide the hydraulic connection between the water table and deeper stratigraphic units, the *in situ* measurements would be much larger than the measurements from cores which reflect matrix properties. This suggests that the vertical hydraulic connection in the stratigraphic section penetrated by the c-holes is limited by the matrix hydraulic conductivity of the nonwelded tuffs. Taken together with other information on fracture orientation and density, and fault boundaries, these results indicate that an areal two-dimensional flow model cannot adequately represent the flow geometry at the scale of the well tests, or at larger scales. Further, because of potential stratigraphic bounds on fracture connectivity, a combination of discontinuum and continuum flow mechanics may be required.

Fractures and Faults

Fracture flow is evident from well production surveys and well hydraulic stress tests. Spatially, the distribution of fractures and thus the connectivity of fracture networks is in part determined by lithologic properties. These properties are correlated to stratigraphic boundaries, that are largely perpendicular to the subvertical orientation of fractures. This realization, coupled with the emerging evidence that matrix hydraulic properties may be controlling the vertical hydraulic connection through nonwelded units, suggests that large contrasts in aquifer hydraulic properties in the vertical dimension will need to be accounted for in representative flow models of the saturated tuffs. Within a given fractured lithologic unit we expect the nature of flow through the fracture network to be relatively less continuous in the horizontal than in the vertical. If a lithologic correlation of fracture connectivity can be made, we would expect that each lithologic unit would have a unique fracture network geometry. For a relatively less fractured, and certainly for unfractured units, a single continuous fracture flow path from boundary to boundary may not exist. In these units a flow continuum based on matrix properties would be more representative of ground-water flow. Perhaps a realistic ground-water flow model would include layers of discontinuous flow fields representing fractured units interspersed with layers of unfractured tuff units with matrix continuum properties of flow.

While the above model may be adequate for the fault-bounded blocks of tuff, it does not capture the nature of the block boundaries—the faults themselves. Several pieces of evidence suggest that the c-holes intersect one or more faults [Arthur Geldon, U.S. Geological Survey, written commun., 1990; Ken Grossenbacher, Lawrence Berkeley Laboratory, written commun., 1988]. A fault could act as either a hydrologic barrier or conduit, or both, and increase or decrease the overall transmissivity over what it would be for fractures alone. The role of faults in the hydraulic structure of the ground-water flow field is one of the questions to be addressed during the multiple-well interference testing at the c-holes. Knowledge obtained at the c-holes may help understand the role of faults on the regional flow.

DESIGN OF FIELD EXPERIMENTS

Rock and fluid-flow properties consist of a scale-based hierarchicy of structured heterogeneities. An infinite number of boreholes would be necessary to deterministically characterize the highly heterogeneous, large-volume of rock at the candidate repository site. The approach that is envisaged here, therefore, is one of hypothesis testing and confidence building: One would make assumptions regarding the structure of the system using available data and then plan the next field experiment to test those assumptions. One would then either reject or modify the assumptions based on the new data. This process is repeated until sufficient confidence in those assumptions is obtained. Experiments planned at the c-holes are one step of this iterative process. In addition to collecting pertinent data for site characterization, the c-hole complex is also used as a method development site. Because a limited number of tests are possible and because interpretation of hydraulic test data is inherently non-unique, a multidisciplinary approach is envisaged, where geologic, geochemical, geophysical, geomechanical, and hydrological investigations are combined. In this section we outline the seismic tomography and the hydraulic and tracer tests planned for the c-holes.

Seismic Tomography

Cross borehole seismic tomography surveys will be conducted at the c-holes to help narrow the range of possible interpretations of geologic and hydrologic data [8]. For example, these surveys may be able to confirm the existence of faults that thus far have not been confirmed using geologic data alone. The seismic tomography will also provide information on the structure of the fracture system which will then be used to construct a fracture network model. In the seismic method attenuation and velocity are measured as a seismic wave travels through a rock, thus the seismic velocity structure is a measurement of the mechanical properties of the rock. While the hydraulic behavior is closely related but not entirely governed by the mechanical properties of a rock, it is the connectivity of the void spaces that controls the overall hydraulic properties. Therefore, seismic methods provide only indirect measurements of rock hydraulic properties and the information obtained by them should be treated as such.

The primary target of the tomography is the Bullfrog Member of the Crater Flat Tuff, which has been identified as the most productive unit by the previous hydraulic tests and at the c-holes contains the suspected fault. Seismic tomography will also be conducted between one of the c-holes and UE-25p#1, which is located roughly 500 m east of the c-holes, if a strong enough seismic source can be obtained. It would provide a critically needed large-scale image of the geologic structure.

Design of Hydraulic and Tracer Tests

Multi-zone, cross-borehole hydraulic and conservative Three five-packer strings are currently being constructed. Each string will allow water to be pumped from or injected into any one of the packed-off intervals. This is made possible through the use of mechanically controlled down-hole valves fitted in each interval. Each interval is also equipped with an independently controlled solenoid attached to the tracer line so that a tracer can be released from any interval. The spacing between the packers is adjustable and each interval is equipped with a pressure transducer and temperature sensor.

Because flow at the c-holes is highly localized and controlled by fractures, test designs based on the classic homogeneous porous medium assumption will probably be inappropriate. Instead, the tests are designed so that the heterogeneous and discontinuous flow and transport pathways can be characterized. By alternately stressing different intervals in all three holes and recording pressure transients in all the intervals in a crude tomographic fashion (Figure 3), it is expected that the hydraulic structure between the holes can be estimated. Conservative tracer tests will be carried out in much the same way by creating a convergent flow field into an interval and releasing various tracers from other intervals. Ground-water flow paths will be estimated by analyzing the tracer arrivals from the various release points. Both organic and inorganic tracers are planned for use and the analytical methods are currently under development. Single-well hydraulic and tracer tests will also be conducted and the results will be compared to those of multiple-well tests to determine whether single-well tests can be reliably applied in fractured rocks.

Another objective of the experiments at the c-holes is to test the hydrologic significance of strata boundaries and the suspected fault(s). The knowledge obtained at the c-holes may provide a first approximation toward understanding these boundary influences that could be applied and tested elsewhere throughout the site. Scale dependency of the parameters will be addressed by conducting tests at various scales. For example, the distance between c#1 and c#3 is roughly twice that between c#2 and c#3, and a planned fourth c-hole would be drilled at a distance at least twice that between c#1 and c#2. Pumping tests are planned so that interference responses may be observed in the c-holes at these scales and in other boreholes located even farther away. Transient pressure data at the pumping well may also be used to assess the existence of a scale dependent permeability structure.

Testing at the c-hole complex will provide information on local horizontal and vertical spatial variability of hydraulic properties. Site scale variability will be addressed by conducting numerous tests throughout the site. These tests may be conducted at one or more multiple well complexes or at single wells located throughout the site. Any correlation structure that may exist will be identified through statistical analyses. Cross-correlational relationships among various observed data will also be analyzed. In order to facilitate these analyses a database is being compiled that integrates all pertinent geologic, hydrologic, geochemical, and geophysical data [Joseph Downey, U.S. Geological Survey, oral commun., 1990]. Specifically, the data include borehole geophysical logs, lithology, fracture and fault information, hydraulic head, hydraulic and tracer test results, as well as cross-hole and vertical seismic images. The data base will be linked to a 3-D Geographics Information System.

DEVELOPMENT OF ANALYSIS METHODS

Heterogeneities exist at all scales. This is particularly true for fractured rocks. Simply stated, there are three different scales of interest, small, intermediate, and large. At the small laboratory scale, studies indicate that there is a large variation in the roughness within a single fracture, and that fluid flows preferentially in tortuous channels of varying flow properties. This channeling effect is observed to be further enhanced when stress is applied across the fracture. At an intermediate scale, such as at the scale of a well test, the transmissivity is often observed to vary markedly along the length of a borehole and from borehole to borehole. The heterogeneous transmissivity observed at this scale is a compound effect of the variability in the fracture density, conductance, and connectivity. Intermediate scale features including faults and fracture zones also affect the transmissivity. The large scale is the scale at which well test interference responses can not be observed at distant observation wells. Heterogeneities at this scale can be attributed to large faults and changes in geologic settings.

The overall flow system consists of the hierarchically structured heterogeneities of all scales. Therefore, the manner in which smaller scale features affect the next larger scale phenomena must be understood. This is particularly true for the regional scale hydrology because direct measurement of hydraulic properties at such a scale is not possible. One exception is the earth tide and atmospheric loading analyses, which may provide a separate estimate of hydraulic properties at the large scale. Generally, the hydraulic test results conducted at the intermediate-scale will have to be extrapolated to the larger scale. Similarly, to analyze intermediate-scale tests an understanding of the small-scale phenomena is necessary. In this section, methods for analyzing and interpreting hydraulic and tracer tests in such heterogeneous systems are discussed.

Equivalent Discontinuum Model

At the scale of well tests, a conventional porous medium model is likely to prove inappropriate to simulating ground-water flow. A model that accounts for the discontinuous and highly heterogeneous nature of fractured rocks is necessary. Because it is impossible to identify, characterize, and simulate every detail of the geometry and flow properties of small scale heterogeneities such as fractures, it is necessary to make some simplifying assumptions. One such assumption is that geometric details of the fracture system are unimportant. An equivalent discontinuum model (EDM) is thus being investigated as an approach to model the c-hole hydrology. The EDM does not attempt to reproduce every geometrical detail of the real system. Instead, it attempts to reproduce the observed behavior of the fracture system using simplified geometry while preserving the system's inherent discontinuous nature.

In order to construct an appropriate EDM an inverse method that uses hydrologic measurements to obtain fracture geometry, permeability, and storativity [9] is being investigated. The method uses an algorithm called simulated annealing which employs a statistical relation to perform a random global search for the fracture network that best describes the system behavior.

This search is equivalent to making a simulation of the fracture network, conditioned on hydrologic measurements of the network. By chosing different seeds for the pseudo-random number generator which drives the search, one can also use the method to obtain confidence intervals for prediction of the hydrologic properties of the fracture system. In this way it is possible to quantify the uncertainty in the hydrologic properties of a fracture network. The resulting network is an equivalent discontinuous system that reproduces the hydrologic behavior of the real system but not necessarily every detail of the fracture geometry. The method can also be modified to incorporate geologic and geophysical measurements of the fracture system.

An example of the EDM using the simulated annealing technique is shown in Figure 4. A hypothetical fracture network was created as the unknown "real" system to be modeled (Figure 4a). A "well test" was conducted in the network with a well located in the center of the network pumping at a constant rate. The transient pressure from the pumping well and eight observation wells were then used as the "data" to be inverted. A regular hexagonal grid was used as the starting configuration (initial guess). A change was then made to the configuration and the well test was simulated (forward modeling). The simulated annealing algorithm either rejected or accepted the new configuration based on a statistical rule evaluating the improvement made by the change. The process was repeated until the difference between the "data" and the model predictions was minimized. Figure 4b shows the resulting EDM for the hypothetical network. The model has successfully recaptured the hydraulic features of the "real" system.

Fractal Analysis

The problem of scaling-up is an essential element in the site characterization effort. Field tests can not be designed to stress a large enough volume of rock nor can enough boreholes be drilled to sample and test every aspect of the site. Scaling-up is extremely difficult in a highly heterogeneous system and one needs to make some assumptions regarding the structure of the heterogeneity at the large scale. One appealing assumption is that the heterogeneity has a fractal structure.

Previous works have applied a fractal approach in describing scale heterogeneities in porous media. Barton [10] observed that geometric parameters of fractures, such as the trace length distribution, exhibit fractal characteristics. Barker [6] solved the equation of flow to a well in fractional dimension space (as opposed to integral dimension space, i.e.; two or three-dimension space) and presented type curves for various dimensions. One can intuitively draw an association between a fracture system and a fractal. Simply put, a fractal implies that the space is fragmented or irregular, which is the very characteristic of fracture systems. Polek *et al.* [11] showed through numerical studies that a flow system with a fractal structure displays a characteristic signature in the well test response curve as predicted by Barker. Neuman [12] in a recent paper related the scale dependent dispersivity to fractal structure.

The design and analysis of the hydraulic and tracer tests to be conducted at the c-holes and elsewhere in the Yucca Mountain area will include testing of this fractal hypothesis. Pumping tests will be conducted to estimate parameters at different scales. Preliminary analysis of past c-hole hydraulic tests indicate that the flow dimension is between two and three. Although it is known that the flow dimension is always less than the geometric fractal dimension, and that the flow geometry is a subset of the actual geometry [11], outcrop mapping is planned to obtain independent information regarding the fracture structure. One of the questions to be addressed is whether there is a consistent fractal dimension to describe the fracture system over a wide range of scales. More than one fractal dimension may exist because various geologic features are generally caused by mechanisms acting on discrete scales. Nonetheless, if it can be shown that the system behaves like a fractal, and the structure of the system can be estimated through the use of well tests, fractal analysis will become a powerful tool in characterizing otherwise difficult heterogeneous systems.

SUMMARY

The geology of the saturated zone at Yucca Mountain primarily consists of rhyolitic ash-flow and air-fall tuffs. Outcrop mapping and borehole logs revealed extensive sub-vertical fractures in the tuffs. Many north-south trending extensional faults are also present in the area. Preliminary hydraulic tests indicate that ground-water flow in the saturated zone is typically dominated by a few fractures or groups of fractures. The majority of fractures mapped in boreholes do not contribute to flow. Hydro-mechanical analyses indicate formation fluid at depth is hydraulically connected to the water table. The hydrologic role of faults is yet to be determined. The overall hydrologic system of the area is expected to be highly heterogeneous.

Because an infinite number of boreholes would be necessary to deterministically characterize the highly heterogeneous, large volume of rock at the candidate repository site, the approach that is envisaged is that of hypothesis testing and confidence building: One would make assumptions regarding the structure of the system using available data and then plan the next field experiment to test the assumption. One would then either reject or modify the assumption based on the new data. This process is repeated until sufficient confidence is obtained. Because interpretation of hydraulic test data is inherently non-unique, a multidisciplinary approach is envisaged, where geologic, geochemical, geophysical, geomechanical, and hydrological investigations are combined.

The experiments planned at the c-hole site include seismic tomography and multi-level, cross-borehole hydraulic and tracer tests configured in a crude tomographic fashion. The data will be analyzed using the equivalent discontinuum approach, which is specifically designed to capture the discontinuous and heterogeneous nature of the fracture-controlled flow structure. Use of fractal representation will be investigated as a means to scale-up information obtained at smaller scales. The conceptual model thus constructed will be tested and calibrated against data from tests conducted in new and existing boreholes located throughout the site.

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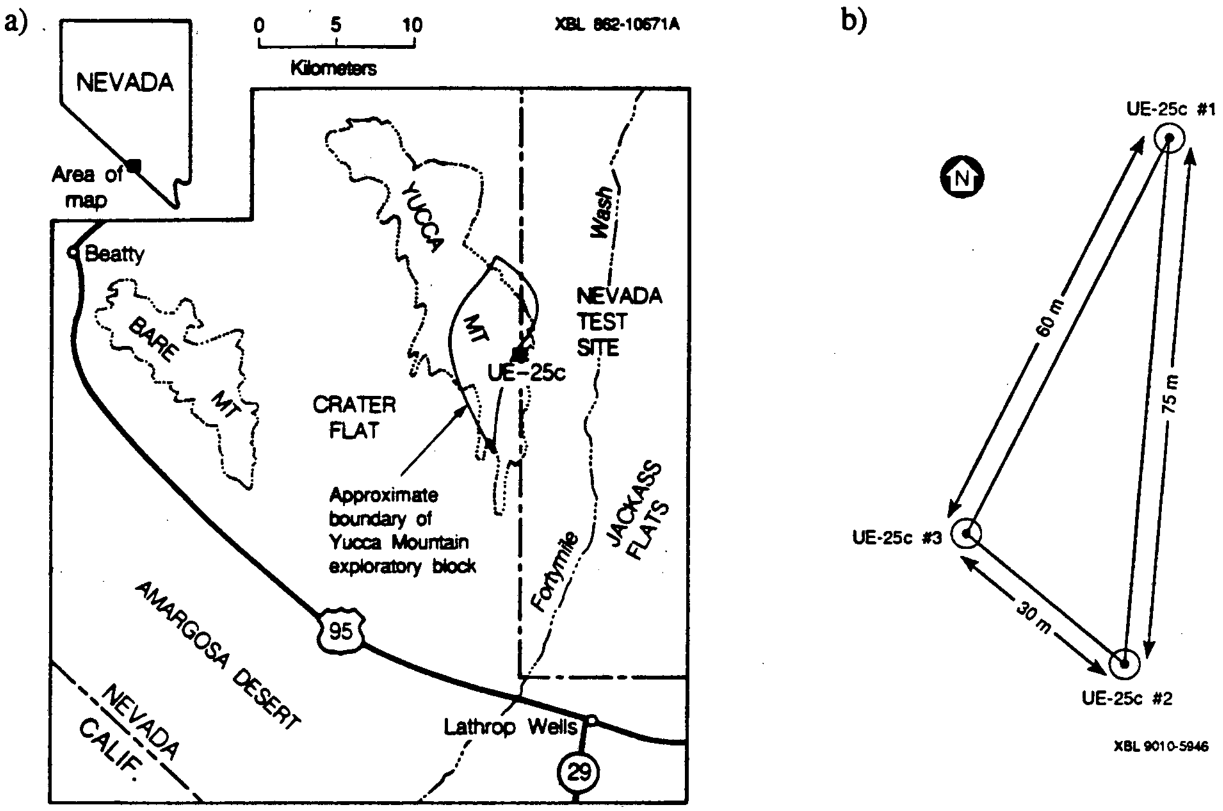

Figure 1. a) Location map of Yucca Mountain and vicinity, and b) surface layout of UE-25c-holes.

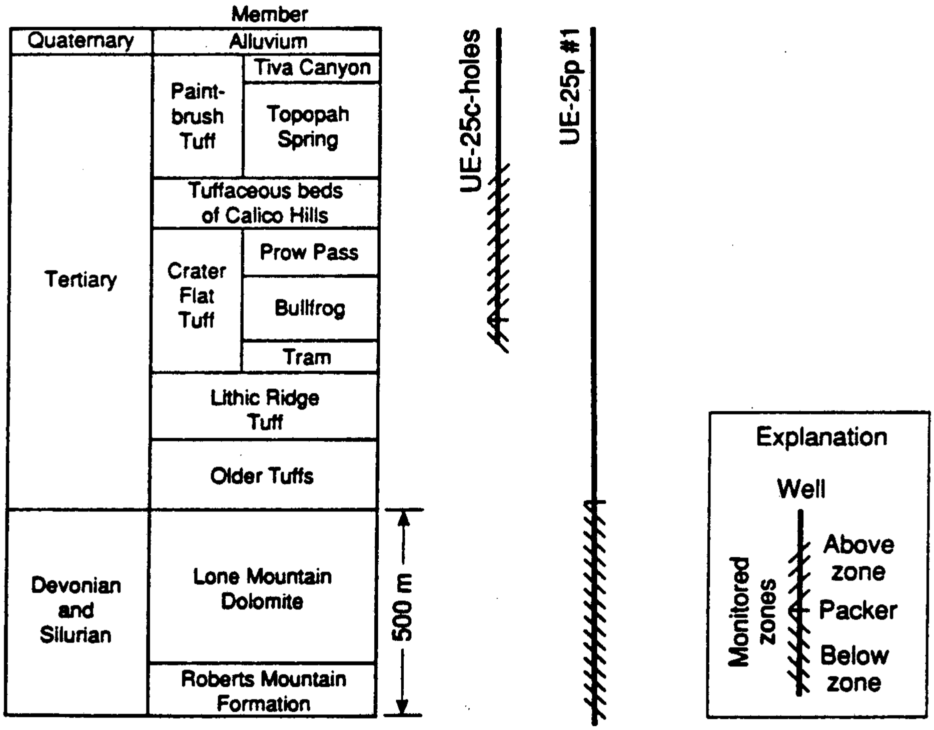

Figure 2. Schematic stratigraphic column of the rock units penetrated by UE-25p#1 and the c-holes.

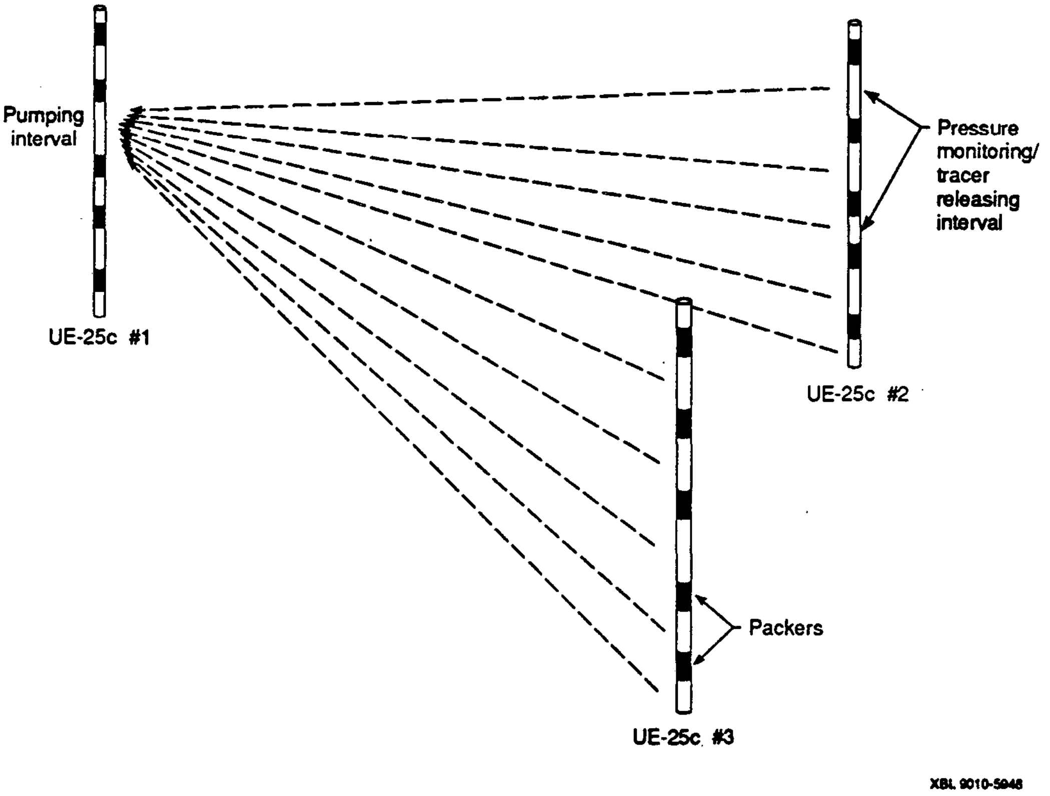

Figure 3. Tomographic configuration of multi-level, cross-hole hydraulic and tracer test.

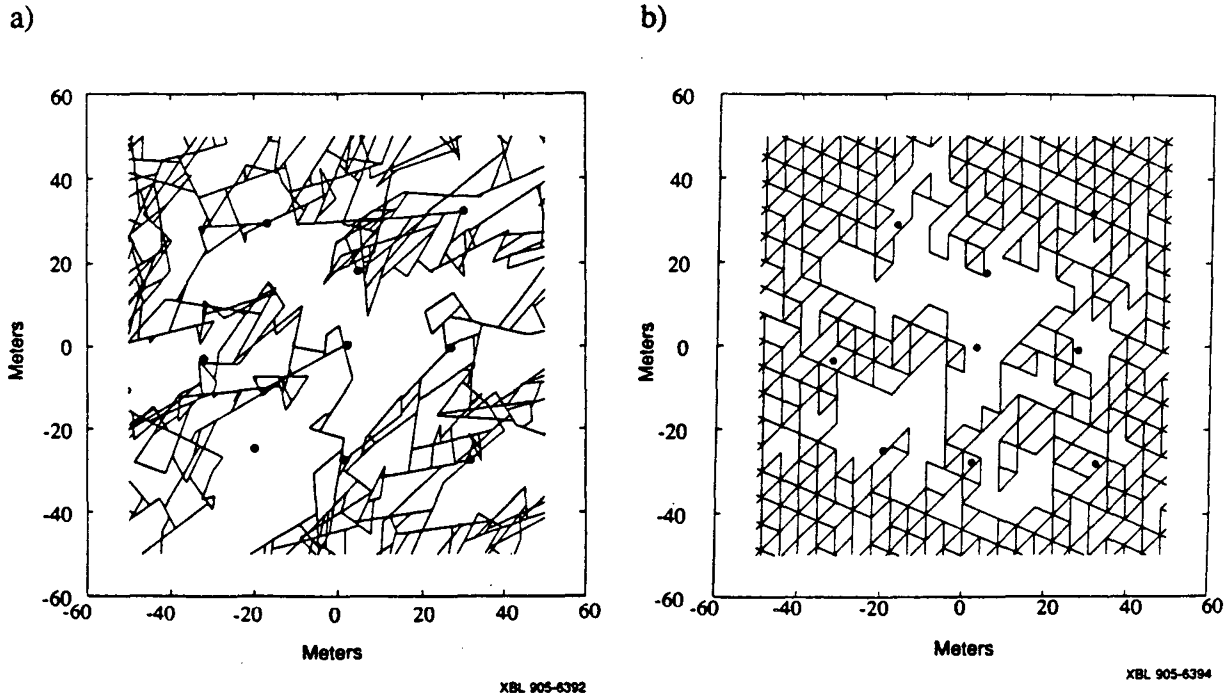

Figure 4. a)"Real" fracture network and b) Equivalent Discontinuum Model of "real" fracture network.