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Authors
Karasaki, K.
Landsfeld, M.
Grossenbacher, K.A.

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K. Karasaki, M. Landsfeld, and K. Grossenbacher

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*K. Karasaki, M. Landsfeld, and K. Grossenbacher**

Earth Sciences Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

*Department of Earth and Planetary Sciences
Johns Hopkins University
Baltimore, Maryland 21218

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BUILDING OF A CONCEPTUAL MODEL AT THE UE25-C HOLE COMPLEX

Kenzi Karasaki and Martin Landsfeld
Earth Sciences Division
Lawrence Berkeley Laboratory
Berkeley, CA 94720
(415) 486-6759

Ken Grossenbacher
Dept. of Earth and Planetary Sciences
Johns Hopkins University
Baltimore, MD 21218
(301) 338-8000

ABSTRACT

U.S. Geological Survey and Lawrence Berkeley Laboratory are attempting to construct a conceptual model of the UE25-c hole complex. An interdisciplinary approach is discussed where all the available data are integrated. Site geology, borehole geophysics and hydraulic test results at UE25-c hole complex suggest that groundwater flow may be controlled by fractures and faults. Significant clusters of fractures in the C-holes are perpendicular to bedding and may be cooling cracks or may be tectonically induced. Unresolved evidence indicates that a fault may intersect the C-holes. For these reasons a porous medium approximation of the rock in the saturated zone at the scale of a well test may be inappropriate. Instead, an Equivalent Discontinuum Model is proposed to model the UE25-c complex hydrology. EDM does not reproduce every geometrical detail of the real system, but instead, attempts to reproduce the observed behavior of the fracture system while preserving the inherent discontinuous nature of the system.

INTRODUCTION

The planned high level nuclear waste repository at Yucca Mountain, Nevada will lie in fractured welded tuff, in the unsaturated zone. One possible pathway for contaminants into the biosphere is transport by groundwater flow down to and then laterally through the saturated zone. As a way of investigating this process, three wells; UE25c-1, 2, and 3 (hereafter called the C holes), were drilled by the USGS to study hydraulic properties of rock formations underlying the planned waste repository (Fig. 1). The location of the holes is ideal in that the formations in the unsaturated zone occur at the same depths and with the same thicknesses as at the repository site. The C-holes penetrate to a depth of 3000 ft, and form a triangular prism with separation among the wells of 100–250 ft. Geophysical and geologic logs are available for these holes. Information on the degree of welding of the tuffs and formation stratigraphy are included in these logs. The surface geology has also been mapped.[1]

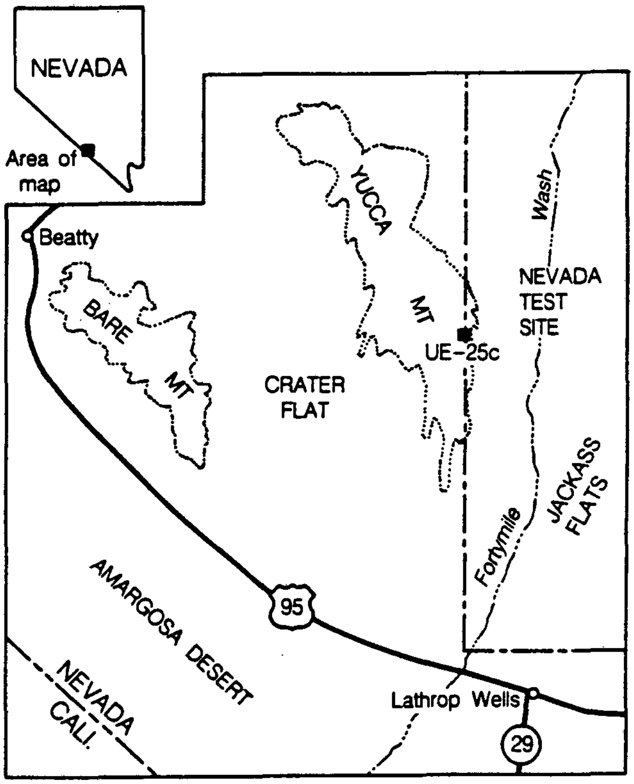

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Figure 1. Location of Nevada Test Site and UE25-c hole complex.

As a first approximation, the geology near the C-holes consists of layer cake stratigraphy, with many layers of Miocene rhyolite tuffs, each a few hundred feet thick. The bedding is flat, strikes approximately N2W and dips 18 E. Folding is virtually absent. Most faults trend North-South, dip steeply westward, and are extensional. Because the rock matrix in the saturated zone is relatively impermeable, it is believed that the groundwater flow takes place mainly in fractures.

It is most important that the conceptual model is based on a good understanding of the fracture system and embodies the essential hydrologic features observed in the filed. Al pertinent data should be integrated and possible correlations among different types of data should be identified. The data to be integrated include site geology, borehole logs, past and future hydraulic and tracer tests, VSP (vertical seismic profiling) and crosshole seismic tomography. The USGS and LBL are undertaking a multi-disciplinary approach where geologists, hydrologists, geophysicists, and statisticians work interactively. The model constructed at this multi-well complex will be applied to and calibrated against the future hydraulic and tracer tests planned elsewhere in the mountain.

DATA AND MODEL FORMULATION

Data interpretation and conceptual model development are closely intertwined. Without data, a realistic conceptual model can not be formulated. On the other hand, how data are interpreted often depends on the conceptual model for which the interpretation method is originally conceived. Let us take well test analysis for example. Well testing is a means of estimating the parameters and geometry of a groundwater flow system by inducing some artificial disturbance in a well and monitoring the response of the system. The response of the system is a function of the geometry and the flow parameters of the system. Therefore, given a conceptual model of the system, one can deduce the parameters appropriate to that model by analyzing the response. In order to estimate the flow parameters and geometry from the well test data, one must first establish a conceptual mathematical model for the theoretical behavior of the system. This is done by comparing the well test data to the behaviors of various known conceptual models subjected to the same test conditions. Geologic information obtained through some other means may help this process. Once a model is adopted, the flow parameters and geometry may be calculated by using an analysis technique developed for the model. Similarly, conceptual models are applied in the analysis of other field tests such as geophysical measurements.

System behavior predicted by conceptual models may not be unique. A number of possible conceptual models with different combinations of geometry and flow parameters may yield the same theoretical response at a given point. For this reason, there is always an inherent question about the uniqueness of a solution to a well test problem like many other inverse problems. The degree of uncertainty can be reduced by having many observation points, although it is not usually practical to do so. Because there are only three wells at the C-hole complex, the problem of non-uniqueness will probably not be resolved. An alternative to drilling many more holes is to utilize all the available non-hydrologic data such as site geology, borehole logs and seismic data as well as hydrologic data (see Fig. 2). The current conceptual model should be consistent with those data. This interactive process should help bracket the range of possible conceptual models. On the other hand, it is sometimes impractical to construct a model that explains all the data. In such cases the various data need to be prioritized in terms of hydrologic significance. Only the features that have first order effects on the overall hydrologic behavior of the system should be modeled. For example, small fractures that do not contribute to the permeability and first arrival of tracers may be disregarded. A parametric study will help determine these relationships.

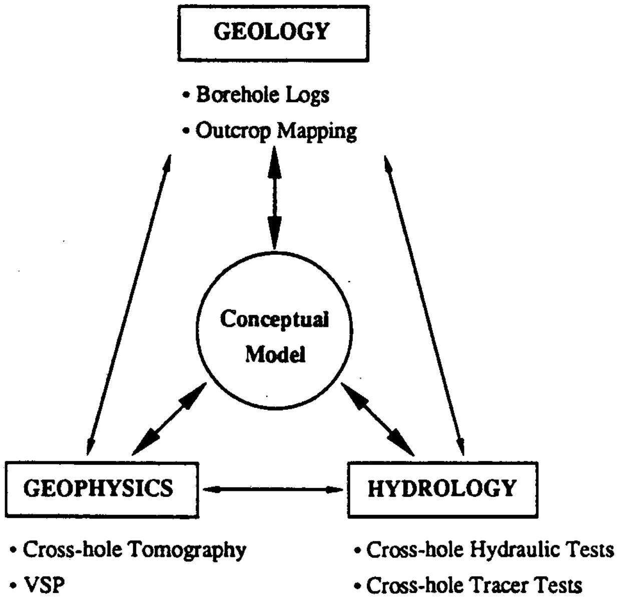

Figure 2. Interdisciplinary and iterative approach to conceptual model development.

A conceptual model should be constantly updated as more data become available. In the case of the C-holes, future data collection plan includes outcrop mapping of the saturated zone intervals, crosshole seismic tomography, crosshole hydraulic and tracer tests.

C-HOLE FRACTURES AND HYDRAULIC PROPERTIES

In the process of conceptual model development for the C-holes, one of the issues of interest is how flow occurs within fractures and through network of fractures. As a way to help further the understanding of flow in C-hole fractures, a database that integrates all pertinent data is being compiled. The database is being used to identify possible correlations among different parameters through statistical analyses. The database includes geological, hydraulic, and borehole geophysical and geochemical data. Results from the future crosshole hydraulic and tracer tests as well as seismic tomographic and outcrop studies will be added to the database as they become available. Knowledge obtained at the C-holes may help understand how the flow occurs in the regional scale, which is vital in the site characterization effort.

Hydraulic tests conducted by USGS in 1984 include a series of falling head injection tests in C-1, involving 27 separate packed off intervals.[2] These hydraulic tests were of preliminary nature and the pressure data do not fit existing analytical curves very well. Therefore, absolute values of the flow parameters are very difficult to estimate. However, relative decay times for the pressure in each of the tests yield relative transmissivity for each interval. These interval results are combined to form a graph of transmissivity as a function of depth. Data from the seisviewer, a sonic device which shows the depth, strike, and dip of fractures, allows comparison of transmissivity to fracture location. Because more than one fracture are observed in each zone, each fracture is assigned a maximum possible transmissivity and a theoretical average transmissivity. The former is the transmissivity of a zone itself and the latter is the transmissivity of a zone divided by the number of fractures in a zone when there are no overlapping zones. When there are overlapping zones, transmissivities are 'sifted' among overlapping and non-overlapping sections and a maximum possible transmissivity is assigned for each section. A maximum possible transmissivity of a fracture is therefore equivalent to that of the section that contains the fracture.

The angle that a fracture makes with the bedding plane can be significant in deciding the origin of the fracture, so two new parameters are introduced; restored strike and dip. To find these parameters, all fractures are rotated about a horizontal axis (the line of bedding strike), so they appear as they would if the bedding plane were horizontal. In analyzing the fractures, 9 parameters were defined for each one: depth, strike and dip, restored strike and dip, stratigraphic unit, degree of welding, and transmissivity, both average and maximum. A computer aided statistical analysis tool was used to produce: histograms of each parameter, scatter plots of transmissivity versus each of the other parameters, and perspective plots of transmissivity as a function of strike and dip. In analyzing the histograms, several patterns appear: Depths of fractures tend to cluster around the central, more welded portions of each tuff. Histograms for both restored and unrestored dips are shown in Fig. 3. As can be seen in the figure, restored dips tend to cluster logarithmically around 90 degrees. This implies that most of the fractures may have been formed during the cooling stage, although it cannot be stated conclusively.

A single high transmissivity fracture shows up as a clear outlier on both the maximum transmissivity and the average transmissivity histograms (not shown). This fracture apparently accounts for 60 percent of all water production in C1. That the transmissivity is highly localized is an indication that a porous medium approximation may not be appropriate to model hydrologic processes at the C-hole scale. Scatter plots of average and maximum transmissivity versus each of the other parameters show that average and maximum transmissivities correlate well with one another (not shown). Average fracture transmissivity varies among the stratigraphic units, and fractures that dip steeply have the highest transmissivity. To investigate the correlation between transmissivity and orientation, strike and dip are plotted horizontally and transmissivity is plotted vertically. Four such three-dimensional graphs can be plotted, showing average and maximum transmissivities as functions of strike and dip, and of restored strike and dip. Figure 4 shows an example of such plots. These plots all show humps in the transmissivity of fractures which strike

```
UE25C#1 Fracture Dips                   UE25C#1 Rotated Fracture Dips
---------------------                   -----------------------------

 2 : 59
 3 :
 3 :                                        3 : 6
 4 : 344                                    4 : 013
 4 : 7899                                   4 : 59
 5 : 02224                                  5 : 0024
 5 : 56666677888999                         5 : 7899
 6 : 01111111222222223334                   6 : 001123
 6 : 55677888889                            6 : 5556789
 7 : 000000111123 4444                      7 : 112233334444
 7 : 55556677888899 9                       7 : 55556666677888888999
 8 : 000111122233                           8 : 0000122223333 3334
 8 : 67                                     8 : 5555555666666667777778 8899
                                            9 : 00

    N = 105   Median = 67                      N = 105   Median = 78.1
    Quartiles = 58.3, 75.2                     Quartiles = 67.4, 84.7

           Decimal point is 1 place to the right of the colon

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Figure 3. Dip histograms of restored and unrestored fractures.

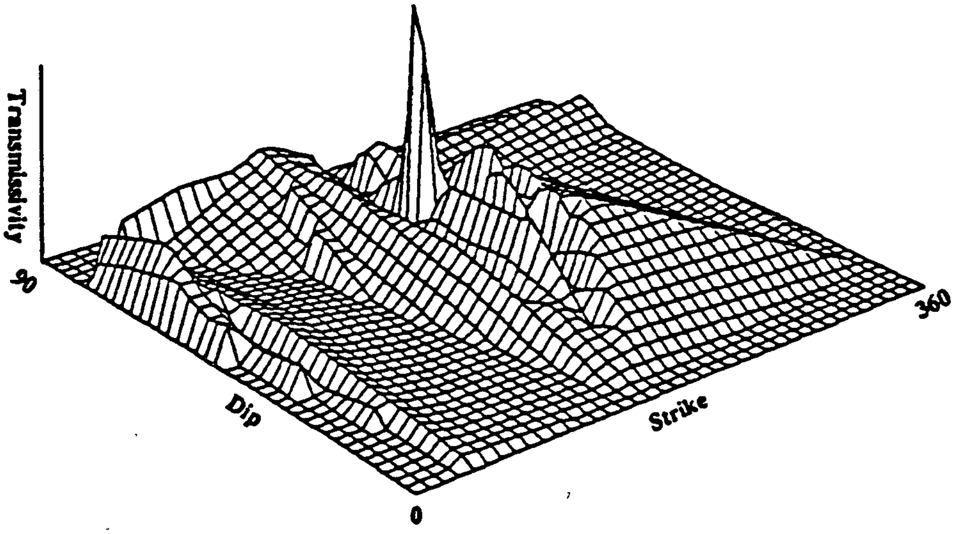

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Figure 4. Perspective plot of transmissivity as a function of strike and dip.

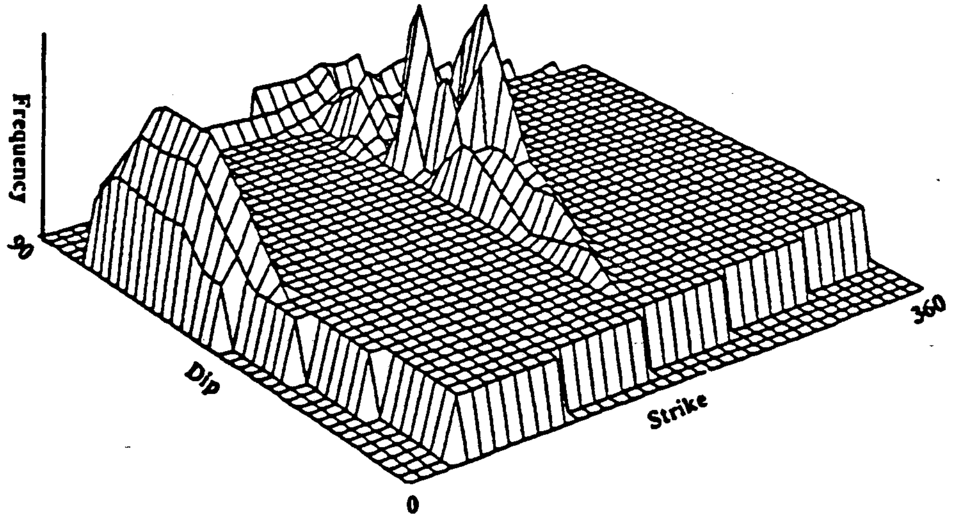

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Figure 5. Perspective plot of frequency as a function of strike and dip.

150–200 degrees and which dip either 60–90 degrees, for rotated strike and dip, or 30–70 degrees, for the non-rotated strike and dip. One problem in interpreting these graphs of transmissivity as a true function of strike and dip is that the frequency of fractures with respect to strike and dip space will affect the transmissivity plotted. A 3-D smoothed histogram of frequency with respect to strike and dip closely resembles the corresponding graphs of transmissivity (see Fig. 5). The apparent correlation between transmissivity and orientation seen earlier may in fact be an artifice due simply to having a large number of fractures with similar orientation.

Two pumping tests conducted in C-3 in May 1984 and November 1984 recorded markedly different drawdowns despite comparable pumping rates. The only difference in the test configuration is the packer locations in the remaining two wells. This contradiction is likely to be a result of discontinuous flow paths that are short-circuited by one of the boreholes. This is another indication why a porous medium approximation of the rock in the saturated zone may be inappropriate.

LOCATION OF A FAULT

Site geology, borehole geophysical logs and pumping test results all suggest an existence of a fault in the vicinity of the C-holes. The geophysical logs correlate from hole to hole in the upper 2700 ft of the well, however, below 2700–2800 ft, they abruptly stop correlating in one of the wells. Presumably, this break occurs within the bottom most formation in the wells, so formation boundaries are useless in figuring out the reason for this break. Also at 2700–2800 ft, the well diameters increase by a factor of two for vertical distances of 5–10 ft. Taken together, the break in correlation and the hole enlargements suggest departure from simple layer cake stratigraphy. Possibly a fault runs through the bottom of the wells. A projection of the plane containing the hole enlargements, when projected up to the surface, aligns with the mapped trace of a major fault. Drawdown curves from all three wells during pumping tests flatten at intermediate times. This may be an indication of a constant pressure boundary caused by a fault, although other hydrologic features such as leakage or spherical flow can also cause flattening of drawdown curves.

USGS and LBL are planning to conduct cross-hole seismic tomography imaging in the C-holes, which may help resolve the question of the fault's existence. A fault, if present, could drastically affect groundwater flow, and therefore change the interpretation of the hydraulic tests. It could act as either a hydrologic barrier or conduit, and either increase or decrease the overall transmissivity over what it would be for fractures alone. It is the key issue yet to be answered: what influence does other geologic features besides fractures, such as the fault, have on the overall hydrology at the C-holes. In fact, many faults are mapped throughout the Yucca Mountain area. Knowledge obtained at C-holes may help understand the role of the faults on the regional flow.

FRACTURE DEVELOPMENT THEORY

Understanding how the fractures at the C-holes developed will help understand the C-hole hydrology, although some fractures subsequently get filled or altered in a geologic time. Cooling cracks form due to thermal contraction as the tuff cools after emplacement. If the tuff cooled purely through conduction through the rock, the isotherms would be horizontal, and so would the maximum tensile stress. Therefore the cooling fractures should be vertical. If meteoric waters enter the initial cracks, however, they will cause the isotherms to form a depression around the crack.[3] Subsequent cooling cracks will then be perpendicular to these new isotherms, and will tend to radiate away from the tip of the original fracture. In a cooling basalt flow, water infiltration through initial cooling cracks can cause the crack tip to propagate into the liquid portion of the flow.[4] If an analogous process happens in a tuff, the fracture patterns associated with cooling a tuff may be similar to those in cooled basalts. Computer programs developed for predicting the formation of dikes[5] could be modified to analyze formation of these cooling cracks in tuffs (Steve Martel, oral communication).

3-D RENDERING OF STRIKE, DIP AND DEPTH

In interpreting well data and understanding fracture patterns, one problem is the difficulty in visualizing both strike and dip simultaneously as they vary with depth. One way of resolving this problem is to plot level surfaces of the density of fracture orientation as a function of strike, dip, and depth. Depth would plot vertically, then strike and dip horizontally on a stereo net projection. This would plot as a vertical cylinder representing the borehole. A computer, could then plot a series of cut away level surfaces of the fracture frequency as a function of both orientation and depth. This approach could include shading the plot, with tone as a function of transmissivity. The final plot would simultaneously illustrate depth, strike, dip, orientation, and fracture transmissivity.

As a first approach to producing these level surfaces, stereo-scope plots of fracture orientation versus depth have been produced (see Fig. 6). This yields a 3-D image of a

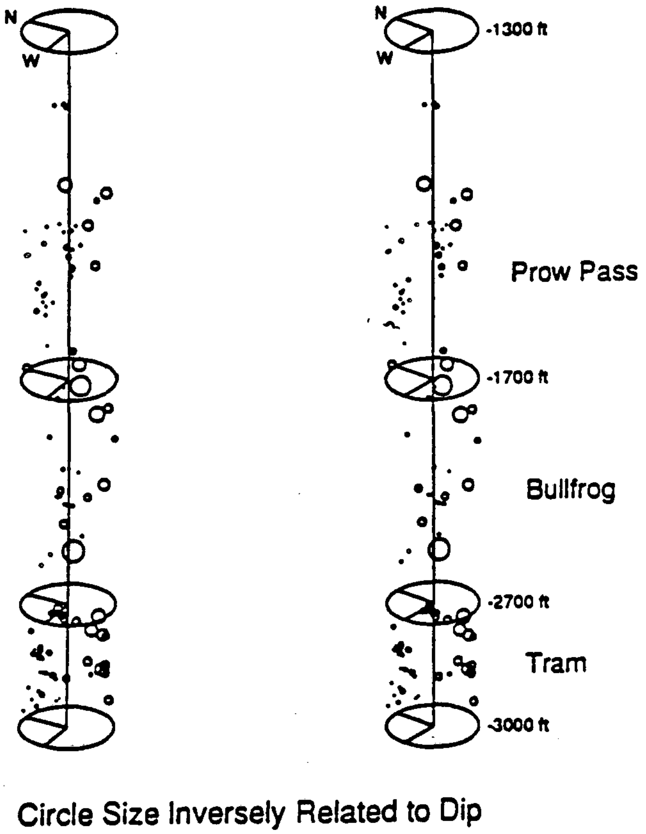

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Figure 6. Stereoscopic plot of fracture orientation versus depth.

cylinder, as described above. The distinctive cluster of fractures around the vertical (much more so than for the unrestored dips) suggests some controlling mechanism may be responsible. One such mechanism is the formation of cooling cracks perpendicular to the bedding plane. Another possibility is that the cracks are tectonically induced, and due to the tensile stresses formed during folding along the outer radius of a fold, thus causing the fractures to be perpendicular to the bedding plane.

One problem with trying to separate cooling cracks from tectonically induced cracks on the basis of orientation, is the lack of calibration. This problem could be resolved by using a database for fracture orientation from the detailed outcrop mappings, where particular fractures are known to have formed during cooling (Chris Barton, oral communication).

EQUIVALENT DISCONTINUUM MODEL

A conceptual model needs to be translated to a numerical model that can be used to predict hydrologic behaviors. In the case of the C-holes it is believed that flow is controlled by fractures and possibly by a fault as well. Therefore, a conventional porous medium model seems to be inappropriate. Instead, a model called EDM (equivalent discontinuum model) is proposed to model the C-hole hydrology. EDM does not need (and practically, it is impossible) to reproduce the every geometrical detail of the real system. Instead, it attempts to reproduce the observed behavior of the fracture system while preserving the inherent discontinuous nature of the system.

In order to construct an appropriate EDM we are investigating an inversion method that uses hydrologic measurements to find fracture geometry, permeability and storativity.[6] 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 conditional 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 find confidence intervals for prediction of 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 the every detail of the fracture geometry (see Fig. 7). The method can be easily modified to incorporate geologic and geophysical measurements of the fracture system. Further, the method is simple to implement and is mainly restricted by computation time.

SUMMARY

The USGS and LBL are attempting to develop a conceptual model of the groundwater flow system in the saturated zone at the C-hole site. Knowledge obtained at the C-holes may help understand how the flow and transport process occur in the regional scale, which is vital in the repository site characterization effort. An interdisci-

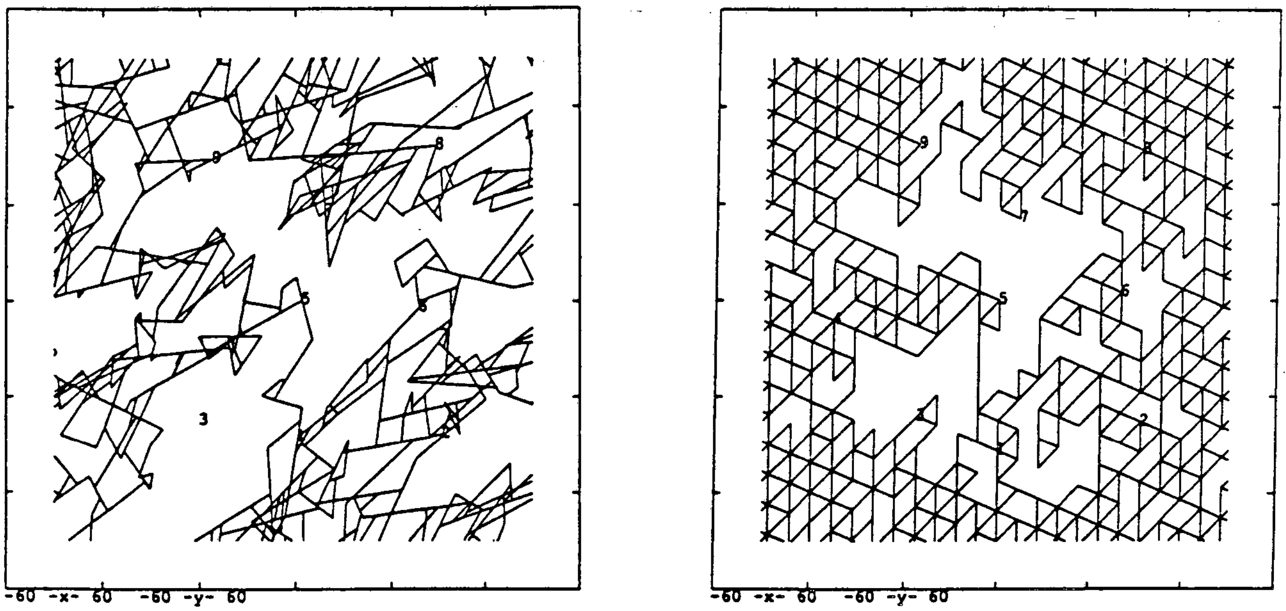

Figure 7. Equivalent discontinuum representation (left) of fracture network (right).

plinary approach is being used where all the available data including site geology, borehole logs, hydraulic test results and crosshole seismic tomography data are integrated.

Significant clusters of fractures in the C-holes are perpendicular to bedding and may be cooling cracks or may be tectonically induced. Further analysis of these clusters could help form a basis for building a model of the fracture network. Other clusters of fractures appear associated with zones of high permeability. Further analysis of these fractures could help yield a basis for relating fracture orientation to permeability.

Unresolved evidence indicates that a fault may intersect the C-holes. If so, it could act hydraulically as either a barrier or conduit, and overwhelm the effect of fracture permeability on the hydraulic test response. Therefore, successful interpretation of the well data depends on an accurate determination of the fault's location. Toward this end, crosshole seismic tests are planned to locate any such fault.

The Equivalent Discontinuum Model is proposed to model C-hole hydrology. EDM does not reproduce every geometrical detail of the real system, but instead, attempts to reproduce the observed behavior of the fracture system while preserving the inherent discontinuous nature of the system.

ACKNOWLEDGEMENTS

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