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The Nagra-DOE Cooperative Project

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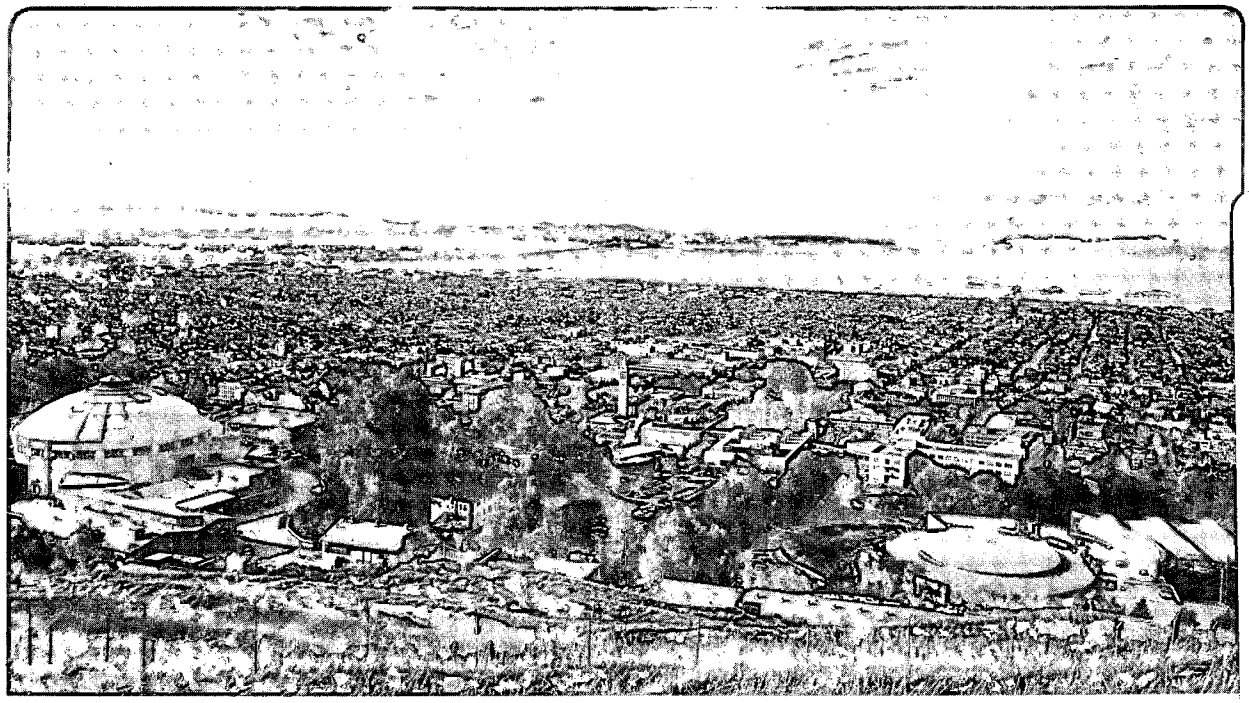

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The Nagra-DOE Cooperative Project

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THE NAGRA-DOE COOPERATIVE PROJECT

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ABSTRACT

The Nagra-DOE Cooperative (NDC-I) research program was sponsored by the U.S. Department of Energy (DOE) through the Lawrence Berkeley Laboratory (LBL), and the Swiss Nationale Genossenschaft für die Lagerung radioaktiver Abfälla (Nagra). Scientists participating in this project explored the geological, geophysical, hydrological, geochemical, and structural effects anticipated from the use of a rock mass as a geologic repository for nuclear waste. The principal investigators for LBL were Jane C. S. Long, Ernest L. Majer, Karsten Pruess, Kenzi Karasaki, Chalon Carnahan and Chin-Fu Tsang for LBL and Piet Zuidema, Peter Blümling, Peter Hufschmied and Stratis Vomvoris for Nagra.

Six joint tasks were defined and are described briefly below. Tasks 1, 2, 3 and 5 were concerned with the characterization of fractured rock. Task 5 in particular was focused on investigations at the Grimsel Underground Laboratory in the Swiss Alps (Figure 1). Tasks 2 and 6 focused on the phenomenology associated with storing radioactive waste underground.

A series of sixteen technical reports document the results of the three year NDC-I project which concluded in 1990. The reports in this series are given in the reference list below. The accomplishments of the six tasks are summarized below.

TASK 1. DETERMINATION OF FRACTURE HYDRAULIC PARAMETERS BY MEANS OF FLUID-LOGGING IN BOREHOLES

Fractures in relatively impermeable rocks are considered to be the main conduits for the transport of nuclear waste. The only way to access these rocks and characterize the fractures before excavation is through boreholes. Thousands of meters of borehole are being drilled for this purpose. Characterization of the distribution of permeability in these holes can be time consuming and expensive. Fluid logging is a possible alternative to packer testing which may be very efficient.

The purpose of this study was to develop interpretation methodology for fluid logging[1,2,3] able to quickly identify and characterize the permeable zones in a wellbore, even if these zones are of low permeability and to determine key fracture parameters.

In this technique, the borehole is flushed with deionized water and the resistivity of the borehole fluids is monitored as the more saline native waters flow into the borehole through the fractures. Figure 2 shows a typical resistivity log taken under these conditions at several different times after flushing has ceased.

The analysis of this data is able to yield the location of inflow, the amount of inflow at each point, and the concentration of inflowing water

A comparison of fluid logging interpretation and packer testing interpretation was made. Fluid logging compared favorably, indicating that fluid logging may provide an excellent alternative to the more expensive and time consuming packer testing technique.

TASK 2. DEVELOPMENT AND APPLICATION OF NEW SOLUTIONS FOR WELL TEST ANALYSIS IN FRACTURED MEDIA

Slug tests are widely used to estimate the flow parameters of rocks in the field because they are relatively inexpensive and easy to conduct. However, in low permeability rocks, it takes a long time to complete these tests. Therefore, they are often terminated prematurely. This task developed a solution to this well test behavior and an analysis method for interpreting prematurely terminated slug test (PTST) data.[4,5] A systemized procedure of a PTST is proposed, where a slug test is terminated in the midpoint of the flow period, and the subsequent shut-in data is recorded and analyzed. This method requires a downhole shut-in device and a pressure transducer, which is not more than the conventional deep-well slug testing equipment. As opposed to slug tests, which are ineffective when a skin is present, more accurate estimates of formation permeability can be made using a

PTST. Premature termination also shortens the test duration considerably. Because in most cases no more information is gained by completing a slug test to the end, PTST are recommended over traditional slug tests.

This interpretation was applied to available data from the deep boreholes in Northern Switzerland showing a much improved fit to the data than otherwise available. The analysis indicated that the formation permeability may be as much as one order of magnitude larger than the value based on no-skin analysis.

TASK 3. INTERDISCIPLINARY METHODOLOGY FOR CHARACTERIZING FRACTURE HYDROLOGY

Efforts to develop an interdisciplinary approach to the characterization of fracture hydrology have been ongoing at LBL over the past several years. The methodology incorporates the many kinds of geologic, geophysical, and hydrologic data into models of the fracture hydrology. This task documented the methodology in its current state and provided example illustrations of applications at several sites, including the Grimsel Rock Laboratory in Switzerland.[6]

The purpose of the report is to show how different types of information can be combined to develop a hydrologic model of a fractured rock. Geologic investigations provide an understanding of the systematic of the fracture system. The systematics help to identify the types of fracture features that may be important conductors of fluid. Geophysical measurements are then focused on finding these important features. Well tests are designed based on the structures identified with the geologic and geophysical data. Analysis of the well test data provides a diagnosis of the hydrologic role of the features identified in the geologic ad geophysical interpretation.

The next step is the development of a conceptual model for fluid flow. For example, in a number of granitic sites, the conceptual model gives the location of the major conductors which are fracture zones. These zones are discretized in the process of building a numerical model. A final step employs inverse methods to define the hydrologic properties of the zones and build a model capable of predicting flow.

Figure 1. A view to the South of the Swiss Alps in the vicinity of the Grimsel Underground Laboratory. The lab lies under the mountain which is behind the lake on the right.

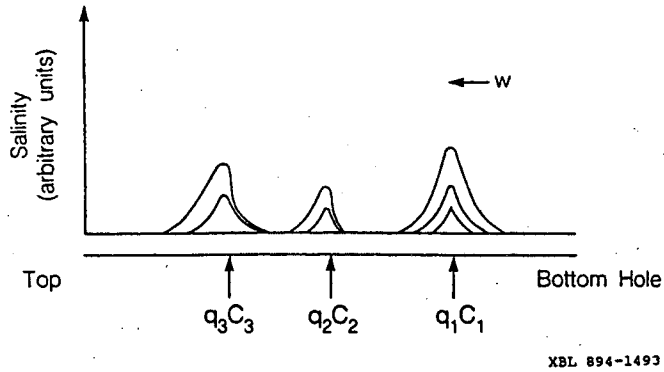

Figure 2. Schematic picture of alinity curves from three inflow points in a wellbore at three early times. Higher curves correspond to later times.

TASK 4. INVESTIGATION OF TWO-PHASE GAS-LIQUID FLOW IN FRACTURED MEDIA

Some nuclear waste repositories may release significant amounts of gas due to corrosion. This task helped to define the potential impacts of this gas release using a multi-phase code, TOUGH.[7] This effort in modeling unsaturated conditions is useful for understanding the behavior of the unsaturated zone at Yucca Mountain where two fluid phases (liquid water and formation gas) are present under natural conditions. A schematic two-dimensional vertical section through a potential swiss site was modeled with TOUGH. Two reference cases were considered which represent the formations as a porous and as a fractured-porous (dual permeability) medium, respectively. Both cases predict similar and rather modest pressure increases, from ambient 10 bars to near 25 bars at the repository level. These results are to be considered preliminary because important parameters affecting two-phase flow, such as relative permeabilities of a fracture medium, are not well known at present. This work points to the need to determine two-phase flow parameters for fractured rock.

A second part of this task performed scoping studies for a gas injection test at the FRI (Fracture Research Investigation) site at Grimsel (see Task 5 below) and mini-ventilation tests also performed at Grimsel.[8] Results again indicated the need to understand two-phase flow in fractures on a fundamental level.

TASK 5. UNDERGROUND ROCK LABORATORY STUDIES

This task had several sub-tasks, the largest of which was concerned with an experiment called the FRI (Fracture Research Investigation).[9] The FRI centered on a clearly identified and accessible fracture zone. This zone was subjected to geologic, geophysical, geomechanical and hydrologic characterization in an effort to calibrate our ability to find and understand fracture zones. The largest part of the effort was extensive geophysical imaging with seismic techniques which gave insight into how hydrologically significant features can be seen with geophysics.

The FRI fracture zone cuts across two parallel tunnels approximately 20 m apart. Two boreholes were drilled between the tunnels approximately 10 m apart. Tomographic data were collected from the boreholes and the drifts. Thus four-sided tomography of the FRI was possible. The 1987 tomogram is shown in Figure 3. The tomogram clearly shows the fracture zone and the damage zones near each of the tunnel walls. The 1988 tomograms were conducted at a higher frequency. The FRI fracture zone is not as visible at this frequency. The example demonstrates the need to adjust and calibrate geophysical techniques to the rock type and feature of interest.

A second part of Task 5 was an analysis of the Migration Investigation (MI) fracture zone data.[10] The task focused on the analysis of hydrologic interference data taken within a fracture zone (the MI zone) similar to the FRI zone. A new inverse technique based on simulated annealing was applied to this data to develop equivalent discontinue models of the fracture hydrology. An equivalent discontinuum model is a lattice of conductors where some of the conductors have been removed such that the inherent connectivity of the fracture system is reproduced The lattice configuration is found by simulating the well tests on the lattice and searching through a series of configurations until a good match is found. An example of one of the matches to the MI data is shown in Figure 4. A cross-validation study showed that the median of the predictions made with a series of inverse solutions was the best predictor of well test behavior.

A third effort focused on a joint geological and geophysical interpretation of data from a site called the US/BK site.[11,12,13] This effort showed how conceptual models can be developed from a combination of geologic mapping and geophysical tomography. Data from the surface, drift walls and boreholes were used to map features of importance to hydrology. Three types of features were identified: S-zones, K-zones and lamprophyric dykes. S-zones are shear zones that are parallel to the schistosity of the rock. They are characterized by a braided, anastomosing pattern of fractures. K-zones are shear zones that are oblique to the schistocity. These are characterized by a stepping morphology. The steps are formed by extension features that may form important hydrologic conductors. The dykes are highly deformed and are accompanied by horizontal tension fractures at their margins. The dykes themselves are apparently impermeable, but their margins may be significantly permeable. After mapping these features in the vicinity of the US/BK site, a series of seismic and radar tomograms were used to extrapolate these features into the rock mass The tomographic information provided data that distinguished between several alternative models for the site.

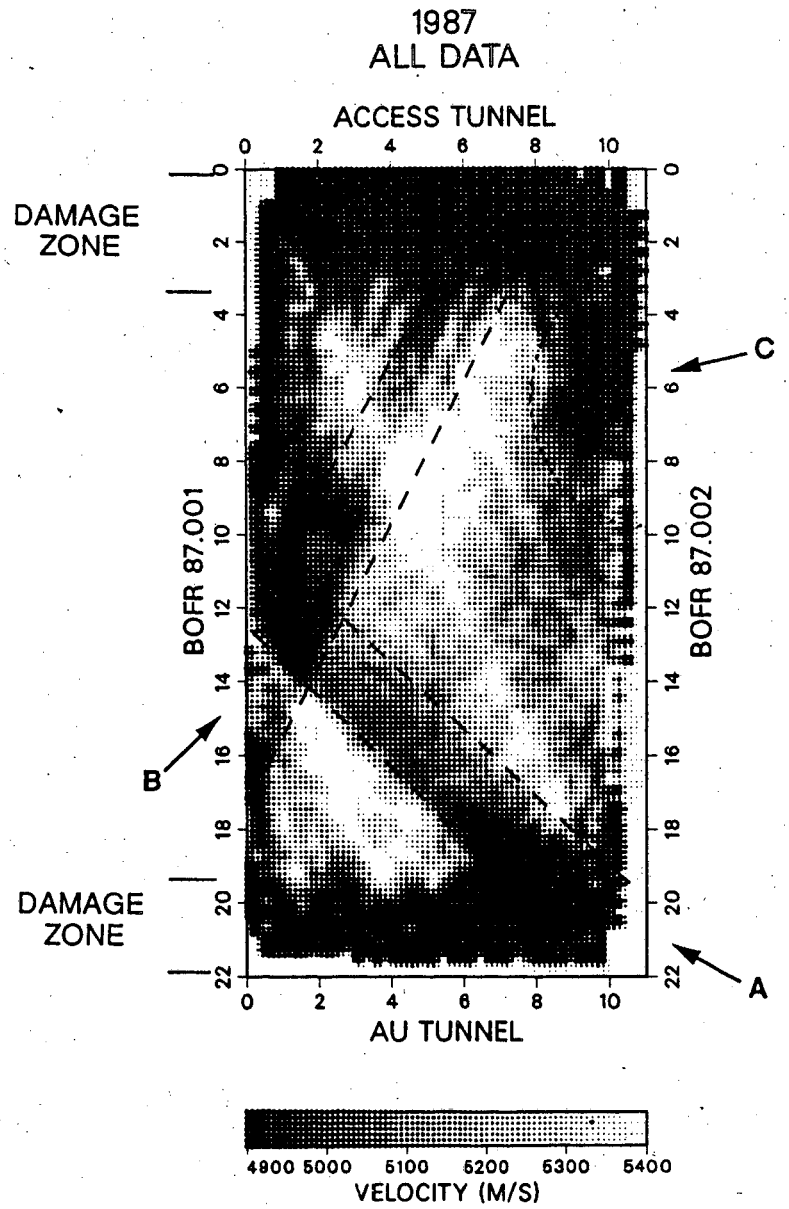

Figure 3. Velocity tomogram of the FRI fracture from data taken in 1987.

TASK 6. COUPLING OF TRANSPORT AND GEOHEMISTRY

A variety of processes can affect the transport of nuclides from a repository. The objectives of this task were to evaluate the changes of physical and chemical properties of backfill materials caused by post-emplacement interactions with major dissolved components of ambient groundwaters and to evaluate the effects of these changes on subsequent migration of waste radionuclides released from the waste form.[14,15,16]

As an example the conversion of sodium bentonite to calcium bentonite by ion exchange was simulated. The models allowed evaluation of the effect of the conversion on the migration of cationic radionuclides, such as Cs^+. The results show that changes in the bentonite occur over thousands of years. The numerical simulations also show that neglecting spatial and temporal variations in the ion exchange properties of bentonite results in over predicting the amounts of Cs^+, sorbed by bentonite.

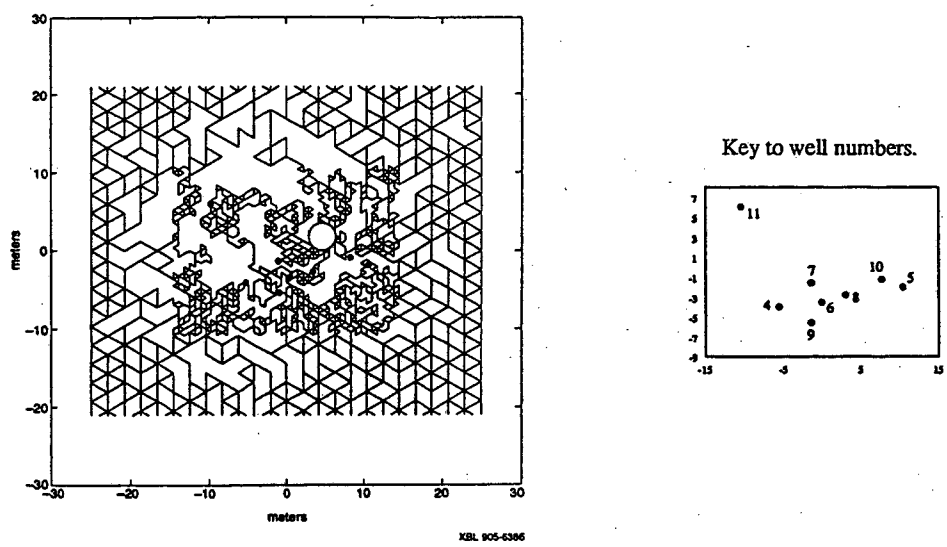

Figure 4. One of many Simulated Annealing inversions of the MI steady state interference data.

The uptake and distribution of water by backfill materials in contact with partially or completely saturated porous matrix in the presence of thermal gradients was evaluated. The Stripa Project heater experiments and laboratory studies in Switzerland were the basis of this study. In the Stripa experiment, a cylindrical cavity was drilled and filled with bentonite with a heater in the center to simulate a waste canister. A borehole drilled on the margin of the hole was filled with water to simulate a fracture intersecting the canister hole. Modeling was successfully able to predict that the saturations in the backfill were controlled by the temperature. Further, small but significant coupling between heat and pressure was surmised and matched the data very well.

CONCLUSION

The cooperation between DOE and NAGRA described here has led to a new cooperative project which began in 1991 and is expected to last for five years. New emphasis will be placed on two phase flow phenomena. Important results have been obtained that are beneficial to both programs.

ACKOWLEDGMENTS

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Flow and Transport in Hierarchically Fractured Systems

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FLOW AND TRANSPORT IN HIERARCHICALLY FRACTURED SYSTEMS

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ABSTRACT

Preliminary results indicate that flow in the saturated zone at Yucca Mountain is controlled by fractures. A current conceptual model assumes that the flow in the fracture system can be approximated by a three-dimensionally interconnected network of linear conduits. The overall flow system of rocks at Yucca Mountain is considered to consist of hierarchically structured heterogeneous fracture systems of multiple scales. A case study suggests that it is more appropriate to use the flow parameters of the large fracture system for predicting the first arrival time, rather than using the bulk average parameters of the total system.

INTRODUCTION

The potential high-level nuclear waste repository at Yucca Mountain, Nevada (Figure 1) would be built in unsaturated, fractured, welded tuff. Yucca Mountain is composed of a thick sequence (approximately 4000 m) of Tertiary Miocene ash-flow and ash-fall tuffs. A generalized stratigraphic section of the volcanic rocks at Yucca Mountain is shown in Figure 2. One possible contaminant pathway to the accessible environment, which is defined as a distance greater than 5 km from the potential repository perimeter, is transport of radionuclides by water flowing through the fractured rocks of the saturated zone. Much of the saturated zone consists of rocks of the Crater Flat Tuff, approximately 13.5 million years old in age. Fractures associated with cooling of the ash-flow and ash-fall tuffs are present in these rocks. Structural deformation during the Tertiary near Yucca Mountain resulted in different styles of faulting.[1] Within the fault blocks defined by these structural features are tectonically-induced fractures which were formed by changes in stress field of the associated fault(s). From this association a simplified conceptual model can be formulated wherein there are multiple scales of features superimposed such as faults that bound the block and fractures within the block.

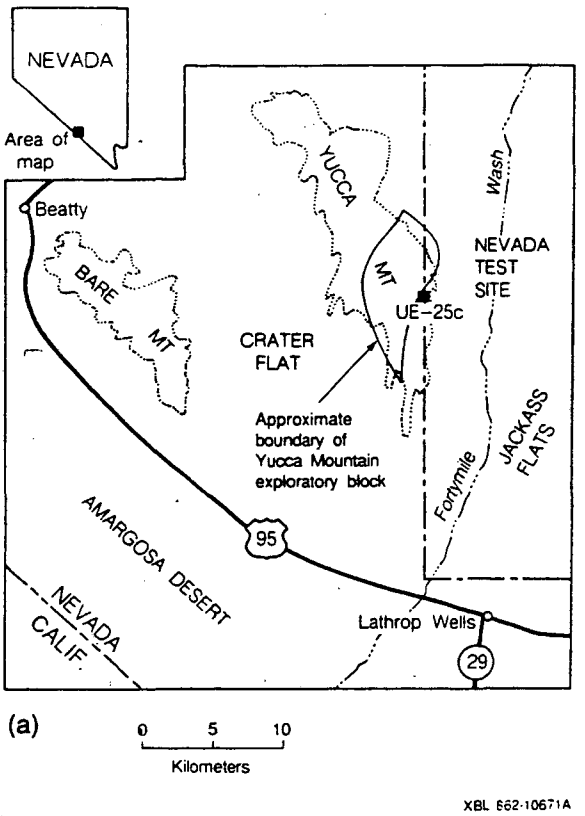
Preliminary results from crosshole hydraulic-stress tests at the UE-25c-hole complex (Figure 1) in the saturated zone suggest that apparent transmissivity values are highly localized, and related to fractures and a brecciated zone associated with a fault.[2] Combined with the fact that the tuff has a very low matrix permeability, flow in the saturated zone can be presumed to be mainly controlled by fractures, at least at the scale affected by the aquifer tests. These fractures are often non-uniformly distributed and possess highly heterogeneous flow properties, which must be accounted for by the conceptual and numerical models.

It is necessary to understand how flow and transport occur in such a system to reliably characterize the hydrology of the saturated zone. The most direct information regarding fracture flow can be obtained by conducting in-situ hydraulic-stress and tracer tests. However, such tests can be done only at a limited number of locations and scales. It is virtually impossible to characterize every detail of the geometry and flow properties of fractures at all scales. Therefore, simplifying assumptions must be made to model flow through heterogeneous fracture systems. One such assumption is that not all of the geometric details of the fracture system are important. Another is that the overall fracture flow system consists of discrete features of multiple scales that are superimposed on top of each other. In this paper a discussion on how the flow and transport in fractures is conceptualized is presented. Then a case study of flow and transport simulation in a hypothetical hierarchical fracture system is given.

CONCEPTUAL MODEL OF FLOW IN FRACTURES

For this paper, a conceptual model is defined as conceptualization of the system geometry and the controlling physical properties and a numerical model refers to incorporation of the conceptual model into a computer program that simulates physical processes such as fluid flow and transport in the identified system geometry. Therefore, the numerical model consists of input data and the numerical code. Numerical models have the advantage of being able to simulate flow and transport in complexly fractured systems at scales larger than those represented by a single borehole or aquifer test, and may be used for the testing of hypotheses about flow through fractured rock.

Many investigations of fracture flow have been undertaken using parallel plate assumptions.[3,4,5] More recently, however, various field and laboratory observations have indicated that flow in a fracture is not entirely identical to flow between two smooth parallel plates.[6,7,8] Fractures generally have contact areas where no flow occurs, and the fracture walls are not always smooth. Because of these irregularities, the velocity profile may deviate from that predicted by Poiseuille's Law and there may



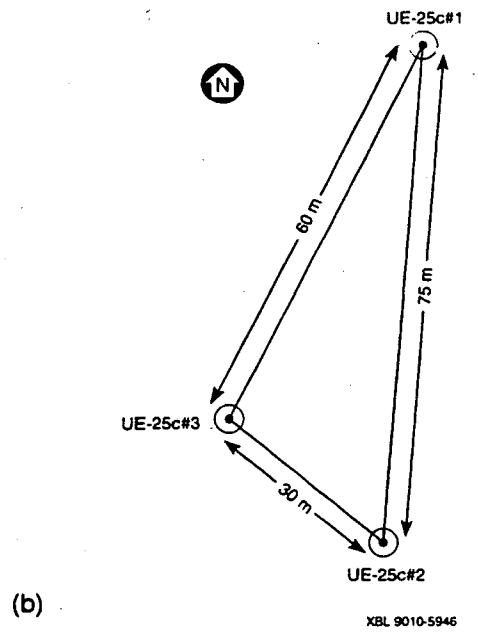


Figure 1 - a) Location map of Yucca Mountain and vicinity and b) surface layout of UE-25c-holes.

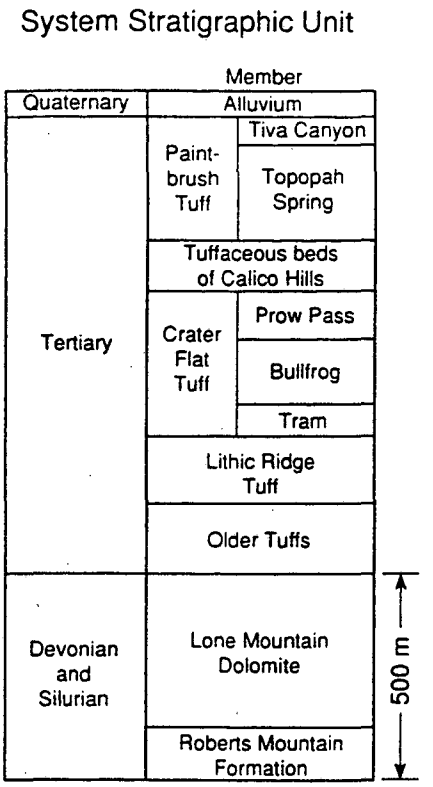


Figure 2 - Generalized stratigraphic section of the Miocene ash-fall and ash-flow tuffs at Yucca Mountain.

exist preferred fluid paths or channels that are more lineal in geometry, rather than sheet-like. Furthermore, the intersections of fractures can behave like linear conduits for fluid flow. Consequently, flow in a fracture system may be better approximated by a network of three-dimensionally interconnected line segments rather than planar segments. Flow in each line segment is assumed to be that of laminar flow in a one-dimensional porous medium pipe, i.e., Darcy flow.

FLOW AND TRANSPORT MODEL

A numerical model that can simulate flow and transport in complex fracture systems can be a useful tool in improving our understanding of the flow systems. The model also can be used to help design hydraulic-stress and tracer tests, interpret the results of these tests, and make predictions.

Observed transport behavior is a result of phenomena occurring at two levels; phenomena associated with transport within individual fractures and that which is a consequence of network geometry. For the reasons discussed in the previous section it is assumed that a fluid conduit in a fracture system is best approximated by a one-dimensional porous medium pipe.

The transport within each fracture, as represented by a line conduit, then can be described by the one-dimensional advection-dispersion equation:

$$\frac{\partial C}{\partial t} = D^* \frac{\partial^2 C}{\partial x^2} - u\frac{\partial C}{\partial x}$$

where C is the chemical concentration, D^* is the dispersion coefficient, u is the fluid velocity, t is the time, and x is the distance variable. Dispersion as a result of spatial variability in fluid velocity is modeled explicitly by the network geometry.

The advection-dispersion equation is very difficult to solve numerically especially at large Peclet numbers, where $P_e = uL/D^*$, and L is the characteristic length. Large Peclet numbers make the advection-dispersion equation hyperbolic in nature. Conversely, small Peclet numbers result in parabolic behavior. When modeling transport in fracture networks, the Peclet number is expected to vary over a wide range of magnitudes because of the heterogeneity among fractures, especially under tracer tests with an induced flow field, such as pump-back tests and two-well recirculation tests.

Classical numerical treatment of the advection-dispersion equation inevitably introduces either an artificial (numerical) dispersion or oscillation. Many works have been devoted to the subject of avoiding these numerical difficulties.[9,10,11,12,13] Neuman[10] proposed a mixed Eulerian-Lagrangian method with adaptive gridding. However, the method of Neuman[10] retains some numerical dispersion when the advected front is projected back to the fixed finite element grid. Karasaki[13] modified the approach of Neuman[10] and proposed a mixed Lagrangian-Eulerian scheme with a moving grid. Karasaki's[13] model further minimizes numerical dispersion by creating new Eulerian grid points, instead of interpolating the advected profile back to the fixed Eulerian grid.

The moving grid technique is generally difficult to apply. However, application to linear elements is relatively easy. Therefore, Karasaki's[13] model is well-suited to the conceptual model discussed in the previous section. In the following section a case study is presented, using the conceptual model discussed above and the numerical model of Karasaki.[13]

HIERARCHICAL FRACTURE SYSTEM

Rock heterogeneities exist at all scales. This is particularly true for fractured rocks such as those encountered at Yucca Mountain. Roughly stated, there are three different scales of interest: small; intermediate; and large. A number of works have been published on hierarchical porous media.[14] Schwartz and others[15] also have investigated a stochastic approach of modeling transport in fractures.

At a small scale, defined as the scale which can be studied in the laboratory, research indicates that there is a large variation in the aperture within a single fracture, and that fluid flows preferentially in tortuous channels with varying flow properties. Tsang and Tsang[8] proposed a model to describe such channelized flow in fractures. The channeling effect is observed to be further enhanced when stress is applied across a fracture.[16]

At an intermediate scale, defined as the scale of a block of rock affected by hydraulic-stress tests, the transmissivity often is observed to vary markedly along the length of a borehole and from borehole to borehole. In general, the more fractures an interval in a borehole includes, the more transmissive the interval is. However, an interval with few fractures can sometimes be more transmissive than one with many more fractures. This is because the fracture conductance itself can differ greatly from one fracture to another, as well as within a fracture. The transmissivity of an interval also depends on how the particular conductive fractures in the interval are connected to the rest of the fractures that constitute the flow system. The heterogeneous transmissivity observed at this scale is a compound effect of the variability in the fracture density, mineralization, conductance, and connectivity. Features such as faults and fracture zones can also affect the transmissivity.

At the large scale, defined as the scale beyond which the effects of hydraulic-stress tests can be observed, heterogeneities can be attributed to large faults and changes in the geologic setting. The manner in which the smaller scale features affect the next larger scale phenomena must be understood. This is especially the case for large scale hydrology, because a direct measurement of hydraulic properties at such a scale is not possible. Generally, hydraulic test results conducted at the intermediate-scale have somehow to be extrapolated. Similarly, to analyze intermediate-scale tests, an understanding of the small-scale phenomena are necessary.

A CASE STUDY

A case study of flow and transport phenomena in hierarchical fracture systems is presented in this paper. A simplified hierarchical system was constructed by superimposing fracture systems of different scales. Figure 3 shows an example of a two-dimensional system created by superposition of two fracture systems with distinctly different scales. In the present case a conductivity contrast of 100:1 magnitude was chosen.

Both fracture systems are assumed to be continuous. Thick lines, in Figure 3, represent high transmissivity fractures associated with block-bounding features. Thin lines, in Figure 3, represent fractures with small permeability, such as joints within fault blocks. Although the present model appears similar to a classical double porosity model, one important difference is that in the model discussed herein, flow is allowed to take place through the blocks. Furthermore, mechanical dispersion as a result of the fracture network is considered explicitly in the present model. Radially converging tracer tests were simulated by releasing a solute at various locations on the perimeter of the network, the boundary of which was held at constant pressure, and by simulating a well withdrawing water in the center of the model. In order to focus on the effects of hierarchical structure on dispersion, diffusion within individual fractures was not modeled. Only one eighth of the system is modeled, assuming radial symmetry; the sides are designated to be no-flow boundaries. This assumption is somewhat inconsistent, because complete mixing is assumed at interior fracture intersections, whereas no mixing is allowed to occur at the intersections on the side boundaries.

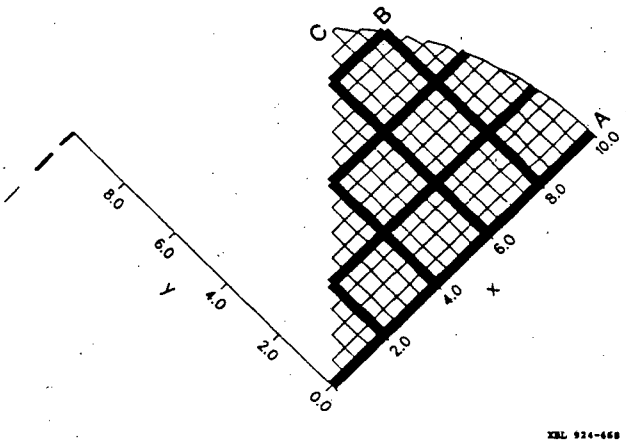


Figure 3 - A simplified hierarchical fracture system.

RESULTS AND DISCUSSION

Figure 4 shows breakthrough curves for tracers released at points A, B and C in Figure 3. A is located on the x axis, B is located approximately 37 degrees from the x axis on an intersection of the large fracture system, and C is located 45 degrees on the small fracture system. Case A, Figure 4, indicates that the solute stays entirely in the large fracture system and that breakthrough occurs in a plug-flow fashion. For Case B, Figure 4, the breakthrough of concentration takes roughly twice the time of Case A. In addition, there is slow and steady increase in tracer concentration after a sharp breakthrough as compared to Case A. The longer breakthrough time of Case B can be attributed to the fact that flow toward the simulated well follows a more tortuous pathway, which includes tangentially-oriented fracture segments. The hydraulic gradient is small in these tangentially-oriented segments. The solute effectively samples twice the porosity in Case B as compared to the more abrupt breakthrough in Case A. Figures 5a and 5b illustrate solute concentration distribution as a function of time, for Case B. The thickness of the lines in Figures 5a and 5b are proportional to the solute concentration. After 10,000 seconds (2.7 hours), Figure 5a, most of the solute stays in the large fracture system, but later in time at 20,000 seconds (5.5 hours), Figure 5b, some portion of the solute travels through the small fracture system. This phenomena accounts for the slow and steady increase in solute concentration after the sharp breakthrough for Case B. No breakthrough occurs for Case C, Figure 4, in a period comparable in duration to the time for breakthrough in Cases A and B. The solute in Case C is in a relatively stagnant zone which is bypassed by the major water-bearing fractures.

One purpose of this study is to investigate how to simplify, scale-up, and model the hydrologic behavior of a complex fracture system, while still retaining the salient flow and transport properties as measured in the field. One simplification might be treating the hierarchical fracture system as a single fracture system with equivalent bulk permeability and porosity as the system of hierarchical fractures. Shown in Figure 4 is breakthrough curve S, which represents this hypothetically equivalent fracture system. Comparison of Case S, Figure 4, with Cases A, B, and C indicates that simple volume-averaged transmissivity and porosity cannot adequately describe the variability in transport properties of hierarchical fracture systems. For the cases considered, it is probably more appropriate to use the flow parameters of the large fracture system for predicting the first arrival time rather than using the bulk average parameters of the total system, although the prediction is likely to err on the conservative side.

The case study discussed in this paper is a simple example of how fractures in rock may be represented by a hierarchical system of interconnected linear conduits and how solute is transported in such a system. In constructing a numerical model of complexly fractured rock, one goal is to represent the fracture network with minimum complexity and still account for the more important physical processes that take place in the network. Initial modeling demonstrates that hierarchical representation of fractured rock seems to be a reasonable approach for representing the fracture network. Also, this conceptual model intuitively is consistent with the way in which faults and fractures are formed in rock.

The large fracture or the fault system may not form a continuous pathway as depicted in Figure 3. It instead may be more accurately simulated by the type of model as shown in Figure 6. In Figure 6, the large fracture system is discontinuous. In such a system there may be an appropriate set of average parameters for predicting flow and transport phenomena. The study of discontinuous networks is currently being performed.

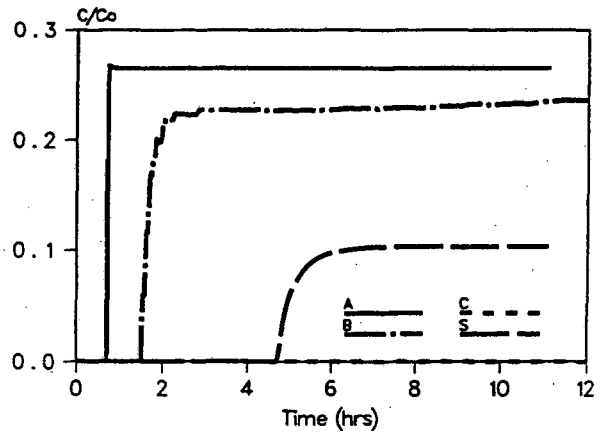


Figure 4 - Breakthrough curves for Cases A, B, C and S for radially convergent tracer tests.

SUMMARY AND CONCLUSIONS

The overall structure of discontinuities within the rocks at Yucca Mountain is considered to consist of hierarchically structured heterogeneous fracture systems of multiple scales. A current model, presented in the case study, assumes that the flow in the hierarchical fracture system can be approximated by a

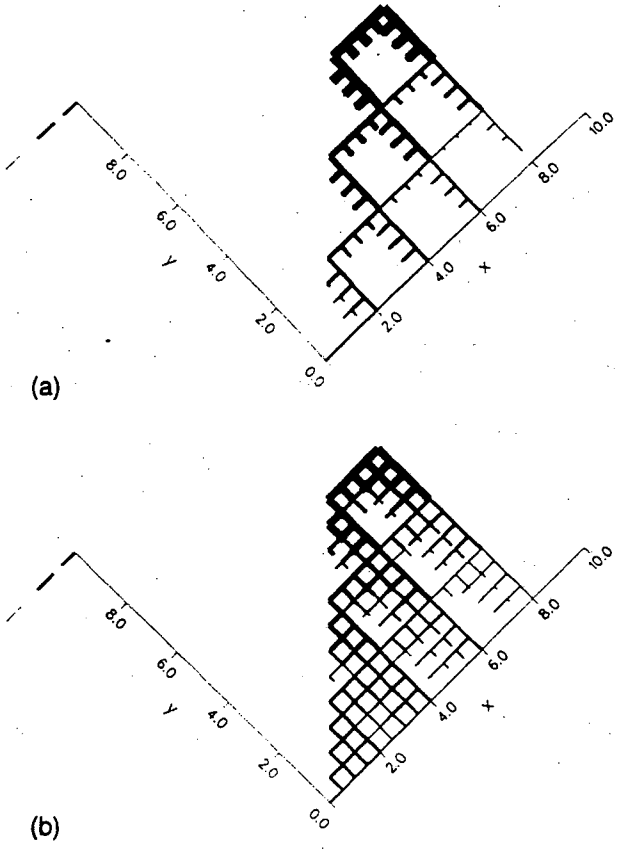


Figure 5 - Concentration distribution for Case B at a) 10,000 seconds, and b) 20,000 seconds.

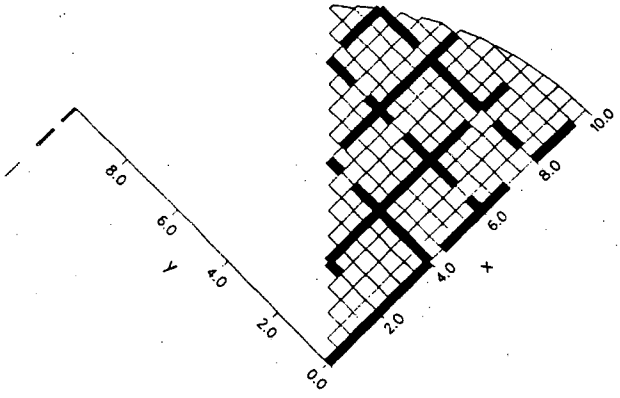


Figure 6 - A simplified hierarchical system with a discontinuous fault system.

three-dimensionally interconnected network of linear conduits. A numerical code based on Eulerian-Lagrangian scheme with moving grid technique is suitable for simulating flow and transport in such systems. The case study suggests that it is more appropriate to use the flow parameters of the large fracture system for predicting the first arrival time rather than using the bulk average parameters of the total system.

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