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Characterization of Fracture Networks for Fluid Flow Analysis

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Abstract

The analysis of fluid flow through fractured rocks is difficult because the only way to assign hydraulic parameters to fractures is to perform hydraulic tests. However, the interpretation of such tests, or "inversion" of the data, requires at least that we know the geometric pattern formed by the fractures. Combining a statistical approach with geophysical data may be extremely helpful in defining the fracture geometry. Cross-hole geophysics, either seismic or radar, can provide tomograms which are pixel maps of the velocity or attenuation anomalies in the rock. These anomalies are often due to fracture zones. Therefore, tomograms can be used to identify fracture zones and provide information about the structure within the fracture zones. This structural information can be used as the basis for simulating the degree of fracturing within the zones. Well tests can then be used to further refine the model. Because the fracture network is only partially connected, the resulting geometry of the flow paths may have fractal properties. We are studying the behavior of well tests under such geometry. Through understanding of this behavior, it may be possible to use inverse techniques to refine the a priori assignment of fractures and their conductances such that we obtain the best fit to a series of well test results simultaneously. The methodology described here is under development and currently being applied to several field sites.

Introduction

With the advent of problems such as the storage of nuclear waste and production from fractured oil reservoirs, characterization of fracture networks in rock has been the focus of increasing study. The goal of much of this work is to develop a numerical model which can be used to predict the flow and transport of fluids through the rock. Building such models is difficult because fracture networks are complex, three-dimensional systems which can not be seen inside the rock.

One approach to the problem has been to attempt to build a statistical model of the network based on sampling fracture data in outcrops and boreholes. This stochastic method can be used to produce non-unique simulations of the fracture network. In a fundamental sense, this approach makes the assumption that one can infer the properties of the material on a large scale through statistical analysis of the features on a small scale. Typically, we measure the number, orientation and length of traces seen on an outcrop or drift wall and the number and orientation of fractures intersecting boreholes. Further, we can perform packer tests in the boreholes to gain some knowledge about the conductivity properties of the fracture network at a small scale. We then develop stochastic parameters describing the distribution of fracture occurrence, size, orientation, truncation and conductivity.

This approach is compromised by: 1) limitations of the underlying conceptual model, and 2) limitations of the statistical data. Evidence abounds that the use of continuum assumptions is inappropriate in many fractured rocks. So we must have some replacement physical model, which in fact is exactly what the network model purports to be. To design the network, we must make many assumptions: Are the fractures disc shaped or polygonal? What is the spatial relationship between fractures? Does fluid flow in each fracture resemble flow in a slab of porous material or flow in distinct channels or flow between parallel plates? Does water flow mainly along the intersections between fractures and not in the fractures themselves? Once we have made such decisions, we have chosen the conceptual model, and then it is relatively easy to use a numerical algorithm to predict flow in the network. However, the wrong choice of conceptual model will lead to the wrong prediction. Also, until we know which conceptual model to choose, we cannot know what data to collect. We can only suggest that the field efforts collect as much data as possible so that we may have a chance of having the right data. This is financially crippling in most cases.

As we go through the process of building the fracture network up from the small scale data, we do not get a good statistical sample of unusual features. Consequently, it is very difficult to come up with a model which includes the effect of unusual features, for example fracture zones. However, it is the fracture zones that often dominate the behavior of the fracture network. Hence the "building up" approach fails to give us the dominant behavior of the network.

Another problem with the model occurs with the definition of boundary conditions when we abandon the continuum model. The nugget of this problem is that two points which are geometrically close to each other may be hydraulically far apart. This means that if we measure head at two different points and divide by the distance between them to get the hydraulic gradient, we do not have a measure of the gradient which controls flow. Further, if we measure head at a point on the boundary, it may not be representative of the average head controlling flow. Such ambiguity in the definition of boundary conditions causes ambiguity in the model results.

There are also serious difficulties in getting the appropriate data for the models. First, most available data come from boreholes or outcrops. These data are one- and two-dimensional respectively. Fracture networks are three-dimensional. We can propose stochastic three-dimensional models and test the resulting one- and two- dimensional properties of the models against the real data. However, this problem is ill-posed: The goodness of fit is insensitive to the choice of solution. So we can find many three- dimensional fracture networks which seem to fit the data. With only statistical information, it is not possible to differentiate between the possible solutions and select the best one.

Maps of fractures do not discriminate between fractures which conduct water and those that do not. This results in developing a fracture network which is far too dense to explain observed non-continuum behavior. Such models predict millions of fractures in volumes of rock with the dimensions of tens of meters (Figure 1). From the hydrologic point of view, this model is wrong.

Fracture hydraulic parameters are hard to obtain. We may be able to get distributions of fracture density, orientation and size, but it is nearly impossible to get a good estimate of the distribution of fracture conductivity. A geometric measurement of the aperture does not include the hydraulic effect of roughness and contact area in the fracture and therefore does not estimate the hydraulic aperture. Alternatively, packer tests, which use a hydraulic measurement to get hydraulic parameters have a variety of problems: They emphasize the values near the well; they measure more than one fracture at a time; it is hard to account for interconnectivity effects and to distinguish between an impermeable fracture and a part of the fracture which is impermeable. So, we can not get the statistical distribution of fracture permeability needed as input to the numerical model.

If it is difficult to get the individual parameters governing flow, then it is certainly difficult to obtain the correlations between the various parameters. Correlations between the size and conductivity of fractures have a large effect on the permeability and transport properties.

In summary, experience with this approach of building a fracture network from the details up has some severe drawbacks. The remainder of this paper describes some of the research we are doing to attack these problems.

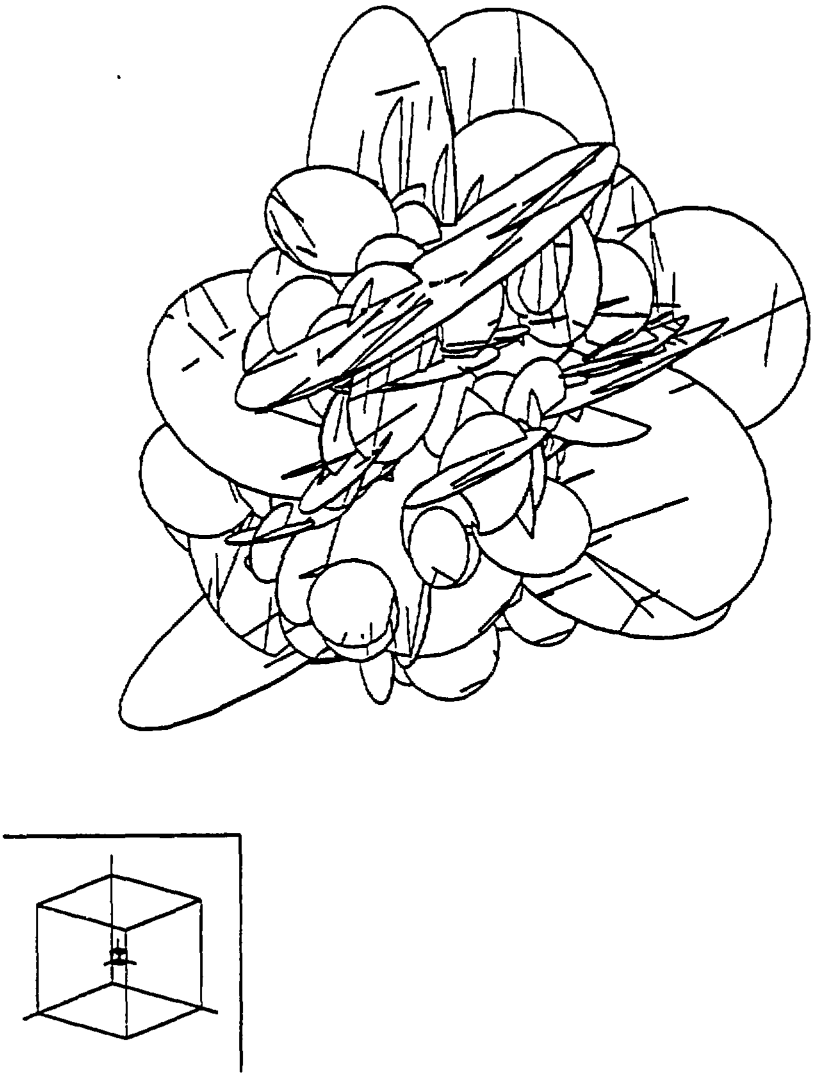

Figure 1. Shown are the 220 fractures with diameters larger than 1m intersecting a sphere with a 2.5m radius based on data from the Fanay- Augres.

New Perspectives

Three major areas in network modeling deserve more effort: development of the conceptual model, location and characterization of fracture zones, and the use of parameter identification techniques. In this section we describe these briefly; in the next section we show examples of efforts to apply these ideas to field sites.

In order to develop better conceptual models, we need to know more about how the geometry of a fracture controls the flow in that fracture. To that end we are using a new technique for quantifying the void geometry of single fractures (Billaux et al, 1988). This technique involves using a pliant, translucent casting material called RTV manufactured by Rhône-Poulenc. We inject a translucent, dyed RTV into a fracture and apply a normal stress. When the cast is hardened, the top of the fracture is lifted off and a clear RTV is poured over the existing cast of the voids. This clear layer allows the void cast to be removed from the fracture surface without tearing.

When the two layer cast is removed, it can be placed on a light table and photographed with a video camera which records the grey levels over the surface. The darker the picture the larger the aperture at that point. Figure 2 shows an example of such a digitized picture made from an RTV cast. By simultaneously casting and photographing a wedge with a known thickness, the digitized image can be calibrated. In this way we have been able to quantify the aperture of a fracture in a 6 inch core at four million points. This represents a phenomenal data base for the study of flow and deformation in a fracture.

Based on the data, we can develop conceptual models for flow and test them against laboratory measurements. From this we hope to learn how to average, or "scale up" the behavior of flow in a fracture. For example, Figure 3 shows an image analysis treatment of the aperture data called "skeletonization". This analysis essentially finds all the possible paths around all the contact areas and reduces them to a line on the plot. A good model for fluid flow might be found by assigning a conductivity and volume to each of these lines. Such a model would naturally include most of the tortuosity in the plane of the fracture.

We also need to conceptualize fractures on the network scale. Studies of the geology and geomechanics of fractures may help to determine the fracture network geometry which controls the flow. For instance, one might wish to model a shear zone in the rock as a highly permeable slab. Because stress and failure conditions vary within a shear zone, one expects that permeability will vary within the zone. The way in which shear zones form may provide insight into how the permeability in the zone is distributed. For instance Figure 4 (from Deng and Zang, 1984) shows a conceptual model of a shear zone which has regions of shear, tension and compression. Regions of tension are probably more permeable than regions in compression. These regions can be identified by the direction in which the fault steps with respect to the overall direction of movement along the fault. So, if we can determine the direction of movement and predict or measure the steps in the fault, we can learn something very valuable about where the water might be flowing.

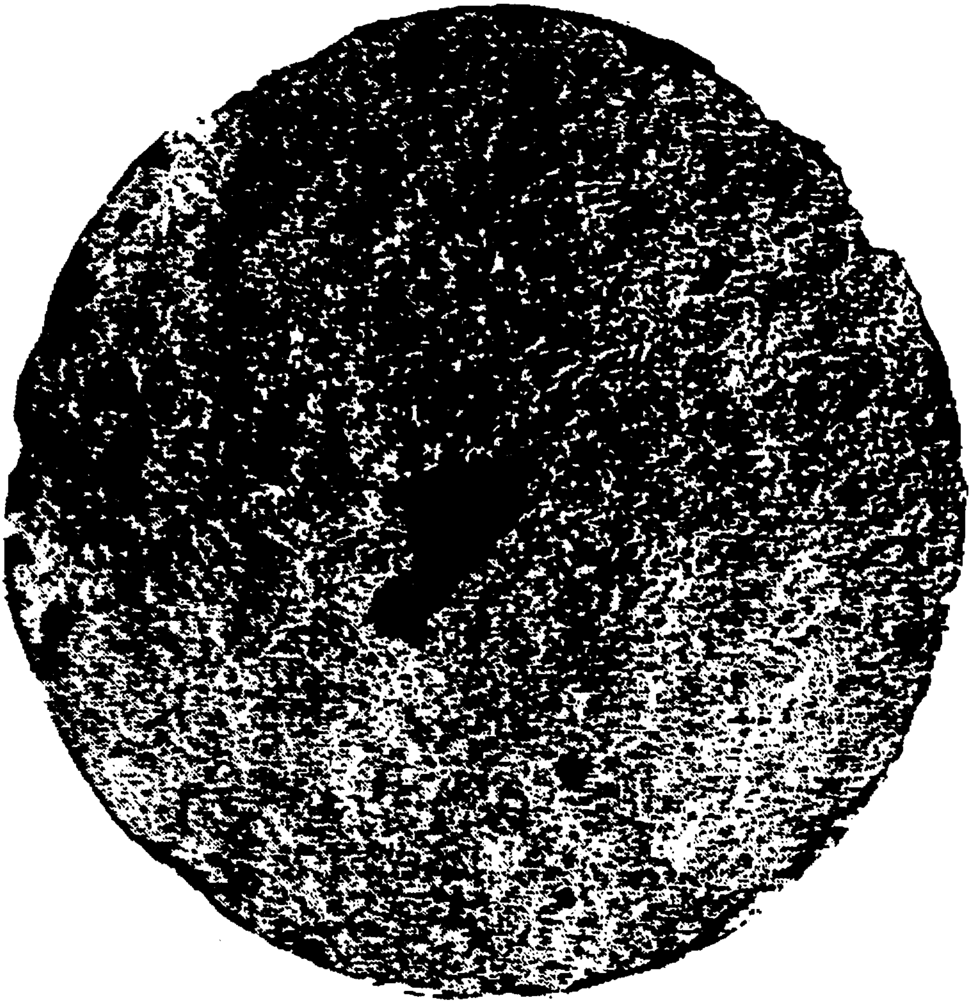

Figure 2. Digitized picture of a fracture cast.

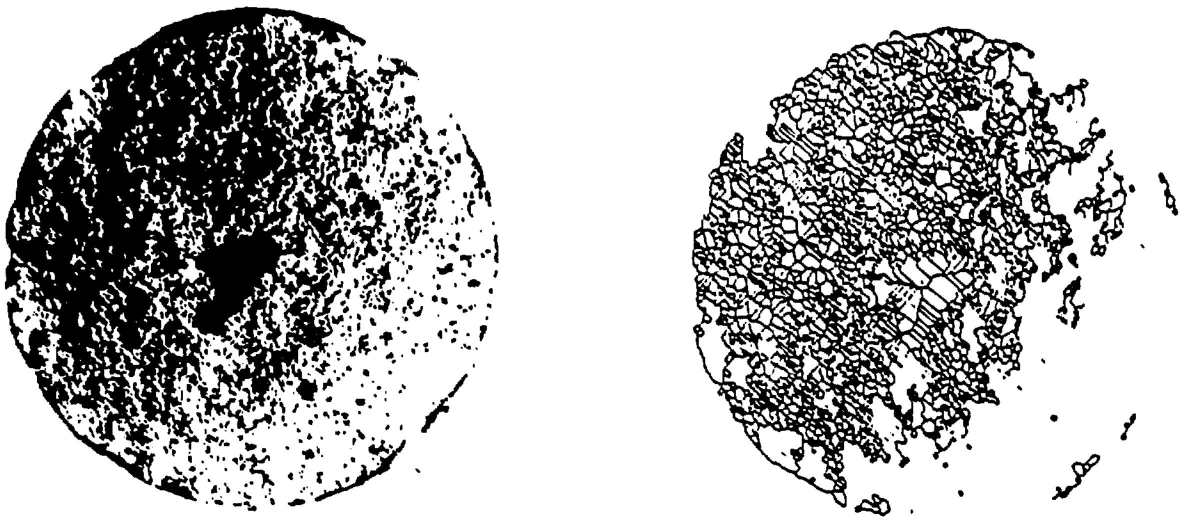

Figure 3. A: Binary image of fracture aperture for the fracture in figure 2.
B: Skeletonized image of flow paths of the same fracture.

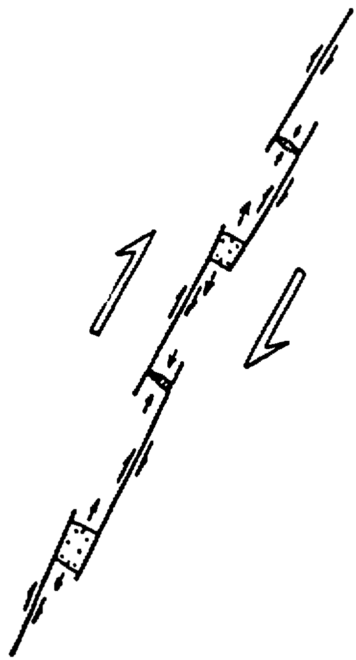

Figure 4. Conceptual model of a shear zone after Deng and Zang, showing zones of tension and compression.

Usually, mechanical studies of shear zones are focussed on the plane of the major and minor principal stresses, and in the field one can at most observe the fault in two-dimensions. This often leads to an understanding of the fault in a plane perpendicular to the intermediate principal stress. Referring to Figure 4, if the tension zones in this zone are the most permeable, they will form a channel for flow in the direction of the intermediate principal stress. We need to understand how these permeable zones interact (Figure 5). This problem can be approached in three ways: field observation, laboratory and numerical studies.

Before we can characterize these fracture zones, we need to find them. If a zone intersects a borehole we can locate the point of intersection. However, the fractures in the zone are not necessarily in the direction of the zone itself. So, it is very difficult to know where the zone is going. If the zone does not intersect a borehole or outcrop, a hydrologist has no tools to find it. For instance, Figure 6 shows a hypothetical fracture zone between two vertical wells on the upper left of the figure. If we performed cross-hole well tests between the wells we could not necessarily "see" where the fracture is because the pressure signal we send from one well to the other is diffusive. In other words, we put a signal in at one point and monitor the response at another point, but we have no idea how the signal traveled between the two points.

On the other hand, if cross-hole geophysics is used, the data can be inverted to find the tomogram shown on the lower right. This can be done essentially because the geophysicist can approximate the ray path between the signal generator and receiver as a straight, or semi-straight line. So, the geophysicist can perform an inverse analysis to find the zone.

Once the location of the zone is known, it may be possible to include the zone in a fracture model and calculate flow through the system. For example, on the lower left we show a permeability tensor calculated using the network on the upper left. The hope is that if we can use geophysics to find the zone, perhaps it may be possible to get a reasonable solution to the corresponding hydrologic inverse problem.

Differential geophysical techniques are especially interesting. For example, radar tomography can be performed before and after injecting saline water into the fractures. The difference between the two tomograms is a strong indication of where the saline water was flowing.

Once we have developped a conceptual model for flow in the fractured rock and found the major features which control flow, we still do not have a complete hydrologic model. We have a description of where the conductors might be, but we still need to find out if, and how conductive they are. At this point, we must have hydrologic data such as pressure test and tracer test data which will form the basis of parameter identification procedures.

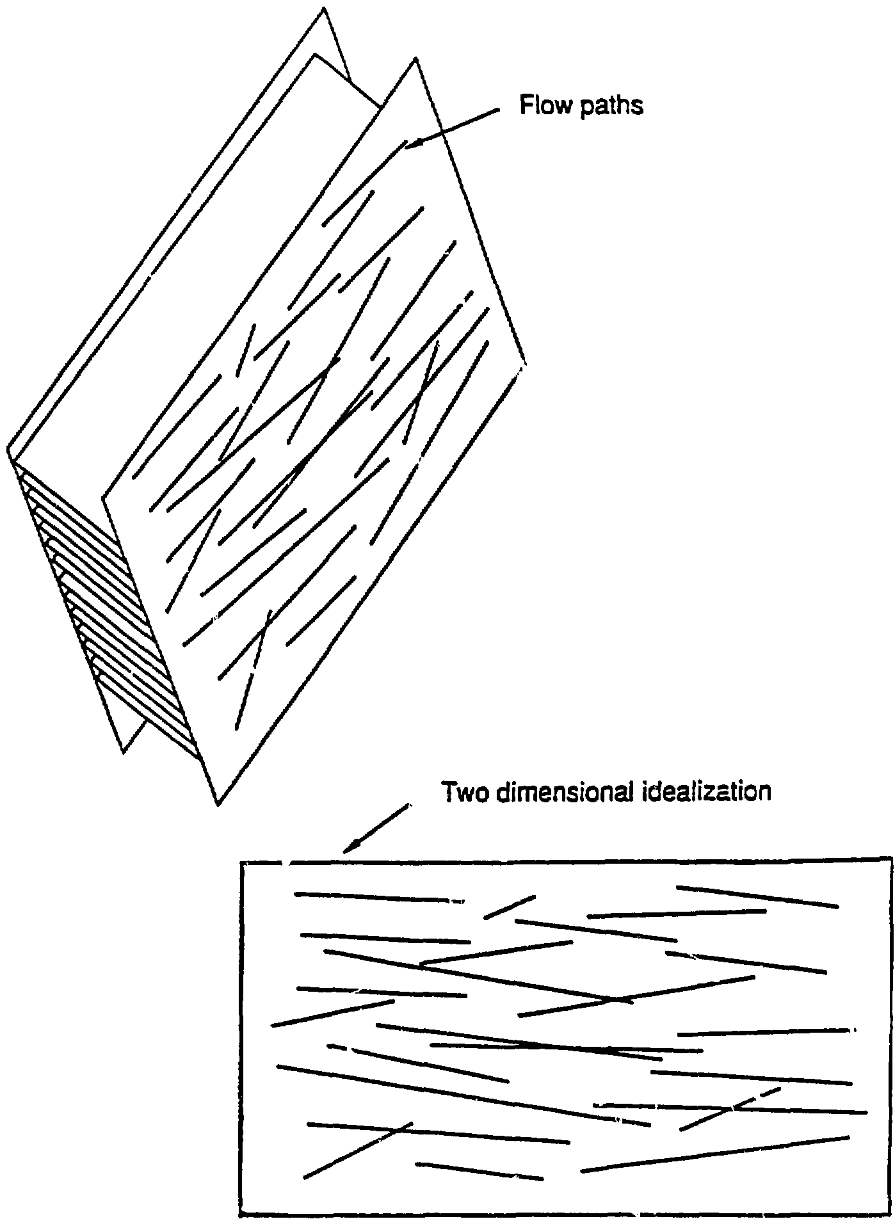

Figure 5. What do fault zones look like in three dimensions?

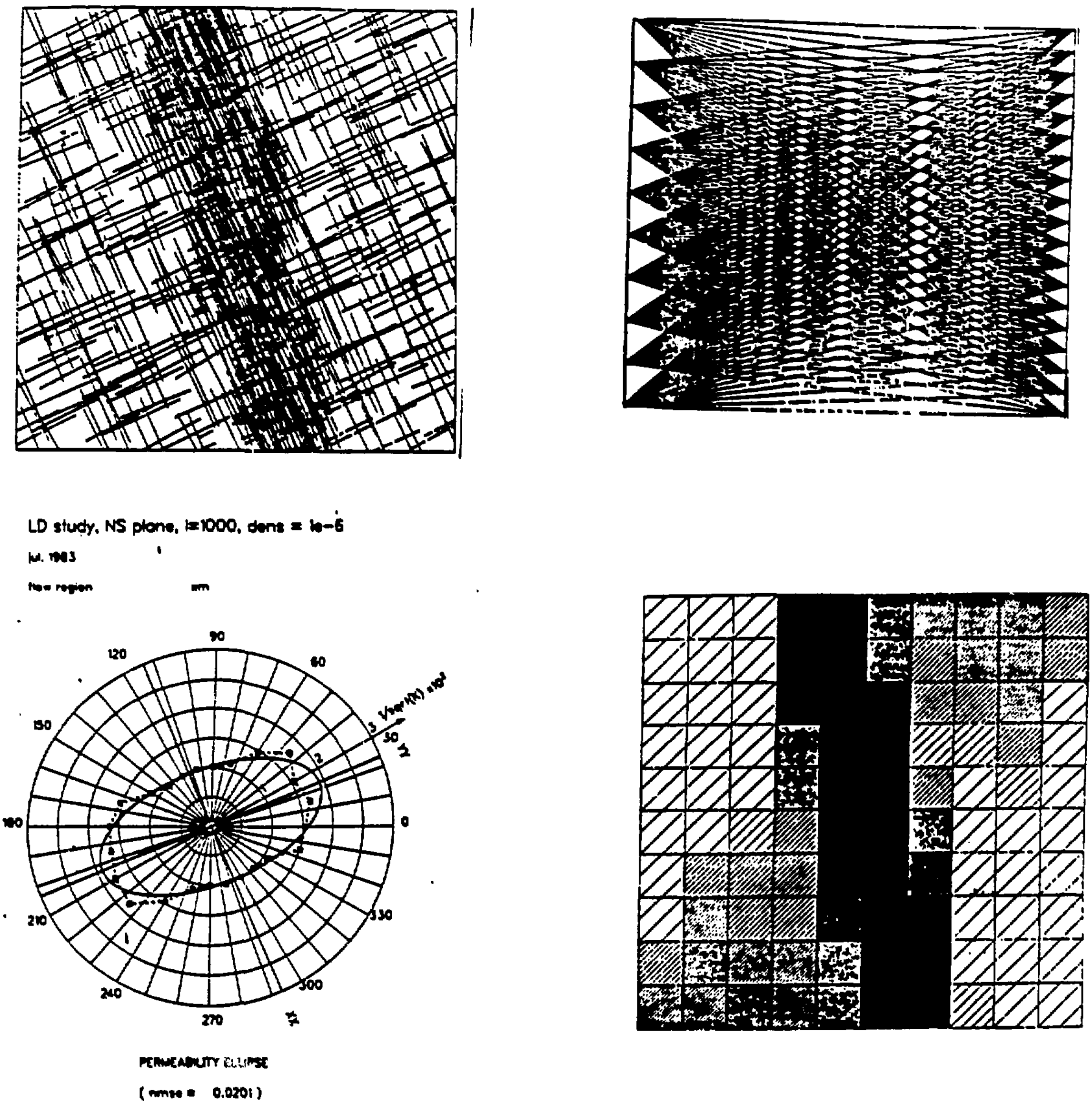

Figure 6. Hydrologic and geophysical analysis of fracture zones.

There is an important difference between using parameter identification techniques in porous media as opposed to fracture media. In porous media, the conducting elements are everywhere, so it only remains to determine how conductive various regions are. In fractured media, we need to determine where the conductors are, how they interconnect and then how conductive they are. In a sense, we are proposing to use geophysics and geomechanics to condition the model before trying to parameterize it.

In summary, we propose a new multi-tiered approach to developing fracture network models. In this approach, we first identify the fracture zones using geophysics and geology. Then, we conceptualize the zones using geomechanics, and geology. The next step is to develop an initial model of the fractured rock which has been conditioned by the geophysical, geological, geomechanical and statistical data. Finally, this model becomes the basis for inverse hydrologic analysis.

We present several preliminary examples of ongoing research from two field sites, the Stripa Mine in Sweden under investigation by the Stripa project, and the Grimsel Test Facility in Switzerland under investigation by the DOE-Nagra Cooperative project.

Examples of Field Data Analysis

The first example comes from the Grimsel test facility in Switzerland. Here, LBL and Nagra are jointly pursuing an experiment called the FRI experiment. The site of the experiment is shown in Figure 7 in plan view. At this site, there is a sub-vertical shear zone which transects the rock between two parallel horizontal drifts. Two holes have been drilled on either side of the zone, between the two drifts. In addition, many small holes have been drilled along the drift walls between the two holes. From these holes LBL performed four-sided cross-hole seismic measurements resulting in the P-wave slowness tomogram shown in Figure 8. In this tomogram the dark zones represent slower velocities than the light zones.

The tomography shows the shear zone quite clearly. The damaged zones due to excavation of the drift are visible as dark horizontal bands at the top and bottom of the figure. The drift at the bottom of the figure was excavated with a tunnel boring machine (TBM) and the drift at the top was excavated with conventional drill and blast technology. The tomogram shows the damage zone in the TBM drift is much smaller than the drill and blast tunnel.

The next step is to use the tomogram to estimate the hydrologic features relevant to well tests that could be performed in the boreholes. If we inject into the shear zone from borehole 87.001, water flow will not restrict itself to flowing in the plane of the tomogram. Most likely, water will flow in the plane of the shear zone. So, we want to use the tomogram to predict the properties of the shear zone in its plane. This can be done using techniques of geostatistical simulation.

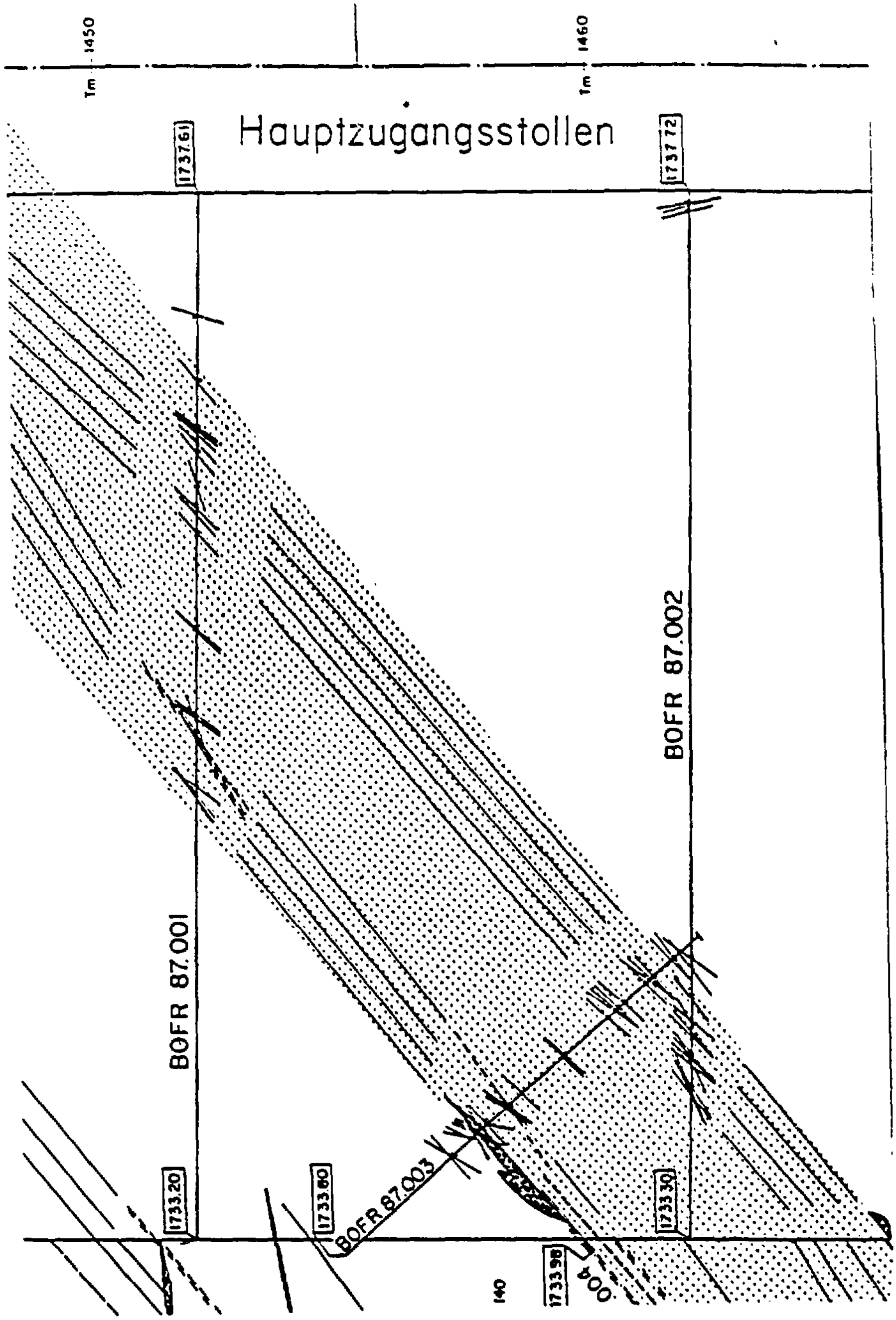

Figure 7. Plan view of the FRI experiment site showing the trace of the sub-vertical shear zone crossing between two parallel horizontal drifts.

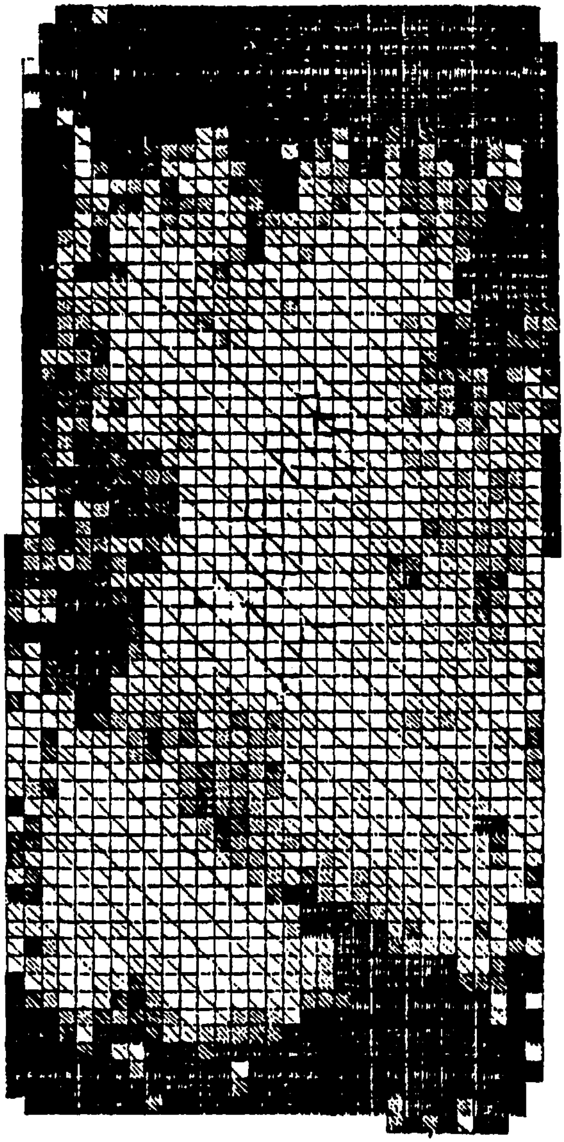

Figure 8. Tomographic results for the FRI zone.

We note that the shear zone is not homogeneous: the slowness varies along the trace of the zone on the tomogram. We make the assumption that the variation of properties in the plane of the fracture zone is isotropic. Then, using the tomogram, we calculate a variogram for slowness along the trace of the zone. The variogram is in turn used as the basis for simulating slowness in the plane of the fracture zone (Figure 9).

This simulation is not directly a picture of the hydrologic properties. It is a picture of a mechanical property. To use this map to predict hydrologic properties we must find a relationship between the elastic parameters and permeability. For this discussion we turn to a second example from the Stripa Mine in Sweden.

At the Stripa mine, SGUab has performed radar tomography and identified several fracture zones for the Stripa Project. The zone called RB makes a steep angle with respect to three parallel boreholes, N2, N3, and N4 and thus is similar to the geometry of the FRI zone. In this case we have made a simulation of the variation of geophysical properties in the plane of the fracture zone in the same way as in the FRI experiment. This is not a map of the hydrologic properties. To get a map of the hydrologic properties we follow the procedure outlined in Figure 10.

The first step is to propose a base geometry for hydrologic conductors. In the case of Figure 10, we have chosen one of the simplest possible geometries, a square grid of conductors. However, we anticipate that future investigations of shear zone morphology will provide a more sophisticated "template" for conductors. This template model is superimposed over the geophysical simulation. We then remove conductors from the grid according to a probabilistic rule. We use the simulated tomogram to calculate the average slowness in the region of each conductor. Then we remove a conductor with a probability inversely proportional to the slowness. Thus if the rock is slow, there is a high probability of fractures, therefore there is a high probability of having a conductor. For example, from the simulation of Figure 9 we get the conductors of Figure 11.

Going one step further, we can simulate a well test in the resulting pattern of hydrologic conductors. Figure 12 shows such a simulation where the pumped well, N3 was centrally located between N2 and N4. The results clearly show that N4 is more connected to N3 than is N2. Given real well test data from N3 we could adjust the pattern shown in Figure 11 so that it better matched the hydrologic data. In fact such "adjustment" constitutes performing hydrologic inversion.

Two techniques are envisioned. In the first technique we note that flow to a well through a porous media or a very well connected fracture network is either two- or three- dimensional. However, in a partially connected fracture network, the flow may not have a integral dimension (Figure 12).

Barker (1988) has developed a solution for the well test equation which treats dimension as a variable. From this solution, he can develop type curves for partial

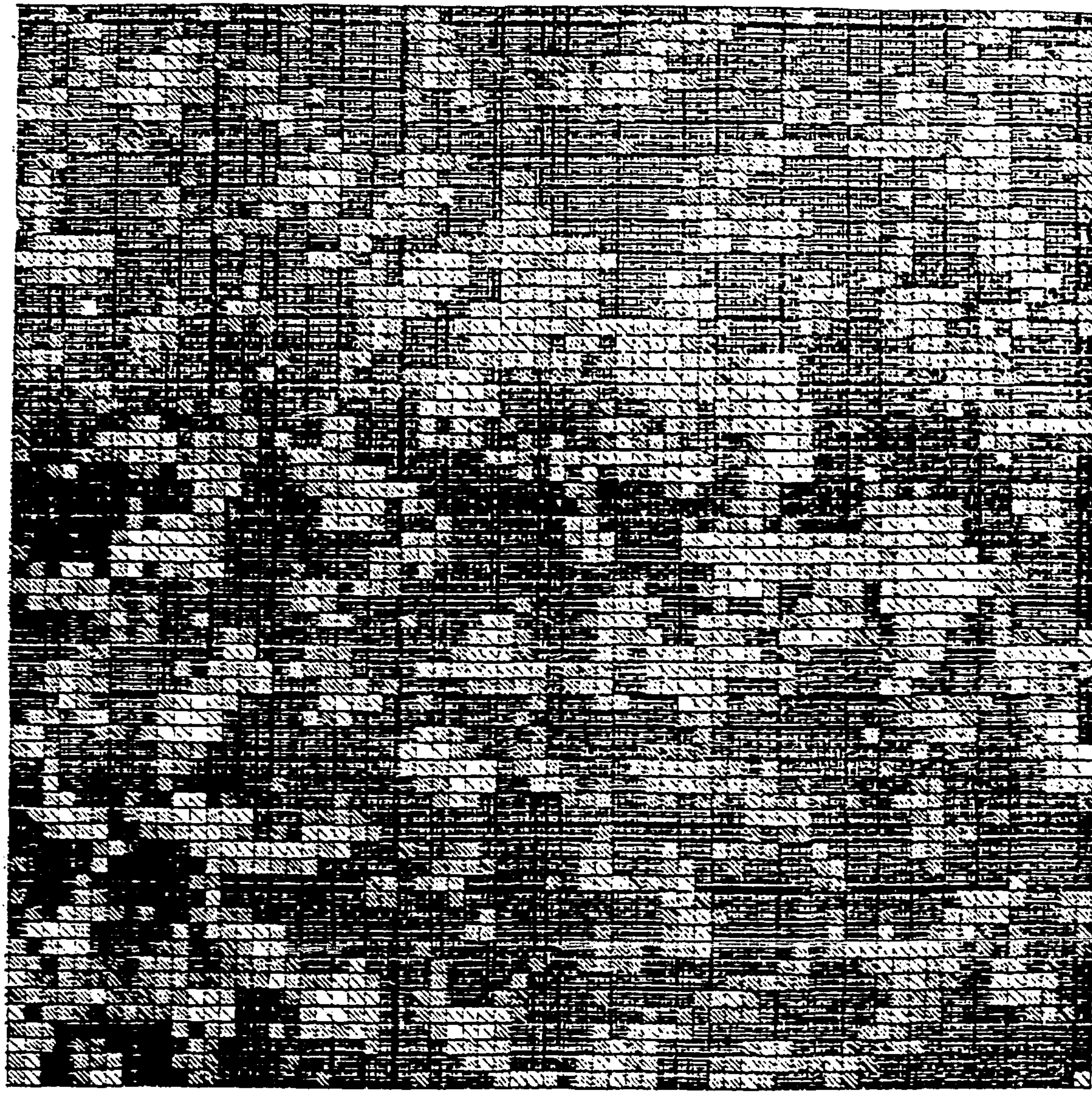

Figure 9. Simulation of slowness in the plane of the fracture zone for FRI.

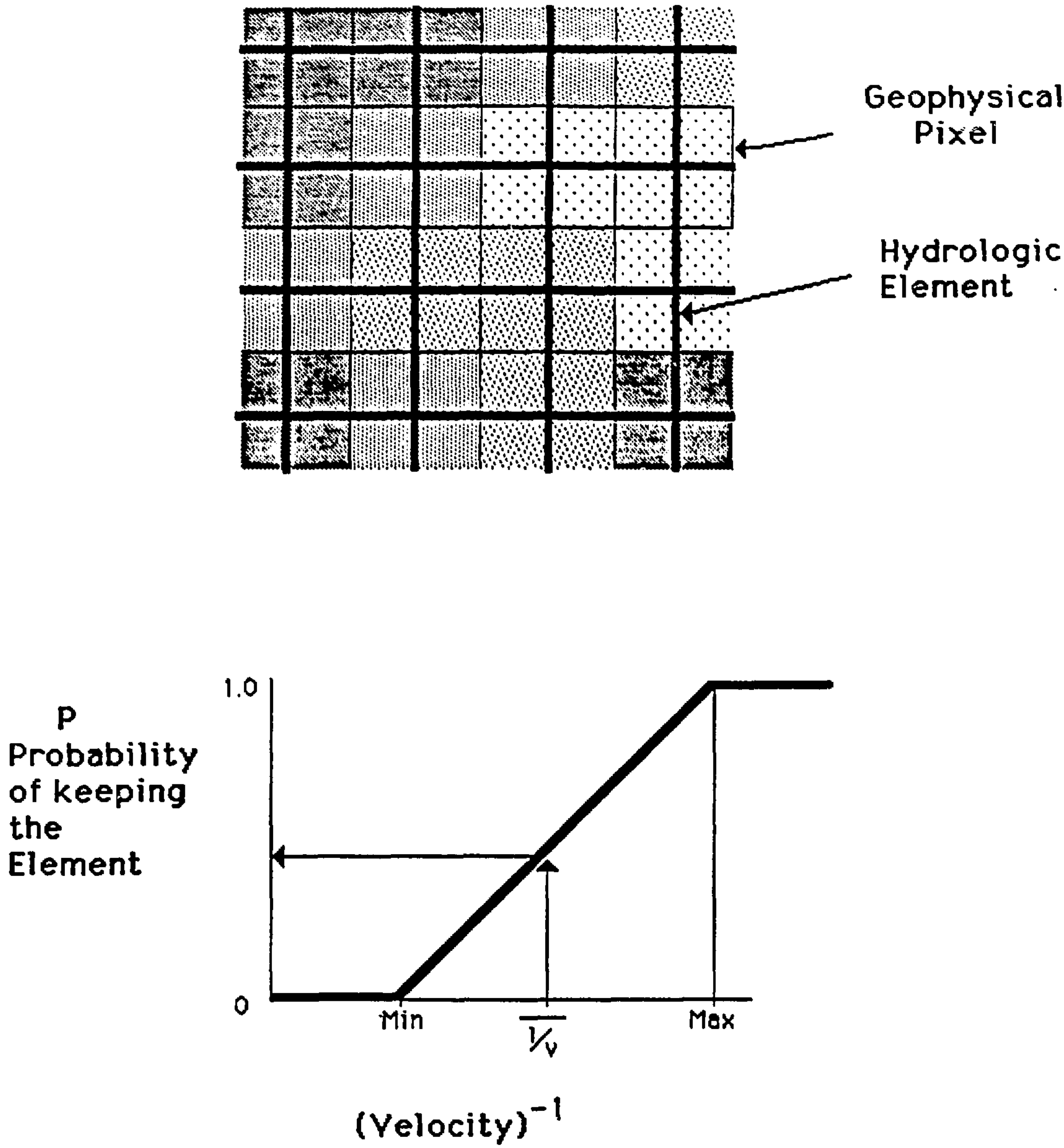

Figure 10. Mapping between geophysics and hydrology.

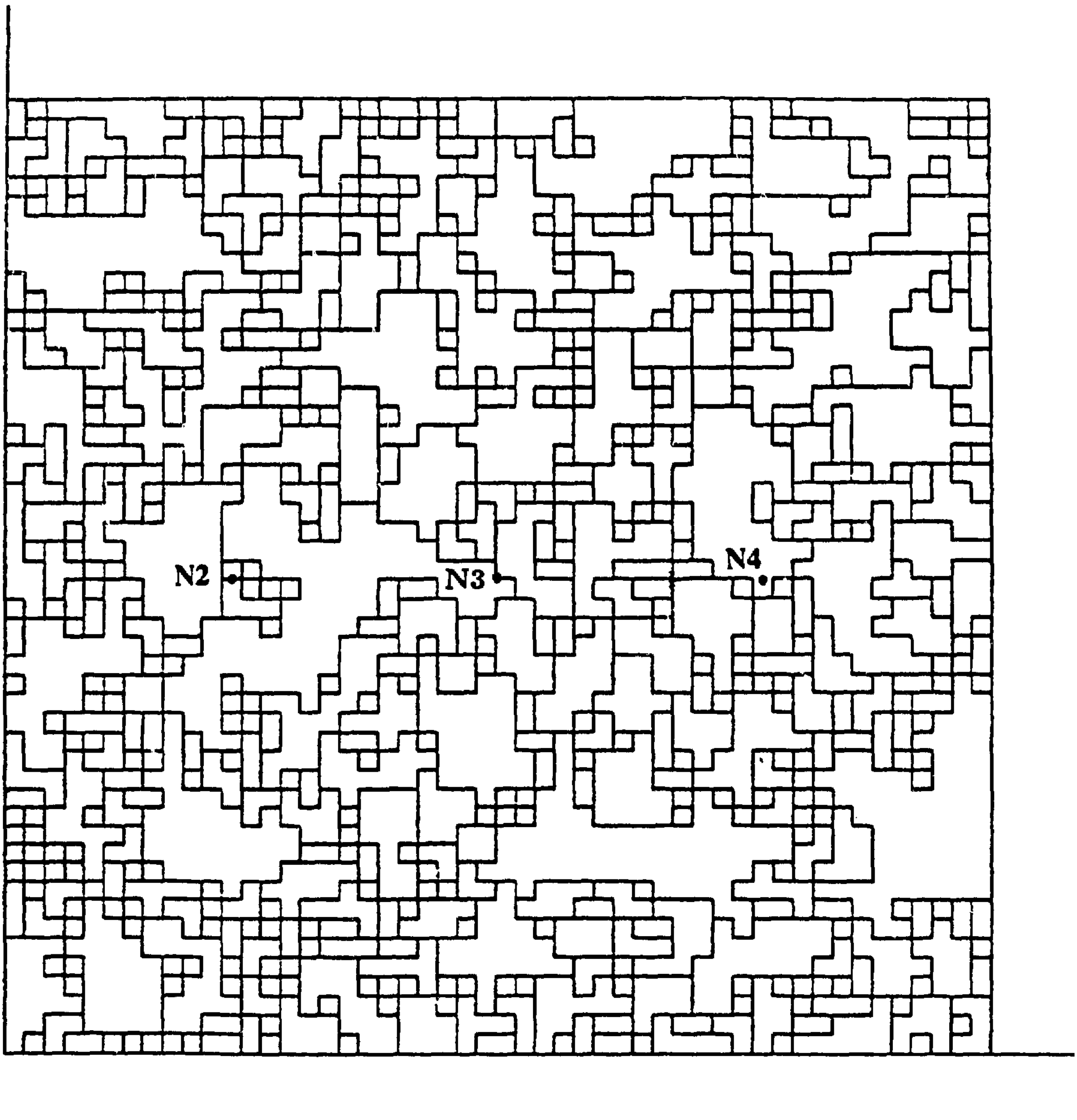

Figure 11. Pattern of hydrologic conductors resulting from analysis of radar slowness tomograms.

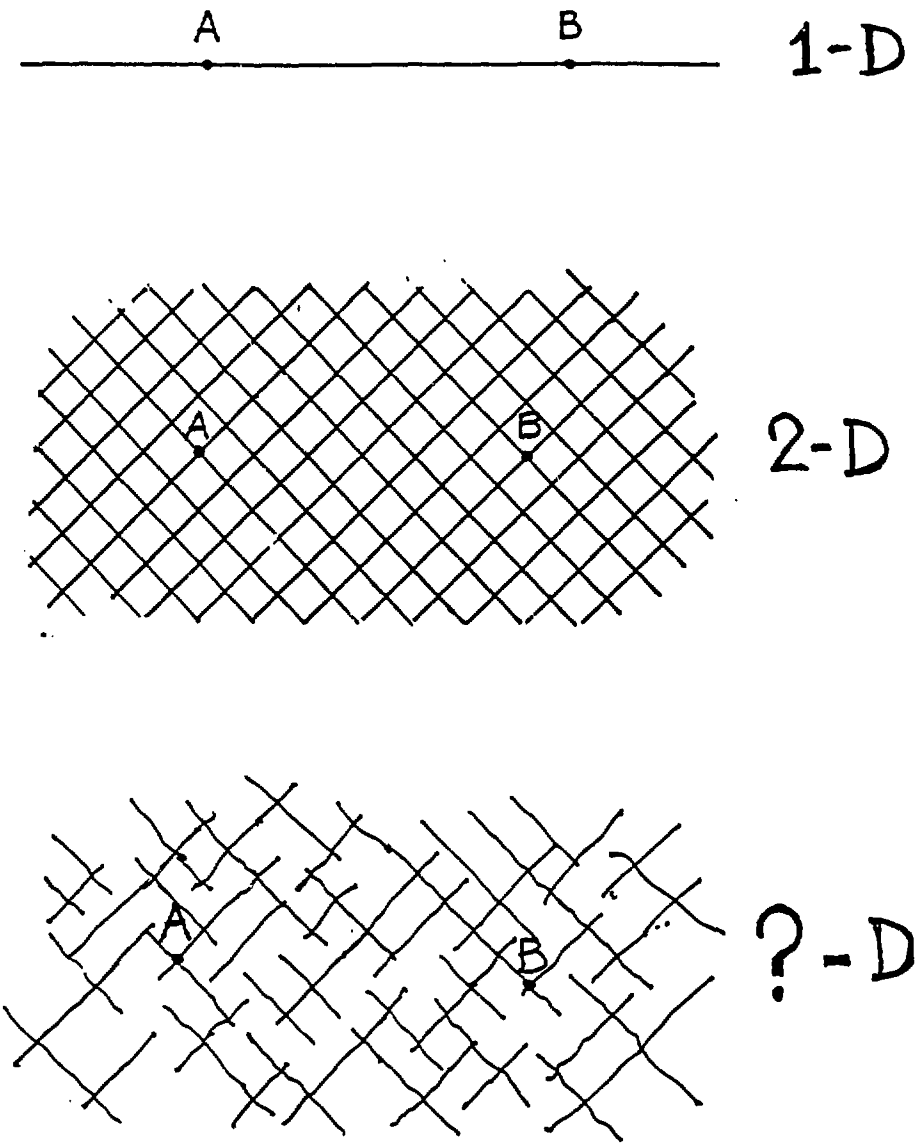

Figure 12. Dimension of flow in a fracture network.

dimension. We have examined the permeability of partially connected fracture networks (Long and Witherspoon, 1985). Such systems look like fractals between the scale of the individual fracture and the scale of correlation length where they look homogeneous. Thus we believe that the degree of interconnection may be evidenced by fitting the well test results to Barker's partial dimension well test curves.

As an example, we have numerically modeled a well test in a system of theoretical fractal dimension equal to 1.465 (Figure 13). When the numerical results are fit to Barker's curves they give a partial dimension of 1.40. The difference may be due to the fact that the numerical example is only "fractal" between an upper and lower limit. It remains to relate the connectivity of a random fracture network to its fractal dimension. If this can be done, the Barker solution can be used to find connectivity.

A second possible technique is a structured way to make changes in the model of the fracture system such that it behaves more like the real system. In this technique, we model hydraulic tests and compare the results with the field results. Then we change the model by adding or deleting a conductor. We remodel the hydraulic test and see if the change makes the model act more like reality. If it does, then we keep the change. If the change makes the behavior less like reality, we keep the change with a probability equal to:

$$P = e^{(E_1 - E_o)/T}$$

where E is equal to the square difference between the prediction and the measurement, o refers to the previous iteration, 1 refers to the present iteration, and T is a factor that decreases geometrically with the number of iterations. This technique allows one to get closer to a global minimum instead of getting caught in a local minimum.

Any hydraulic test that can be modeled can be used to calculate E. Figure 14 shows an artificial example of the change in E with each iteration based on well tests in a partially filled grid. Probably, first arrival of tracer tests data would be a more ideal type of data to use. However, one must be able to do a large number of large computations which may be a limitation.

Conclusion

All of the above ideas are in a partial state of development. Put together, they are the basis of a new methodology for characterizing fractured rock. In following this methodology, we could come up with a variety of systems which all fit the data. It is unlikely that any of these solutions are unique. Therefore, if we can determine a system which behaves like the real system for our test cases, is that good enough? Of course the answer to the question depends on the application but it is clear that this is an area which itself deserves research.

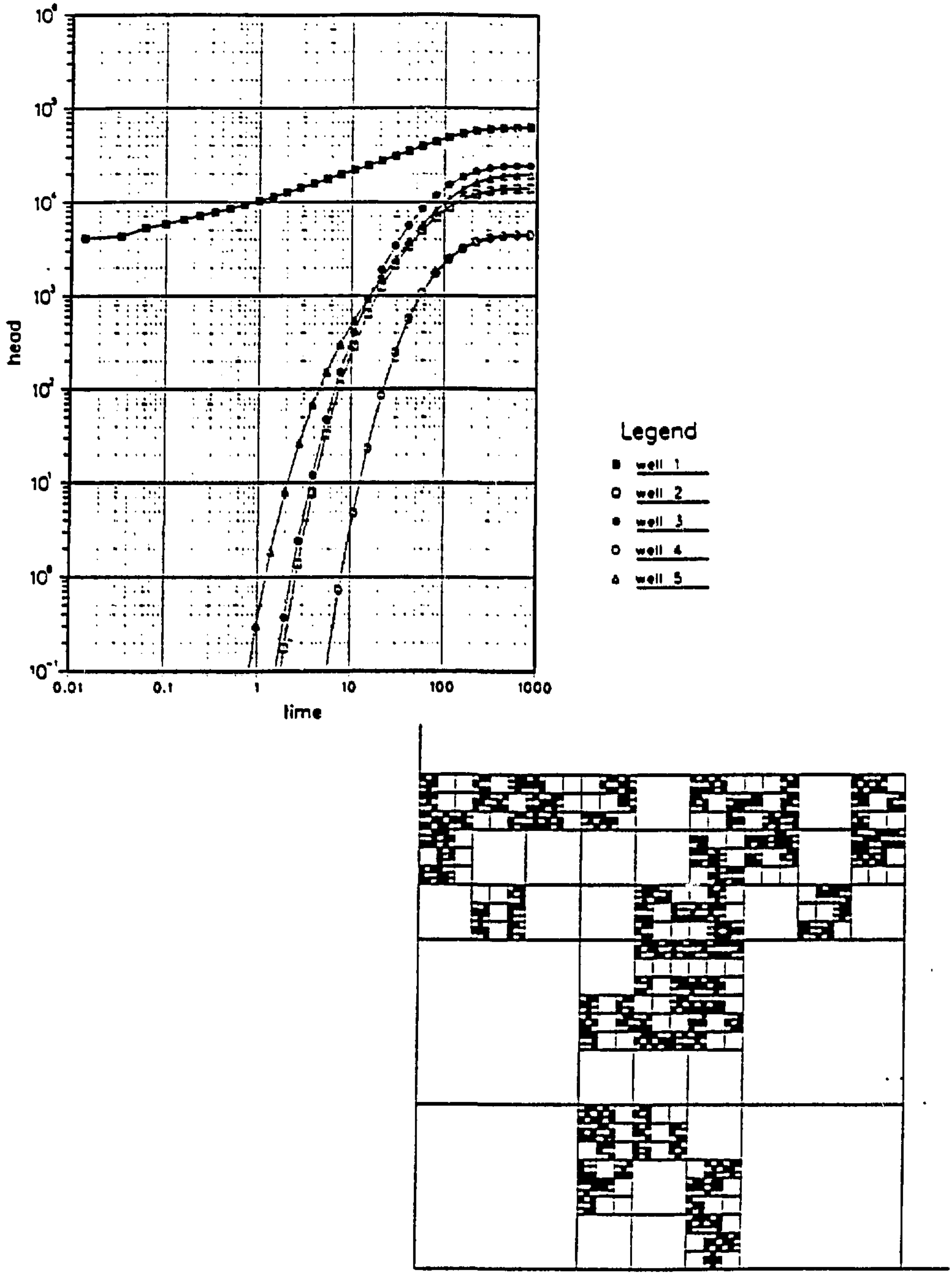

Figure 13. Well test results in a fractal network.

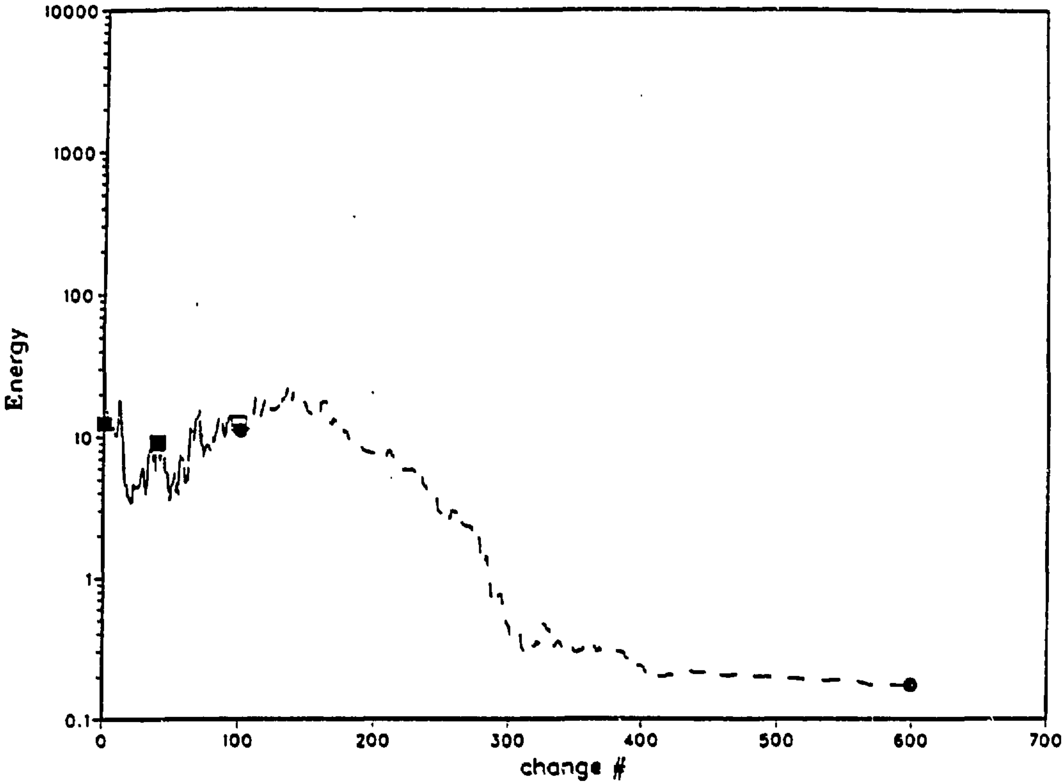

Figure 14. Example of the change in error, E with iteration towards a model which better matches field data.

Acknowledgments

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