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DISCRETE FRACTURE SIMULATIONS OF THE HYDROGEOLOGY AT KOONGARRA, NORTHERN TERRITORY, AUSTRALIA

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ABSTRACT

The U.S. Department of Energy is studying the Alligator Rivers Natural Analogue Project site at Koongarra, Northern Territory, Australia to investigate and simulate radionuclide migration in fractured rocks. Discrete fracture simulations were conducted within a cubic volume (180-m edge length) of fractured Cahill Formation schist oriented with one major axis parallel to the trend of the Koongarra Fault. Five hundred fractures are simulated within this domain. The fractures have a mean orientation parallel to the idealized plane of the Koongarra Fault dipping 55° SE. Simple flow modeling of this fracture network was conducted by assigning constant head boundaries to upgradient and downgradient vertical faces of the cube, which trend parallel to the fault. No-flow boundaries were assigned to all other faces. The fracture network allows hydraulic communication across the block, in spite of relatively low fracture density across the block.

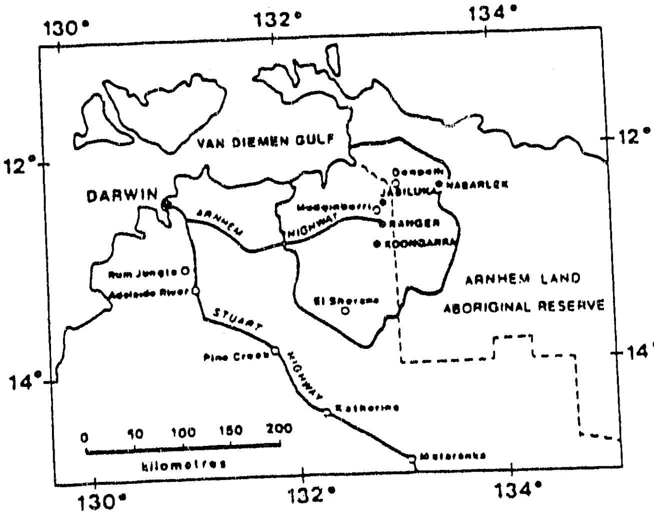

Figure 1. Map showing location of Alligator Rivers Analogue Project site at Koongarra, Northern Territory, Australia.

INTRODUCTION

The Koongarra uranium ore deposit in the Alligator Rivers Uranium Province, Northern Territory, Australia (Fig. 1) is being studied by an international team of scientists in the Alligator Rivers Analogue Project (ARAP) to evaluate the hydrologic and geochemical processes that affect radionuclide mobilization. The Koongarra site consists of a subsurface uranium deposit in fractured rock that has undergone oxidation and mobilization of dissolved uranium species over the past several million years. The uranium ore body is contained within Early Proterozoic Cahill Formation consisting predominantly of quartz, chlorite schist. The site is structurally located in the hanging wall of the Koongarra reverse fault. Proterozoic Kombolgie Formation sandstone forms the foot-wall side of the fault.

Mineralogic and radiographic investigations indicate that uranium tends to concentrate along the fractures within the rock. The enhanced movement of ground water through the fractures tends to produce uranium adsorptive weathering rinds that are enriched in ferrihydrite, vermiculite, and kaolinite; therefore, the hydrogeologic problem at the site is to adequately simulate the movement of water through the fractures and begin to assimilate the geochemistry data into an understanding of uranium migration within the system.

Study of the evolution of the uranium deposit will allow the U.S. Department of Energy's Office of Civilian Radioactive Waste Management (OCRWM) to gain insight into the long-term performance assessment of uranium and other radionuclide species through the geosphere. Research is focused on geologic, hydrologic, geochemical, contaminant transport, and numerical model validation aspects of the site. The site will be useful for 1) understanding processes involved in long-term migration of radionuclides through fractured rock, and 2) providing a data set to refine the validation process for performance assessment models. These are both critical issues for OCRWM in any license application to the U.S. Nuclear Regulatory Commission for a deep geologic repository in fractured rock.

CONCEPTUAL MODEL OF GROUND-WATER FLOW

A discrete fracture approach to the hydrogeology of Koongarra is being considered as an alternative to porous media representations of the flow system. Several investigators have reported information pertinent to fracture flow at the site. The geology of the Alligator Rivers region, including composition, structure, and metamorphism of the Cahill Formation has been described[1]. The fractured rock aquifer at the Jabiru bore field northeast of the Koongarra site was characterized during development of the Jabiru water supply[2]. A series of aquifer tests have been conducted as part of the hydrogeologic and hydraulic characterization of the Cahill Formation host rock at Koongarra[3,4]. The structural geologic trends and mineralogy of the Koongarra site have been documented[5,6], and geophysical and geotechnical investigations provide mapped resistivity, magnetic, and spontaneous potential trends across the ore body and laboratory measurements of the hydraulic properties of core specimens[7,8,9,10]. Borehole television logging of approximately 500 m of borehole at the site has significantly improved the characterization of the schistosity and fracturing in the schist[11].

Most of the annual average precipitation of 1.5 m occurs during the November-March wet season[1]. Much of the water in the vicinity of the site feeds Koongarra Creek via overland flow to the east-southeast, with the remainder of the water forming subsurface infiltration across the surface of the site. Inspection of hydraulic head measurements indicates that ground water also flows predominantly to the east-southeast towards Koongarra Creek. Some water may flow from Kombolgie Formation across the Koongarra Fault and into the Cahill Formation; infiltration to the surface may supply significantly more water to the vicinity of the ore body than ground water flowing across the fault. Flow to the south-southeast is predominantly perpendicular to the strike of the schistosity in the Cahill Formation during times of peak water levels but may potentially be more parallel to strike during times of low water level.

Work has been undertaken over the past several years and is currently in progress to better characterize ground-water flow at the site. This work includes aquifer testing, geophysical investigations, and borehole image analyses. Hydraulic characterization of the Koongarra site has been conducted by several researchers. The system may be defined as a low- permeability, semiconfined, fractured schist aquifer based on water levels, aquifer tests, and slug tests[4]. The dominant anisotropy is subparallel to the lithologic layering and the reverse fault[4]. Slug tests reveal regions exhibiting low storage with high fracture conductivity as well as isolated regions of low conductivity.

Drilling records indicate the effective saturated thickness ranges from 30 to 90 m below the land surface[4]. Transmissivities calculated from aquifer tests indicate a range from 11 to 60 m^2/day. A reasonable conductivity for the schist matrix would be approximately 1 x 10^{-6} m/day, which would produce transmissivities in the range of 3 x 10^{-5} to 9 x 10^{-5} m^2/day. Therefore, the calculated transmissivities indicate enhanced permeability of the aquifer.

The most likely mechanism for enhanced permeability within the aquifer is fracturing[4]. Core samples from a number of bores at the site are well fractured. Rock quality designations (RQD) at the 10-cm level for these cores range from 25 to 50%[12].

Additional aquifer tests provide further evidence for fracturing[3]. The hydraulic responses are characterized by elongated, asymmetric cones of depression. Theis plots of drawdown show early time segments that are linear with a slope less than the type curve[3]. Later time data show less drawdown than would be predicted by the Theis model, indicating some form of leakage or recharge boundary. Fractures are the only likely source of water in the system[3].

The results of the aquifer tests indicate that fractures are present in at least the portions of the rock hosting the ore body. The tests revealed erratic responses within the borehole network that imply a fractured rock environment. Observation wells near the pumped well had little or delayed water level response, while observation wells much farther distant showed almost instantaneous response. The aquifer tests reveal that the principal direction of transmissivity is subparallel to the strike of the Koongarra Fault and schistosity of the adjacent host rocks. Borehole television results indicate that the measured direction of schistosity is generally coincident with the measured direction principal transmissivity[11].

The aquifer stress tests indicate that at least some fractures in the vicinity of the ore body are able to transmit water under conditions of induced pumping stress; careful analyses of fracture systems within the natural potential field will be necessary to determine the extent to which ground water and uranium species in solution can flow under natural conditions. The following discussion technique describes a discrete fracture approach to this problem.

DEVELOPMENT OF THE FRACTURE NETWORK

The discrete fracture approach to the hydrogeology of Koongarra is being considered as an alternative to equivalent porous media representations of the flow system. The fracture network geometry was generated with the FracMan software package[13]. The fracture network domain for fracture generation is cubic with an edge length of 200 m. For flow simulations, the cube is trimmed to 180 m to account for edge effects. A surface projection of the cube with respect to primary features at Koongarra is shown in Fig. 2. The cube is oriented with two vertical faces parallel to the mapped strike of the Koongarra Fault (Fig. 2). The top surface of the cube is coincident with the upper surface of the Cahill schist; however, no attempt was made to differentiate weathering or geochemical zones within the schist rock matrix.

Five hundred fractures were generated within the cubic domain. A mean dip of 55° SE was assigned equal to that of the approximate orientation of the rock fabric and Koongarra Fault[6]. For comparison, other investigators have modeled the fault with dips ranging from 45° to 65°[14,15]. A Fisher distribution with a dispersion of 10 was used to vary the fracture orientation. The mean fracture radius

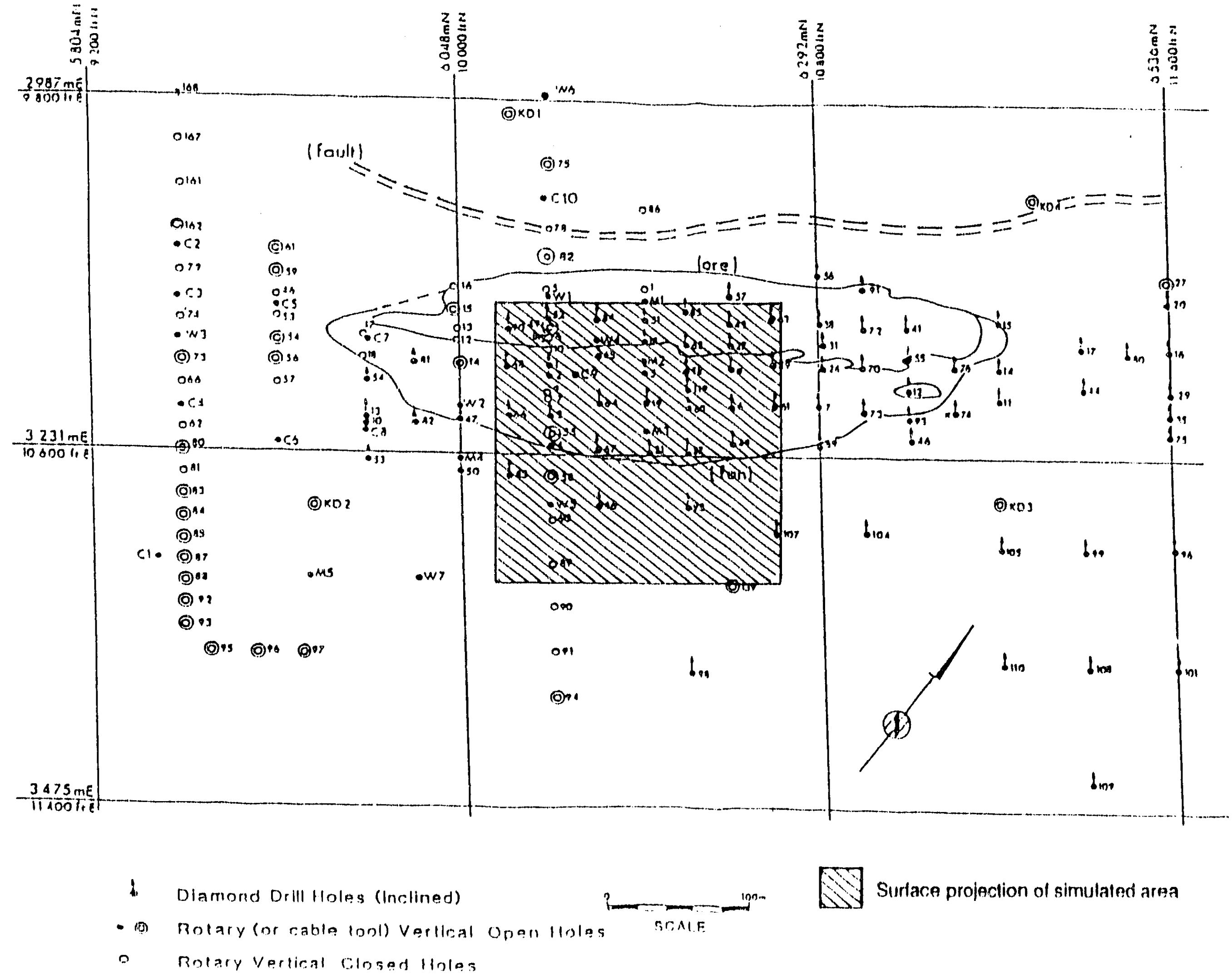

Figure 2. Surface projection of cube showing orientation relative to Koongarra Fault.

was 30 m, distributed with an exponential distribution. The elongation was equal to zero with an aspect ratio equal to 1.

FRACTURE GEOMETRY SAMPLING

The fracture network was sampled using trace planes and a borehole. The fracture network and trace plane locations are shown in Fig. 3. The complete network had a fracture density of 0.2 m^2/m^3. The statistics for the planes of intersection are shown in Table 1. The planes generally intersect similar numbers of fractures, although there are fewer through the middle of the cube (plane 2). This is most likely due to randomness in the generation of the geometry.

Table 1. Fracture Geometry for Three Trace Planes

Plane	Cross-Cutting	Non-Cross-Cutting
1	258	8
2	213	6
3	282	16

Intersections/m^2	0.006
Fractures/m^2	0.003
Termination %	4
Intensity (m/m^2)	0.2

An equal area projection for the fractures intersected by the planes is shown in Fig. 4. The projection shows plotted points of poles to fracture planes which incorporate the strike and dip orientation of each fracture. The projection is oriented with mean strike along the equator (E-W) and with mean dip direction toward the south pole. Horizontal fractures plot at the center of the projection and vertical fractures along the circumference. The projections show dispersion of

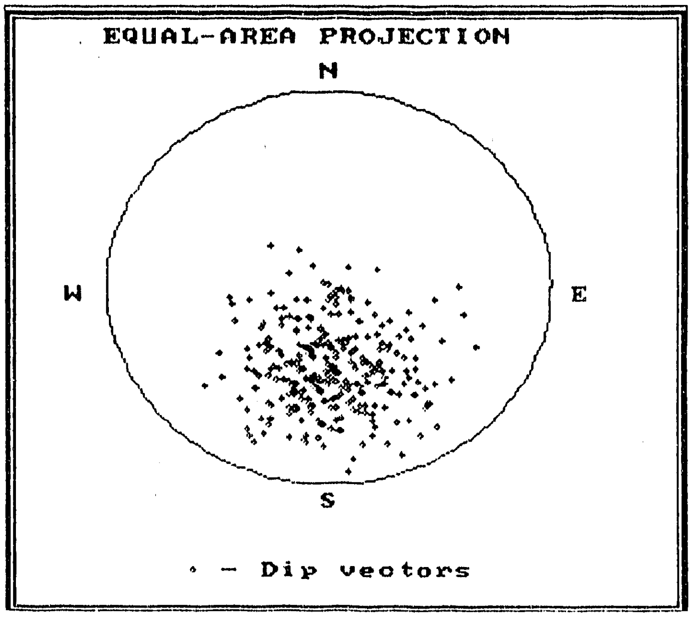

Figure 4. Equal area projection for fractures intersected by sampling planes.

fracture orientation about the specified mean orientation of 55° SE and serve as a visual check on the generation statistics.

A simulated borehole was drilled through the fracture network (Fig. 5). The sample results for the borehole are shown in Table 2. An equal-area projection for the borehole is shown in Fig. 6. The borehole intersects 30 fractures through 200 m with a rock quality designation of 100%, indicating no core segments less than 10 cm.

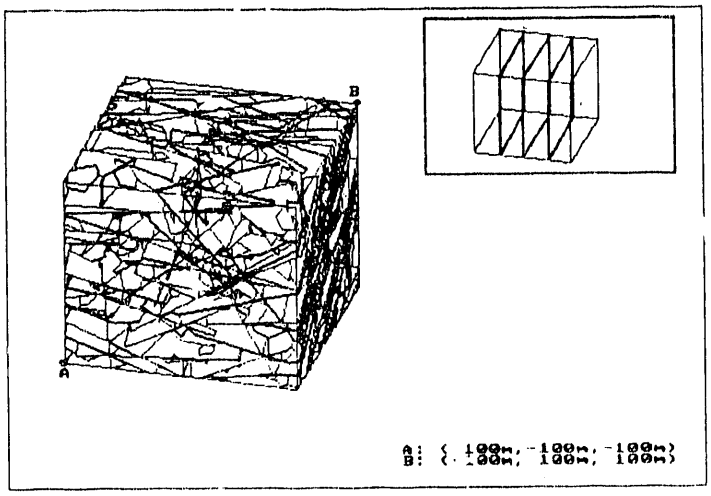

Figure 3. View of cubic domain showing fractures and location of sampling planes.

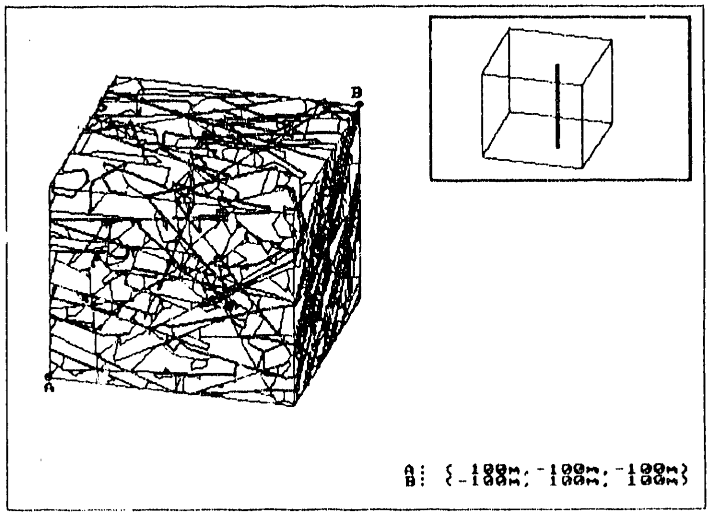

Figure 5. View of cubic domain showing fractures and location of sampling borehole.

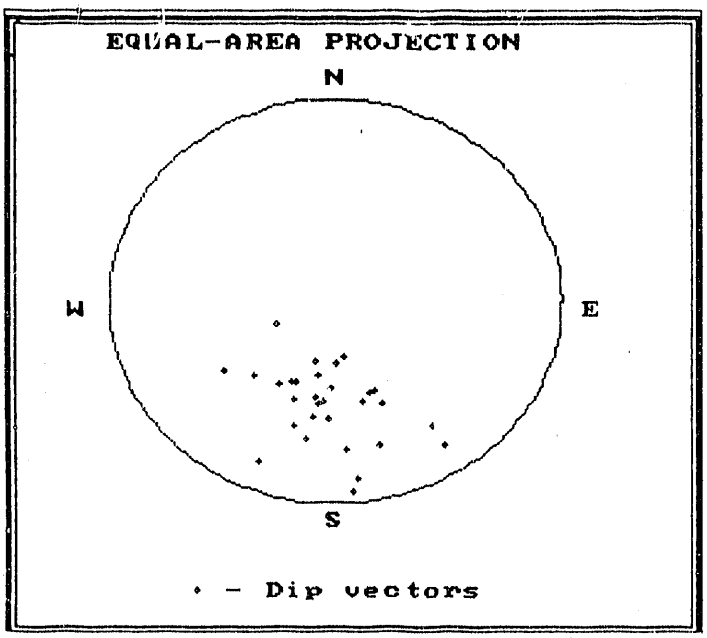

Figure 6. Equal area projection for fractures intersected by sampling borehole.

Table 2. Borehole Dimensions and Fracture Intersections.

Borehole Diameter (m)	0.03
Borehole Length (m)	200
Fracture Intersections	30
Rock Quality Designation	100%

FLOW MODELING

The discrete fracture geometry was automatically discretized into a finite-element grid for ground-water flow simulations using the FracMan postprocessing programs Meshmonster and Edmesh. Ten-meter-thick slices were removed from each cube face to account for edge effects during generation of the network geometry with FracMan; therefore, the cubic domain for flow simulations has an edge length of 180 m. A constant transmissivity of 0.0001 m^2/day was applied to all fractures. A steady-state flow problem was modeled by assigning constant heads of 32 m and 24 m to the front and back of the cube, respectively, and no-flow nodes around the other four faces. The bottom no-flow boundary approximates the depth below which fractures would be unable to maintain significant apertures due to the stress from overlying rocks. The upper no-flow boundary is highly simplified based loosely on the theory that most of the annual recharge flux is evapotranspired by the vegetation cover. These hydraulic head values and vertical no-flow boundaries were based on hydraulic head map overlays on the surface projection of the cube. The computer program Mafic calculated the ground-water flow through the fracture network. The program was operated such that all flow was through the fracture network with no flow in the schist rock matrix.

The hydraulic head distribution through the fracture network is shown in plan view in Fig. 7 (flow is from left to right). The figure is a black-and-white reproduction of a color image; consequently, some of the resolution is lost in the gray tones, but it shows the distribution of fractures near the top of the cube. The fracture density across the network is relatively sparse at 0.2 m^2/m^3, but it allows for sufficient hydraulic connection for flow across the 180 m of the block. Relatively small hydraulic gradients are generally observed across individual fractures. Such a response would be expected given good hydraulic connection in a parallel plate representation of a fracture with reasonably high transmissivity. The mean fracture radius of 30 m is less than the cube edge length of 180 m, with a resulting small likelihood of any single fracture intersecting both constant head boundaries. Consequently, any single fracture would be expected to bear only a portion of the imposed hydraulic head gradient.

Mass balance was achieved for the simulation, with a total flow of 894 m^3/day moving through the fracture network under steady-state conditions. The corresponding flux is approximately 28 mm/day through a unit area parallel to the constant head boundary planes. The unit area would be assumed to be generally perpendicular to the direction of flow, although variations in fracture orientation and hydraulic gradient may locally violate this assumption. Note that the simulated flux is calculated based on limited data; however, data recently collected by Miyakawa[11] will provide significant input to simulations using discrete fractures as discussed below.

DISCUSSION

Preliminary discrete fracture modeling has allowed the FracMan, Meshmonster, Edmesh, and Mafic programs to be tested on Pacific Northwest Laboratory computer systems. The code operation and postprocessing infrastructure is complete. Preliminary results indicate that discrete fracture modeling on the field scale is computationally feasible; the availability of data will be the primary limiting factor.

The results described in this report are based on a hypothetical fracture network derived from the best available information on the existence and orientation of fractures, orientation of the schistosity in the Cahill Formation, and the orientation of the Koongarra Fault. The borehole video logging[11] will provide fracture orientation, distribution, and estimates of fracture aperture. This information will

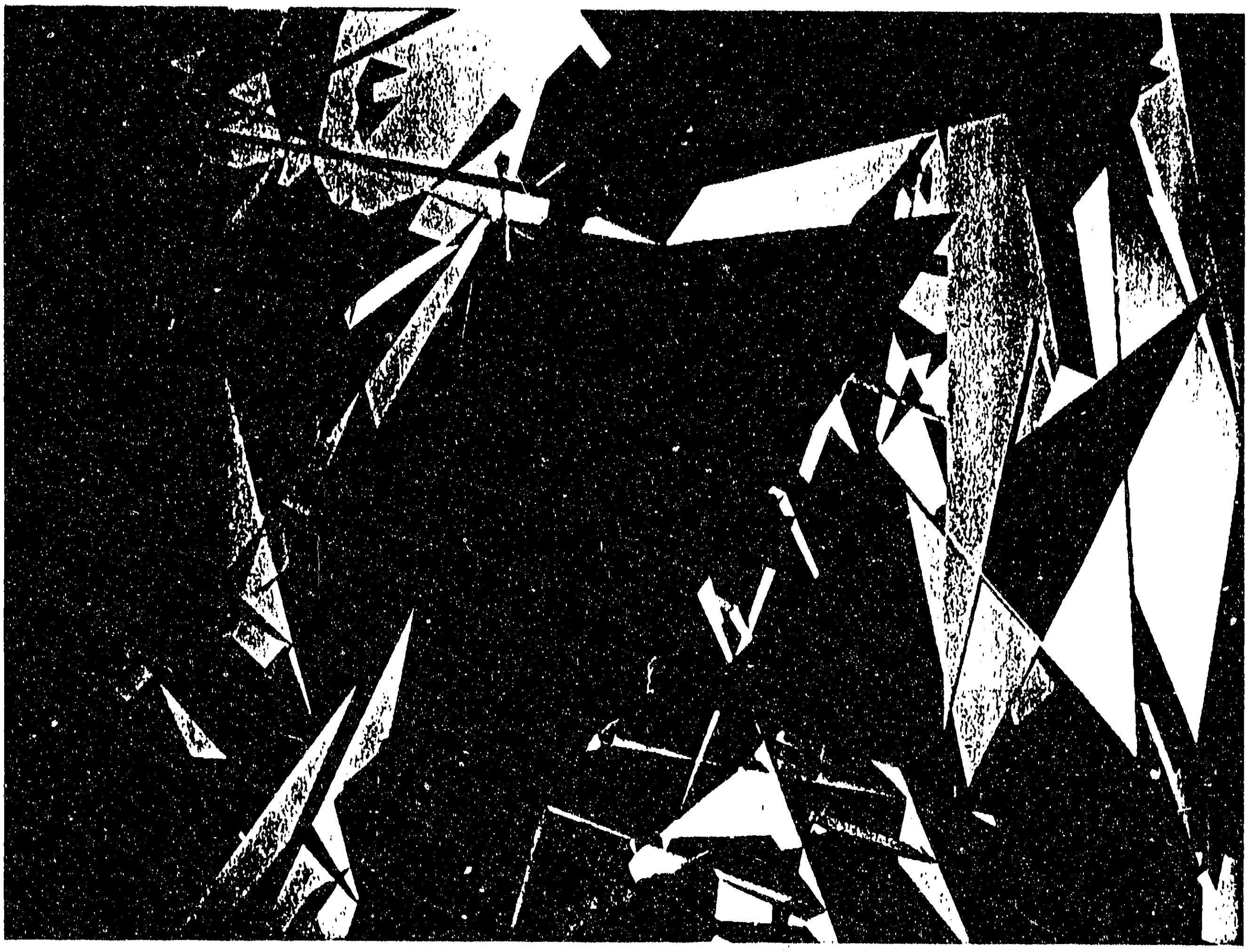

Figure 7. Map view of discrete fracture flow field showing hydraulic head distribution (flow is from left to right).

improve the input data base for the fracture network geometry in the vicinity of a number of boreholes at the site. Major problems requiring further analysis include the hydraulic connection of the fractures between the boreholes and the refinement of boundary conditions. Future modeling work will focus on integrating the borehole video data with the geologic framework and the simulation of aquifer test responses to obtain a better understanding of the connectivity of the system.

ACKNOWLEDGMENT

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