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COMPARISON OF LABORATORY, *IN SITU*, AND ROCK MASS MEASUREMENTS OF THE HYDRAULIC CONDUCTIVITY OF METAMORPHIC ROCK AT THE SAVANNAH RIVER PLANT NEAR AIKEN, SOUTH CAROLINA

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ABSTRACT

In situ testing of exploratory wells in metamorphic rock indicates that two types of fracturing occur in the rock mass. Rock containing small openings that permit only extremely slow movement of water is termed virtually impermeable rock. Rock containing openings of sufficient size to permit transmission of water at a significantly faster rate is termed hydraulically transmissive rock. Laboratory methods are unsuitable for measuring hydraulic conductivity in hydraulically transmissive rock; however, for the virtually impermeable rock, values comparable to the *in situ* tests are obtained. The hydraulic conductivity of the rock mass over a large region is calculated by using the hydraulic gradient, porosity, and regional velocity. This velocity is determined by dividing the inferred travel distance by the age of water which is determined by the helium content of the water. This rock mass hydraulic conductivity

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value is between the values measured for the two types of fractures, but is closer to the measured value for the virtually impermeable rock. This relationship is attributed to the control of the regional flow rate by the virtually impermeable rock where the discrete fractures do not form a continuous open connection through the entire rock mass. Thus, laboratory methods of measuring permeability in metamorphic rock are of value if they are properly applied.

INTRODUCTION

The scale of testing is important in all geohydrologic investigations. It is a commonly held notion that geohydrologic testing at different scales will yield different results. This paper presents several sets of tests for hydraulic conductivity at vastly different scales on the same body of rock that yield nearly identical results. To achieve this, an adequate conceptual model of the distribution of hydraulic conductivity is necessary.

All of these tests were made on slightly fractured metamorphic rock buried beneath 300 m of Coastal Plain sediments at the Savannah River Plant (SRP), which is located in South Carolina adjacent to the Savannah River (Figures 1 and 2). These tests were made as part of a broader study at SRP from 1961 to 1972 to evaluate the safety of storing radioactive waste in metamorphic bedrock.

The metamorphic basement rock consists of chlorite-hornblende schist and hornblende gneiss with lesser amounts of quartzite. Water occurs under confined conditions in small fractures in the rock and is separated from the water in the overlying Coastal Plain sediments by a layer of dense clay or sandy clay called saprolite. This clayey layer is the residual weathering product of the crystalline rock.

From water injection and removal tests on isolated sections of rock, Marine [1966] concluded that there are two types of fractures in the crystalline rock. The first type consists of minute fractures that pervade the entire rock mass but transmit water extremely slowly. Rock that contains only this type of fracture is called virtually impermeable rock. The other type of fracture is restricted to definite zones and has larger openings that transmit water at a faster rate. Rock that includes this type of fracture is called hydraulically transmissive rock.

LABORATORY TESTS FOR HYDRAULIC CONDUCTIVITY

Hydraulic conductivity was measured on 29 samples of unbroken rock core from well DRB 1 (Figure 3) by the U. S. Army Corps of Engineers. About two-thirds of the measurements were less than 3.8×10^{-11} cm/sec, which was the lowest value measurable by the testing equipment and procedure (145 Kpa differential pressure for 30 days). However, the other one-third of the samples had measurable hydraulic conductivity up to a maximum of 9.2×10^{-8} cm/sec and averaged 2.3×10^{-8} cm/sec (Table 1). The water leakage through the samples that had measurable hydraulic conductivity occurred at some inhomogeneity in the sample such as a minute fracture, a healed fracture, a chlorite seam, or the contact between schist and gneiss. In the mass of crystalline rock, these inhomogeneities probably occur so commonly that they render large sections of apparently sound rock nearly homogeneous with respect to permeability.

These laboratory tests were illuminating but were thought to be nonrepresentative of the hydraulic conductivity of the metamorphic rock because hydraulically transmissive rock could not be transported to the laboratory. However, later testing on a more regional scale showed that the laboratory tests were more representative than was first believed.

IN SITU BOREHOLE TESTS

A series of packer tests were made in eight boreholes (Figure 3) that penetrated 300 m of metamorphic rock within a circle of diameter 2760 m. These packer tests consisted of both instantaneous injection tests (slug tests) and instantaneous water removal tests (swabbing tests). A number of these tests were specifically designed to include hydraulically transmissive rock. In these tests, apparent transmissivities were obtained, but due to the discrete nature of the water transmitting fractures, hydraulic conductivity was not (Marine, 1967).

For the *in situ* tests in virtually impermeable rock, the minute fractures were assumed to be sufficiently distributed for the concept of hydraulic conductivity to be applied. For 25 tests on virtually impermeable rock, most about 30 meters in length, the average hydraulic conductivity was 1.4×10^{-8} cm/sec. The range was from a minimum of 9.4×10^{-10} cm/sec to a maximum of 3.8×10^{-8} cm/sec. However, in two other tests that were still considered to be in virtually impermeable rock, the hydraulic conductivity was 1.8×10^{-7} and 9.4×10^{-8}, respectively. Thus, as shown on Table 1, the average value for the hydraulic conductivity of virtually impermeable rock obtained by both laboratory and *in situ* tests are almost the same.

The maximum value from each testing method is also almost the same. The minimum value for the laboratory tests is almost two orders of magnitude lower than the minimum value from the *in situ* tests because, indeed, smaller specimens are less likely to incorporate even virtually impermeable fractures.

Pumping Tests

Pumping tests were not, and in a practical sense could not be, made on virtually impermeable rock. However, several were performed on hydraulically transmissive rock. The resulting transmissivity from a pumping test of 30 days duration was equal to the summation of the transmissivities obtained from packer tests on two wells exposed to the hydraulically transmissive zone (Figure 4). This pumping test gave a transmissivity of 2.0 m^2/day for hydraulically transmissive rock that averaged 68 m in thickness. Thus, if homogeneity is assumed for this zone, the apparent hydraulic conductivity would be 3.3×10^{-5} cm/sec.

However, in a later pumping test of one year's duration, as the drawdown cone extended in space, the rock appeared to become less permeable (discharge boundary). The water level graphs of observation wells shown in Figure 5 indicate that equilibrium was not achieved while pumping 57 L/m for 1 year. This feature implies that the hydraulically transmissive zone is not semi-infinite in extent but gives way to virtually impermeable rock at some distance from the pumping well.

Two-Well Tracer Test

A tritium tracer test was conducted between two wells in a zone of hydraulically transmissive rock (Figure 6). In this test, the tracer was forced to flow through the hydraulically transmissive zone from an injection well to a pumping well. The pumped water was then returned to the injection well by a plastic pipe on the ground surface. Analysis of the arrival of this tracer at the pumping well (Webster and others, 1970) gave a value for hydraulic conductivity of 1.6×10^{-5} cm/sec. As shown on Table 1, the value obtained from the two-well tracer test was very close to that obtained from the pumping test.

ROCK MASS HYDRAULIC CONDUCTIVITY FROM AGE OF WATER

The water from the metamorphic rock contains a dissolved gas that contains as much as 6 percent helium. The helium content was used by Marine (1979) to determine that the age of the water was 840,000 years. This is the length of time that the water has been in contact with the metamorphic rock. Form piezometric information, the inferred flow path in this type of rock is 51 km long (Figure 7). Assuming flow along this path constitutes the residence time for the water, the velocity of the water is about 0.06 m/yr.

The hydraulic gradient over this flow path is 6×10^{-4} m/m. The fracture (effective) porosity in a hydraulically transmissive fracture zone is 0.08 percent (Webster and others, 1970). These values may be used to determine the effective hydraulic conductivity for the rock mass averaged over the entire flow path by use of the following equation.

$$K = \frac{VE}{I}$$

where K = hydraulic conductivity

V = velocity

E = effective porosity

I = hydraulic gradient

For the metamorphic rock upgradient from SRP

$$K = \frac{0.06 \text{ m/yr} \times 0.0008}{6 \times 10^{-4} \text{ m/m}} \left(100 \frac{\text{cm}}{\text{m}} \frac{1}{365 \text{ day/yr}} \frac{1}{86{,}400 \text{ sec/day}}\right)$$

$$= 2.5 \times 10^{-7} \text{ cm/sec}$$

CONCLUSION

Table 1 shows the comparison of these five methods of measuring hydraulic conductivity. Laboratory tests gave values similar to those obtained from *in situ* tests on virtually impermeable rock. Analyses of pumping tests gave values similar to a tracer test for hydraulically transmissive rock. The hydraulically transmissive rock is about three orders of magnitude more permeable than the virtually impermeable rock. The hydraulic conductivity obtained from the age of the water and the inferred gradient and flow path represents a composite average of a large mass of rock consisting of both virtually impermeable rock and hydraulically transmissive rock. This value is two orders of magnitude less than the values from hydraulically transmissive rock. It is an order of magnitude greater than the average of laboratory tests and *in situ* tests, and it is about the same as the maximum laboratory and *in situ* values.

Fracture zones in the metamorphic rocks are not infinite in extent but terminate in virtually impermeable rock. Thus, the regional average hydraulic conductivity is dominated by that of virtually impermeable rock. Thus, for this study, the laboratory measurements of hydraulic conductivity would provide values that are indeed applicable to calculations of regional flow within an order of magnitude.

REFERENCES

Marine, I. W., Hydraulic correlation of fracture zones in buried crystalline rock at the Savannah River Plant near Aiken, South Carolina, Geological Survey Research 1966, *U.S. Geol. Surv. Prof. Pap.*, *550-D*, D223-D227, 1966.

Marine, I. W., The permeability of fractured crystalline rock at the Savannah River Plant near Aiken, South Carolina, Geological survey research 1967, *U.S. Geol. Surv. Prof. Pap., 575-B,* B203-B211, 1967.

Marine, I. W., The use of naturally occurring helium to estimate groundwater velocities for studies of geologic storage of radioactive waste, *Water Resources Res.* 15 (5), 1130, 1979.

Webster, D. S., J. F. Proctor, and I. W. Marine, Two-well tracer test in fractured crystalline rock, *U.S. Geol. Surv. Water Supply Pap., 1544-1,* 1970.

TABLE 1

Comparison of Laboratory, *In Situ*, and Rock Mass Measurements of Hydraulic Conductivity of Metamorphic Rock at the Savannah River Plant Near Aiken, SC

	Virtually Impermeable Rock		Hydraulically Transmissive Rock		
	Laboratory Measurements (cm/sec)	*In situ* Packer Tests, (cm/sec)	Pumping Test (cm/sec)	Tracer Test (cm/sec)	Rock Mass (cm/sec)
Maximum	9.2×10^{-8}	1.8×10^{-7}			
Average	2.3×10^{-8}	1.4×10^{-8}	3.3×10^{-5}	1.6×10^{-5}	2.5×10^{-7}
Minimum	3.8×10^{-11}	9.4×10^{-10}			

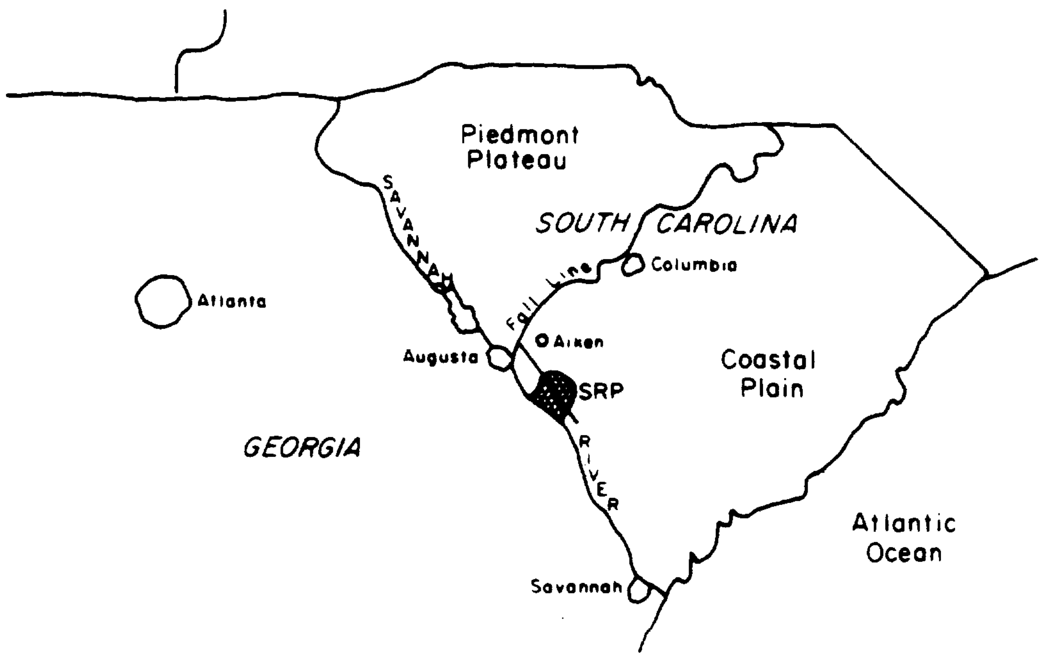

Fig. 1. Location of the Savannah River Plant and nearby geologic provinces. The line of section for Figure 2 is also shown.

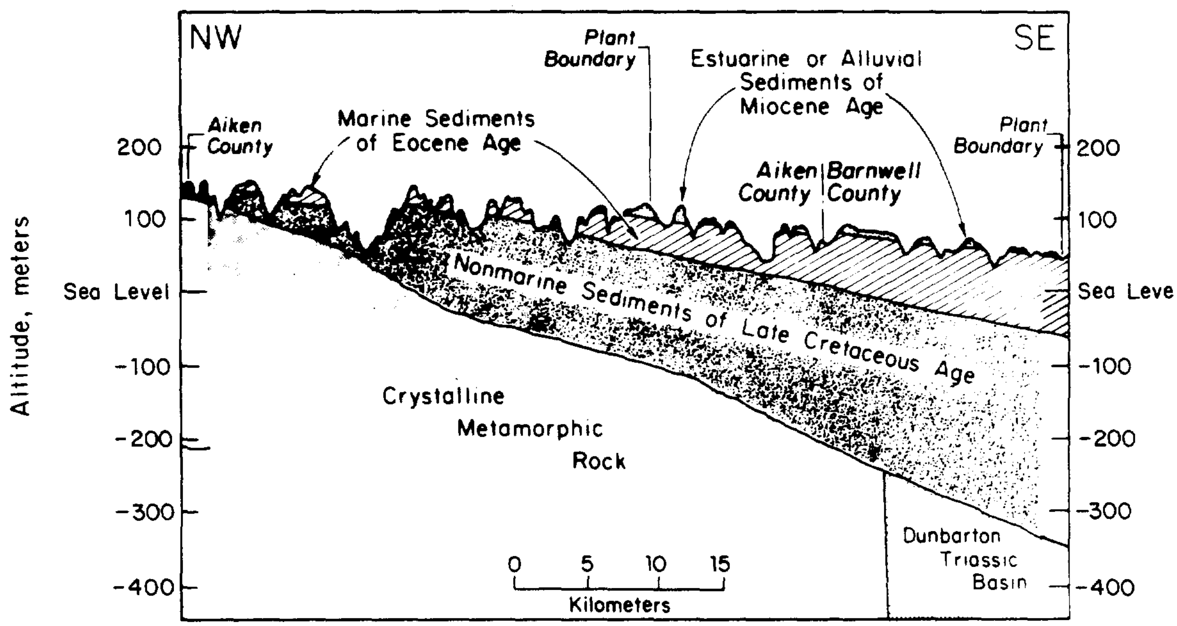

Fig. 2. Generalized Northwest to Southeast Geologic Profile Across Savannah River Plant

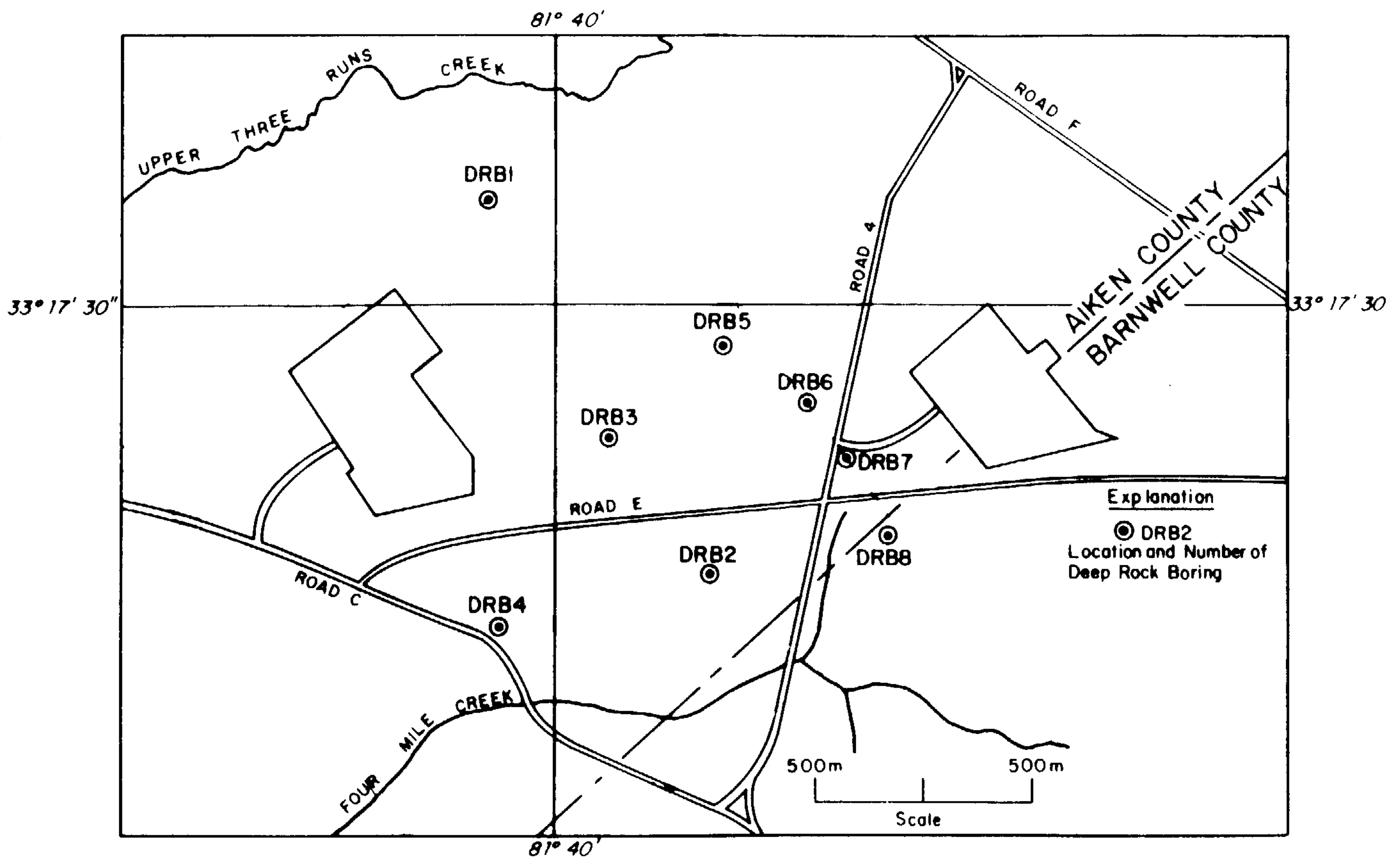

Fig. 3. Map showing the location of exploration wells that were cored through crystalline rock (deep rock borings).

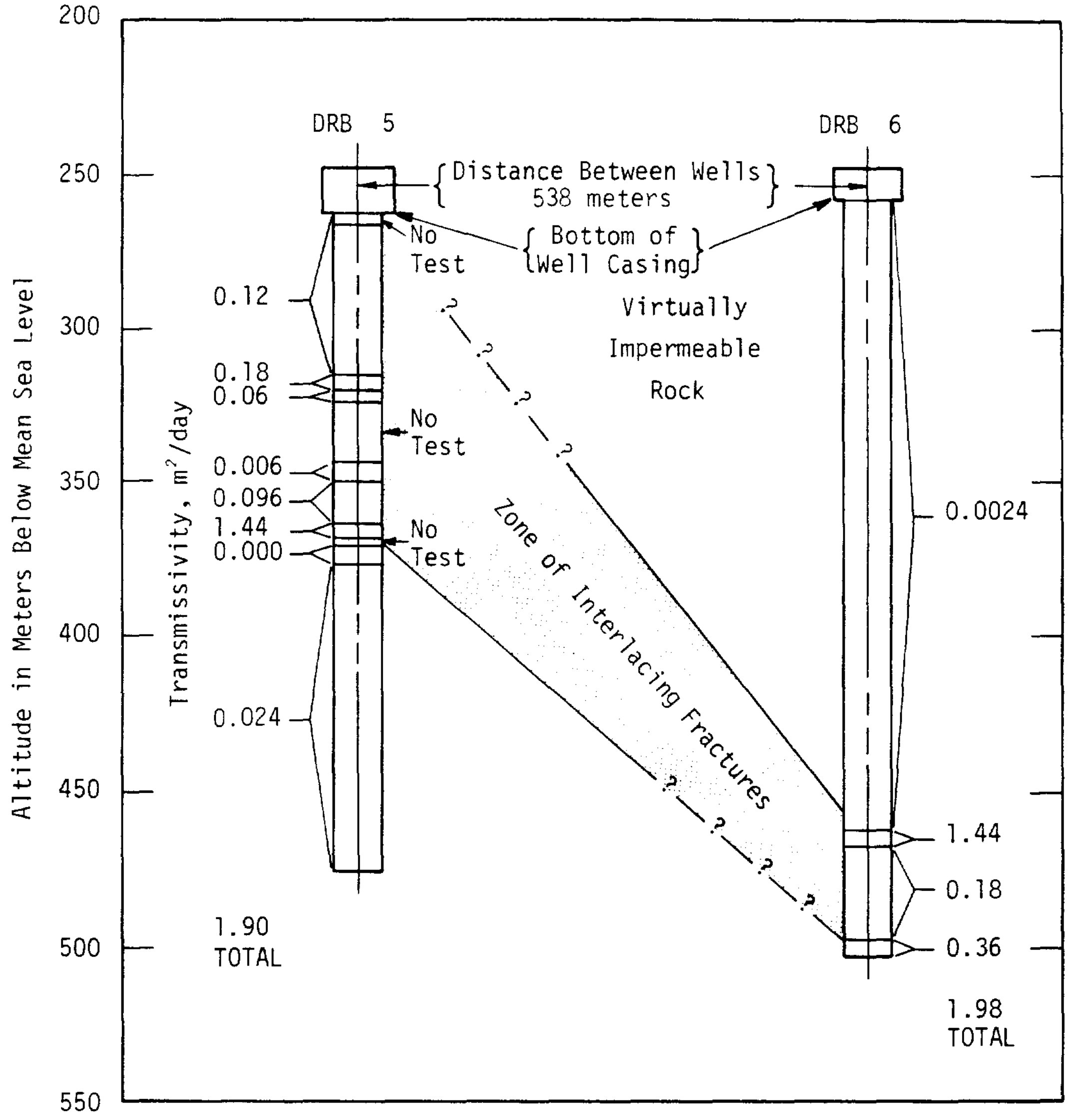

Fig. 4. Results of slug tests in wells DRB 5 and DRB 6.

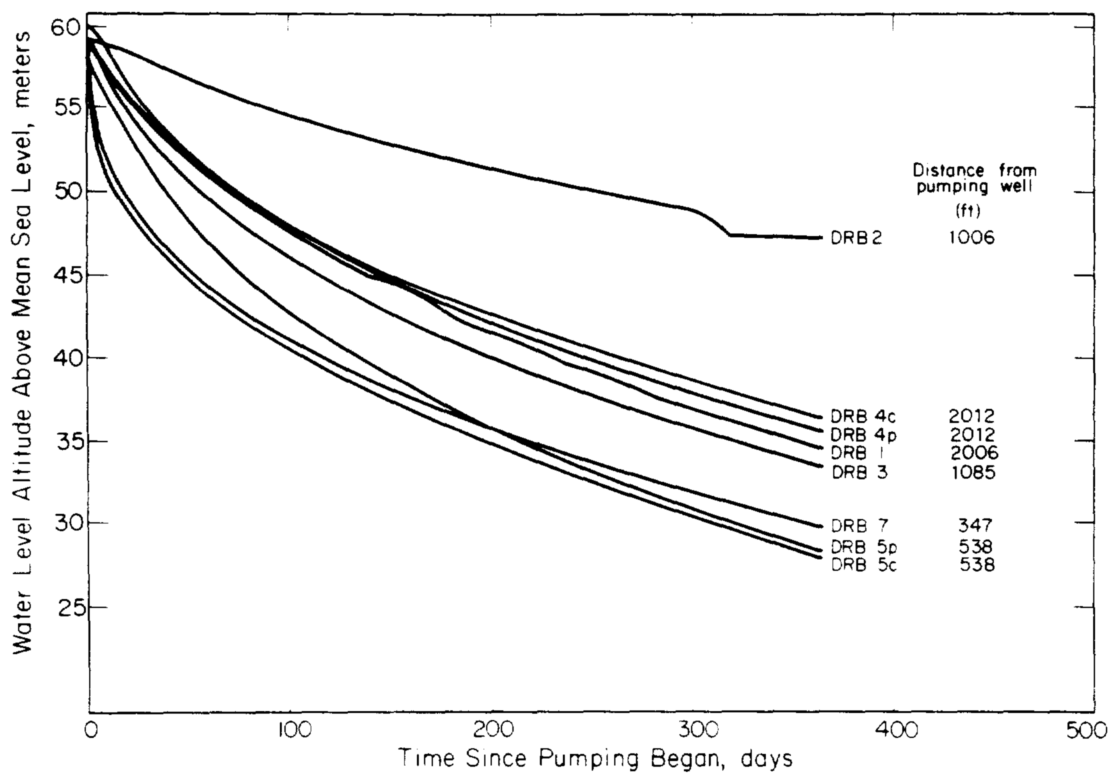

Fig. 5. Graph Showing Water Levels in Observation Wells while Pumping DRB6 at 57 L/m from August 7, 1968 to August 7, 1969

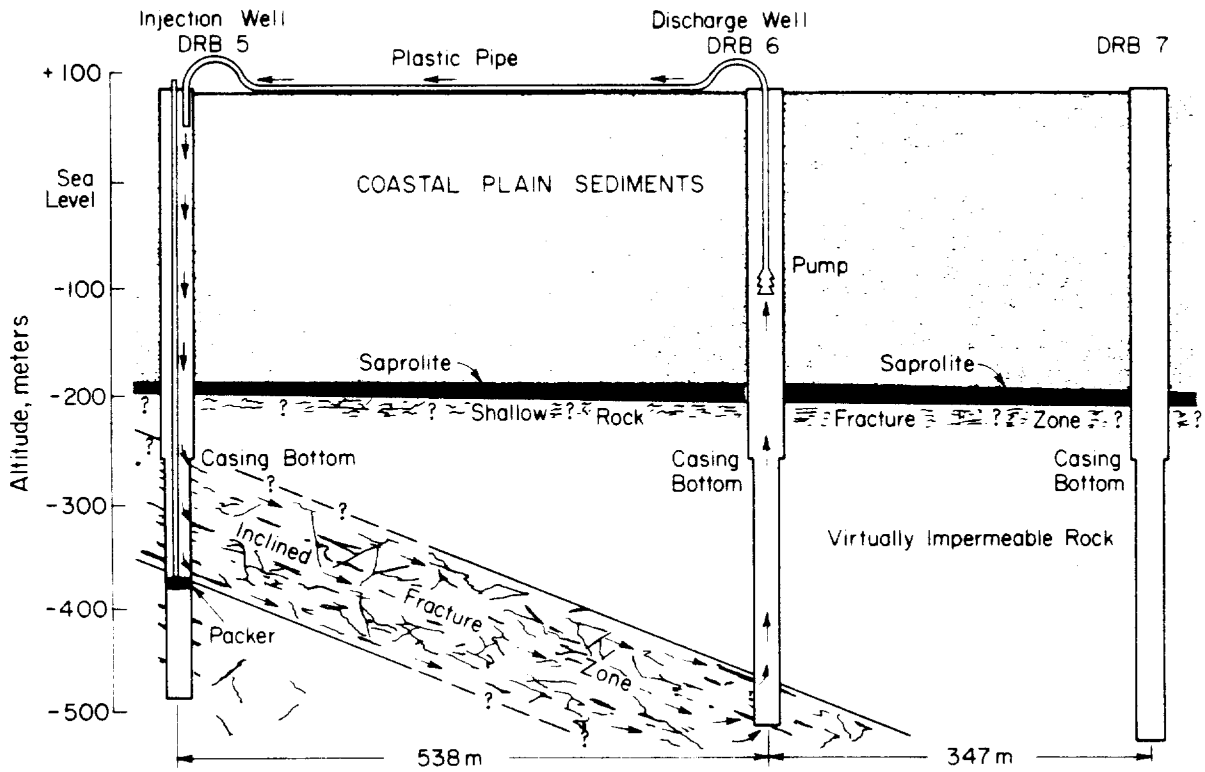

Fig. 6. Geologic section showing the wells and fracture zone used in the two-well tracer test. Arrows show the generalized direction of water flow.

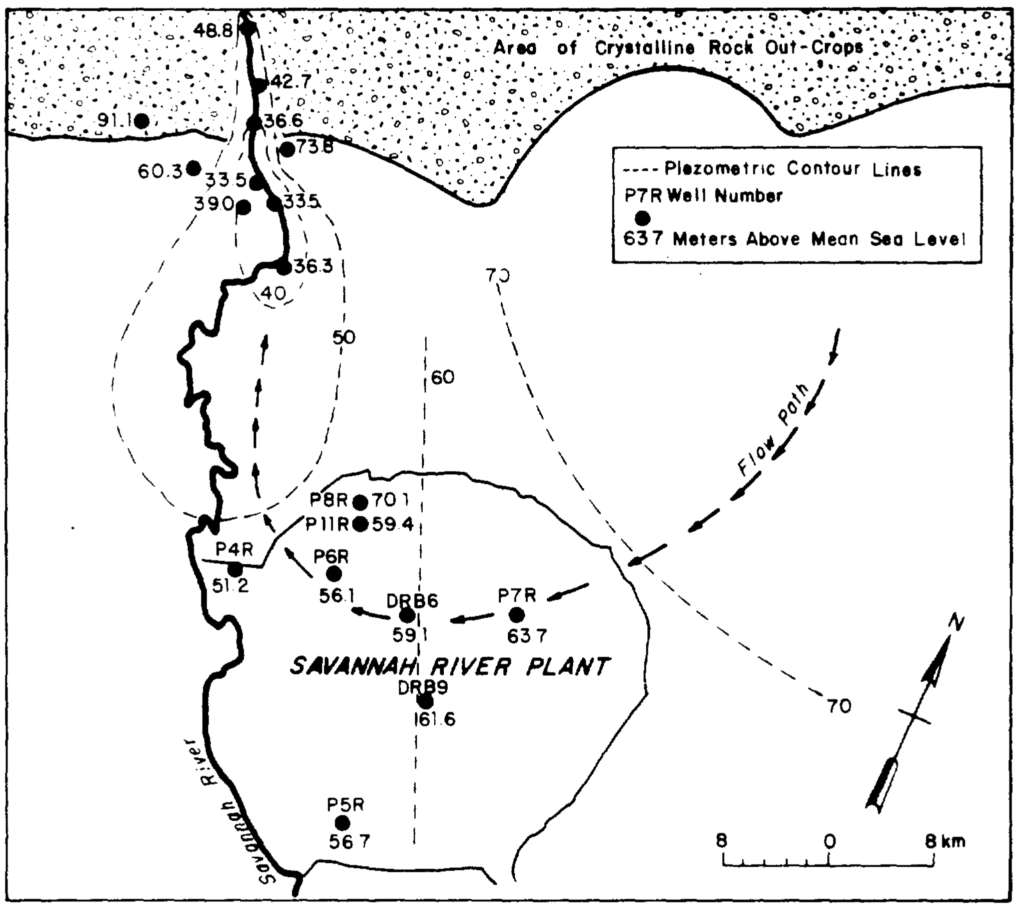

Fig. 7. Piezometric map of water in crystalline metamorphic rock and inferred flow paths.