DETERMINATION OF THE LOCATION AND CONNECTIVITY OF
FRACTURES IN METAMORPHIC ROCK WITH IN-HOLE TRACERS

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ABSTRACT

In-hole tracer tests were used in a geohydrologic investigation of metamorphic rock at the Savannah River Plant near Aiken, SC to locate water-transmitting fractures and to determine the connectivity of these fractures between boreholes. Only after development of a conceptual model of the fracture occurrence and connection could the proper methods of analysis for the hydraulic parameters be selected.

In-hole tracers were used to locate fractures in a borehole and supplemented other methods, such as core inspection, geophysical logs, borehole wall imaging techniques, dry drilling, and packer tests. The first three of these do not necessarily investigate fluid-transmitting fractures.

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In the study of the connectivity of fractures between boreholes, the in-hole tracer techniques supplemented determinations by the rapidity of hydraulic response and the use of between-well tracer tests.

In hydraulically transmissive rock, fractures were located by changes in the velocity of the tracer pulse in response to adding fluid to the well. In virtually impermeable rock, the movement of the tracer pulse in the rock was normalized to the movement of another tracer pulse in the cased portion of the well because the movement was so slow that direct measurement was difficult. Connectivity of fractures between boreholes was determined by placing an in-hole tracer in one hole and measuring the movement induced by pumping a nearby borehole. From this test, it was determined that the fractures were interlacing, and single fractures did not extend from one borehole directly to the other.

INTRODUCTION

Ground water movement through crystalline igneous and metamorphic rock is primarily through fractures. One of the objectives of detailed investigation of the hydrogeologic system in these rocks must be to understand the fracture system. The method for developing this understanding consists of three steps:

- (1) Determining the exact location of the fractures in exploratory boreholes and their approximate magnitude;
- (2) Determining the connectivity of fractures from one borehole to another; and

(3) From steps (1) and (2), developing a conceptual model of the system so the proper analytical methods can be applied to determine the hydraulic constants.

In-hole tracers were used to address steps (1) and (2) in a hydrogeologic investigation of buried crystalline metamorphic rock at the Savannah River Plant near Aiken, South Carolina.

This particular study was performed in 1964 as part of an investigation into the feasibility and safety of storing radioactive waste in the metamorphic rock below the Plant site that was conducted from 1961 to 1972. The entire investigation was indefinitely postponed in 1972, but the methods applied may be of interest for metamorphic rock investigations elsewhere.

Hydrologic Systems at the Savannah River Plant

The Plant is located on the Atlantic Coastal Plain about 32 km southeast of the Fall Line, which separates the Piedmont and Coastal Plain physiographic provinces (Figure 1). There are three separate geologic and hydrologic systems (Figure 2) at the Plant: (1) the Coastal Plain sediments, (Miocene, Eocene, and Late Cretaceous sediments on Figure 2) where water occurs in porous unconsolidated to semiconsolidated sand and clay; (2) the crystalline metamorphic basement rock, consisting of chlorite-hornblende schist and hornblended gneiss with lesser amount of quartzite where water occurs in small fractures; and (3) a buried Triassic basin, consisting mostly of red consolidated mudstone with some poorly sorted sandstone, where water occurs in the

intergranular space but is very restricted in its movement due to the extremely low hydraulic conductivity.

The water in the Coastal Plain sediments is separated from the water in the crystalline metamorphic rock by a layer of dense clay or sandy clay, called saprolite. This layer is the residual weathering product of the crystalline rock from the period when the rock was last exposed to the atmosphere before being covered by Cretaceous sediment, perhaps 100 million years ago. The gross separation of these two systems is shown by the following observations. Water in the Coastal Plain sediment contains about 30 mg/l of dissolved solids while the water in crystalline rock has about 6,000 mg/l. Pumping tests in the crystalline rock (up to a year in duration) show no indications of leakage from the sediments above. Water in the crystalline rock contains dissolved gases including helium. The presence and composition of the gases indicate that they do not escape to the sediments at a significant rate.

The locations of the exploratory boreholes are shown on Figure 3. These boreholes are all cased through the Coastal Plain sediments and into the metamorphic rock. Most borings expose about 300 m of metamorphic rock.

Crystalline rock that is pervaded by small fractures which transmit water extremely slowly is termed virtually impermeable rock. These small fractures occur at inhomogeneities in the rock, such as along chloride seams, at the contact of gneiss and

schist, and along healed fractures. Because this system of small fractures apparently extends through the full thickness of crystalline rock that was penetrated by the drill, there is reason to believe that at least the upper 300 m of crystalline rock is hydraulically connected, and consequently that the entire mass constitutes a single hydraulic unit. Thus, even where an open hole is drilled into the rock cut only by these fine fractures, the slow inflow of water eventually fills the hole to a level indicative of the piezometric surface in that section of rock. This water level responds to changes in pressure due to the withdrawal or injection of water at other places within the rock, but the response is both delayed and protracted compared with that in a hole open to one or more zones of larger fractures.

The second type of fractures in the crystalline rock have larger openings than those of the virtually impermeable rock and therefore transmit water at significantly faster rates. These fractures appear to occur in vertically restricted but laterally extensive zones. Rock containing fractures that yield or accept 3.8 l/min or more will be termed transmissive rock. Although the definition of such a zone is somewhat arbitrary, most of the rock is divisible into zones that yield 3.8 l/min. or more and into zones that yield hundredths or thousandths of l/min.

The hydraulic conductivity of both types of crystalline rock was discussed by Marine (1967, 1975) and representative values are 1.2×10^{-5} m/day for virtually impermeable rock and 3.3×10^{-2} m/day for hydraulically transmissive rock.

Location of Individual Fractures in Boreholes

Core Inspection

The rock cores from the exploratory wells are transected by many fractures, however, only some of these breaks represent open fractures in the *in situ* rock mass. The number of fractures shown by the core has little relationship to the occurrence of water-transmitting fractures in the rock mass. Many former fractures have been filled by calcite, and even though techniques that image the borehole wall show them to be fractures, they do not necessarily transmit water.

Geophysical Logs

The interpretation of geophysical logs in relation to rock and fluid properties is a refined science for consolidated and unconsolidated sediments that yield most of the world's supply of petroleum. However, determining the exact location of an individual transmissive fracture that may be only a fraction of a millimeter wide is extremely difficult with the present state of technology.

Packer Tests

In order to test individual sections of the rock for their *in situ* water-transmitting properties, packers were set at the top and bottom of the well section to be tested, and water was either injected into or removed from that section. Packers are two rubber elements that are expanded so that part of the hole is isolated from the remainder. This section is connected to the surface with drill pipe (Figure 4).

The results of many of these packer tests were given by Marine (1967). The difficulty in using packers to determine the exact location of fractures is that there is a minimum interval between the packers, less than which there is no resolution. In this testing program, the minimum distance was 4.6 m; thus, within this interval the location or number of fractures could not be determined.

In-Hole Tracer Tests

A method employing a radioactive tracer in the borehole was used to exactly determine the location of the fractures. Equipment used in this method consisted of a cable-hung tool that contained a small reservoir, in which the liquid tracer (iodine-131) was placed, and an ejection pump that could be controlled from the surface. The lower part of the tool contained a gamma radiation detector. The tracer could be placed at any desired depth in the hole and its movement followed with the gamma probe. Iodine-131 was used because it emits high energy gamma rays that are easily detected by an in-hole gamma detector, and because it has a short half-life (~ 8 days).

As generally used in this investigation, the in-hole tracer testing steps were: (1) the reservoir in the tool was loaded with the tracer at the surface using a hypodermic syringe, (2) the tool was lowered in the well to be tested to about the top of an interval known to contain a water-transmitting fracture (3) a selected amount of tracer was ejected from the

reservoir into the well (0.08 to 0.42 mCi of iodine-131 depending on the length of the test and expected flushing from the well), (4) water was injected into the well from the surface causing the tracer to move down the hole, (5) this movement was followed with the gamma-ray detector and its velocity measured in 0.6, 1.5 or 3.0 m intervals depending on the rapidity of movement. The velocity of the tracer decreased as a water-accepting fracture was passed giving its location more exactly than was known from testing packed-off intervals of rock.

The most transmissive fractures in wells DRB 3, 5, and 6 were located in this manner (Table 1). However, fractures which did not transmit as much water as the most transmissive fractures, but were known to exist from the packer tests, could not be located by this method. Slight variations in velocity are difficult to detect, and in these particular tests, the rate of injection of water at the top of the casing was not precisely constant.

In addition to a decrease in velocity as the tracer pulse moves past a water-accepting fracture, there is also a decrease in the intensity of gamma activity. This is caused by losing a large part of the tracer from the well bore into the fracture. Figure 5 shows the change in shape of a typical tracer pulse as it moves down the hole. From an initial high activity in a narrow band when injected, the pulse seemed broader and less intense as it moved, with the sharper front in the direction of movement. As the pulse moved past a water-accepting fracture, it lowered the intensity and decreased its vertical span, as shown in Figure 5.

The in-hole tracer work in DRB 2 was conducted in a different manner from the other holes because this boring consisted entirely of virtually impermeable rock. The iodine injections, which were made at four separated points in the well, quickly diffused vertically throughout a large region of the well as shown on Figure 6. This occurred with no addition of the water to the well. In the testing of this hole after the 9-day period shown on Figure 6, water was added every morning except two for a period of 13 days and then twice more during the next 8 days. Gamma-ray logs were made periodically to follow the movement of three pulses and one pulse in the casing. By using the movement of a pulse in the cased section as a reference in plotting, the analysis could be made without consideration of the volume of water injected or the frequency of injection. The results of the tests are shown on Figure 7.

In Figure 7, movement of three tracer pulses (β , γ , and δ) in the uncased part of the hole is plotted against movement of a tracer pulse (α) in a cased part of the hole; both movements are caused by periodically filling the well with water. The depth of an arbitrary, but correlative, point on the tracer pulse is shown beneath each plotted point. The early points shown appear to be erratic. Line A has a slope of 45° showing that within the sensitivity of this method, no water is lost between the bottom of the casing at a depth of 299 m and a depth of about 453 m. Line B has a slope of 25° showing that 20% or 45 percent of the injected water left the well between 448 and about 453 m.

Line B and Line C are parallel showing that within the sensitivity of this method no water is lost between a depth of about 453 m and about 558 m. Line D has a slope of 13° showing that within the sensitivity of this method 12° or 27 percent of the injected water left the well at about 558 m. Line D and Line E are approximately parallel showing that little or no water left the hole between the depths of about 558 and 568 m. Line F has a slope of 3° showing that within the sensitivity of this method, 10° or 22 percent of the injected water left the well at about 568 m. As there is no change in slope on Line F, apparently no water left the hole between 568 and 576 m. Between 576 m and the bottom of the hole at 604 m, 3° or 7 percent of the injected water is lost.

In summary, the in-hole tracer tests greatly refined the location of the largest water-transmitting fractures in individual wells, but contributed little to the knowledge of the location or spacing of fractures that transmitted water at a lower rate in the same well. However, where all fractures are small, in-hole tracer tests indicated the exact locations of fractures not detected by packer tests.

Dry Drilling

Compressed air was used as a circulating fluid for the drilling DRB 8 after the Coastal Plain sediments and saprolite had been cased off. When air is used as a circulatory fluid, information on the location of transmissive fractures is obtained

from the water yield while drilling. Before any water-yielding fractures are penetrated, the drill cuttings come to the surface as dust. After penetrating a small yield of water, the cuttings make a paste which cannot be blown or flushed out with the small amount of water being produced by the well. It is common practice to inject a small quantity of soap solution or foaming agent in order to remove the cuttings when they are in this condition. When the water yield is greater, the drill cuttings will be washed out as water is blown from the hole. If the hole is deep, a foaming agent may still be added to reduce the load on the air compressors. When the water yield becomes large, the hole cannot be evacuated by compressed air, and injected water must be substituted for air as a circulatory fluid.

When no liquid is being added to the well, water-yielding fractures can be detected readily by measuring the amount of water produced by the well. While a foaming agent is being injected, water flows can be detected only if they are significant in relation to the rate of fluid injection. Once a zone of large water yield has been penetrated, small ones will no longer be detectable. Figure 8 gives the results of water-yield observations and the inferred location of water-yielding fractures for DRB 8 while air was being used as a circulating fluid.

In DRB 8 there were three depths at which the water inflow increased abruptly: 329 m, 422 m, and 475 m. The last two of these depths can be correlated with the upper and lower contact

of quartzite with the hornblende schist. From estimates of water flow, it appeared that additional water inflow may have occurred at about 482 m. Later packer tests confirmed this. At a depth of 497 m, the water inflow was so great that the compressors could not lift the water that entered the hole while adding a drill rod section. At this point water circulation was begun. While using air the well was yielding 1.0 L/min per meter of drawdown. When the well was near total depth, it is estimated by a very inaccurate method that its acceptance rate was about 0.57 l/min per meter of head increase. The difference between these values is probably due to the error in estimating the acceptance rate, but the comparison indicates that no additional large water-yield or water-accepting zones were penetrated while the well was being drilled with water as a circulating fluid (from 497 to 591 m). Packer tests confirmed this conclusion.

CORRELATION OF FRACTURES BETWEEN BOREHOLES

Knowledge of the location and nature of fractures in individual boreholes is a necessary, yet insufficient state of knowledge for understanding the hydrologic regimen in metamorphic rock. It is also necessary to know if these fractures are connected over significant distances. This may be investigated by determining if they connect between boreholes and, if they do, what the pattern and nature of these connections are. To this end, several types of tests were devised to aid in understanding fracture connectivity between borings.

Geologic Correlation of Fractures

The strike and dip of the foliation or schistosity is a preferred direction of fracturing in the core and may be in the *in situ* rock. Wells DRB 2 and 7 are about on strike with each other; as are wells DRB 4 and 6, and wells DRB 3 and 5 (Figure 9). If the location of fractures could be correlated with the schistosity, one would expect a similar location of fractures in DRB 2 and 7, DRB 4 and 6, and in DRB 3 and 5. Referring to Figure 9, it may be seen that both DRB 2 and 7 intersect only virtually impermeable rock. Both DRB 4 and 6 have fractures near the bottom of the hole and near the top of the rock. The transmissive fractures in DRB 3 and 5 do not appear to correlate as well as the other sets of wells that are along strike with each other.

In order to determine the likelihood that fractures might correlate along the schistosity, a tabulation was made of the orientation of fractures in the core from DRB 1, 3, and 7. From this tabulation it appears that between 89 and 96 percent of the fractures are either horizontal or strike parallel to the strike of the schistosity. As previously mentioned, most of these fractures do not transmit water, but represent planes of weakness that become apparent only when the rock is cored or excavated. However, under tectonic stresses it is more likely that fractures would orient themselves along these weaker planes.

At an average dip of 55° , two wells that penetrate 305 m of rock would have to be less than 213 m apart in the direction of the dip in order to intersect the "same" schistose layer. The

two wells that are nearest together (DRB 6 and 7) are 347 m apart, thus no wells penetrate the "same" schistose layer except perhaps those that are along strike with each other. In spite of this, known hydraulic correlations of fractures as discussed below indicate that several wells do intersect the same fracture system.

Drilling Activity and Packer Tests

Early in the investigation it was realized that pressure effects were transmitted quite rapidly along some pathways in the transmissive fracture zones. Marine (1966) described methods of correlating hydraulically transmissive fracture zones by water-level responses at one well which were caused by hydraulic activity at another well. By using this method he developed a model of the connectivity of fractures between seven of the exploratory boreholes. This correlation is shown in Figure 9. Subsequent packer tests, pumping tests (Marine, 1967), two-well tracer tests (Webster, Proctor, and Marine, 1970), and the drilling of DRB 8 have not contradicted this model. However, nothing in this model that was developed from hydraulic responses demonstrates whether the fracture zones consist of a single fracture or a zone of interlacing fractures. This point is critical in choosing the method of analysis for determining the hydraulic parameters, i.e., whether methods developed for porous media are applicable. Thus other tests were needed to determine the nature of the fracture zones.

Between-Wells Tracer Test

Even though there are fractures below 463 m in DRB 5 it was suspected that these had no immediate connection with the inclined fracture zone (Figure 10).

In addition to the short term evidence from the packer tests, additional evidence was afforded by the hydraulic data obtained during a between-wells tracer test using DRB 5 and 6 (Webster, Proctor, and Marine, 1970). In this test (Figure 10) a packer and piezometer pipe were installed at a depth of 457 m in DRB 5 in a section of rock from 455 to 459 m that previous straddle packer tests had proved to be the most impermeable rock tested in this investigation. Water was pumped from DRB 6 through a plastic pipe to DRB 5 where it was injected in the zone above the packer (Figure 10). In spite of an increase in head of about 24 m above the packer for about 2 years (Figure 11), the head increase in the fractures below the packer was only about 0.9 m, showing that these fractures below the packer were not directly connected to either the shallower fractures at DRB 5 or the deep fractures at DRB 6.

The slight head increase shows that fractures below 457 m in DRB 5 are connected to the inclined fracture zone through the network of minute openings that constitute the virtually impermeable rock. The water level below the packer in DRB 5 declined whenever there was a small leak in the plastic pipe connecting DRB 5 and DRB 6 (Figure 10) causing water to be lost from the system, (that is, the discharge from DRB 6 exceeded the injection

at DRB 5). When such a leak occurred, water levels in all of the observation wells (including the zone below a depth of 457 m in DRB 5) declined. (See the leak in June and July 1965 on Figure 11).

Connectivity Test Using an In-Hole Tracer

A test using iodine-131 determined the degree of connection of the individual fractures intersected by DRB 5 in the inclined fracture zone to those in DRB 6 (Figure 10). Radioactive iodine was placed at a depth of 442 m (α) and 458 m (β) in DRB 5, (Figure 12) and DRB 6 was pumped at a rate of 31 l/min for 43 hours. During this period, the iodine that was placed at a depth of 442 m (α) ascended to a depth of 354 m, a distance of 88 m (Figure 12). As this tracer (α) was placed above the most open fracture in DRB 5 at a depth of 449 m, (Table 1) it diminished more or less gradually in concentration as it passed the many fractures that were drawing water out of the well. The tracer that was placed at a depth of 458 m (β) also ascended in the hole reaching a depth of 358 m, a distance of 100 m. The amplitude of the tracer pulse (β) decreased considerably between the depths of 454 and 431 m and it is assumed that most of this decrease occurred as the tracer pulse (β) passed the most open fracture in DRB 5 at a depth of 449 m. Above this depth, the decrease in intensity varied gradually.

Analysis of the velocity of the two tracer pulses in this test gave inconsistent results. The velocity varied erratically, and sometimes artificial peaks of activity were held up in areas

of irregular well diameter. For example, at a depth of 440 m the diameter of DRB 5 enlarges abruptly from 18 to over 23 cm, and in this connectivity test after the upper tracer pulse (α) passed this enlarged section, a stationary peak of activity remained at this point until near the end of the test. The velocity of the upper tracer pulse (α) varied from 0.00 to 0.046 m per minute, whereas the velocity of the lower tracer pulse (β) varied from 0.007 to 0.097 m per minute. (Logs from which these velocities are calculated are not among those selected for Figure 12). At these low velocities, accurate measurement of the rate of movement of a tracer pulse, which may be spread vertically over 15 m of the well, is difficult. In the latter part of the tests, the two tracer pulses (α and β) merged as shown on Figure 12, but the peaks of intensity remained separate.

Neglecting the erratic variation in individual velocity measurements, the upper tracer pulse (α), appears to have decreased gradually in velocity throughout its ascension from about 0.04 to 0.009 m per minute. The lower tracer pulse (β) appears to have increased in velocity from 0.01 to 0.05 m per minute as it ascended from a depth of 458 to about 422 m, then it appears to have decreased to 0.01 m per minute. While the upper tracer pulse (α) was above the large fracture at 449 m and the lower tracer pulse (β) was below, the separation of the two tracer pulses (α and β) increased (Figure 12). This was possibly due to removing the top of the lower tracer pulse (β) as it passed the fracture

at 449 m. When both tracer pulses (α and β) were above this fracture, their separation decreased as they ascended the hole. This was caused by the water being removed from the hole at numerous places above the depth of 449 m, thus causing progressively less movement higher in the well. The upper of the two peaks (α) therefore moved slower than the lower peak (β) causing the lower peak to appear to catch up with the upper peak. Once the cone of depression had been established, the velocity of both peaks as they pass an equivalent depth should have been equal. Unfortunately, in this test the transient effects of establishing the cone of depression are present and defy attempt at precise analysis.

A third tracer pulse (γ) is also shown on Figure 12. It ascended from a depth of 492 to 449 m, a distance of 43 m, during the test. Its upward movement was essentially stopped at a depth of 449 m, the depth of the most transmissive fracture in the well (Table 1). The influence of this fracture in removing the tracer is shown on the log of 2207 hours on March 11, 1964, and subsequent logs on Figure 12.

This test shows that as DRB 6 was pumped, the pressure was lowered in all of the fractures in the inclined fracture zone that were intersected by DRB 5. This induced a vertical circulation in DRB 5 with water rising from the fractures below about 457 m and flowing into the fractures of the inclined fracture zone. Even though the fracture at a depth of 449 m is the most transmissive as demonstrated by the in-hole tracer packer tests,

it appears to have only a slightly more direct connective path through the inclined fracture zone to DRB 6 than the other fractures of this zone in DRB 5. This is shown by the fact that not all of the tracer exits from the well at this point and that the movement of water upward continues above this fracture. The upward movement of water was traced to a depth of 354 m, only 10 m below the bottom of the casing, indicating that there are fractures with relatively direct connections to DRB 6 from the bottom of the casing in DRB 5.

While water moved at least 100 m vertically in DRB 5, the composite water level in the hole, reflecting the net pressure in all of the fractures, declined only 2.3 m. This illustrates that measuring the decline in water level gives very little indication of the complex hydraulic flow that may be going on in the well.

In summary, the connectivity test using an in-hole tracer indicated that the largest fracture in DRB 6 was not directly connected to the largest fracture in DRB 5. The two wells were connected by a zone of interlacing fractures as indicated schematically in Figure 10. This conclusion permitted the use of equations developed for porous media in analyzing hydraulic constants, using pumping tests (Marine, 1967), and a two-well tracer test (Webster, Proctor, and Marine, 1970).

CONCLUSIONS

Although knowledge of the location and magnitude of fractures in boreholes for investigation of fractured metamorphic rock is necessary, it alone is not adequate to provide a model for selecting methods of analysis for determining hydraulic parameters. It is necessary to know if the fracture zones consist of a single fracture or of many interlacing fractures. There are several tests that can be applied to develop a model of the fracture zones, but perhaps the most useful is performing a between-wells connectivity test using an in-hole tracer in one well while pumping a selected fracture zone in another well.

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TABLE I

Results of In-Hole Tracer Tests

<u>Well</u>	<u>Approximate Depth, meters</u>	<u>Percent Loss of Total Injected Water^a</u>
DRB 2	299 - 453	0
	453	45
	453 - 558	0
	558	27
	558 - 568	0
	568	22
	568 - 576	0
	576 - 604	7
	Total	101
DRB 3	301	100
DRB 5	344 - 347	? ^b
	347 - 402	27
	402 - 449	0
	449	59
	449 - 471	12
	471 - 520	0.5
	520 - 560	0.5
		99
DRB 6	335 - 544	0
	544	73
	544 - 579	5
	579 - 583	22
	Total	100

a. The rates of injection varied from well to well, so the magnitudes of fractures in different boreholes cannot be compared.

b. Not included in calculated percentages of water loss.

FIGURE 1. Location of the Savannah River Plant and Nearby Geologic Provinces. The line of section for Figure 2 is also shown.

FIGURE 2. Generalized NW to SE Geologic Profile Across SRP

FIGURE 3. Map Showing the Location of Exploration Wells that were Cored Through Crystalline Rock (Deep Rock Borings)

FIGURE 4. Schematic Diagram Showing Packer Assembly for Testing the Water-Transmission Characteristics of Individual Sections of Rock

FIGURE 5. Graph Showing Change in Size and Shape of a Tracer Pulse as it Passes a Water-Accepting Fracture. Gamma logs are from an in-hole tracer test on DRB 6.

FIGURE 6. Graph Showing the Shape of the Tracer Pulses in DRB 2 at Selected Times After Releasing Radioactive Iodine-131 at Depths of 335 m (0.8 mCi), 436 m (5.2 mCi), 486 m (0.3 mCi), and 586 m (1.2 mCi).

FIGURE 7. The Results of In-Hole Tracer Movement Caused by Water Injection in DRB 2

FIGURE 8. Water-Transmitting Fractures in Well DRB 8

FIGURE 9. Correlation of Fracture Zones Inferred from Swabbing, Pumping, and Injection Tests

FIGURE 10. Section Showing Correlation of Fractured Rock Zones in a Plane through DRB 5, 6, and 7

FIGURE 11. Graph Showing Flow Rates and Water Levels in the Pumping, Injection, and Observation Wells in the Between-Well Tracer Test. Well DRB4 is Separated into Two Zones by a Packer and Cement Plug from a Depth of 475 to 529m into DRB4p, the Deeper and DRB4c, the Shallower. Well DRB5 is Divided by a Packer 1m Thick at a Depth of 457m into DRB5p, the Deeper and DRB5c, the Shallower. The Abrupt Rise in the Water Level in DRB5p in February and August 1966 is Due to a Leak in the Packer.