DIVERGING FLOW TRACER TESTS IN FRACTURED GRANITE;

EQUIPMENT DESIGN AND DATA COLLECTION

by

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ABSTRACT

Down-hole injection and sampling equipment was designed and constructed in order to perform diverging-flow tracer tests. The tests were conducted at a field site about 8 km southeast of Oracle, Arizona, as part of a project sponsored by the U. S. Nuclear Regulatory Commission to study mass transport of fluids in saturated, fractured granite. The tracer injection system was designed to provide a steady flow of water or tracer solution to a packed off interval of the borehole and allow for monitoring of down-hole tracer concentration and pressure in the injection interval. The sampling system was designed to collect small volume samples from multiple points in an adjacent borehole.

Field operation of the equipment demonstrated the importance of prior knowledge of the location of interconnecting fractures before tracer testing and the need for down-hole mixing of the tracer solution in the injection interval.

The field tests were designed to provide data that could me analyzed to provide estimates of dispersivity and porosity of the fractured rock. Although analysis of the data is beyond the scope of this thesis, the detailed data are presented in four appendices.

CHAPTER ONE

INTRODUCTION

Low permeability fractured, granitic rock is presently being considered for the containment and storage of radioactive wastes. A primary concern in evaluating a geologic formation for waste containment is the rate at which possible contaminants might be able to move through it. Prediction of that rate requires, among other things, values for the effective porosity and dispersivity of the formation. These values are best obtained through *in-situ* tracer tests, however the methodology for conducting such tests in low permeability rocks is not well developed.

1.1 Goals of the Tracer work

The general goal of this work was to collect data from a series of diverging-flow tracer tests which could be used to calibrate a numerical model and thereby obtain estimates of the advective and dispersive properties of the fractured granite. In order to do this, it was necessary to design and construct much of the specialized equipment needed for tracer injection and sampling.

Two phases were originally planned. Phase one was to develop equipment and techniques and conduct tracer tests in the more permeable zones of the study site. The second phase of the work would involve modifications to equipment and techniques to run similar tests in the less permeable zones. This thesis documents the first phase of the tracer work which was conducted throughout most of 1985. Lack of funding resulted in termination of the project before phase two began.

1.2 Description of the Study Site

This work was done at a study site operated by the University of Arizona about 8 km (5 mi) southeast of the community of Oracle, Arizona. The Oracle study site is near the north end of the Santa Catalina Mountains at an elevation of about 1300 m (4300 ft) above mean sea level near the base of Oracle Ridge, a prominent feature of the local terrain which extends northward from Rice Peak, through Apache Peak and Oracle Hill, decreasing in elevation from about 2100 m (6900 ft) to 1500 m (4900 ft) (Fig 1.1) The site lies on a pediment surface which slopes to the northeast from an elevation of about 1500 m (4900 ft) near the ridge to 1200 m (3900 ft) at the contact with the basin fill sedimentary sequence (Fig 1.2).

The pediment rock is a coarse-grained biotite quartz monzonite of Precambrian age known locally as the Oracle granite. It is part of a Precambrian massif that is intermittently exposed over a wide region of southeastern Arizona. Weathering of the pediment in the vicinity of the study site extends to a depth of approximately 15 m and has produced a thin, sandy soil about 2 m thick. Intrusive dikes are a significant feature of the unit and occur within and around the field site. The geology of the Oracle granite was studied in detail by Banerjee (1957), Davis (1981) evaluated its geologic history, and Jones *et al* (1985) present a detailed description of the local field-site geology.

Average annual precipitation in the area ranges from 48 cm at Oracle to 63 cm in the high elevations of the Santa Catalina Mountains. Precipitation is about equally divided between summer and winter rainy seasons occurring from July through September and December through February. Oracle Ridge represents a surface drainage divide between the San Pedro river basin to the east and the Santa Cruz river basin to the west. Streams in the area are intermittent.

The regional water table tends to follow the land surface. Figure 1.3 is a water table contour map constructed with data from existing wells (Winstanley, 1985). Depth to water is generally less than 30 m (100 ft) and is about 10 m (33 ft) at the study site. In figure 1.3, the Mogul fault is assumed to be an impermeable feature. Winstanley (1985) concluded, however, that this fault had little efect on the water table contours in the vicinity of the study site.

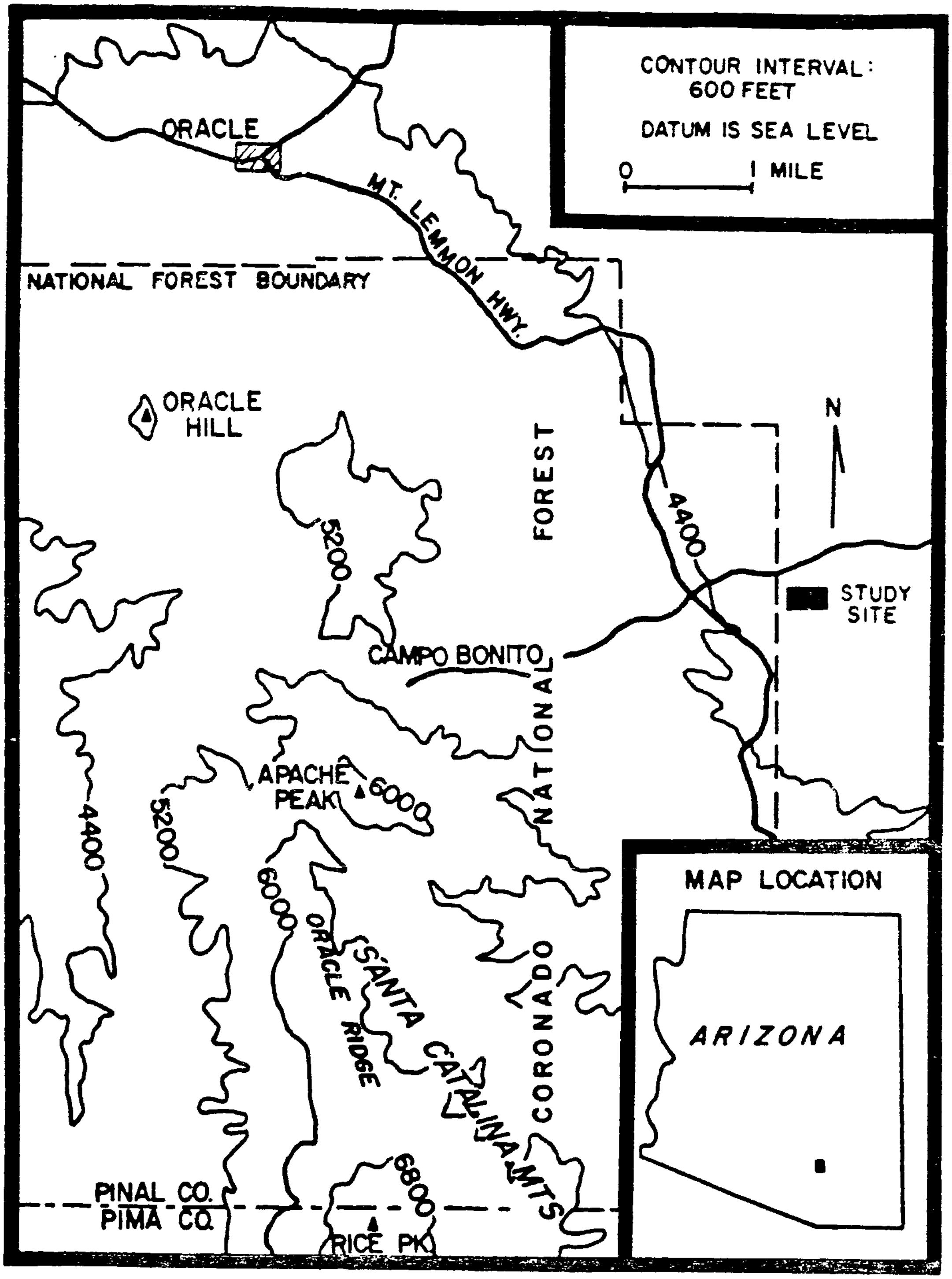


Figure 1.1. Topographic map of northern Santa Catalina Mountains. (From Jones *et al.* 1985)

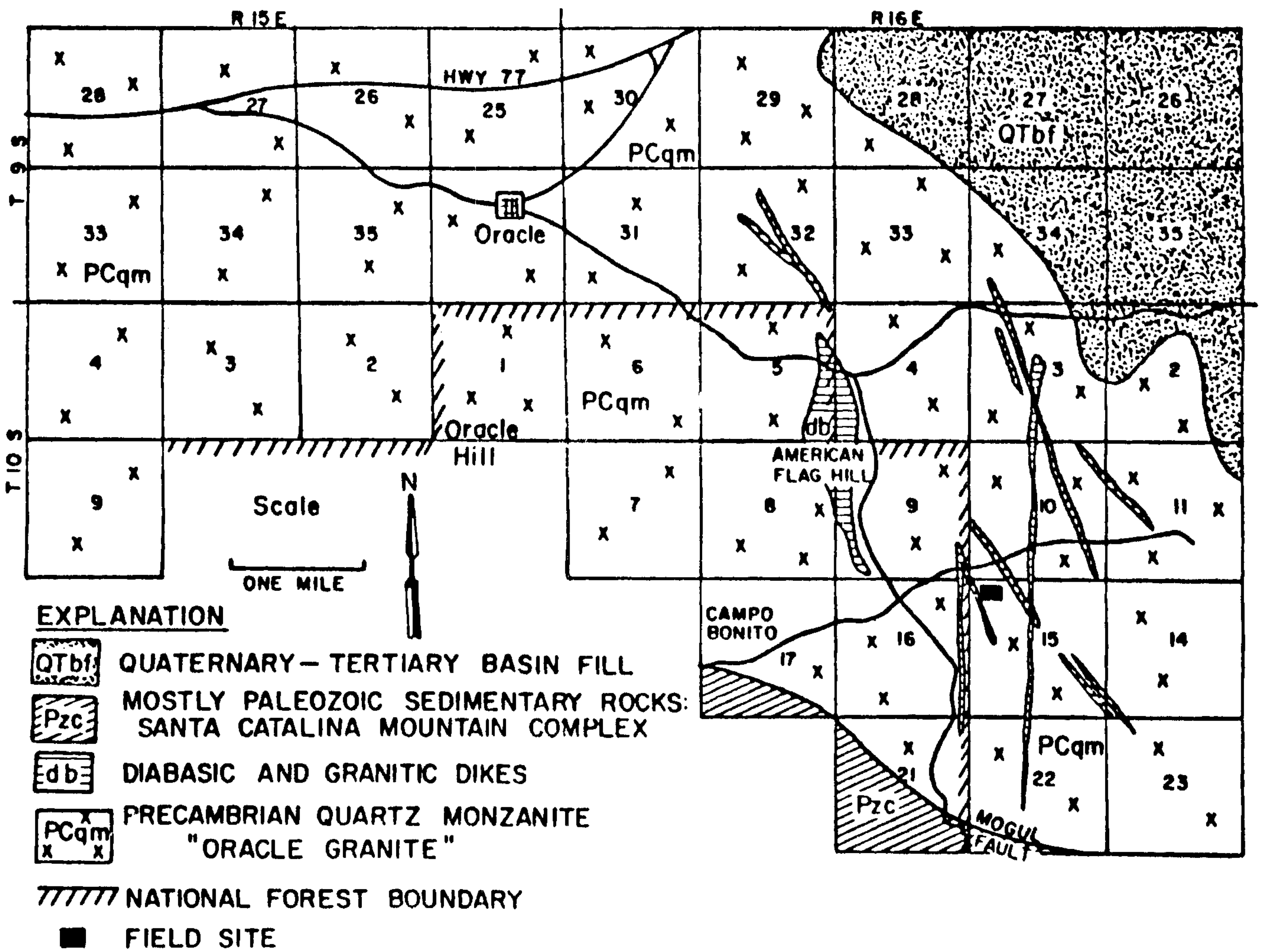


Figure 1.2. Geologic map of Oracle area, Pinal County, Arizona. (From Jones *et al.* 1985)

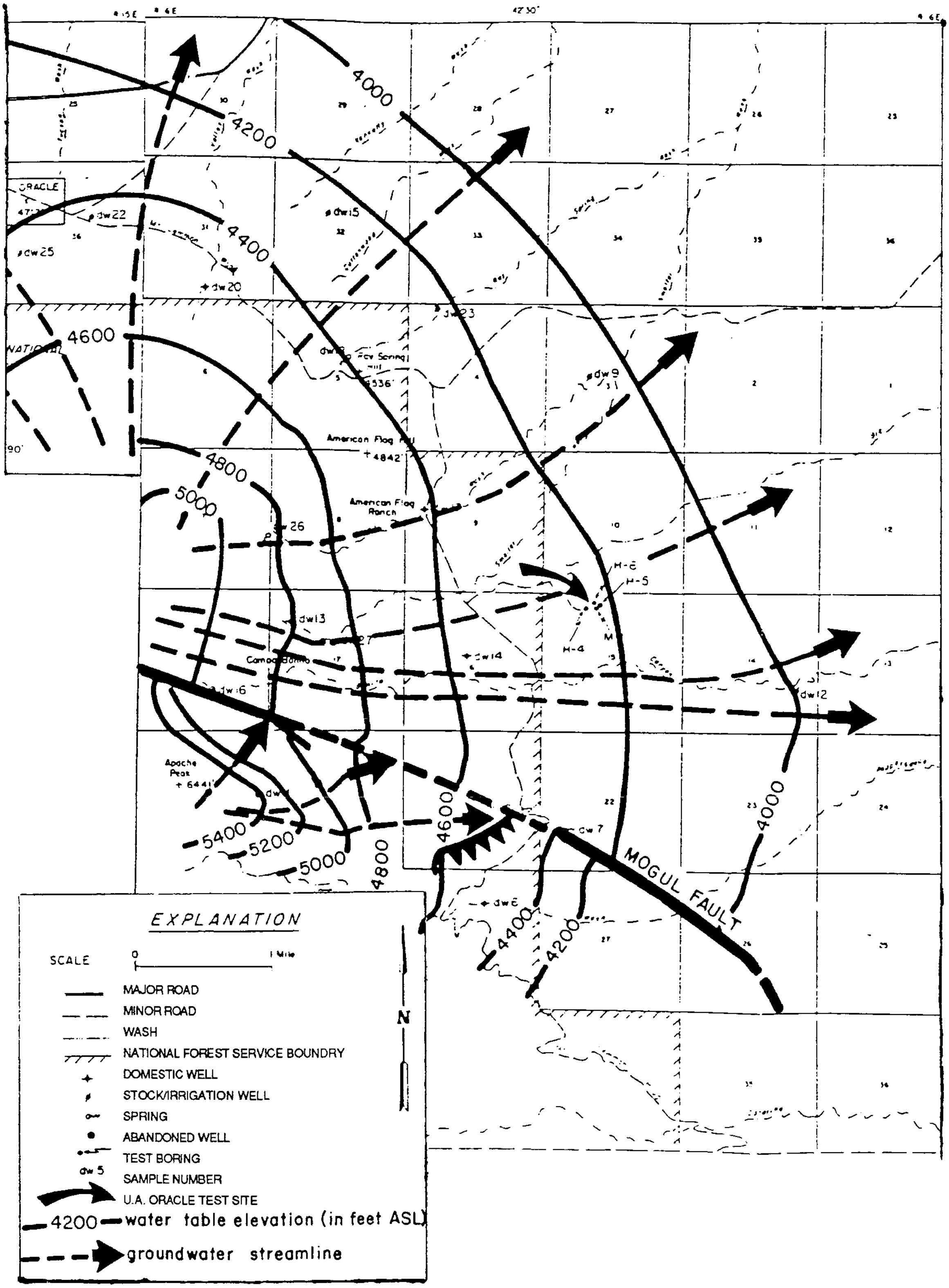


Figure 1.3. Regional water table. (From Winstanley, 1985)

1.3 Previous Work at the Oracle Site

Eight boreholes were drilled at the Oracle site. Figure 1.4 shows the layout of the holes and Table 1.1 gives the details of their construction. Geophysical logs of these boreholes, done by members of the U. S. Geological Survey, included caliper, temperature, single point resistivity, neutron, natural gamma, induced gamma, interval acoustic velocity, and acoustic televiewer logs. An interpretation of many of these logs was reported by Keys (1981). A borehole inclination survey was conducted by personnel from Lawrence Livermore National Laboratory in conjunction with an an experimental geotomography log (Ramirez *et al.,* 1982).

Jones *et al.* (1985) interpreted these logs together with drill core and cutting analysis, surface geologic mapping, and the results of a series of single hole straddle-packer injection tests to develop a detailed description of the fracture system at the site. Three semi-orthogonal sets of primary fractures were identified, which are believed to be associated with the original formation of the granite pluton. Superimposed on these are three sets of secondary fractures, believed to be the result of tectonic processes which have occurred since the formation of the granite. Many vertical or near vertical fractures are present and are encountered in several of the boreholes. Two geologic features affecting the hydraulic properties of the rock, and located within the zone penetrated by the boreholes are a diabase dike intercepting H-2, H-3, and H-4, and a fault zone near the bottom of holes M-1, H-2, H-3, and H-4.

Single-hole and cross-hole hydraulic testing was carried out at the site and is reported in Hsieh *et al.* (1983) and in Jones *et al.* (1985). Some highly fractured intervals of the boreholes could not be tested due to leakage around the packers. In other intervals, where small amounts of leakage occured, it was possible to account for the leakage and adjust the results accordingly (Depner, 1985).

1.4 Special Considerations for Tracer Tests in Low Permeability Rock

Estimates of the hydraulic conductivity, effective porosity, and dispersivity are needed to

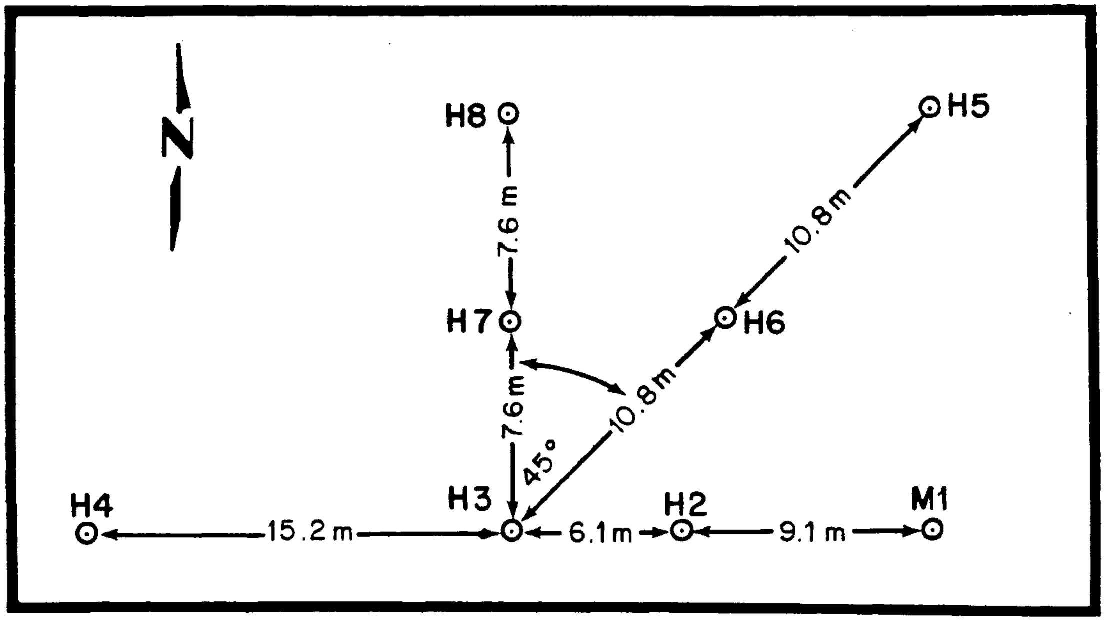


Figure 1.4. Arrangement of boreholes at the Oracle field site.

Table 1.1. Dimensions of boreholes at the Oracle site.

Hole No.	Relative Elevation of Top of Casing (m)	Total Depth* (m)	Casing Depth* (m)	Casing Diam. (cm)	Nominal Hole Diam. (cm)
M-1	0.00	91.4	17.7	20.3	17.7m - 32.3m 20.3 32.3m - 91.4m 17.1
H-2	+0.31	91.4	18.0	12.7	11.4
H-3	+0.72	91.4	17.7	17.8	17.1
H-4	+1.29	87.8	13.1	12.7	10.8
H-5	+0.56	76.2	18.6	12.7	11.4
H-6	+0.69	76.2	19.2	12.7	11.4
H-7	+1.36	76.2	20.1	12.7	11.4

*All depths measured from top of borehole casings.

predict the solute transport properties of a medium. Hydraulic conductivity can be determined by various types hydraulic testing. In fractured media, cross-hole hydraulic tests are useful for determining the degree of anisotrophy and locating conductive zones between boreholes. Effective porosity and dispersivity are best determined through in-situ tracer tests. In low-permeability fractured rock, special consideration must be given to the methods of conducting tracer tests in order to obtain reliable data.

Effective porosity is a ratio of the volume of pore space contributing to flow and the total volume of the medium. This concept applies to a porous or fractured medium only if a large enough volume of the medium is considered so that it can be treated as a homogeneous material. For example, if a homogeneous porous medium is sampled at the level of a few grain sizes, the porosity may vary greatly from sample to sample due to slight differences in packing arrangement or grain size. However if the same medium is sampled at the level of a few thousand grain sizes, these slight differences will no longer be apparent and the porosity measured for each sample will approach a unique value that is representative of the medium. The smallest volume of material for which this unique value can be assigned is a representative elemental volume (REV). The REV for a uniformly fractured rock medium is much larger than for a porous medium but, at some scale, the concept will apply and an effective porosity value can be determined. At this scale, the fractured medium can be modeled as an equivalent to a porous medium with that same effective porosity.

In order to move a tracer through a groundwater system in a reasonable amount of time, an artificial gradient should be established, either by pumping water out of the system, injecting water into it, or both. The simplest means doing this is a convergent-flow test, in which water is pumped from one borehole while a high concentration tracer slug is placed near the conductive zone in another borehole. The tracer is drawn toward the pump and samples are collected from the pump discharge. Convergent-flow tests require less complicated equipment and, because ideally all of the tracer will be drawn into the pump, a mass balance can be obtained. Because water from everywhere in the flow field is eventually drawn toward the pump, there is little chance of "missing" the tracer breakthrough. In fractured rock of low permeability such as the Oracle granite, convergent flow tests have some drawbacks. The pumped borehole may be dewatered forcing termination of the test or alteration of the flow rate before all the tracer has been recovered. The turbulence caused by the pump mixes the water in the borehole so that if more than one zone contributes to the flow, the samples taken from the pump discharge may reflect the average of two or more tracer breakthroughs and the parameters estimated from the data may be in error. The tracer slug placed in the adjacent borehole may undergo diffusion prior to entering the connecting fracture, or if it is placed in wrong section of the borehole, may not be drawn into the fracture at all.

Recirculating-flow tests, in which water is pumped from one borehole and returned to another, can reduce the dewatering of the pumped borehole. Because of the steep hydraulic gradients generated, water velocities between the pumped and recharged boreholes are higher and tracer breakthrough occurs in less time than in converging or diverging tests with similar pumping rates. Complications can be introduced if recirculation continues for long periods of time after tracer breakthrough occurs and significant amounts of tracer are recirculated along with the water.

Divergent-flow tests, in which traced water is injected into a packed off interval of one borehole and tracer breakthrough is monitored is in surrounding boreholes, require more complicated equipment and a supply of injection water. It is also necessary to have prior knowledge of the location of the conductive zones between the boreholes in order to properly place the injection and sampling equipment. The advantages are that, by isolating the injection interval and sampling at the depth of the connecting fracture(s) in the monitoring borehole, the effects of mixing in the open boreholes are minimized. Because the tests do not depend on water being drawn from the formation, they can be run as long as necessary to obtain complete tracer breakthrough data. Tracer input concentration and rate can be better controlled than in a convergent or recirculating test where a tracer slug is placed in an open borehole. Multiple boreholes surrounding the injection borehole can be monitored to obtain data on several conductive zones during one test.

In a fractured rock system, there is a large degree of uncertainty in knowing when and where the tracer may appear in a monitoring borehole. In order to track the progress of a tracer test it is desirable to have immediate analysis of tracer concentrations during the test. In some situations removal of water through sampling may introduce unwanted gradients or extract significant tracer mass from the system, affecting results from surrounding monitoring boreholes. Clearly, the best type of tracer monitoring system would be one which would give instant readout of concentration and could be placed downhole, eliminating the need to extract samples. This type of instrumentation for measuring the non-radioactive tracers used in this work was not available; hence, a method was developed to collect samples of minimum volume (~50 ml) and analyze them on site. The time needed to run each sample varied from 5 min to 15 min depending on the tracer used. For these tests, this was found to be sufficient to track the progress of the test in one borehole but was not adequate for scanning more than one borehole at a time.

CHAPTER TWO

METHODS OF LOCATING FRACTURES

In order to conduct a successful tracer test in fractured rock, the location of the hydraulic connections between boreholes should first be determined. In order to minimize the effects of mixing and dispersion that occurs in the open borehole, tracer injection and breakthrough monitoring must be done as close as possible to the connecting fractures. In the worst case, misplacement of the tracer injection interval or point samplers can result in missing the breakthrough entirely due to sampling in the wrong location. Three basic types of data, heat pulse flowmeter, downhole temperature response, and single hole hydraulic conductivity were obtained to determine the location of hydraulic connections for these tests. Acoustic televiewer logs, performed by the U.S. Geological Survey, were used to determine the locations of the fractures intersecting the boreholes.

2.1 Heat Pulse Flowmeter Data

A sensitive heat-pulse flowmeter, that tracks the movement of a small pulse of heated water, was developed to detect vertical flow in the boreholes. Details of its construction and operation are included in Messer (1986). Flow fields were set up by injecting water into one of the boreholes and profiles of vertical flow were measured in the adjacent boreholes. Under these conditions, heads in the adjacent boreholes were continually rising. Typically, water entered the adjacent boreholes through the major connecting fracture and flowed upwards. Below the connecting fracture there was little or no flow. Where the connecting fractures occur, sharp increases in upward flow was observed. In borehole M-1 (Fig. 2.1) this pattern is complicated by the apparent presence of several conductive zones higher up in the hole, but the major zone of inflow appears to be at depth between 84 m and 85.5 m. (All depths are reported as distance below the top of the borehole casing) Boreholes H-2 and H-3 (Figs. 2.2

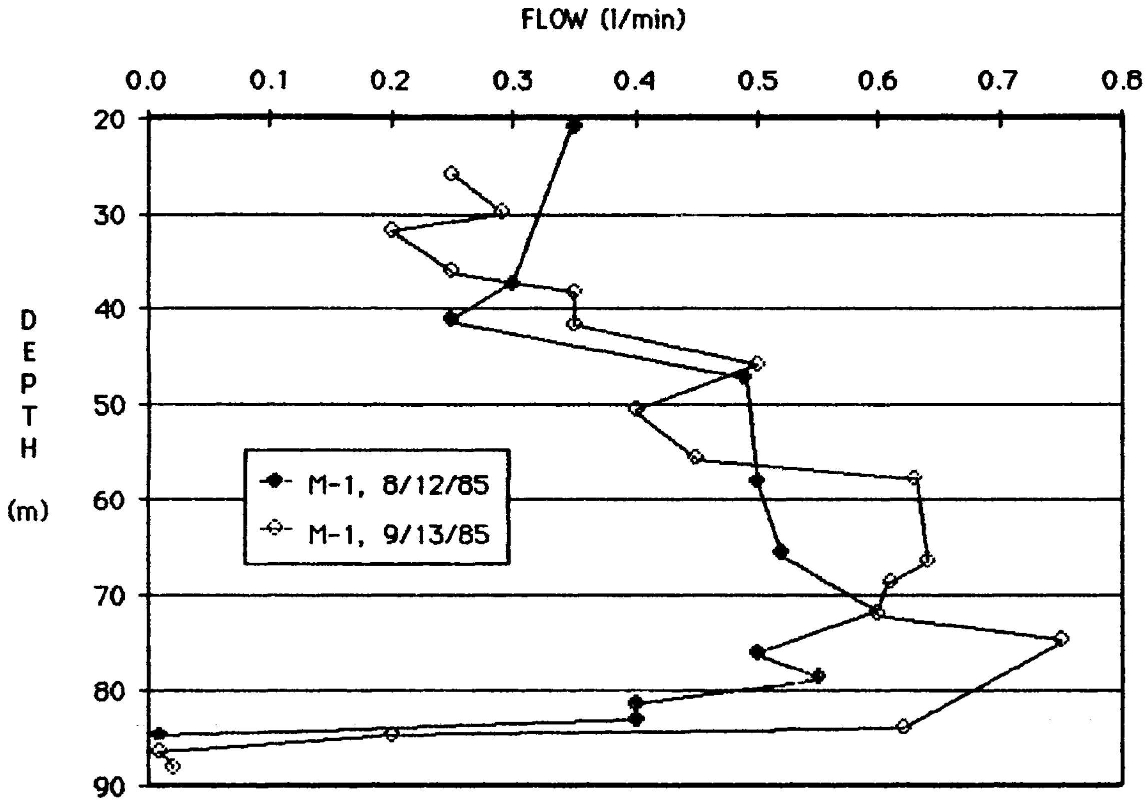


Figure 2.1. Vertical flow in M-1 with1.9 l/min injected at a depth of 74.4-79.6 m into H-3.

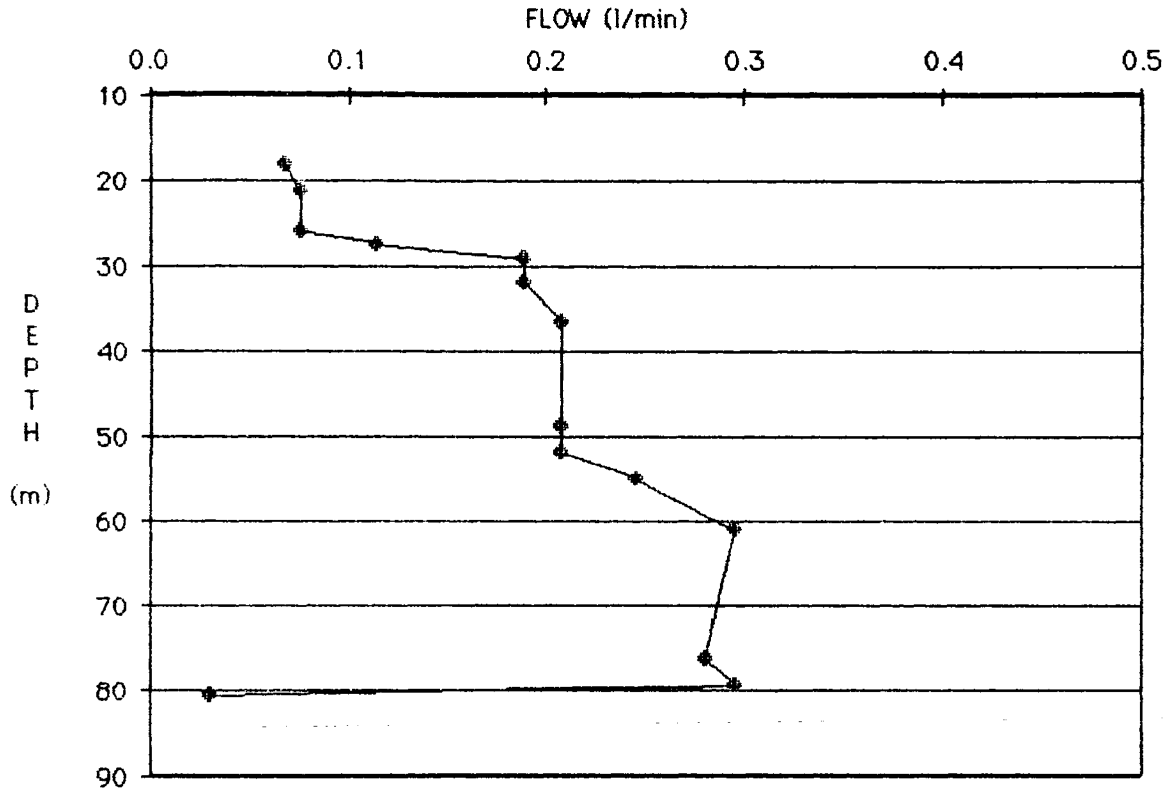


Figure 2.2. Vertical flow in H-2 with1.9 l/min injected at a depth of74.4-79.6 m into H-3.

and 2.3) show consistent flow above their major conductive zones located at 79-81 m and 76-79 m respectively. Of the three methods tried, the heat- pulse flowmeter proved to be the most useful for defining the location of the major hydraulic connections.

2.2 Downhole Temperature Response

Measurement of downhole temperatures with sensitive thermistor probes was carried out at the Oracle site by Flynn (1985). Further work was done by Silliman (1985) prior to and during the series of tracer tests reported herein. Two different probes were used. One consisted of a single, calibrated thermistor that was moved up and down in the borehole to record temperature at different depths. The second consisted of five uncalibrated thermistors that were attached to a string of air-lift samplers. Figure 2.4 shows the results from the single point probe in M-1 with injection in H-3. A full interpretation of these data is beyond the scope of this report. The most important point is that the temperature below 85 m changed relatively little, whereas above that depth, the temperature changed rapidly. The zone between 85 m and 79 m appears to be a zone of mixing whereas above 79 m, the relatively uniform response (vertical line) seems to indicate a shift of the natural geothermal gradient up the borehole. Downnhole temperature and heat-pulse flowmeter data both indicate that the flow pattern in M-1 is more complicated than in either of the other two boreholes.

Temperature data from H-2 was collected with the five thermistor probe. Figure 2.5 shows the results. Note that the thermistors above 81 m showed an increase in temperature, again due to the warmer water from deeper in the well moving upwards, while the thermistors below 81 m showed almost no change, indicating no water movement. The thermistor located at 81 m showed moderate cooling, possibly as a result of cooler water entering the hole from the nearby fracture.

2.3 Hydraulic Conductivity Testing

Previous work at the Oracle site included single-hole packer tests to measure hydraulic

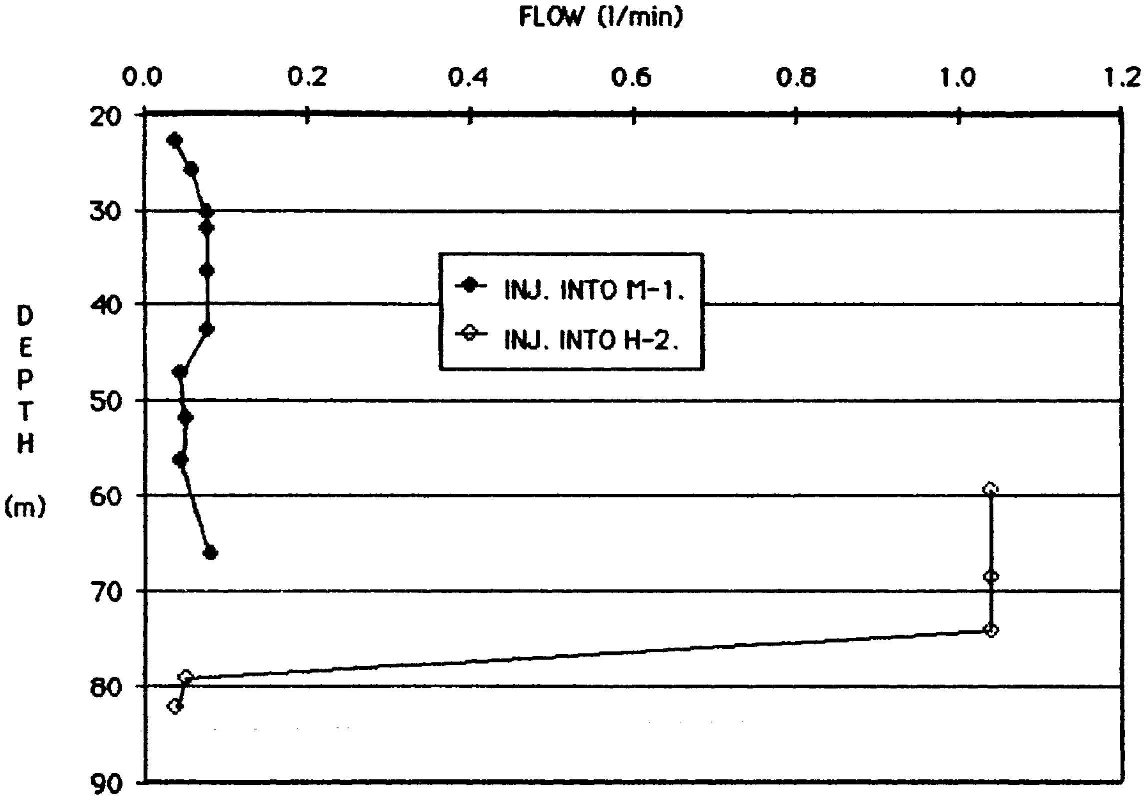


Figure 2.3. Vertical flow in H-3 with1.9 l/min injected at a depth of 80.8-86.1 m into M-1 or H-2 filled to overflow and maintained at constant head.

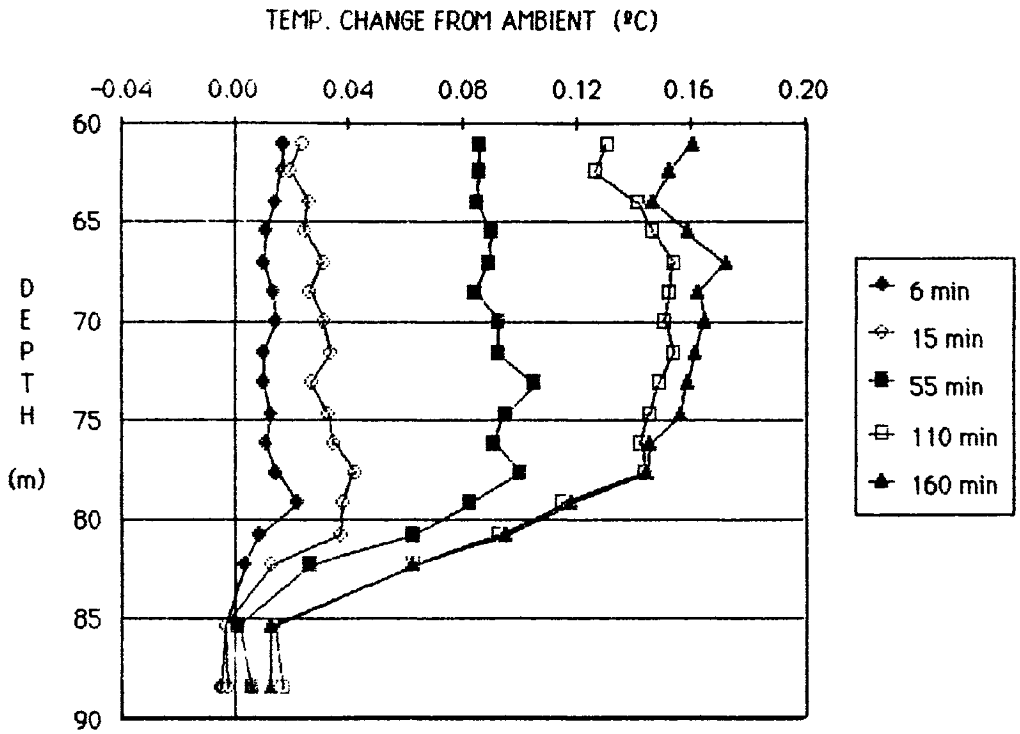


Figure 2.4. Temperature response in M-1 with 5.7 l/min injected at a depth of 74.4-79.6 m into H-3.

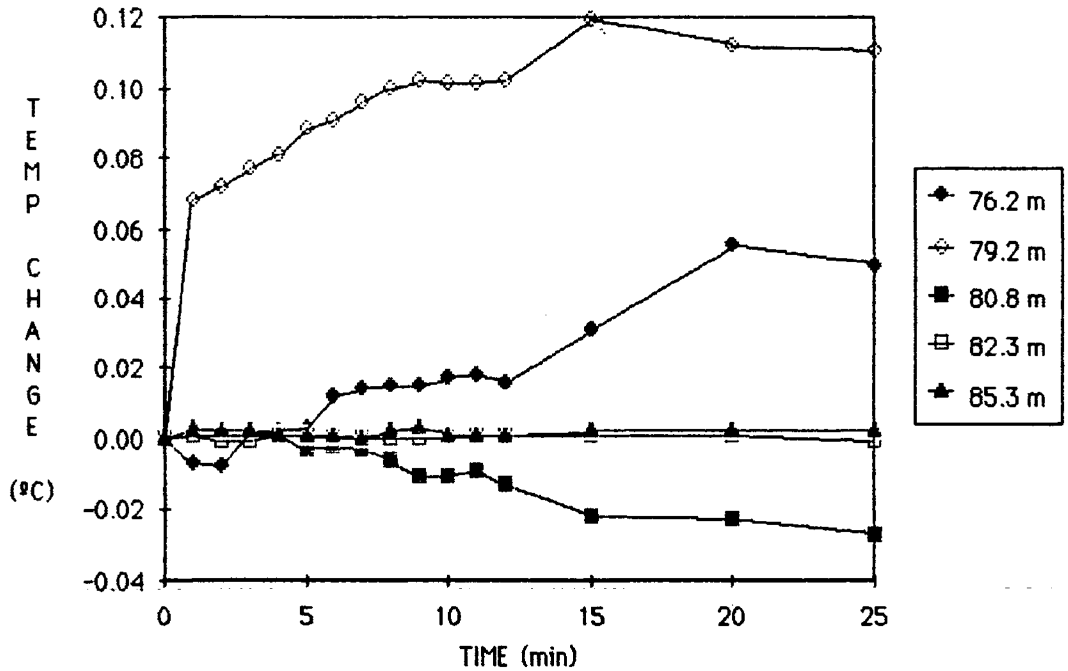


Figure 2.5. Temperature response in H-2 with 5.7 l/min injected at a depth of 80.8-86.1 m into M-1.

conductivity (Hsieh *et al.* 1983 and Jones *et al.* 1985). Many of the hydraulic tests in the more permeable zones of the boreholes were affected by leakage around the packers. Depner (1985) re-examined the basic data and was able to provide corrected values for hydraulic conductivity in some of the intervals where leakage occured. The leakage-corrected data are plotted in Fig. 2.6. The individual values represent the average conductivity over a 3.4 - 4.0 m zone between two packers. The zones of highest reported conductivity are consistent with the flowmeter and downhole temperature data in indicating the major hydraulic connections in all three boreholes.

As a result of these investigations, it was concluded that the major hydraulic connections between M-1, H-2, and H-3 were as shown on the televiewer logs in Figures 2.7 and 2.8. The diverging flow tracer tests were conducted in these zones. Results of the tracer tests reported herein support the conclusion that there are major connecting fractures in these locations.

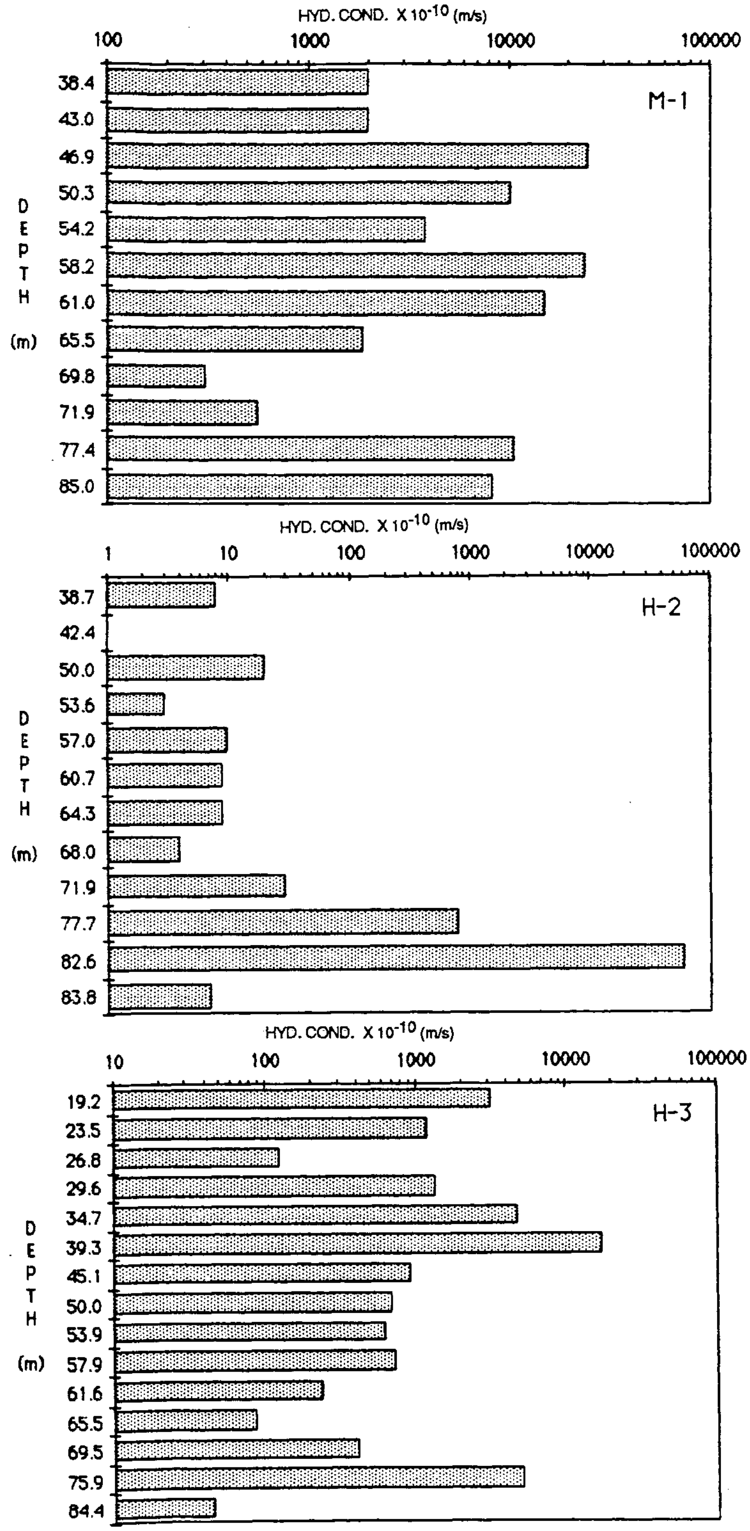


Figure 2.6. Hydraulic conductivity in M-1, H-2, and H-3. (From Depner, 1985)

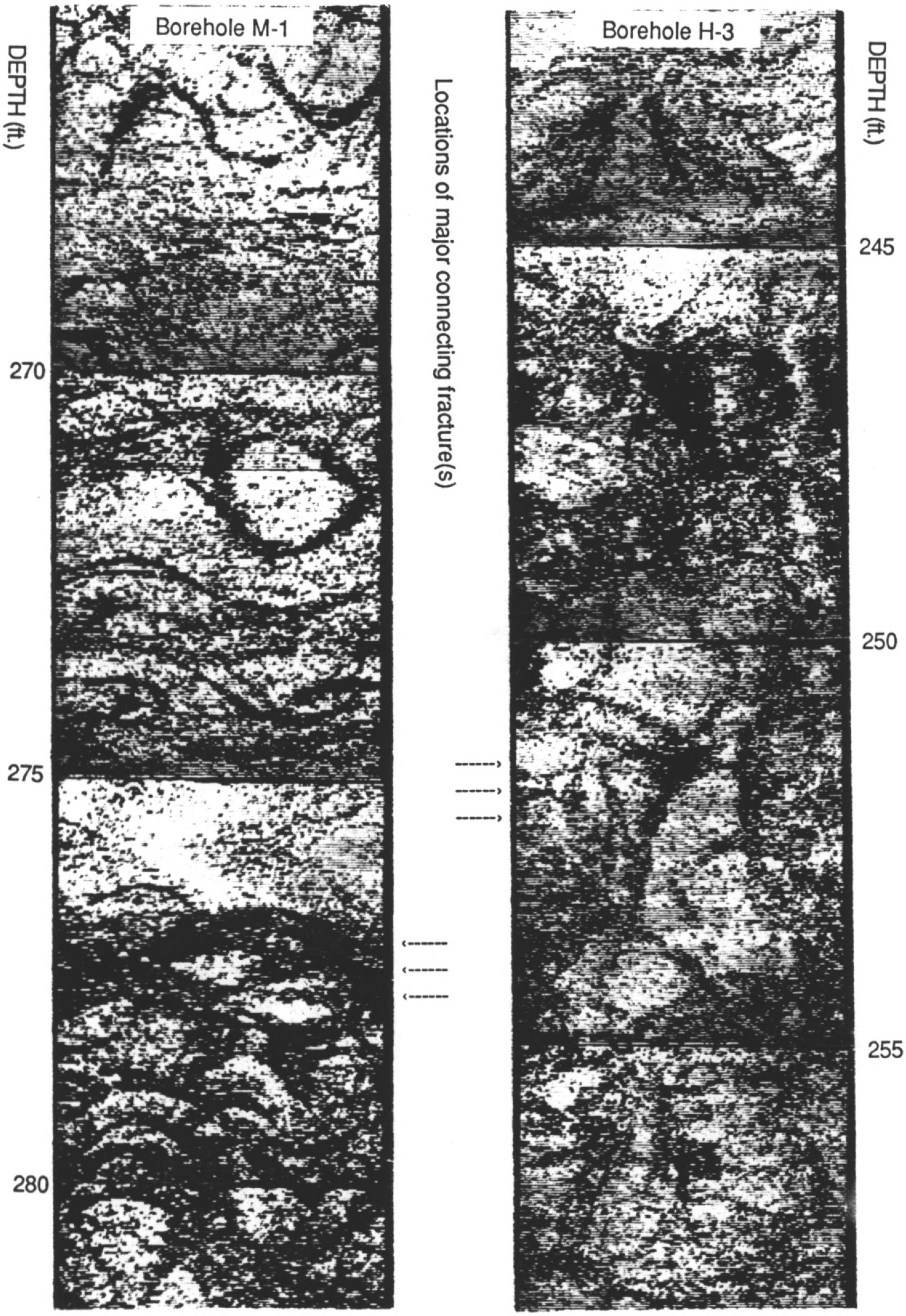


Figure 2.7. Acoustic televiewer logs of the injection intervals in boreholes M-1 and H-3.

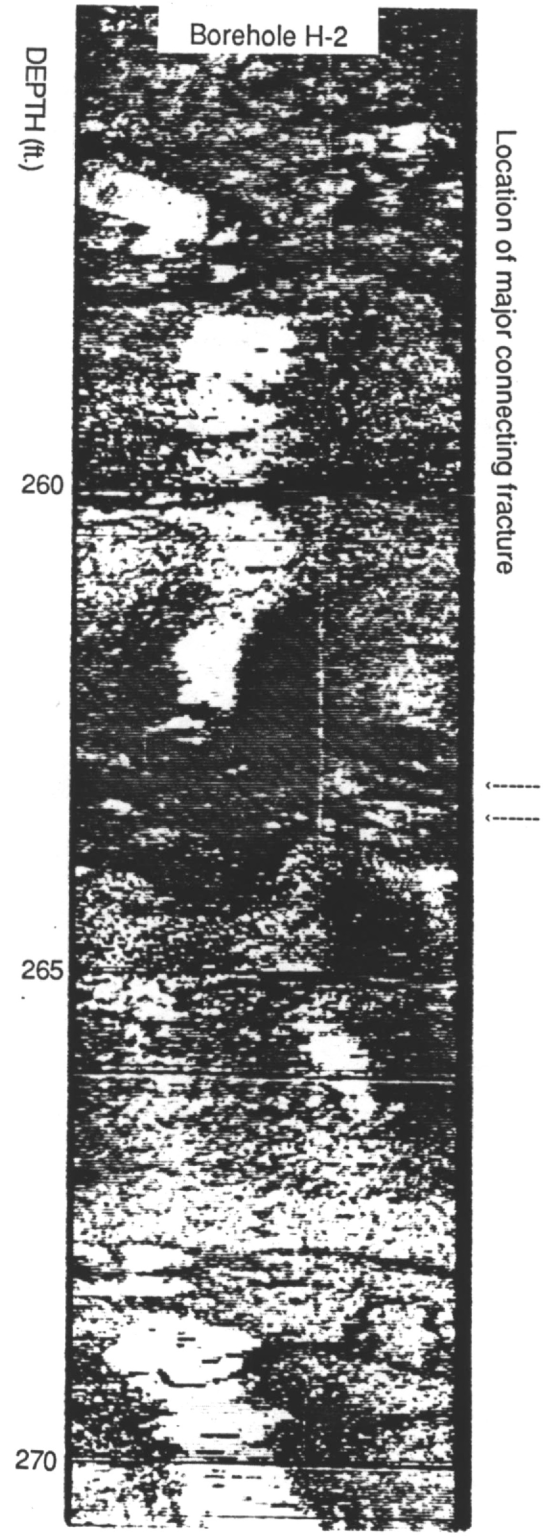


Figure 2.8. Acoustic televiewer log of the major connecting fracture in borehole H-2.

CHAPTER THREE

DESIGN OF TRACER INJECTION AND SAMPLING SYSTEMS

The diverging flow tests required equipment that was not commercially available in an "off the shelf" package. Much of the equipment was designed and fabricated specifically for this project but could be used in other similar applications. Two systems were required, a point sampling system and an injection system.

3.1 Sampling System

The sampling system had to be capable of collecting a small volume of water from depths of up to 90 m. In order to obtain sufficient data points to define the peak of the tracer breakthrough curve, it was necessary to have the capability of sampling on intervals as short as 5 min. Small volume samples were desired in order to minimize distortion of the flow system. In order to get a better idea of the distribution of tracer in the vicinity of the connecting fractures, multiple samplers were needed that could be moved up or down during the test to detect the zone of maximum tracer concentration in the borehole. In order to keep borehole mixing to a minimum during sampler movement, it was desirable to have small diameter samplers. Reliability was also an important factor as it was anticipated that the tests would run for several consecutive days. Because none of the tracers used were known to sorb to plastics, the samplers did not have to be constructed of teflon or other chemically inert materials.

The final design that met all of these goals is an air-lift type sampler constructed of two concentric flexible plastic tubes (Fig. 3.1). The outer tube is 0.95 cm o.d. and 0.64 cm i.d. (3/8" X 1/4") polyethylene with an inner tube of 0.48 cm o.d. (3/16") polyethylene. There is a small check valve (Nupro Valve Co., model 4CP2-1) downhole and all other moving parts are at the

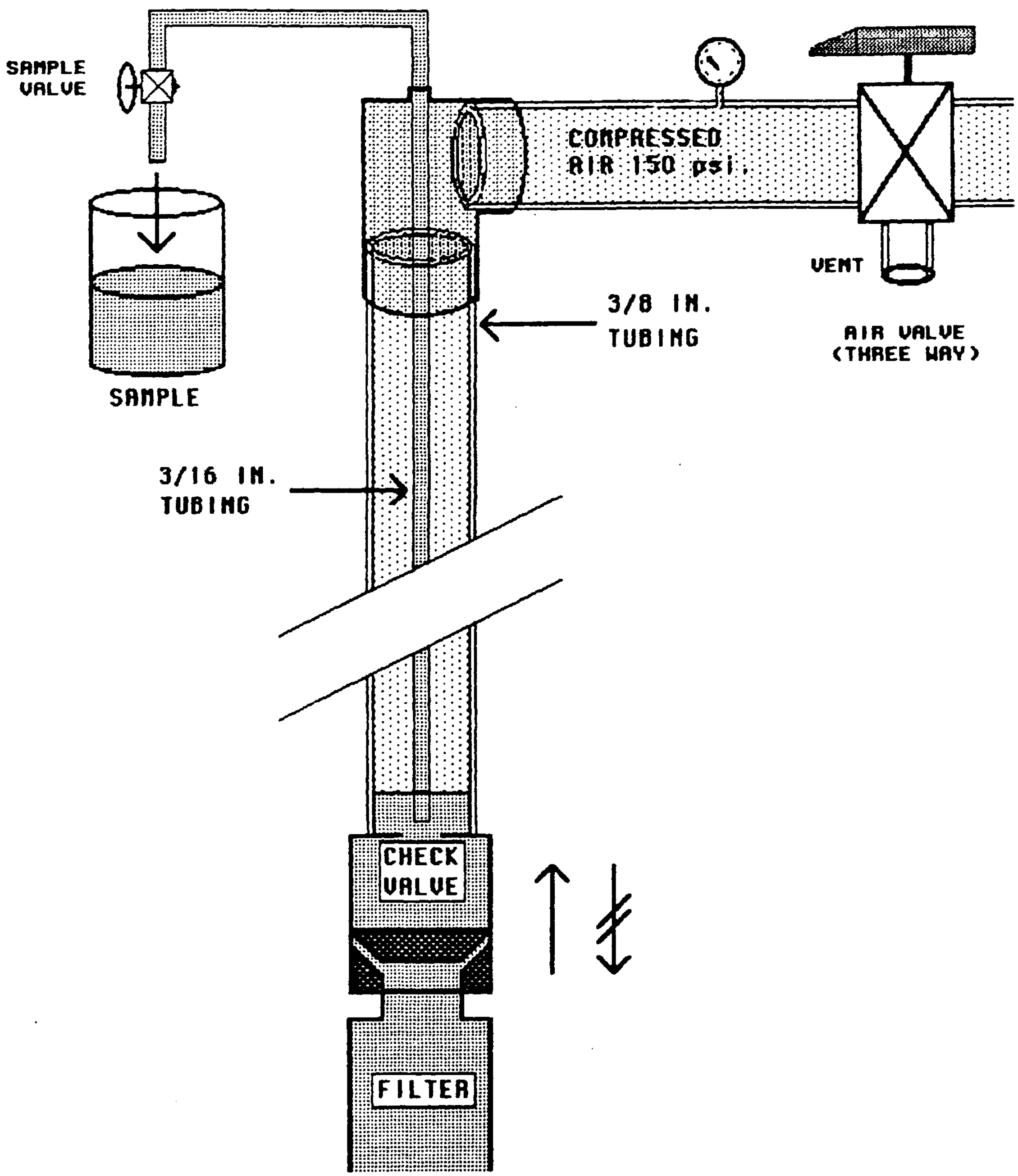


Figure 3.1. Schematic diagram of air lift sampler.

surface. The samplers are operated with compressed air with pressures depending on depth. Samples are delivered to the surface through the 0.48 cm tube that, due to its small diameter, holds the sample in a discrete plug. The larger outer tube provides a conduit for the compressed air and protects the fragile inner tube from kinks and strain. Filters, needed to keep sediment out of the check valves, consist of glass wool packing followed by a fine mesh stainless steel screen.

Operation of the sampler consists of pressurizing it prior to placement in the borehole. Once in place, a sample is drawn by opening both the sample valve and the air valve to atmosphere thereby releasing the air pressure. When the pressure of the air inside the sampler falls below the pressure of the water at the depth at which it is located, the water pressure forces the check valve open and water begins to fill the tubes. When a sufficient volume of water has been drawn in, the sample valve is closed and the air valve is turned to pressurize the outer tube. At this point the check valve closes and the sample is held in the sampler. To deliver the sample to the surface, the sample valve is opened and the compressed air displaces the water upwards through the smaller tube. The diameter of this tube is somewhat critical, for it must be small enough so that the surface tension of the water holds the sample in a discrete plug as it moves through the tube. If the tube is too large, the sample breaks up and is delivered in spurts. On the other hand, if the tube is too small, the friction head becomes so great that delivery times are increased drastically. Testing of this design showed that it was capable of delivering samples from a depth of 90 m on 3 min intervals. The minimum volume of sample that could be reliably delivered from 90 m depth was found to be about 50 ml , although in practice about 3 times this amount was collected in order to minimize the effects of any residue from the previous sample.

In order to determine the magnitude of possible contamination by residue from previous samples, a laboratory experiment was run under worst case conditions. Two columns of water were set up, one containing approximately 200 ppm of thiocyanate tracer solution and the other containing clean, untraced water. The sampler was placed in the tracer solution and a series of minimum volume samples were collected. The sampler was the pulled out of the tracer column, placed in the clean water column and several more minimum volume samples were collected. It was found that after about 250 ml of either solution had passed through the sampler, the samples delivered were representative of the solution (± 5%). If one assumes that a fixed volume of residue is left in the sampler after each sample, the amount of carry-over between samples must be a function of the differences in concentration between subsequent samples. In tracer tests, the concentration differences between subsequent samples are slight so the effects of carry-over would be much less than in this simulation.

Two separate sampler/thermistor probes were constructed, one with a single sampler and thermistor and one with three samplers, 1.5 m apart and 5 thermistors. Thermistors were used to locate the zones of inflow in the boreholes by observing temperature response when the flow was initially started (see Sec.2.3). Samplers were then placed near inflow zones to monitor tracer breakthrough. The same type of sampler were installed on the injection packer assembly to monitor injection concentration and check for leakage past the packers.

3.2 Injection System

The injection system was designed to deliver up to 19 l/min of water or tracer solution at a constant flow rate into a packed-off interval of a borehole. Capability to switch rapidly between traced and fresh water was needed to provide a pulse tracer input desired for numerical analysis. In order to monitor the tracer concentration in the injection interval and the extent of leakage around the packers, three air-lift samplers were incorporated into the packer assembly. The injection pump had to be capable of continuous operation at 800-1000 kPa and up to 19 l/min. The equipment had to operate continuously, for extended periods, in a relatively severe environment with temperatures ranging from -10 ^{o}C to 40 ^{o}C.

The schematic of the uphole components is shown in Fig. 3.2. The pump is a multistage centrifugal submersible pump similar to those used in domestic water wells. The pump body is rated at 19 l/min and this is coupled to an oversized motor rated for a 38 l/min pump. The oversized motor allows for continuous operation of the pump without overheating. The pump is housed in a buried "pump can" constructed from a section of 15 cm diameter steel pipe. Water is supplied to the pump from one of two 570 l steel troughs that drain by gravity into the pump can. Tracer solution is mixed into one trough while the second trough contains fresh water. Valves at the trough outlets allow for tracer or fresh water to be fed into the system.

The flow rate is controlled manually by a ball type valve mounted in the flow control panel. Instantaneous flow rate is monitored on one of two flow meters calibrated from 100 to 1500 ml/min or from 0.2 to 1.85 gal/min (760 to 7010 ml/min). A totalizing flow meter is included to monitor total injected volume and act as a backup for the instantaneous meters. A bypass valve allows for recirculation of water to rapidly flush the pump and associated feed lines during the switch to or from tracer solution in order to obtain a rapid concentration change in the injection interval.

Although pressure in the injection interval downhole is not an important parameter for modeling purposes, it is important to monitor it in order to locate permeable zones, detect major leakage past the packers, or prevent possible expansion of fractures from excess injection pressure. A method was devised for using the outlet pressure gage in the flow control panel to obtain an estimate of the pressure downhole. After the packer assembly was placed downhole at the desired depth but prior to inflating the packers, the flow rate vs. panel outlet pressure was recorded for several different points throughout the expected range of flow. This represents the friction head loss in the tubing as a function of flow rate (Fig. 3.3). After packer inflation, the

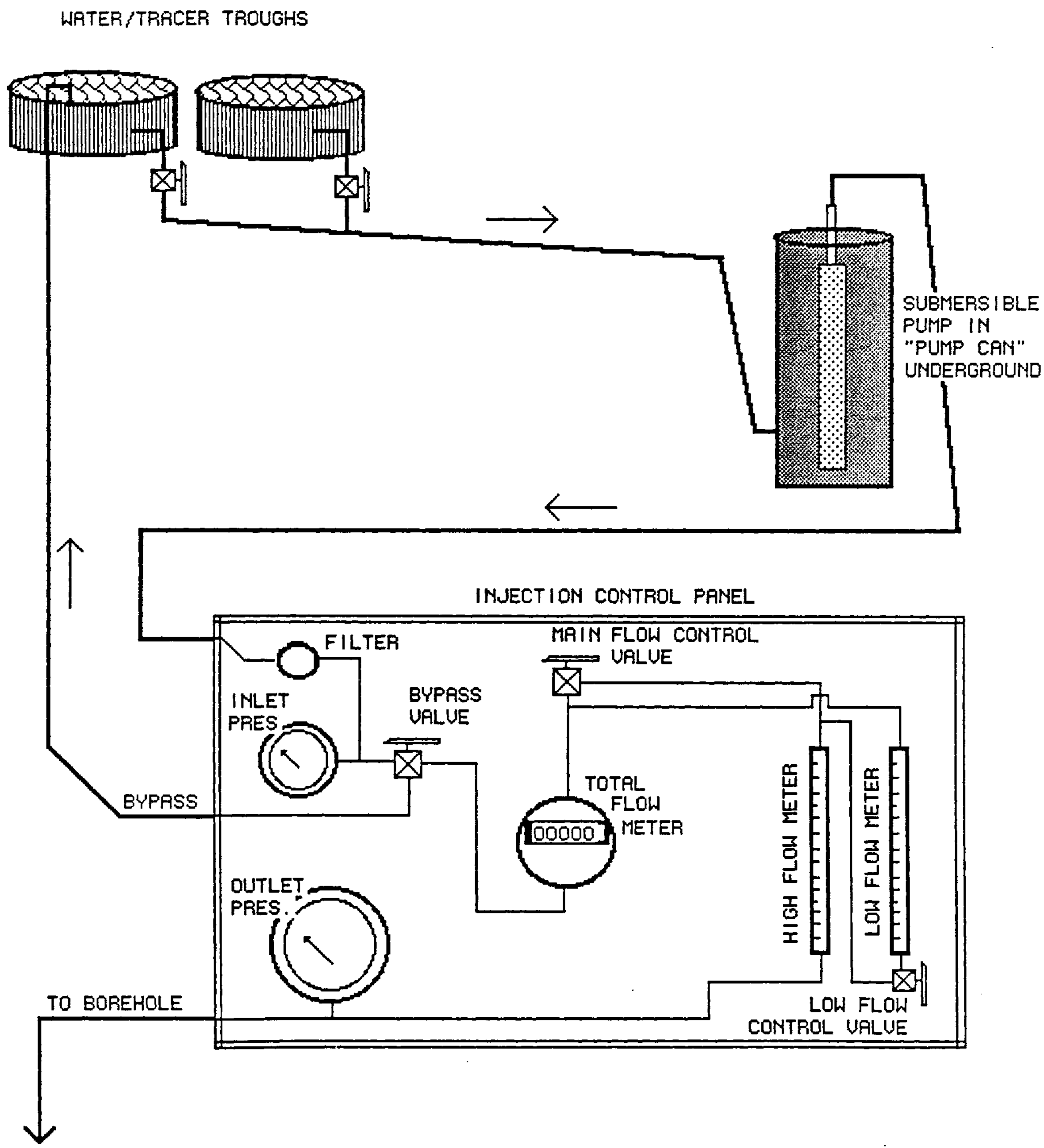


Figure 3.2. Schematic diagram of tracer/water injection system (uphole components).

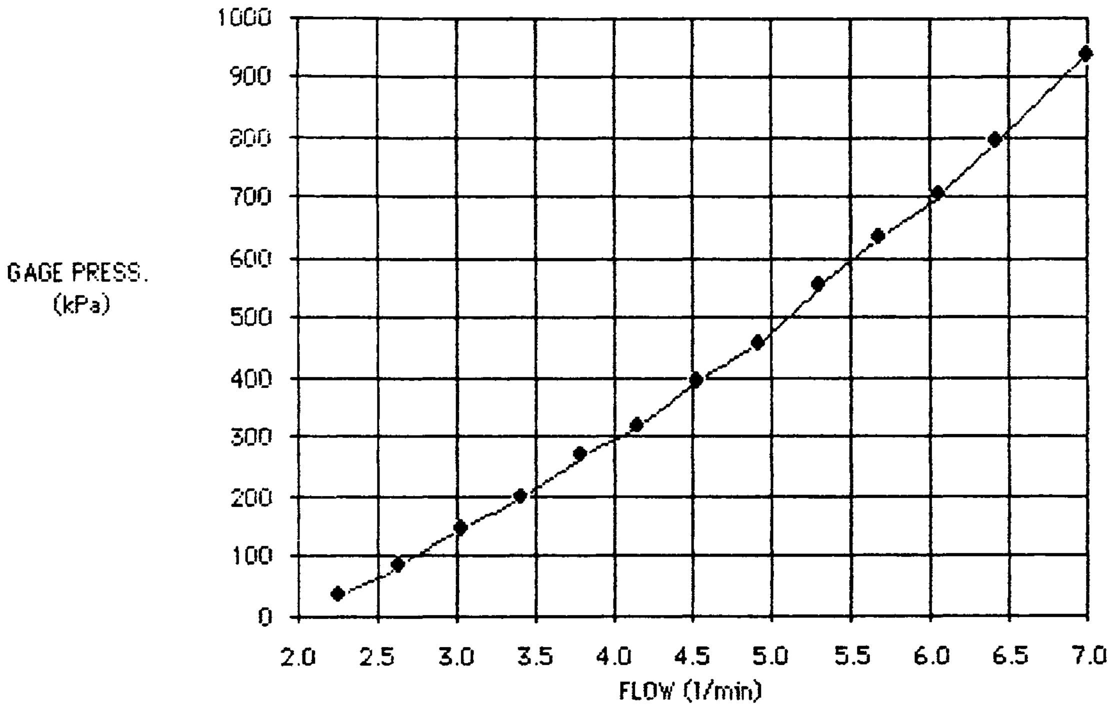


Figure 3.3. Typical injection pressure vs. flow rate calibration curve.

pressure measured during calibration (friction head) was subtracted from the pressure displayed (total head) to obtain the an estimate of the pressure present in the injection interval. This method of downhole pressure measurement provided sufficient accuracy without the added complexity and expense of a separate pressure monitoring system.

The primary down hole component of the injection system, shown in Fig. 3.4, is a straddle packer assembly using two Rocktest Model LP/85-187 inflatable packers. The packers are separated by an injection interval 5.3 m long constructed of 5 cm square steel tubing. Injection lines of 0.953 cm plastic tubing with outlet nozzles every 15-20 cm are attached along the full length of all four sides of the steel tubing. These nozzles are intended to maximize mixing within the injection interval. Air-lift samplers are located above and below the packers to detect leakage of tracer. A third air-lift sampler is located within the injection interval and collects a mixed sample from points near the top, middle, and bottom of the interval. Two thermistors were originally installed in the injection interval to monitor downhole temperatrure when hot or cold water was injected from the surface. These were later removed when it was discovered that, due to heat losses in the 90 m of uninsulated plastic tubing between the surface and the packer assembly, only slight temperature changes could be generated in the injection by injecting hot or cold water. The packers were inflated with compressed air and/or nitrogen gas fed through an inflation line from the surface.

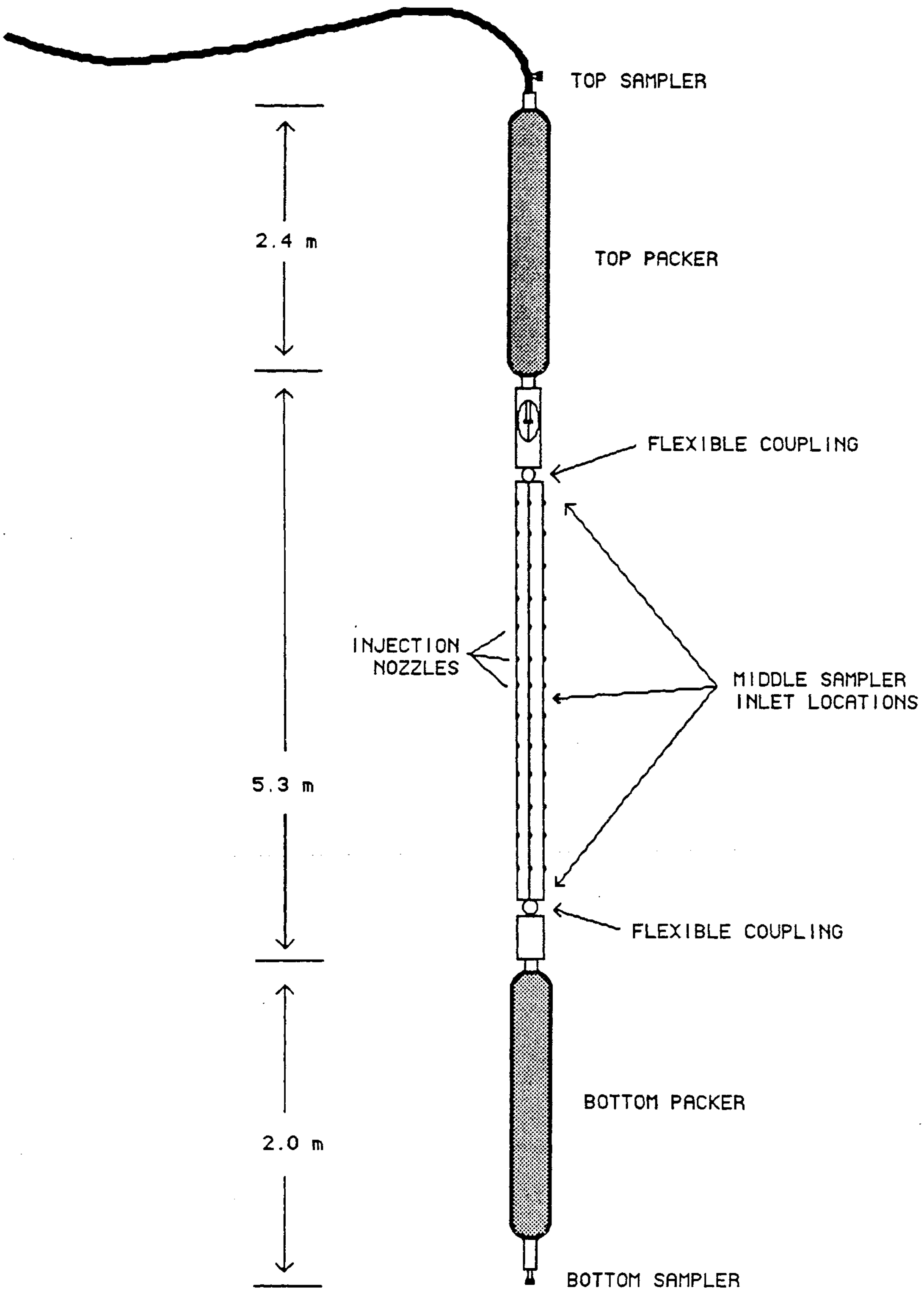


Figure 3.4. Straddle packer asembly showing locations of sampling and injection components.

CHAPTER FOUR

FIELD METHODS

4.1 Equipment Setup

A diagram of the field setup is shown in Fig. 4.1. Typically, the packers were placed downhole at the proper depth to straddle the conductive zone. Prior to inflation the injection pump was started in order to do a pressure vs. flow rate calibration . The packers were then inflated to their working pressure of 1100 kPa above the hydrostatic pressure and the injection pump restarted. The water level in the injection borehole was monitored for any rapid changes that would indicate a leak past the top packer. Pressure response in the injection interval was also used as an indicator of packer leakage. If injection pressure was abnormally low or varied with changes in packer inflation pressure, a leak was indicated. If leakage occured, the packers were deflated, moved a short distance up or down and the procedure was repeated.

Once the packers were set, potable water obtained from the Oracle public water supply system, was injected for an hour or more to establish a near steady state flow field prior to tracer injection. During this time, temperature data were collected from the sampling boreholes to determine the initial placement of the point samplers (Silliman,1985). Temperature data were collected by an automatic data logger (Polycorder™). Water level measurements were made throughout the tests using electric well sounders and Stevens recorders.

Tracer was brought to the site dissolved in about8 l of water. This solution was poured into a trough containing about 400 l of water and mixed by stirring. To inject the tracer solution, the valve on the tracer trough was opened to feed traced water to the injection pump. The bypass valve on the control panel was opened to allow the untraced water contained in the pump can

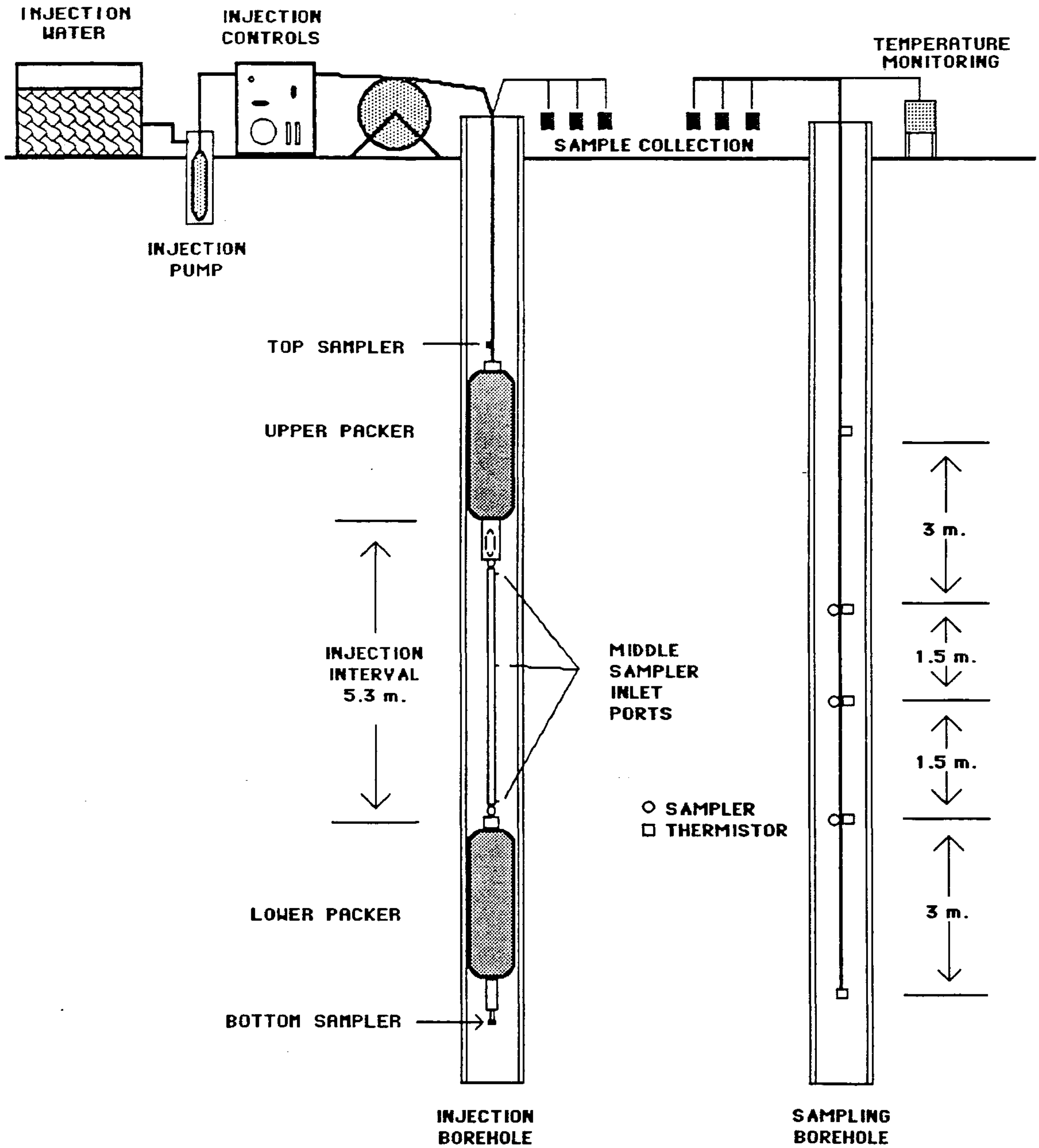


Figure 4.1. Diagram of field equipment set up.

and control panel plumbing to be rapidly displaced with traced water. This bypassed water was recirculated back into the trough containing the tracer and allowed to run for approximately 5 min, after which time it was assumed that all the untraced water in the uphole components had been displaced with tracer solution and the valve was closed. Because the untraced water from the system was introduced into the tracer trough, this recirculation procedure resulted in a slight dilution of the tracer solution. This was considered to be superior to the alternative of running the bypass water to waste on the site, which would have resulted in unnecessary loss of some of the tracer solution and introduced unwanted tracers onto the surface of the site. After the tracer solution was exhausted, the same procedure was used to switch back to fresh water, except that in this case the bypass was run into a separate container and transported off site. Through careful manipultion of the flow control and bypass valves, this procedure could be accomplished with only minor fluctuations in the flow rate.

4.2 Tracer Selection and Analysis

Selection of an appropriate tracer requires consideration of several properties of the tracer itself and the groundwater system in which it will be used. Davis *et al.* (1980) provide a review of this subject. Unless one is specifically interested in studying the sorbtive characteristics of a system, the tracer should be conservative; that is, it remains in solution and moves through the system along with the water and does not react with or sorb on the aquifer material. It should have sufficient biological and chemical stability to resist degradation for the duration of the test. A tracer compound should be one that does not occur naturally in the groundwater at concentrations high enough to produce a significant background level which might interfere with analysis of the tracer. There must be a reliable and relatively fast method for detecting the tracer. For the purposes of tracking the progress of a test, it is usually desirable to have the capability of analyzing for the tracer in the field during the test. Finally, the tracer must be environmentally compatible with the uses of the aquifer into which is introduced.

Because they can be easily detected in minute concentrations, and have low natural background levels, radioactive tracers have been used almost exclusively in other studies of flow in fractured rocks. At the Oracle site, the presence of livestock and domestic water wells within a few kilometers of the site precluded the use of any toxic or radioactive tracers. In order to run a series of tests at the site, it was necessary to have several tracers available. As part of the early work at the Oracle site, Thompson and Stetzenbach (1980) developed a new class of fluorinated benzoic acid groundwater tracers. Stetzenbach and Thompson (1983) reported a new method for analysis of several common ionic tracers. Tracers and analytical techniques used in the work reported herein are those developed by these researchers.

Tracers used in this work included iodide, sodium benzoate, pentafluorobenzoic acid, 2-trifluoromethylbenzoic acid, and 3-trifluoromethylbenzoic acid. Earlier tracer tests had shown that after any one tracer was introduced into the groundwater at the site, a period of several months might be required before the background levels of that tracer were again low enough for its reuse. Because iodide has some sorbtive properties and sodium benzoate is the most biodegradable of theorganic acids (Thompson and Stetzenbach 1980), these tracers were used in the first two tests when the equipment and techniques were still relatively unproved. In this way, the "better" tracers could be saved for later tests when there was more confidence in our ability to get useable data. All of these tracers had been successfully used by others in previous work at the site (Cullen *et al.,* 1985)

Tracer analysis was done both onsite during the tests and in the laboratory using High-Performance Liquid Chromatography (HPLC). Analytical equipment consisted of an Altex model 330 gradient HPLC solvent delivery system (Beckman Instruments Inc., Berkeley, CA), a

Hitachi model 100-40 variable-wavelength detector (Tokoyo, Japan) and a Spectra Physics model SP-4100 integrator (Santa Clara, CA). Various analytical columns were used depending on which tracer was being analysed. Although this equipment was not specifically designed for use in the field, it proved to be remarkaby rugged and was almost unaffected by extremes in temperature and fluctuations in voltage from the generator-driven power supply.

Tracer samples were collected in either 50 ml brown glass bottles or 20 ml polyethylene bottles. As many samples as possible were analysed in the field during the tests. All samples were transported back to the laboratory at the University of Arizona Department of Hydrology and Water Resources and stored in a refrigerator until the analyses were completed. By comparing results of samples run in the field with the same samples run in the laboratory it was possible to determine if any degradation of the tracer had occurred during transport and storage. Sampling intervals were usually between 5 and10 min at the beginning of the tests and 1 hr near the end of the tests when the tracer concentration was changing slowly. Total volume removed with each sample, including the rinse, was between 75 and150 ml.

CHAPTER FIVE

RESULTS OF TRACER TESTS

Five tracer tests were conducted, three with injection in M-1 and two with injection in H-3. Tracer breakthrough was monitored primarily in H-2, although some data were obtained from other surrounding boreholes. Both borehole flowmeter and downhole temperature profile data indicate that, in H-2, a single fracture located 80.3 m below the top of the casing is the major source of inflow. Tracer breakthroughs in the three-sampler probe typically showed first arrival in the sampler located just above this fracture with the samplers located further up in the borehole showing similar breakthrough curves delayed in time. Although breakthrough curves were obtained from all of the tests, problems with packer leakage and poor mixing in the injection interval resulted in unreliable input concentration measurements in three of the tests. Biodegradation of the tracer resulted in loss of most of the data from another test. Thus only one test gave data complete enough for numerical analysis.

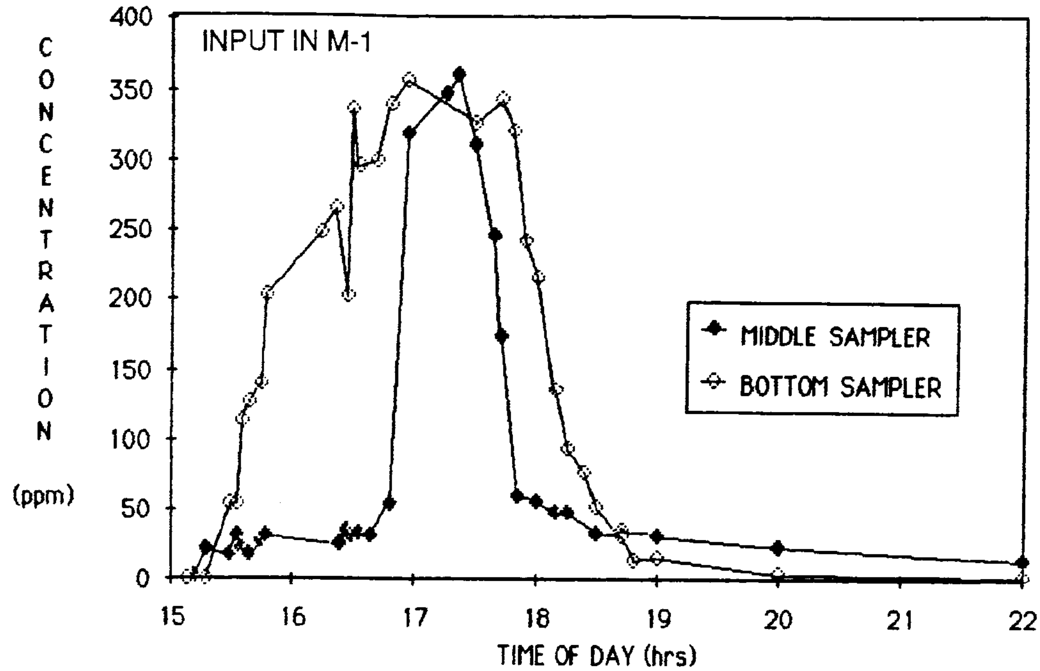
5.1 Tests With Injection in M-1

Three tests were run with injection in M-1 and sampling in H-2. Because both M-1 and H-2 deviate considerably from the vertical, the straight line distance between the injection interval in M-1 and sampling point in H-2 is approximately 5.1 m.

Test 1, Feb. 15, 1985. Hydraulic testing was not done in the bottom section of M-1 because of problems in sealing the packers in this rough section of the borehole. The first test in M-1 was done prior to the development of the borehole flowmeter. Consequently, the exact location of the permeable zone in this hole was not known. It was thought to be about 77 m below the top of the casing so the packers were placed to straddle a zone from 74.7 m to 80 m below the top of the casing. Tracer used was 250 gm of potassium iodide. This was dissolved in approximately 460 l of water and injected at 3.8 l/min. Injection pressure averaged around 800 kPa. Input and breakthrough curves are shown in Fig. 5.1. The high concentration of tracer present at the bottom sampler indicates that a significant portion of the tracer probably leaked past the bottom packer and moved down the borehole before entering the fractures. During the test it was noticed that the injection pressure was fluctuating in response to packer inflation pressure which would also indicate significant leakage.

Test 2, Apr. 10, 1985. After Test 1, a borehole flowmeter log of M-1 was run that showed evidence that the permeable zone connecting M-1 and H-2 was deeper in the borehole than had been previously thought. Flow appeared to be leaving M-1 over a 3 m zone of heavy fracturing about 84 m below the top of the casing. Test 2 was started with the packers straddling 80.8 m to 86.1 m Flow rate was 5.7 l/min and injection pressure was only about 110 kPa, indicating a more permeable zone than in Test 1. Prior to tracer injection, an air leak was detected in the packer. The packers were brought to the surface and the bottom packer, which was found to be leaking, was disconnected. The test was then run with injection below a single packer at 80.8 m. No significant change in injection pressure was observed with the bottom packer deflated, indicating that no major flow paths existed in the bottom of the borehole below the originally chosen injection interval. Tracer used was 225 gm of sodium benzoate dissolved in approximately 425 l of water. Sodium benzoate had been used previously at this site by Cullen, (1985), apparently with good results.

At the time of this test it was noticed that a black bacterial slime was forming on equipment left downhole for more than a day and that water in the boreholes had a musty odor, indicative of bacterial activity. Tracer samples from Test 2 were analysed in the field during the test and showed more or less expected concentrations. The majority of the samples were transported to the laboratory for analysis. The samples were refrigerated at approximately 7 ^{o}C for one week prior to analysis. During this time, drastic changes in tracer concentration occurred in many of the samples, resulting in loss of the data. Sodium benzoate is considered to be more



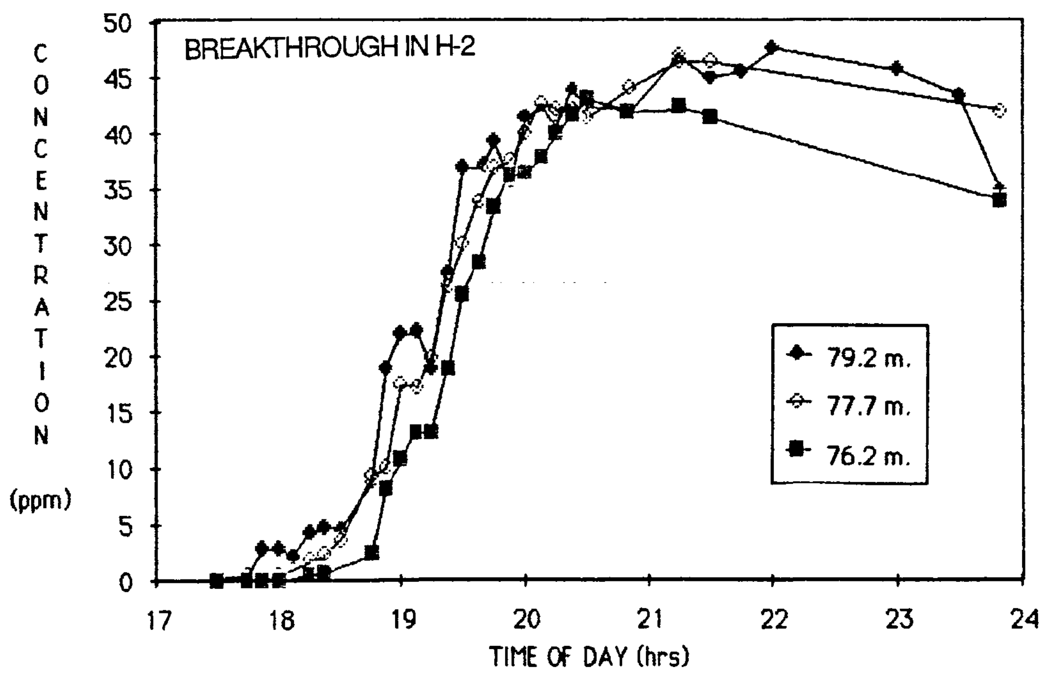


Figure 5.1. Iodide tracer input in M-1 and breakthrough in H-2, Test 1.

biodegradable than any of the fluorinated tracers. There was concern that prolonged use of similar tracers at the site had resulted in an adapted population of native bacteria that could degrade the normally stable trracers.

To test this hypothesis, a batch degradation experiment was set up in which known concentrations of all five tracers were dissolved in water from the site and stored for thirty days. One group of samples was refrigerated and the other was left at room temperature in a darkened cabinet. At the end of that period, all of the sodium benzoate had disappeared from the bottles whereas none of the fluorinated benzoic acid tracers or iodide showed significant degradation, even in the unrefrigerated bottles. Although this test was not sufficient to prove long term stability under natural conditions in the aquifer, it did indicate that the fluoronated tracers were sufficiently stable for short duration tests Prior to the next test the boreholes were chlorinated and pumped and the slime and odor were no longer apparent.

Test 3, July 16, 1985. The same injection interval of 80.8-86.1 m and flow rate of 5.7 l/min were used for Test 3. Tracer was 234 gm of pentafluorobenzoic acid dissolved in approximately 395 l. of water. Injection pressure was again about 100 to110 kPa. Input and breakthrough curves are shown in Fig. 5.2. This test appears to have been successful, with no significant leakage past the packers and a smooth input concentration curve. Numerical simulation of these data is reported by Aikens (1986). Late in this test, samples were collected from various depths in H-3, H-6, and H-7 to determine if tracer had moved into these boreholes. No tracer was detected in any of these samples with a detection limit of 0.2 ppm.

Few water level data were collected during Test 3, but because the injection pressure and flow rate were the same as in Test 2, it is assumed that the water level response was similar throughout both tests. Water level data for Test 2 is displayed in Fig. 5.3. In this figure, all depths are reported using the elevation of the top of the casing on M-1 as zero datum. (Relative casing top elevations for the boreholes is given in Table 1.1) There was little change in M-1

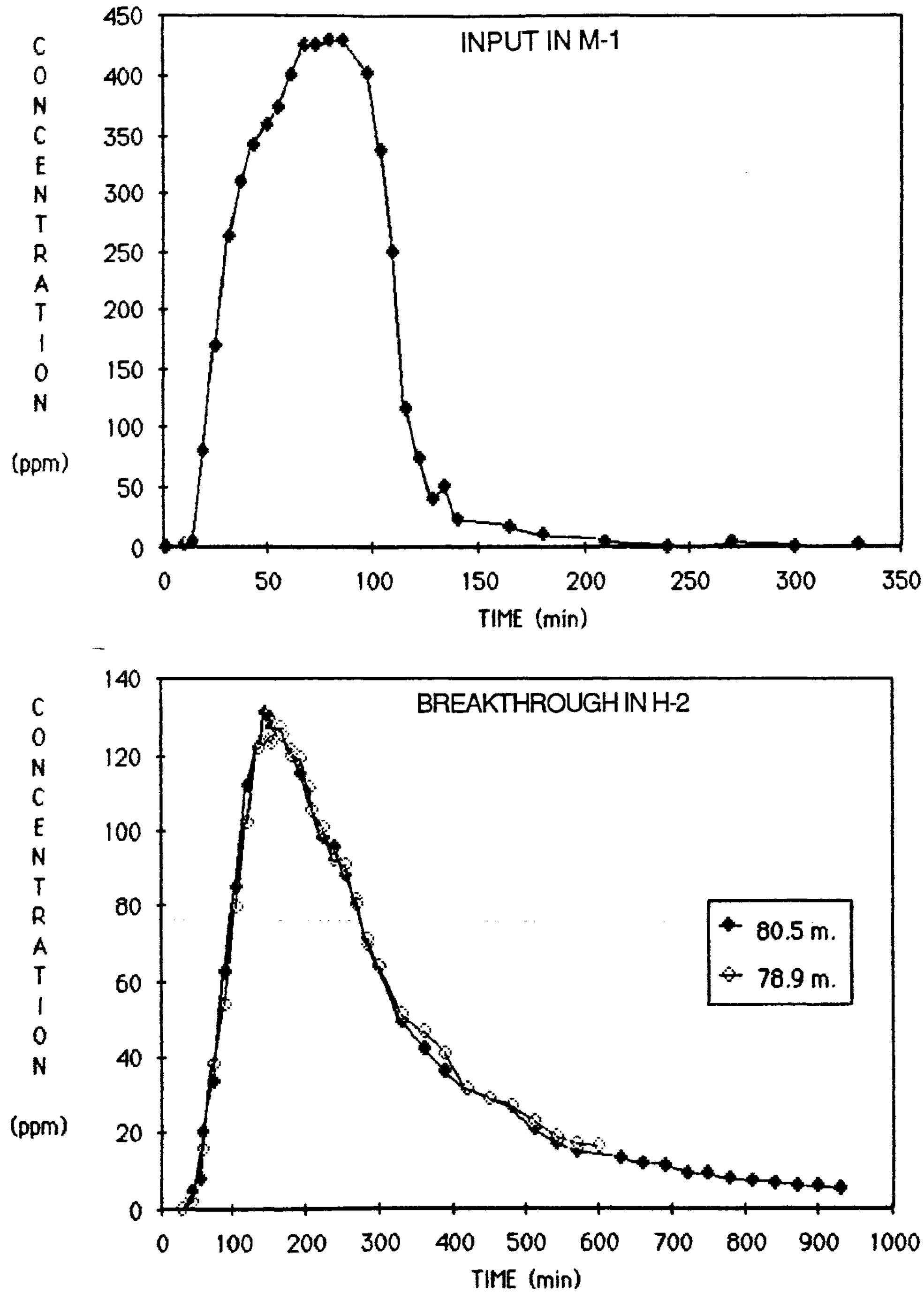


Figure 5.2. Pentafluorobenzoic acid tracer input in M-1 and breakthrough in H-2, Test 3.

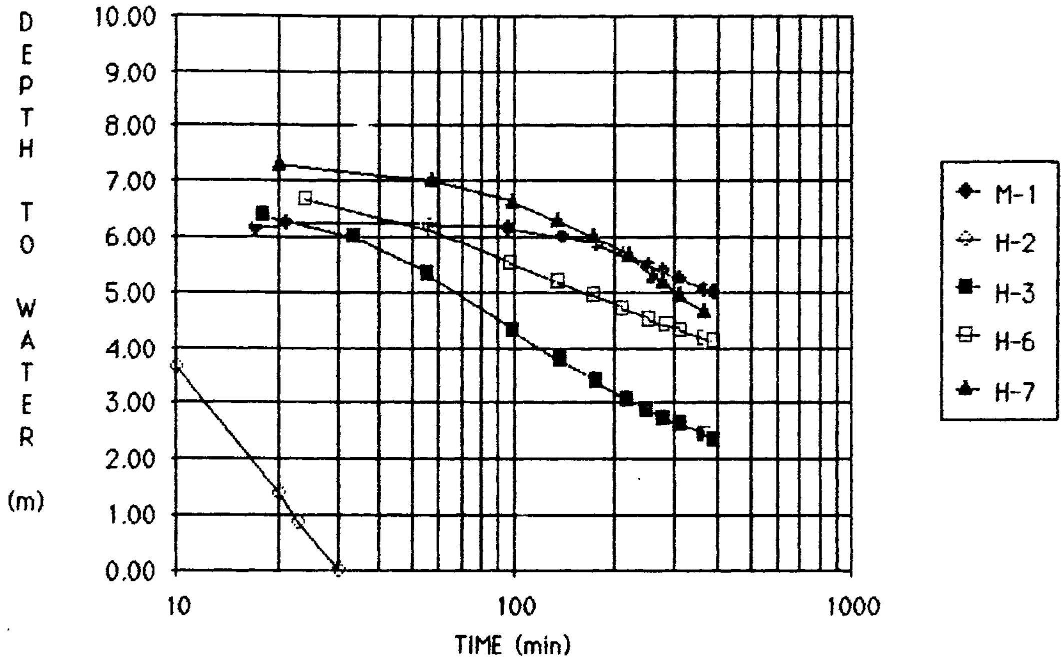


Figure 5.3. Water levels in boreholes during Test 2, (Top of casing in M-1 as zero datum).

during the first two hours of the test, indicating no significant leakage past the top packer. The rise in M-1 later in the test was probably due to inflow from fractures above the packed off interval. H-2 responded rapidly to injection in M-1. During the first 30 minutes, approximately 45% of the 5.7 l/min injected into M-1 can be accounted for by the rise in H-2 alone. This rapid response in H-2 occurs with low injection pressures, indicating a good hydraulic connection between these two boreholes. Response in H-3 was greater than that in H-6 or H-7. This may be because H-6 and H-7 are 15 m shallower than the other holes and therefore don't penetrate the permeable fracture zone.

5.2 Tests With Injection in H-3

Two tests were run with injection in H-3 and samplers in H-2 and M-1. The straight line distance from the injection interval to the sampling point in H-2 is approximately 9 m.

Test 4, Aug. 6, 1985. Borehole flowmeter and acoustic televiewer logs of H-3 indicated that a single primary conductive zone was located in a closely spaced group of steeply dipping fractures around 76.2 m. below the top of the casing. Below this zone there was almost no flow. Thus, only a small part of the injection interval was accepting flow in H-2 while in M-1 it appeared that most of the injection interval was somewhat permeable. Test 4 was conducted with the injection interval located from 73.8 to 79.1 m. Injection rate was 5.7 l/min resulting in approximately 276 kPa of injection pressure in the packed off interval. Tracer was 200 gm. of 3-trifluoromethylbenzoic acid dissolved in approximately 453 l of water. Tracer input and breakthrough curves for Test 4 are shown in Figs. 5.4 and 5.5. Breakthrough was monitored in both H-2 and M-1. Tracer concentration in M-1 was very low compared to H-2, but both curves are reasonably smooth.

Drastic fluctuations in the tracer input curve were experienced with the peak concentration much lower than expected and the concentration in the injection interval remaining high hours after the flow was switched back to untraced water. The presence of tracer in the top sampler

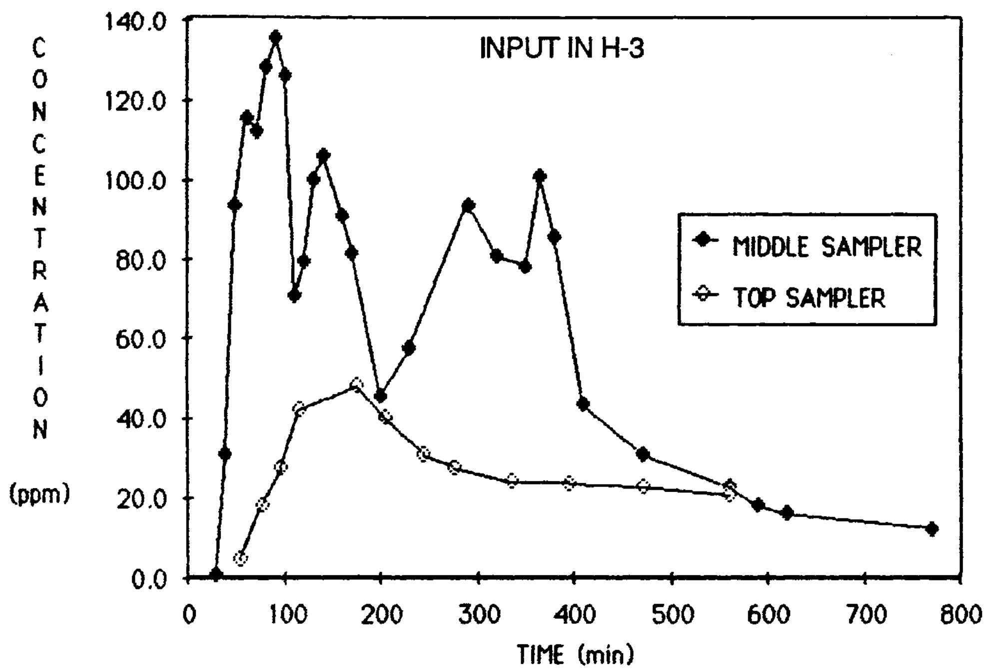
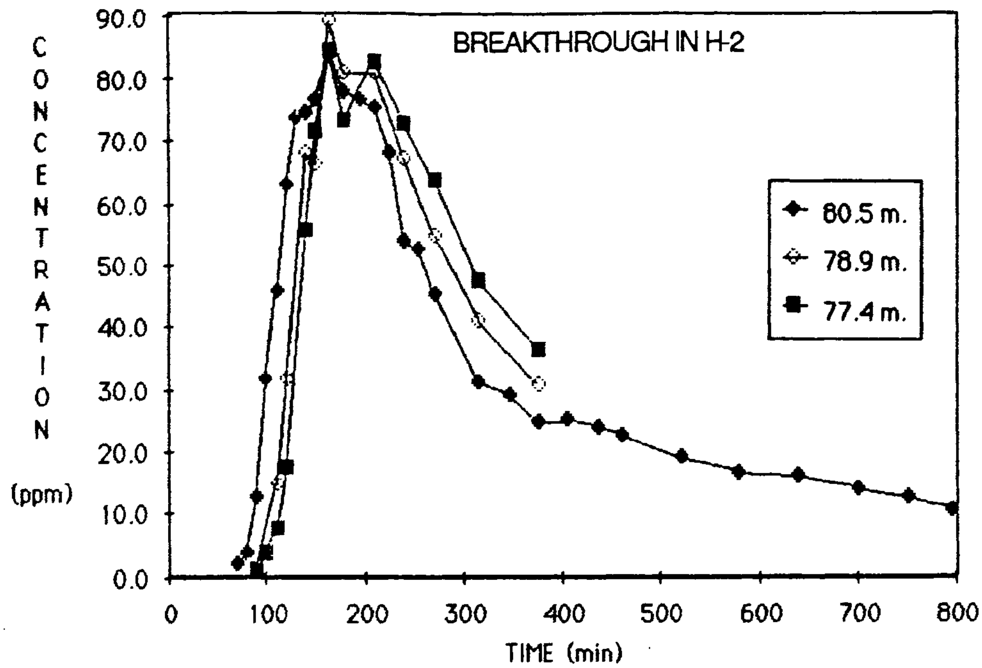


Figure 5.4. 3-trifluoromethylbenzoic acid tracer input in H-3, Test 4.



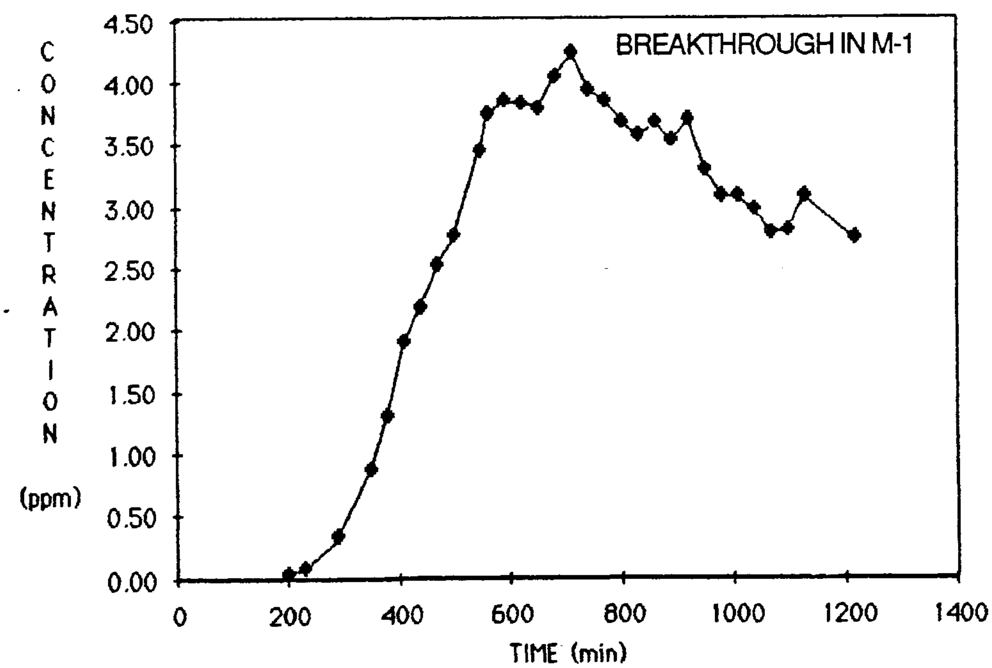
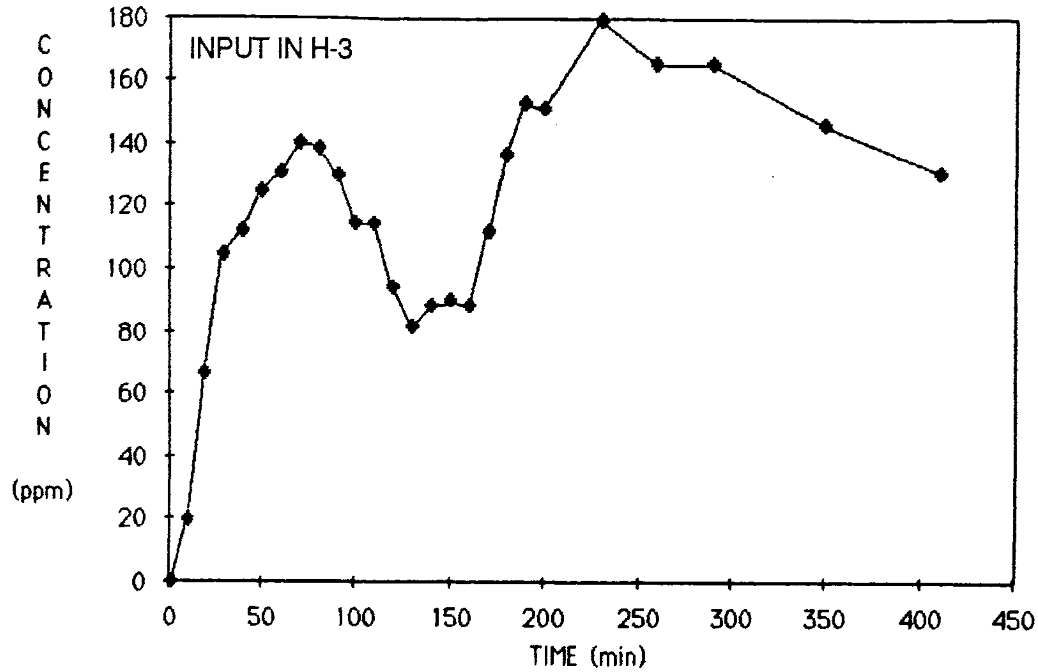


Figure 5.5. 3-trifluoromethylbenzoic acid tracer breakthrough in H-2 and M-1, Test 4.

(located above the top packer) indicated that some leakage, either past the packers or through vertical fractures around the packers, may have occured. The smooth breakthrough curves however, indicate that the tracer concentration actually entering the fracture in the injection interval and did not fluctuate as widely as infered by the input samples. After the test was completed but prior to stopping the flow, a few liters of water colored with food coloring were injected and drawn into the injection systems' middle sampler. The packers were then deflated and brought to the surface where the middle sampler was disassembled to determine which of its three inlet ports had injested the colored water. Color was found in the bottom and middle inlets but not in the top, indicating that the top sampling port was in a portion of the borehole that was not mixing readily. It was theorized that some leakage past the top packer might have drawn a pocket of high concentration tracer solution in to the upper 0.7 m. of the injection interval near a connector housing where no injection nozzles were located and that lack of mixing in this zone caused the fluctuations in the input samples.

Test 5, Aug. 29, 1985. Modifications were done to the packer assembly consisting of the installation of injection nozzles inside the upper connector housing and relocation of the upper sampler inlet port out of the connector housing . The test was conducted under the same conditions as Test 4. Tracer was 200 gm of 2-trifluoromethylbenzoic acid dissolved in 574 l of water. Results of Test 5, (Fig.5.6), again showed an erratic input curve indicating poor mixing. No significant tracer concentrations appeared in either the bottom or top samplers, indicating no leakage around the packers. The breakthrough curves are not as smooth as in previous tests and show somewhat of a bimodal tendency near the peak. It appears that there was inadequate mixing over a substantial portion of the injection interval, not just in the vicinity of the connector housing. The reason that this problem did not occur in M-1 may be because that borehole was permeable throughout the injection interval while in H-3 only a small portion of the interval participated in the flow. Apparently there is a need for a more positive means of mixing the 100 l



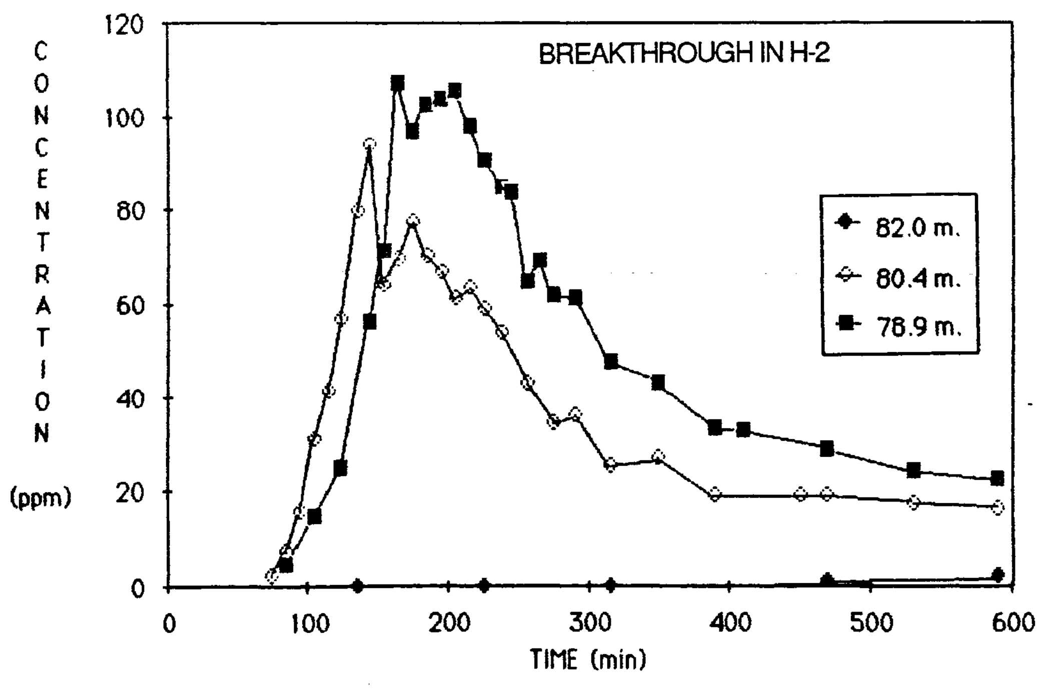


Figure 5.6. 2-trifluoromethylbenzoic acid tracer input in H-3 and breakthrough in H-2, Test 5.

of water contained in the injection interval of the borehole.

Water level data for Test 4 are displayed in Fig. 5.7. These data are believed to be representative of both Tests 4 and 5 where injection took place in H-3. The hydraulic connection between M-1 and H-2 is again evident in the uniform response of these two boreholes. M-1 is further away from H-3 and, due to its larger casing diameter, contains 2.6 times more water per meter of casing than H-2, yet their rate of rise is almost identical. The responses of H-6 and H-7 are very similar to one another with H-7, being closer to H-3, responding slightly more. A rough volumetric calculation shows that approximately 44% of the total volume injected up to the time when H-2 began to overflow (200 min), is accounted for by the rise in the five boreholes shown. As noted previously, there may have been some leakage past or around the packers in this test. The rise in H-3 may be partly due to this leakage.

During Test 5, M-1 was sampled at several different depths to detect the location of tracer breakthrough. The results are shown in Figure 5.8. It appears that the initial breakthrough of tracer occured between 81 m. and 84 m. The fact that the tracer is found over a relatively wide interval supports the earlier conclusions from the heat pulse flowmeter and temperature monitoring work that the flow enters M-1 from more than one single fracture.

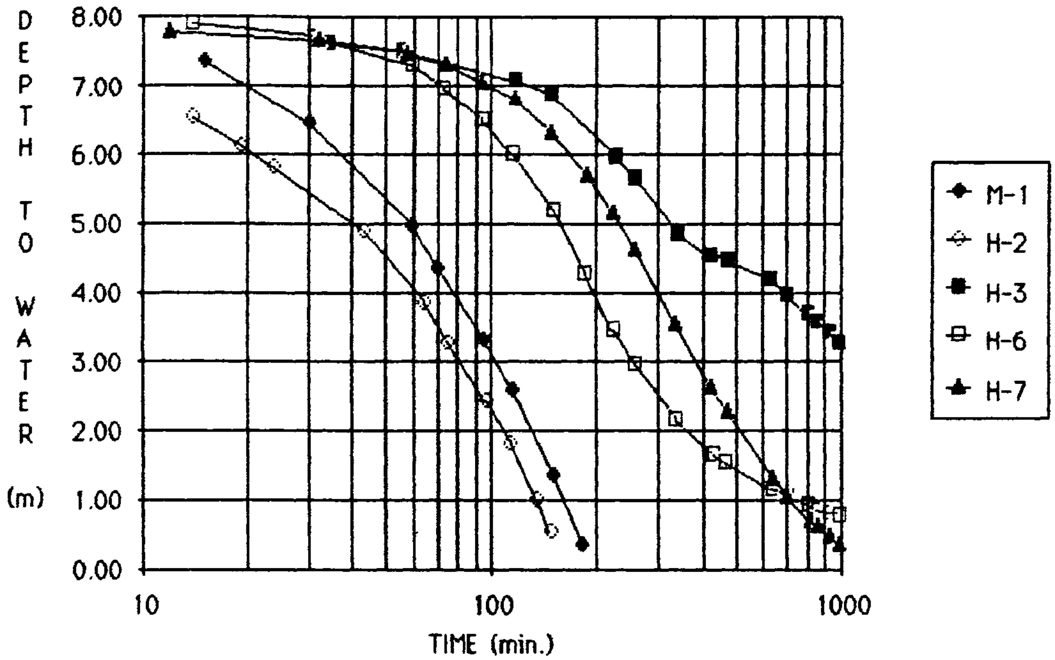


Figure 5.7. Water levels in boreholes during Test 4, (Top of casing in M-1 as zero datum).

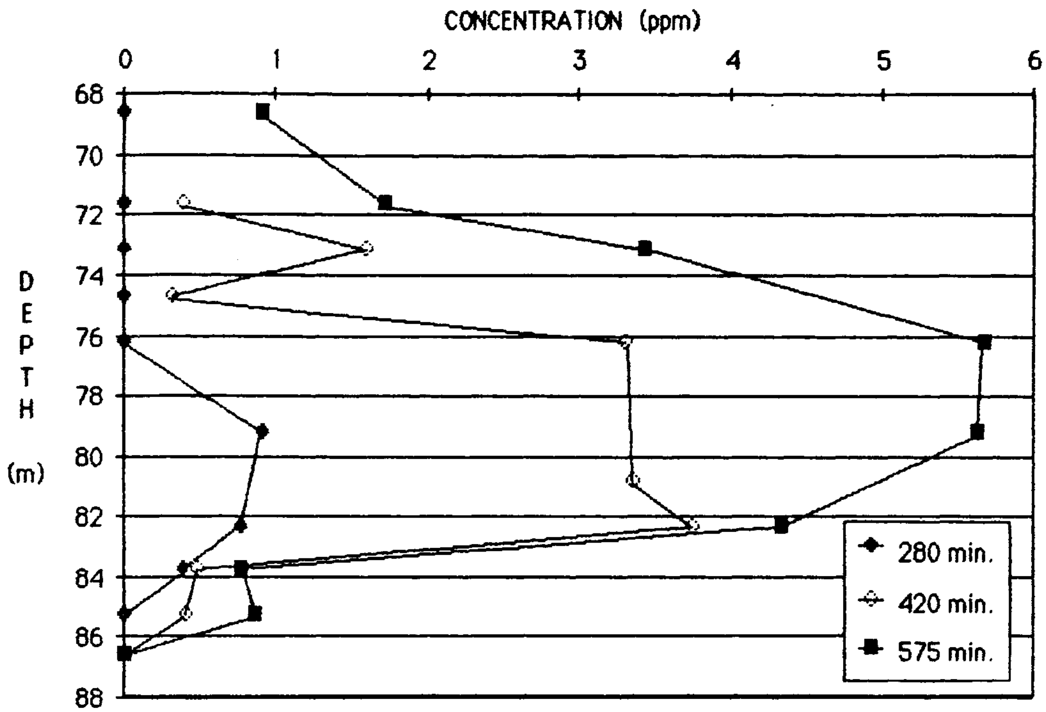


Figure 5.8. 2-trifluoromethylbenzoic acid tracer breakthrough profile in M-1, Test 5.

CHAPTER SIX

SUMMARY AND CONCLUSIONS

Conducting successful tracer tests in low permeability fractured rocks without the use of radioactive tracers is a difficult but not impossible task. The present lack of a suitable downhole sensor that would give instantaneous concentration readout adds considerably to the difficulties in running tracer tests with non-radioactive tracers. Because it is not possible to scan large sections of borehole rapidly to detect tracer breakthrough points, one must use multiple samplers and have accurate prior knowledge of the locations of conducting fractures in order to detect the tracer breakthrough.

A method of locating conducting fractures using downhole temperature logs and heat-pulse flowmeter logs combined with acoustic televiewer logs proved to be reliable and accurate. Tracer breakthrough data from H-2 show that the tracer entered the borehole at the location indicated by the temperature and flowmeter logs for the major conductive fracture. In all tests, breakthrough curves from the multiple samplers in H-2 show that breakthrough occurred first in the sampler closest to the fracture at 80.3-80.5 m , and later in the other samplers as the tracer moved up the borehole. Breakthrough in M-1 also occurred in the location predicted by temperature and flowmeter logs. Initial tracer breakthrough in M-1 during Test 5 (Fig. 5.8) appeared over about 4 m of the borehole, which supports the flowmeter and temperature logs indicating more than one single fracture is contributing to the flow in this section of M-1. In Test 5 (Fig 5.6), the bottom sampler in H-2 was deliberately placed 1.5 m below the fracture and detected almost no tracer throughout the entire test. This demonstrates the importance of knowing the location of the fractures prior to tracer testing. If samplers are not located properly, tracer breakthrough may go undetected.

In general, both the air-lift samplers and the up-hole components of the injection system performed well throughout all the tests. Two minor problems occurred in the air-lift samplers, both of which were easily corrected and neither of which resulted in significant loss of data. The first involved a leak in a check-valve in the multiple sampler system during Test 3. Inspection of the valves after the test showed some light mineralization and scum formation had occurred on valve seats and the o-ring seals. These valves had not been cleaned since they were originally installed so these deposits had accumulated over a period of 6 months or more. After the valves were cleaned, the problem disappeared and regular cleaning of the valves after each test prevented its recurrence. The second problem was associated with the samplers installed on the injection packer assembly. The packer string had to be disassembled each time it was removed from the borehole. Some special fittings were built to allow disconnection of the concentric tubes on the air-lift samplers. Under certain conditions, corrosion of these fittings could result in an intermittent obstruction of the air channel between the inner and outer tubes and a malfunction in the sampler. This problem was corrected with new fittings made of corrosion resistant aluminum.

No problems were encountered with the up-hole components of the injection system (Fig. 3.2). After the first hour of the tests, during which the flow field was changing most rapidly, the flow rate delivered by the system was so stable that manual adjustments were needed only about once an hour or less. The use of a batch method for pre-mixing tracer in a trough prior to injection proved to be adequate and is probably the simplest and most reliable method available.

The only major problem in the design of the equipment was the lack of adequate mixing in the injection interval between the packers. After Test 5, it was concluded that further modifications to the existing system of injection nozzles were probably futile and there was a need for a more positive means of mixing. Plans were made to install a small submersible pump to recirculate the water in the injection interval during the tracer injection period, but the project was terminated prior the the completion of this modification.

It was originally intended for future work at the Oracle site to be directed toward tracer tests in the lower conductivity zones. The mixing problems encountered in the work reported herein have implications for this or other similar future work. With the decreased flow rates expected in less permeable zones, the need for mixing in the injection interval will become even more acute. There may also be a need for some type of mixing in the monitoring borehole, particularly if the sampling intervals in this hole are to be isolated. Because tests in the lower conductivity zones would be expected to run for much longer time periods, further investigations should be done on the biological stability of the organic tracers in the native bacterial population at the site.

APPENDIX A

TRACER INPUT AND BREAKTHROUGH DATA

Table A.1. Tracer input in M-1, Test 1.

(Time listed is time of day in hours and tenths of hours)

MIDDLE SAMPLER	
TIME (hrs)	CONC. (ppm)
15.20	2.9
15.30	21.4
15.50	17.5
15.55	30.6
15.60	22.1
15.65	18.6
15.75	27.6
15.80	32.1
16.40	25.0
16.45	35.1
16.50	31.0
16.55	33.4
16.65	30.4
16.80	55.0
16.95	318.0
17.25	348.0
17.35	360.0
17.50	311.0
17.65	246.0
17.70	175.0
17.85	59.0
18.00	56.0
18.15	49.0
18.25	49.0
18.50	34.0
18.70	35.0
19.00	32.0
20.00	24.0
22.00	14.0

BOTTOM SAMPLER	
TIME (hrs)	CONC. (ppm)
15.15	1.4
15.30	1.2
15.50	54.3
15.55	54.8
15.60	113.0
15.65	126.0
15.75	140.0
15.80	203.0
16.25	249.0
16.35	266.0
16.45	202.0
16.50	336.0
16.55	296.0
16.70	300.0
16.80	339.0
16.95	357.0
17.50	327.0
17.70	343.0
17.80	321.0
17.90	242.0
18.00	216.0
18.15	136.0
18.25	95.0
18.40	77.0
18.50	53.0
18.70	31.0
18.80	15.0
19.00	17.0
20.00	5.5
22.00	2.8

Table A.2. Tracer breakthrough in H-2, Test 1.

76.2 m.

TIME (hrs.)	CONC. (ppm)
17.50	0.1
17.75	0.0
17.87	0.0
18.00	0.1
18.25	0.6
18.37	0.9
18.75	2.5
18.87	8.3
19.00	10.7
19.12	13.1
19.25	13.1
19.37	18.8
19.50	25.6
19.62	28.5
19.75	33.4
19.87	36.4
20.00	36.6
20.12	38.0
20.25	40.1
20.37	41.7
20.50	43.2
20.82	42.1
21.25	42.4
21.50	41.6
23.82	34.0

77.7 m.

TIME (hrs.)	CONC. (ppm)
17.50	0.1
17.75	0.1
17.87	0.1
18.00	0.7
18.25	2.0
18.37	2.4
18.50	3.7
18.75	9.3
18.87	10.1
19.00	17.4
19.12	17.2
19.25	19.9
19.37	26.2
19.50	30.0
19.62	33.9
19.75	37.1
19.87	37.6
20.00	40.0
20.12	42.7
20.25	42.3
20.37	43.0
20.50	41.6
20.83	44.2
21.25	46.6
21.50	46.6
23.83	42.1

79.2 m.

TIME (hrs.)	CONC. (ppm)
17.50	0.4
17.75	0.7
17.87	3.0
18.00	3.0
18.12	2.3
18.25	4.3
18.37	4.8
18.50	4.7
18.75	8.9
18.87	18.9
19.00	22.1
19.12	22.3
19.25	18.9
19.37	27.4
19.50	37.1
19.67	37.2
19.75	39.4
19.87	35.8
20.00	41.6
20.12	42.5
20.25	40.5
20.37	43.8
20.50	42.4
20.83	42.0
21.25	47.0
21.50	45.0
21.75	45.6
22.00	47.7
23.00	45.8
23.50	43.5
23.83	34.9

Table A.3. Tracer input in M-1 and breakthrough in H-2, Test 3.

INPUT IN M-1

TIME (min)	CONC.(ppm)
1	0.00
10	1.34
14	4.25
20	79.70
26	169.00
32	262.00
38	308.00
44	341.00
50	358.00
56	373.00
62	400.00
68	425.00
74	426.00
80	430.00
86	430.00
98	402.00
104	337.00
110	249.00
116	115.00
122	74.40
128	39.60
134	51.10
140	21.90
165	15.60
180	9.07
210	3.28
240	0.00
270	3.03
300	0.00
330	0.44

H-2, 80.5 m.

TIME (min.)	CONC.(ppm)
30	0.00
40	2.22
45	4.21
55	7.97
60	20.20
75	33.60
90	62.30
105	85.10
120	112.00
135	123.00
140	123.00
145	131.00
150	130.00
155	127.00
165	127.00
180	121.00
195	115.00
210	106.00
225	98.10
240	95.30
255	87.90
270	81.30
285	69.70
300	63.20
330	49.00
360	42.30
390	36.20
420	31.30
450	28.70
480	26.30
510	21.00
540	17.10
570	14.80
630	13.30
660	11.60
690	11.10
720	9.34
750	8.98
780	7.61
810	6.83
840	6.25
870	5.78
900	5.99
930	5.30

H-2, 78.9 m.

TIME (min)	CONC.(ppm)
30	0.00
45	2.00
60	15.30
75	38.00
90	53.80
105	79.50
120	102.00
135	122.00
150	124.00
155	123.00
165	127.00
170	125.00
180	120.00
195	119.00
205	111.00
210	105.00
225	101.00
240	92.40
255	90.80
270	80.10
285	70.70
300	63.80
330	51.40
360	46.40
390	40.90
420	31.30
450	28.70
480	27.00
510	23.10
540	19.20
570	17.00
600	16.00

Table A.4. Tracer input in H-3, Test 4.

MIDDLE SAMPLER

TIME (min)	CONC.(ppm)
30	0.5
40	30.4
50	93.3
60	115.0
70	112.0
80	128.0
90	135.0
100	126.0
110	70.6
120	79.1
130	99.6
140	106.0
160	90.2
170	81.1
200	45.1
230	56.9
290	93.3
320	80.6
350	78.1
365	100.6
380	85.3
410	43.0
470	30.8
560	22.7
590	17.8
620	15.6
770	12.1

TOP SAMPLER

TIME (min)	CONC.(ppm)
55	4.4
75	17.6
95	26.9
115	41.8
175	47.9
205	39.7
245	30.5
275	27.3
335	23.7
395	23.4
470	22.7
560	20.6

Table A.5. Tracer breakthrough in H-2, Test 4.

77.4 m.

TIME (min)	CONC.(ppm)
90	1.2
100	3.7
110	7.8
120	17.4
140	55.7
150	71.3
165	84.3
180	73.0
210	82.6
240	72.9
270	63.9
315	47.4
375	36.5

78.9 m.

TIME (min)	CONC.(ppm)
90	1.2
110	14.9
120	31.7
140	68.2
150	66.4
165	89.2
180	81.0
210	81.0
240	67.0
270	54.6
315	41.0
375	30.8

80.5 m.

TIME (min)	CONC.(ppm)
70	1.9
80	3.7
90	12.8
100	31.4
110	45.7
120	62.7
130	73.7
140	74.6
150	76.6
165	84.0
180	77.8
195	76.8
210	75.4
225	67.9
240	54.0
255	52.4
270	45.3
315	31.1
345	29.0
375	24.7
405	25.0
435	23.8
460	22.6
520	19.1
580	16.8
640	16.0
700	14.2
750	12.8
795	10.8

Table A.6. Tracer input in H-3 and breakthrough in H-2, Test 5.

INPUT IN H-3

TIME (min)	CONC.(ppm)
2	0.0
10	18.8
20	66.3
30	104.4
40	112.2
50	124.3
60	131.0
70	139.8
80	138.5
90	129.9
100	114.1
110	114.3
120	93.8
130	81.7
140	88.4
150	89.9
160	87.7
170	111.6
180	136.9
190	152.5
200	150.7
230	179.1
260	165.4
290	165.4
350	145.6
410	130.7

78.9 m.

TIME (min)	CONC.(ppm)
85	4.5
105	14.3
125	24.5
145	55.9
155	71.4
165	106.8
175	96.5
185	102.2
195	103.5
205	105.0
215	98.0
225	90.3
237	84.6
245	83.9
256	64.2
265	68.9
275	61.5
290	60.9
315	47.1
350	42.8
390	33.2
410	32.4
470	28.8
530	24.1
590	22.3

80.4 m.

TIME (min)	CONC.(ppm)
75	2.0
85	7.4
95	15.4
105	31.0
115	41.1
125	56.3
136	79.5
145	93.6
155	63.9
165	69.6
175	77.3
185	69.9
195	66.9
205	61.1
215	63.1
225	58.8
237	53.7
256	43.0
275	34.6
290	36.2
315	25.4
350	26.8
390	18.8
450	19.0
470	18.8
530	17.4
590	16.3

82.0 m.

TIME (min)	CONC.(ppm)
136	0.0
225	0.0
315	0.0
470	1.1
590	1.8

Table A.7. Tracer breakthrough in M-1, Test 5.

280 min

CONC.(ppm)	DEPTH (m)
0.00	86.6
0.00	85.3
0.40	83.8
0.77	82.3
0.91	79.2
0.00	76.2
0.00	74.7
0.00	73.1
0.00	71.6
0.00	68.6

420 min

CONC.(ppm)	DEPTH (m)
0.00	86.6
0.41	85.3
0.49	83.8
3.76	82.3
3.36	80.8
3.32	76.2
0.31	74.7
1.60	73.1
0.39	71.6

575 min

CONC.(ppm)	DEPTH (m)
0.00	86.6
0.87	85.3
0.78	83.8
4.34	82.3
5.64	79.2
5.68	76.2
3.44	73.1
1.72	71.6
0.91	68.6

APPENDIX B

HEAT-PULSE FLOW METER DATA

Table B.1. Vertical flow in M-1 with 1.9 l/min injected at a depth of 74.4-79.6 m into H-3.

M-1, 1.9 l/min into H-3, 8/12/85

FLOW (l/min)	DEPTH (m)
0.35	21.0
0.30	37.5
0.25	41.2
0.49	47.2
0.50	57.9
0.52	65.5
0.60	71.6
0.50	76.2
0.55	78.6
0.40	81.4
0.40	83.1
0.01	84.7

M-1, 1.9 l/min into H-3, 9/13/85

FLOW (l/min)	DEPTH (m)
0.25	25.9
0.29	29.9
0.20	31.7
0.25	36.0
0.35	38.1
0.35	41.5
0.50	45.7
0.40	50.6
0.45	55.5
0.63	57.6
0.64	66.5
0.61	68.6
0.60	71.9
0.75	74.7
0.62	83.8
0.20	84.7
0.01	86.6
0.02	88.1

Table B.2. Vertical flow in H-2 with 1.9 l/min injected at a depth of 74.4-79.6 m into H-3.

H-2, 1.9 (l/min) INTO H-3	
FLOW (l/min)	DEPTH (m)
0.068	18.3
0.076	21.3
0.076	25.9
0.114	27.4
0.189	29.0
0.189	32.0
0.208	36.7
0.208	48.8
0.208	51.8
0.246	54.9
0.295	61.0
0.280	76.2
0.295	79.2
0.030	80.5

Table B.3. Vertical flow in H-3 with 1.9 l/min injected at a depth of 80.8-86.1 m into H-3 or H-2 filled to overflow and maintained at constatn head.

H-3, INJ. INTO M-1	
FLOW (l/min)	DEPTH (m)
0.038	22.9
0.057	25.9
0.076	30.5
0.076	32.0
0.076	36.6
0.076	42.7
0.045	47.2
0.049	51.8
0.045	56.4
0.079	66.1

H-3, INJ. INTO H-2	
FLOW (l/min)	DEPTH (m)
1.140	59.4
1.041	68.6
1.041	74.1
0.049	79.2
0.038	82.3

APPENDIX C

DOWNHOLE TEMPERATURE DATA

Table C.1. Temperature change from ambient in M-1 with 5.7 l/min injected an a depth of 74.4-79.6 m into H-3

DEPTH (m)	TEMPERATURE CHANGE AT TIME INDICATED (ºC)				
	6 min	15 min	55 min	110 min	160 min
61.0	0.017	0.024	0.086	0.131	0.161
62.4	0.017	0.020	0.086	0.127	0.153
64.0	0.015	0.026	0.085	0.142	0.147
65.5	0.011	0.025	0.090	0.147	0.159
67.1	0.010	0.031	0.089	0.154	0.173
68.6	0.014	0.026	0.084	0.153	0.163
70.1	0.015	0.031	0.092	0.151	0.165
71.6	0.010	0.034	0.092	0.154	0.162
73.1	0.010	0.027	0.105	0.149	0.159
74.7	0.013	0.033	0.095	0.146	0.157
76.2	0.011	0.035	0.091	0.143	0.146
77.7	0.015	0.042	0.100	0.144	0.145
79.2	0.022	0.038	0.082	0.115	0.118
80.8	0.009	0.037	0.062	0.092	0.095
82.3	0.004	0.013	0.026	0.062	0.062
85.3	-0.003	-0.003	0.001	0.014	0.013
88.4	-0.005	-0.002	0.006	0.017	0.013

Table C.2. Temperature change from ambient in H-2 with 5.7 l/min injected at a depth of 80.8-86.1 m into M-1

TIME (min)	TEMPERATURE CHANGE AT DEPTH INDICATED (ºC)				
	76.2 m	79.2 m	80.8 m	82.3 m	85.3 m
0	0.000	0.000	0.000	0.000	0.000
1	-0.007	0.068	0.001	0.001	0.003
2	-0.008	0.072	0.001	-0.001	0.002
3	0.001	0.077	0.001	-0.001	0.002
4	0.002	0.081	0.001	0.001	0.001
5	0.003	0.088	-0.003	0.001	0.001
6	0.012	0.091	-0.002	0.000	0.001
7	0.014	0.096	-0.003	0.000	0.000
8	0.015	0.100	-0.006	0.000	0.002
9	0.015	0.102	-0.011	0.000	0.003
10	0.017	0.101	-0.011	0.000	0.001
11	0.018	0.101	-0.009	0.001	0.001
12	0.016	0.102	-0.013	0.001	0.001
15	0.031	0.119	-0.022	0.001	0.002
20	0.055	0.112	-0.023	0.001	0.002
25	0.049	0.110	-0.027	-0.001	0.002

APPENDIX D

WATER LEVEL DATA

Table D.1. Water levels in boreholes during Test 2.

(Top of casing of M-1 is datum)

M-1

TIME (min)	DEPTH (m)
17	6.14
21	6.23
56	6.20
95	6.16
138	6.00
175	5.88
211	5.67
249	5.49
277	5.39
310	5.24
362	5.06
388	4.97

H-6

TIME (min)	DEPTH (m)
24	6.69
58	6.08
97	5.54
135	5.19
171	4.92
210	4.70
251	4.52
278	4.42
307	4.34
365	4.19
388	4.13

H-2

TIME (min)	DEPTH (m)
10	3.65
20	1.40
23	0.85
30	0.00

H-3

TIME (min)	DEPTH (m)
18	6.41
33	5.99
55	5.32
99	4.34
136	3.78
173	3.41
215	3.07
246	2.88
276	2.74
309	2.62
364	2.46
389	2.36

H-7

TIME (min)	DEPTH (m)
20	7.30
57	6.99
98	6.63
134	6.29
172	5.99
218	5.68
257	5.28
277	5.16
308	4.96
365	4.64

Table D.2. Water levels in boreholes during Test 4. (Top of casing of M-1 is datum)

M-1

TIME (min)	DEPTH (m)
15	7.35
30	6.46
59	4.97
70	4.36
95	3.32
114	2.59
150	1.34
182	0.34

H-2

TIME (min)	DEPTH (m)
14	6.52
19	6.12
24	5.79
43	4.87
64	3.84
75	3.26
96	2.40
113	1.79
134	1.00
147	0.51

H-3

TIME (min)	DEPTH (m)
34	7.63
56	7.51
117	7.08
147	6.87
225	5.96
255	5.65
339	4.86
420	4.52
471	4.46
630	4.19
703	3.97
803	3.67
862	3.58
925	3.43
984	3.27

H-6

TIME (min)	DEPTH (m)
14	7.87
31	7.69
59	7.30
73	6.96
94	6.50
115	5.99
149	5.19
185	4.28
223	3.46
257	2.94
336	2.14
426	1.66
466	1.54
636	1.14
700	1.05
810	0.93
860	0.85
925	0.80
983	0.77

H-7

TIME (min)	DEPTH (m)
12	7.78
32	7.66
57	7.48
74	7.30
93	7.05
116	6.81
147	6.32
187	5.68
221	5.16
256	4.61
336	3.52
425	2.60
468	2.27
635	1.29
702	1.05
814	0.68
858	0.59
927	0.44
980	0.35

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