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Project Summary

Hydrogeologic Characterization of Fractured Rock Formations: A Guide for Groundwater Remediators

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Abstract

A field site was developed in the foothills of the Sierra Nevada, California, to develop and test a multidisciplinary approach to the characterization of ground-water flow and transport in fractured rocks. Nine boreholes were drilled into the granitic bedrock, and a wide variety of instruments and methodologies were tested. Fracture properties were measured on outcrops and in boreholes using acoustic televiewer, digital borehole color scanner, and by down-hole camera logs. Conventional geophysical logs were collected. In addition, thermal-pulse and impeller flowmeter logging, fluid replacement and conductivity logging, packer-injection profiling tests, and ordinary open-hole pumping tests were conducted. Transmissive fractures were identified by integrating results from hydrologic and geophysical measurements, and the hydrogeologic structure of the formation was hypothesized. Cross-hole seismic surveys yielded tomograms of inter-borehole rock properties. Visualization software was used in combination with geophysical logs to interpolate inter-borehole properties, and a detailed 3-D model of the subsurface was constructed. Other referenced work at the site includes cross-hole hydrologic tomography, tracer tests, fracture-specific morphology studies, and development of an automated data acquisition system used to collect data and monitor and control test parameters during borehole testing. A novel aspect of the project report is its guidebook format. A description of each tool and methodology, the strengths and shortcoming of each, how they compare with one another, and suggestions of how best to analyze and integrate data are presented.

The Project Summary was developed by the National Risk Management Research Laboratory's Subsurface Protection and Remediation Division, Ada, OK, to announce key findings of the research project that is fully documented in a separate report (see Project Report ordering information at the back). The reader is encouraged to visit the Internet Web page for further information:

http://www.epa.gov/ada/kerrlab.html

1 Introduction

Fundamental to every ground-water remediation effort is a description of the subsurface distribution of contaminants and fluid flow properties. The hydrogeologic complexity of fractured formations makes their characterization very difficult. This difficulty is the primary reason that the majority of fractured portions of contaminated formations have not yet been investigated. Knowledge of new and existing site characterization tools and understanding of analysis methods are necessary first steps toward improved remediation of fractured formations.

1.1 Format of Project Report

The project report describes the work and findings of a hydrogeologic characterization study of a saturated, fractured, granitic rock aquifer in the foothills of the Sierra Nevada, California. A wide variety of new and traditional hydrologic and geophysical characterization tools and methodologies were tested. The numerous field experiments and analyses have provided many insights that should greatly benefit the remediation community. The project report was designed in a guidebook format. First, an overview of the problems associated with remediating fractured aquifers is presented. Case histories are referenced as examples. Second, a brief description of the methods and results of the characterization effort at the experimental field site are presented. The following chapters comprise the bulk of the report. Each chapter describes a particular characterization phase, and a general strategy for hydrogeologic characterization is presented. Each tool and method is described in detail. Descriptions of the tools, how they are used, what are the strengths and shortcomings of each, how they compare with one another, as well as how best to analyze and integrate the data collected, are discussed. Findings obtained at other remedial sites where fractured materials are present are also referenced. Determination of subsurface flow properties is the emphasis of this project rather than contaminant sampling and plume delineation. However, issues regarding the effect of incorrect characterization of flow properties on prediction of contaminant behavior are addressed. The findings and recommendations are not necessarily limited to fractured crystalline rock formations; many apply to fractured subsurface formations in general.

1.2 Experimental Field Site

Studies were conducted at the Raymond Field Site, which is operated by the E. O. Lawrence Berkeley National Laboratory and the U.S. Geological Survey. Sponsorship has been provided by the Office of Civilian Radioactive Waste Management of the Department of Energy, Atomic Energy of Canada, Ltd., and by the U.S. Environmental Protection Agency. The site was established to develop and test a multidisciplinary approach to the characterization of ground-water flow and transport in fractured rocks. No ground-water contamination was present. Research began in 1992 and is ongoing.

The site is situated in the western foothills of the central Sierra Nevada, California, approximately 60 km (37 mi) south of Yosemite Valley and about 5 km (3 mi) southeast of the town of Raymond (Figure 1). Nine vertical boreholes penetrate fractured granitic bedrock to depths ranging between 75 and 90 m. They are arranged in a triangular pattern and are spaced no more than 61 meters apart (Figure 2).

Figure 1. Location of Raymond Field Site

The conceptual model of the site subsurface is based on the integration of all work conducted at the site. Borehole geophysical logs indicate that hundreds of fractures intersect each well. However, borehole flow logs reveal there are only several distinct hydraulically conductive fractures in each. Many of the transmissive fractures are subhorizontal and westwardly dipping, and are associated with pegmatite dikes. A few are subvertical or of different orientation. Most occur within or near one of two zones of relatively low electrical resistivity and increased borehole diameter, both indications of altered rock. These zones dip gently to the west and are separated by about 25 meters. Fractures with minimal transmissivities occur in other portions of the well. The conceptual model consists of two subhorizontal and hydraulically conductive fracture zones that behave as confined units imbedded within a relatively impermeable rock matrix (Figure 3).

1.3 Data Acquisition System

An innovative, automated data acquisition system was developed for the field site. The new system was built around a 486 PC which was used for controlling a sampling table, opening and closing borehole valves, and for logging pressure and chemical concentration data from all the measurement locations throughout the site. Pressures are monitored in up to 29 different packed-off intervals while flow rates and water chemistry are monitored and analyzed simultaneously. The output from the pressure transducers and chemical concentration measuring devices are available in real-time on the computer. In addition, controlled parameters such as flow and sampling rates can be adjusted during the test. A schematic of the new data acquisition system is shown in Figure 4. Pressure transducers, tracer injection or tracer recovery instruments, and pumps were placed within isolated zones during various hydrologic tests. Flowmeters and a spectrofluorometer were located at the surface. The packers have feed-throughs so that both fluids and electric signals can be passed to the surface. Data can be recorded at a rate of 1 Hz. Electrical signals from the well heads are transferred in underground conduits to terminal blocks in the computer room. Analysis of fluorescent tracers is accomplished using a flow-through cell in a fluorometer, and ionic tracer concentration is determined using ion specific electrodes. A computer-controlled, 144 bottle sampling table was built so that samples could be taken back to the lab for further analysis. In several months of field use, the fully automated data collection system has proven to be highly reliable, even for extended multi-week tests.

2 Methods and Results

2.1 Surface Fracture Characterization

Physical properties of fractures exposed on outcrops in the area within a several hundred meter radius from the well field were measured. The report describes findings from several hundred measurements of fracture orientation, trace length, spacing, weathering, secondary mineralization, and relative displacement. Other measurements included fracture aperture, roughness, and planarity, detailed measurements of fracture spacing made at nine outcrops, and mapping of a large fracture pavement.

Regional and site-specific fracture sets were identified. Regional sets consist of

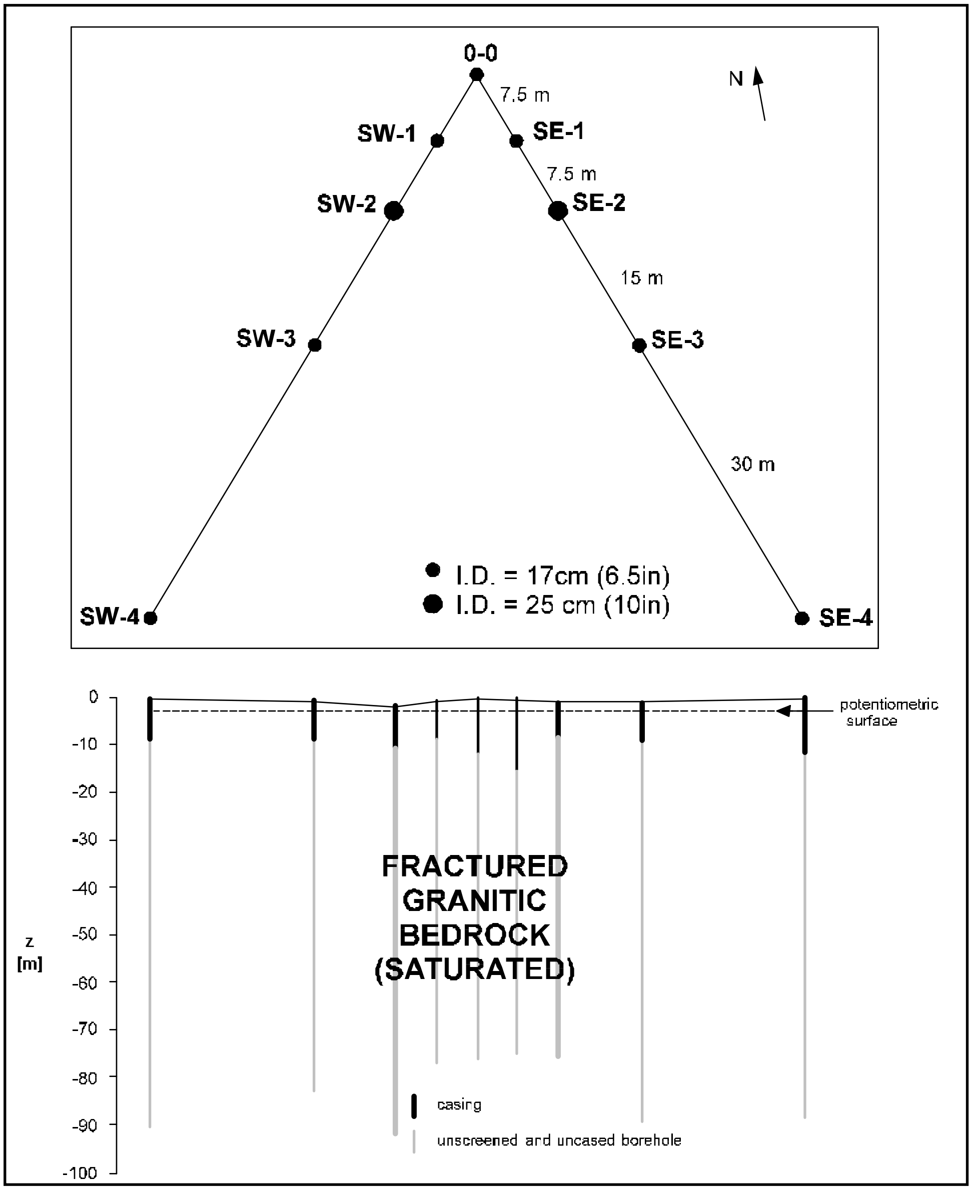

Figure 2. Plan and cross-sectional view of boreholes at the Raymond Field Site.

two orthogonal and steeply dipping tectonic fracture sets, and unloading fractures that are subparallel to the topographic surface. The spatial distribution of fracture density, aperture, and infilling characteristics of these sets is, in general, highly heterogeneous on the scale of the well field, and there is no apparent systematic structure. The characteristics of these sets were heavily altered due to their exposure at the surface. Other fracture sets exposed in the vicinity of the well field are associated with aplite and pegmatite dikes. Pegmatites with thicknesses on the order of centimeters were often observed to contain a discontinuous open fracture near the center and chemical alteration associated with fluid flow. The average continuity of pegmatitic dikes is on the order of 10 m, with some extending 30 meters or more.

Surface fracture characterization provided information useful to other phases of the site characterization. Integration of conventional geophysical logs, hydrologic logs, and borehole fracture detection methods revealed that the upper transmissive zone in many wells is associated with a pegmatite dike. The observation that pegmatite dikes at the surface are laterally continuous for tens of meters and are often fractured and exhibit signs of fluid flow provided support for inference that these intervals are portions of a continuous band of fracturing associated with a westwardly dipping pegmatite. Similarly, tectonic fractures were observed to be planar and laterally extensive, which justified the use of extrapolating these fractures linearly to other boreholes as a means of hypothesis testing and model development.

2.2 Well Drilling

Boreholes were drilled using an air-percussion rotary drill. Boreholes were cased at shallow depths where the rock was weathered and weak, and left uncased and unscreened below these zones. Detailed logs of the wells were made by a geologist as drilling proceeded. The location of some fractures was identified by observing drill behavior and cuttings. Drilling rates increased in fracture zones. Fluid-bearing intervals were encountered, and changes in fluid flow with depth were measured. These observations, in combination with changes in drilling rate and cutting characteristics, indicated the possible locations of transmissive fracture zones. Total fluid flow observed at the final drilling depth was measured and used as an indication of the relative discharge capacity of each well. Comparison of the geologist's logs with conventional geophysical logs and fluid flow logging results show that several of the dominant transmissive fracture zones were identified during drilling.

2.3 Conventional Geophysical Logging

Three-arm caliper, fluid conductivity, 16- and 64-inch normal resistivity, natural gamma, temperature, single-point resistance, spontaneous potential, and lateral logs were collected in each well. Results and uses of these logs are described in Section 3.6.

2.4 Pumping Tests

Constant rate pumping tests were performed for several well combinations. Pressure transducers that can detect water level changes on the order of 0.1 mm were used to measure drawdown. Measurements in the pumping well and observation wells were recorded as often as every 10 seconds. Wells that exhibited low yields during drilling could not be sustained since water levels would fall beneath the upper fracture zone, and well bore storage effects almost completely dominated the pumping well pressure response. Observation well pressure transients typically deviated from an ideal confined aquifer response at early pumping times. Some fit the ideal curve almost exactly. Transmissivities calculated from standard semi-log pressure transient analysis were very similar from well to well,

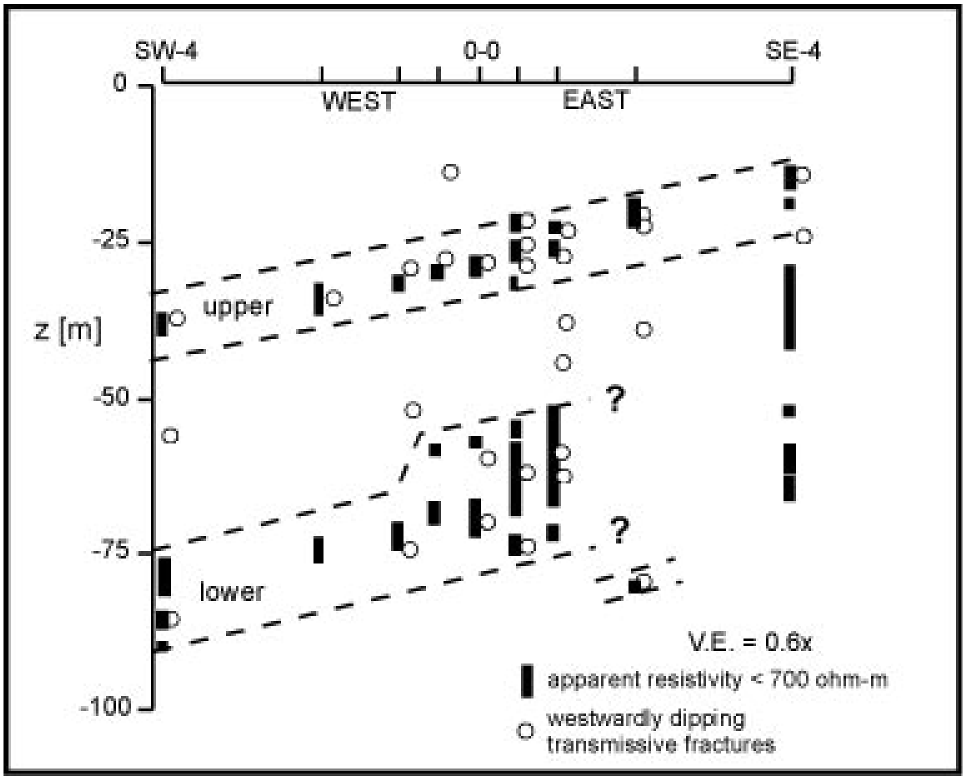

Figure 3. Conceptual model of hydrogeologic structure at the Raymond Field Site.

and did not reflect the large degree of heterogeneity found from borehole flow logging tests. The report describes how highly heterogeneous fractured formations can respond like homogeneous porous formations. Potential misinterpretations of pressure transients, in general, are also discussed. Vertical flow profiling in observation wells shows that the boreholes act as short-circuiting fluid pathways.

2.5 Detection and Measurement of Subsurface Fractures

Several technologies were explored as a means to observe and measure subsurface fractures. Acoustic televiewer (ATV) logs provide images of the acoustic reflectivity of the borehole wall. Fracture signatures are observable and enable measurement of fracture depth, orientation, dip, and apparent aperture. ATV logs were collected for all nine wells. Color television camera logs were obtained for all nine wells and were used to observe fracture alteration and mineralization not observable on the ATV logs. Seven wells were probed with a new digital borehole scanner (DBS). The scanner digitally records the reflected intensity of the red, blue, and green light wavelengths from the borehole wall as a white light source rotates and simultaneously illuminates the borehole wall. High resolution color images of the borehole wall were constructed from the scanner data. Fracture orientation, surface roughness, aperture, identification of fracture mineralization, and other microscale properties are measurable.

A stereonet of measured fractures from the ATV logs shows that at least three fracture sets are present within the well field. Comparison of the ATV logs with the color television and DBS logs revealed that fractures can be divided into more than three sets, as differences occur in mineralization that are not observable on the ATV logs. In general, these comparisons revealed that in the ATV logs: 1) closely spaced fractures or zones of altered rock that were gouged out during drilling appear as a single, large fracture zone with no distinguishable orientation, dip, or aperture; 2) mineral infilled fractures that were slightly gouged-out during drilling appear as open fractures; 3) sealed and mineral infilled fractures not affected by drilling were not detected; 4) partially sealed or very small fractures were not detected or were difficult to identify; and 5) the top and bottom of steeply dipping fractures were gouged out and appear to have greater dip. Subsequent borehole hydrologic tests showed that only several of the hundreds of observed fractures in each borehole are transmissive. Accordingly, spacing distribution of borehole fractures did not correlate with the hydrologic properties around each borehole.

Quantitative measurements from the television camera logs were not possible, but qualitative determinations of whether or not fractures were infilled were possible. Rock discoloration around individual fractures could be seen, and therefore helped locate fractures that might be hydrologically altered. The location of many pegmatite dikes was identified because their large, reflective crystals were easily recognizable on the image. This was very valuable since it was later found that these dikes were one of the significant conductive fracture sets. Orientation and dip of pegmatites were determined by identifying their trace on ATV logs.

The DBS provided borehole wall images of the greatest detail and quality. Many more fractures were observable compared to the ATV logs. The photographic quality of the logs enabled more precise measurement of fracture aperture, orientation, and dip. Mineral infilling in fractures was clearly visible, and enabled distinction between open and sealed fractures. Fluid alteration such as oxidation stains around some fractures was clearly observable. Individual fractures within zones that were gouged out during drilling were measurable. Several disturbed zones were highly transmissive, and the DBS enabled detection and measurement of the individual fractures within these zones.

2.6 Borehole Flow Logging

Impeller flowmeter logging, thermal-pulse flowmeter logging, fluid replacement and conductivity logging, and straddle-packer injection profiling were performed to determine the location of fluid-bearing fractures and their respective transmissivities. Impeller flowmeter profiling was performed in three wells. All nine wells were profiled with a thermal-pulse flowmeter. Fluid conductivity logging was performed in seven wells, and straddle-packer injection tests were conducted in all nine wells. Results were integrated with the borehole scanning logs described above, and with the conventional geophysical logs to determine the specific transmissive fractures within an observed borehole flow interval.

The impeller flowmeter was used to profile the vertical flow in a well while it was pumped. The instrument is composed of an impeller-type flowmeter mounted above a hollow shaft that passes through the center of an inflatable packer. The well was pumped at a constant rate by a downhole submersible

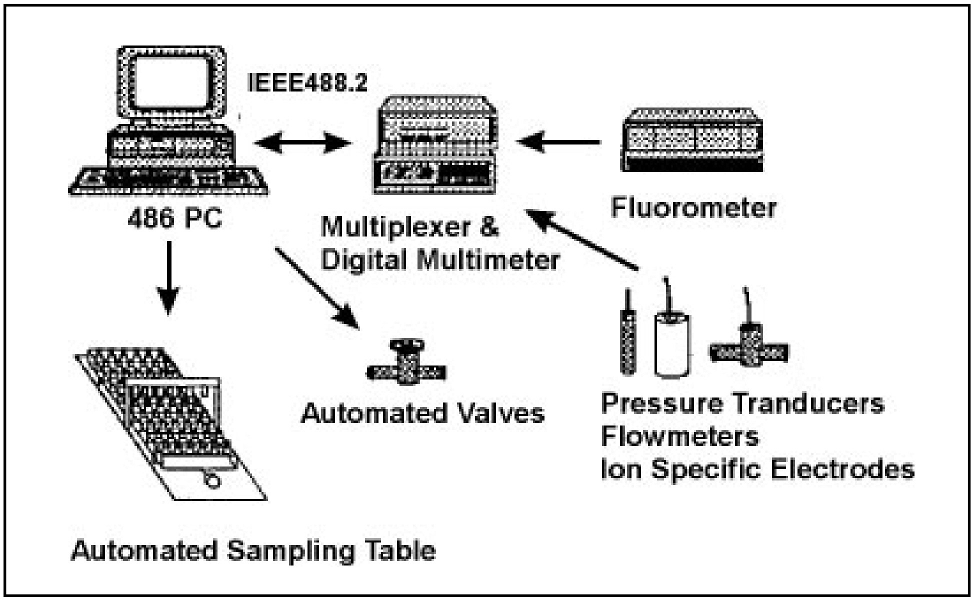

Figure 4. Schematic of data acquisition and control system at the Raymond Field Site.

pump situated near the upper portion of the well. The assembly was successively inflated at different depths and vertical flow measurements were taken (Figure 5a). The drawdown transient throughout the entire test duration was measured by a pressure transducer situated near the upper portion of the well. Flow rate into the borehole from a particular interval was calculated from the difference in vertical flow measured over the interval. Apparent formation transmissivity was determined from the transient drawdown, which responded as a confined aquifer. Transmissivities of particular flow intervals were calculated as the product of fractional inflow and formation transmissivity. The minimum measurable flow rate of the impeller was 4 L/min. This relatively high stall velocity prohibited the profiling of low-yielding wells. Hence, the procedure was only conducted in three relatively high yielding wells. In addition, flow intervals near the lower portions of the wells could not be defined because vertical flow rates were below the stall velocity of the instrument (Figure 5a).

The thermal-pulse flowmeter (also referred to as heat-pulse flowmeter) was used to profile multiple wells during the pumping of a single, high yielding well (Figure 5b). The instrument consists of a heating grid and temperature sensors emplaced within a central tube that passes through an inflatable packer. Vertical flow velocity is determined by heating a small parcel of water at the heating grid and observing the time of arrival of the parcel at temperature sensors located above and below the grid. Response of one of the sensors indicates flow direction. Differences in vertical flow with depth indicated fluid flow into or out of a borehole, but no quantitative estimate of the conductivity of such intervals could be determined. The thermal-pulse flowmeter method detected more flowing intervals than the impeller method. This is consistent with the fact that it has a lower minimum detection limit. Vertical flows on the order of 0.05 L/min were measurable. In theory, the thermal-pulse flowmeter could be used in the same manner that the impeller was used in this study, thereby allowing calculation of interval conductivities. For some wells, measurements at the same depth at different times were different due to the evolving transient flow field. This made the interpretation of some portions of some logs difficult. In one well, the thermal-pulse flowmeter did not detect a flowing interval identified by the impeller method. This is most probably an artifact of the test methodology, not the instrument. A particular fracture may contribute flow differently when a well other than the one the fracture intersects is being pumped. In addition, the vertical flow transient in an observation well associated with flow into a conductive fracture could diminish to unobservable levels by the time the well is profiled.

Fluid replacement and conductivity logging was done in seven of the wells. The method consists of replacing the fluid in the well bore with deionized water, which has a much lower electrical conductivity than the formation water. Replacement was achieved by simultaneously pumping formation water near the upper portion of the well and replacing with deionized water at the bottom using downhole tubing. After replacement was complete, the well was pumped at a low and constant rate and a time sequence of upward and downward logs of fluid electric conductivity were collected. Figure 5c shows the downward logs for well SE-1. The conductivity logs for the seven wells exhibit noticeable peaks at conductive fracture locations. Therefore, determination of the particular fracture contributing to flow was straightforward, requiring only a brief inspection of the acoustic televiewer and/or television logs. Many more conductive fractures were identified by this method than by the impeller or thermal-pulse flowmeter. Equally significant is that the measurements were more precise and enabled quick and confident assessment of the locations and relative magnitudes of the conductivity of particular conductive fractures. The results of the tests are amenable to analysis whereby the transmissivity of particular fractures is determined, although this was not done in this study. The fluid conductivity logs have higher resolution in general, which results in part because measurements were made at many more depths compared to the other methods.

Straddle-packer injection tests were done in all nine wells. Water was injected at a constant rate into a 6 meter packed-off interval in a borehole. Fluid pressure within the interval was measured with a pressure transducer. Two transducers were also mounted above and below the test interval to monitor for possible flow leakage around the packers and/or flow short-circuiting due to interconnecting transmissive fractures. For each test interval injection was continued until a pseudo-steady flow was attained. This was on the order of minutes to tens of minutes. This procedure was repeated at different depths, and the transmissivity of each interval was calculated using the observed flow rates and injection pressures, and assuming radial flow. Short-circuiting occurred in high conductivity intervals and transient injection pressure and flow rates persisted because of flow-line resistance effects. Therefore, the conductivities of the highest conductivity intervals were underestimated. The results are consistent with the other techniques but in some cases indicate very low transmissivity intervals while the others do not.

2.7 Integration of Geophysical and Hydrologic Logs

Conventional geophysical logs were used in conjunction with flowmeter logs in order to identify the particular hydraulically conductive fractures and/or fractured zones

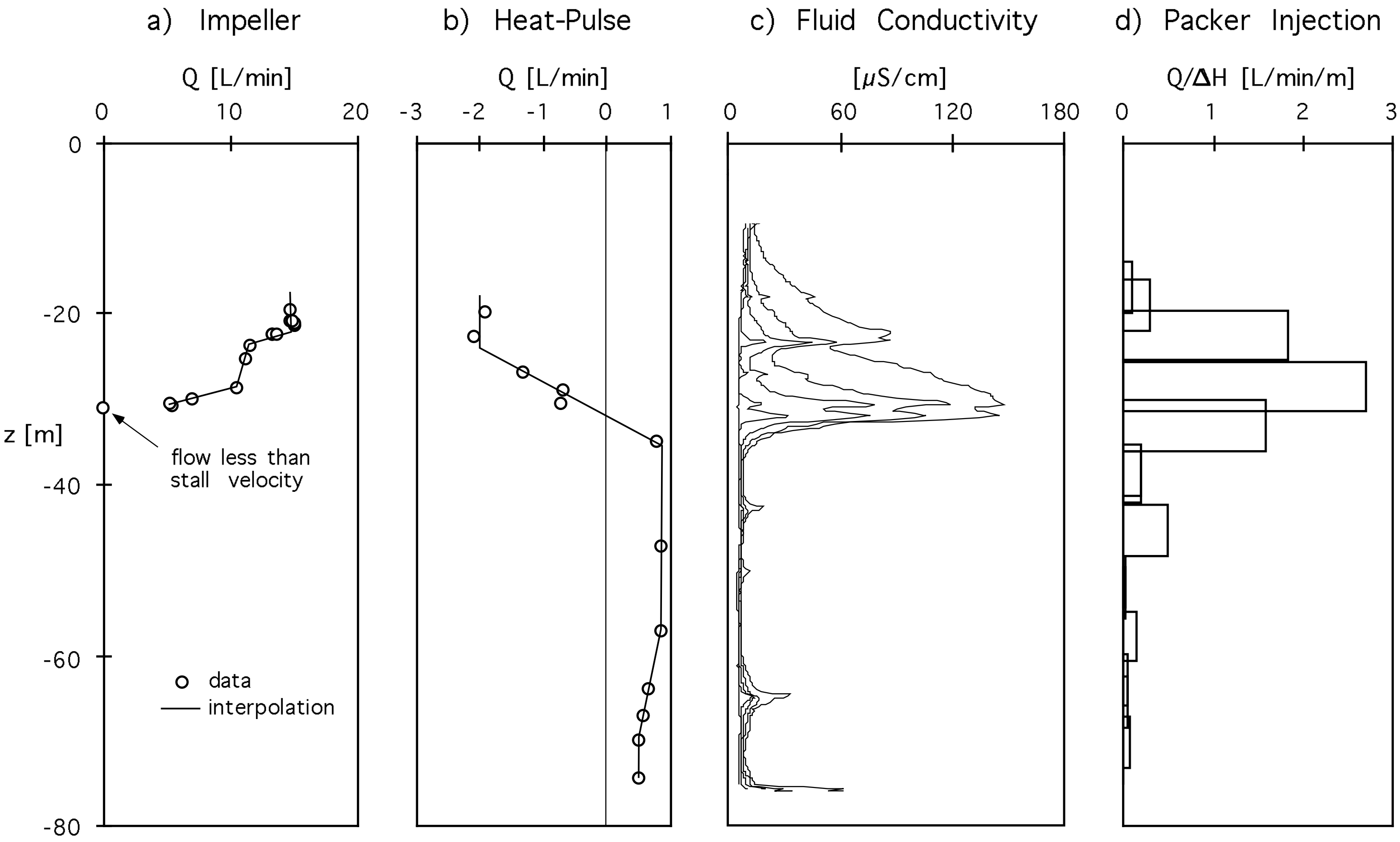

Figure 5. Example results from the various flow logging techniques performed in well SE-1. The impeller measurements were taken during constant rate pumping of approximately 15 L/min just above the most shallow measurement. Measurements below 31 m were not possible because of the high stall velocity of the instrument. Heat-pulse measurements were taken during pumping in well 0-0. Negative flow indicates downward flow. Upward and downward flow is converging and exiting borehole near 30 m. Fluid conductivity profiles exhibit peaks where formation water is flowing into well through discrete fractures while the well is pumped above 10 m. Measurements are in micro siemans per centimeter. Straddle-packer injection tests show the relative magnitudes of transmissivity for 3 m intervals. Values are given as flow rate achieved per given injection pressure expressed as equivalent hydraulic head.

intersecting the boreholes. ATV, DBS, television, 16-inch normal resistivity, caliper, and natural gamma logs were the most useful for this purpose. After specific transmissive fractures were identified in each well, fractures and fracture zones that intersect multiple wells were identified by interpolating fracture geophysical properties using 3-D visualization software.

Figure 6 shows geophysical and flowmeter measurements, and the identification of the particular transmissive fractures in well SE-1, for example. Comparison of the geophysical logs with one another indicated that caliper logs show the locations of increased borehole diameter. Zones of intense fracturing such as in areas where there are many closely spaced, subhorizontal fractures were easily detected. Some caliper anomalies are associated with individual fractures. Peaks on the natural gamma logs indicated the presence of pegmatitic dikes. Regions of resistivity less than 700 ohm-m are associated with hydraulically conductive fractures. Clays and ferric oxides associated with hydraulically altered fractures exhibit high electrical conductivities compared to the parent rock.

In general, several different types of fractures are transmissive: fractured pegmatitic dikes, closely spaced subhorizontal fractures, subvertical tectonic fractures, and to a minor degree various partially infilled aplite veins which are very weakly transmissive. The fractured pegmatite dikes are often found within or near the zones of subhorizontal and closely spaced fractures. Two subhorizontal fracture zones comprised of the westwardly dipping, subhorizontal altered fractures and pegmatites were delineated based on similarities in fracture geophysical properties in adjacent boreholes. These two zones define general hydrologic structures within the well field (Figure 3). Other important features include subvertical tectonic fractures which may connect these zones. The report describes how specific transmissive fractures were identified by integration of different combinations of geophysical and flowmeter logs.

2.8 Computer Visualization

Visualization software enabled viewing of the well field and how particular fractures are positioned relative to boreholes. Borehole lateral logs were used in conjunction with surface mapping to determine the x,y,z coordinates of the well field. The true 3-D perspective of all wells was constructed from these coordinates. This formed the initial 3-D model upon which to superimpose other features. One very useful feature of the model was

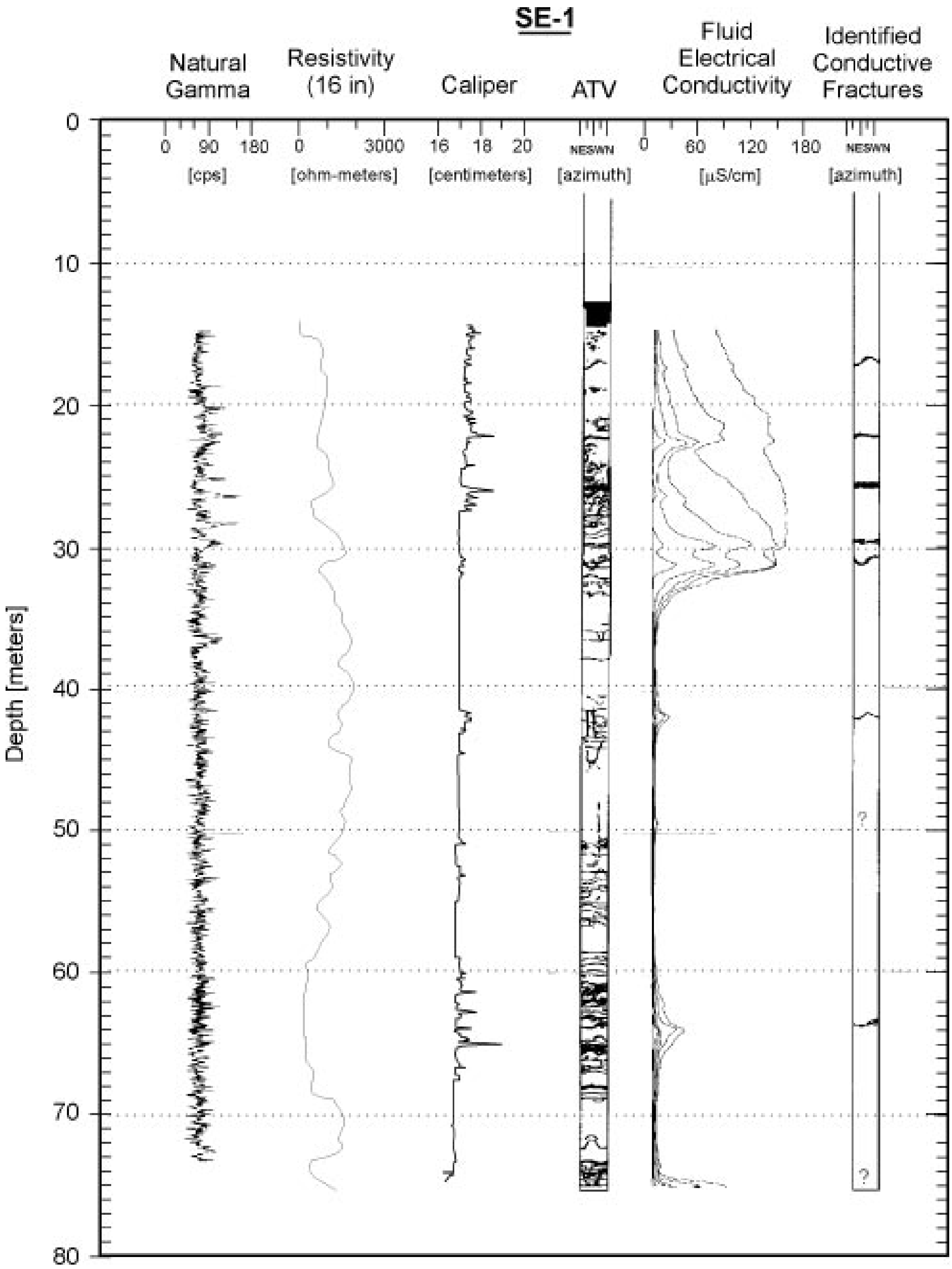

Figure 6. Conventional geophysical logs and borehole fluid replacement and conductivity log of well SE-1. Fractures identified as transmissive shown at right.

deducing subsurface fracture connectivity and structure. For example, a transmissive fracture identified by integrating borehole flowmeter and geophysical data was measured using the acoustic televiewer log, and a plane representing the azimuth and dip of that fracture at its proper location in a well could be displayed. This plane was represented as a disk, and was used to see where that fracture would theoretically intersect other wells. The logs of other wells were inspected to see if such a feature was present at and around the extrapolated location, and in this way quickly determined which features extended between wells. Extrapolation also considered non-planar fractures and fracture measurement error. A complex 3-D model of the site was developed via this hypothesis testing and data synthesis approach.

2.9 Cross-Hole Seismic Imaging

Cross-borehole seismic surveys were performed to deduce the location of fractures and fracture zones between wells. The method consists of equipping a borehole with a piezoelectric source transducer, and an adjacent borehole with a string of hydrophones. The transducer creates a pressure pulse which is measured by the hydrophones. After the transducer is pulsed at a particular depth and measurements are made, it is lowered and pulsed again. This procedure is repeated along the depth of the borehole. The seismic data from each receiver during each depth transmission is analyzed to determine the travel time and amplitude of each received seismic pulse. A numerical matrix that incorporates the positions of each ray path and its respective travel time and/or amplitude is inverted and the velocity and/or seismic attenuation of different pixel elements of a 2-D grid representing the plane between boreholes is determined. Figure 7 shows the concatenated seismic velocity tomograms of well pairs SW3-SW2, SW2-00, 00-SE2, and SE2-SE3. The results support the conclusions regarding the general dual-layer, westwardly dipping fracture zones.

2.10 Interwell Tracer Tests

Radially convergent and two-well partial recirculation tracer tests using both conservative and reactive tracers were conducted. The objectives of this test were: (1) to obtain an estimate of transport parameters; (2) to compare performance of several different tracers; and (3) to compare test methodologies and identify advantages and shortcomings of these methods as tools to describe fracture flow properties.

The upper fracture zone in each well was isolated with pneumatic packers during both tracer tests. A minimum of two packers were used in each well with a total of 22 packers in 9 wells. Twenty-nine (29) transducers were located within and around packed-off zones throughout the well field. For the radially convergent test, well 0-0 was first pumped at a constant rate for a few days prior to the tracer injection to establish a quasi-steady flow field. A three tracer mixture of deuterium, fluoresceine, and microspheres was subsequently injected at the upper fracture zone in well SW-3. A mixture of bromide and fluoride was injected in the same zone two and a half hours later. The pumping continued for about one week, during which time the pressure in all 29 zones and the flow rate at the discharge line were continuously monitored and recorded. Also monitored in real-time were the fluoresceine and bromide concentration in the discharge line using an in-line fluorometer and ion specific electrode as described in section 1.3. Sample water was taken from the discharge line every ten minutes using the automated sampling table

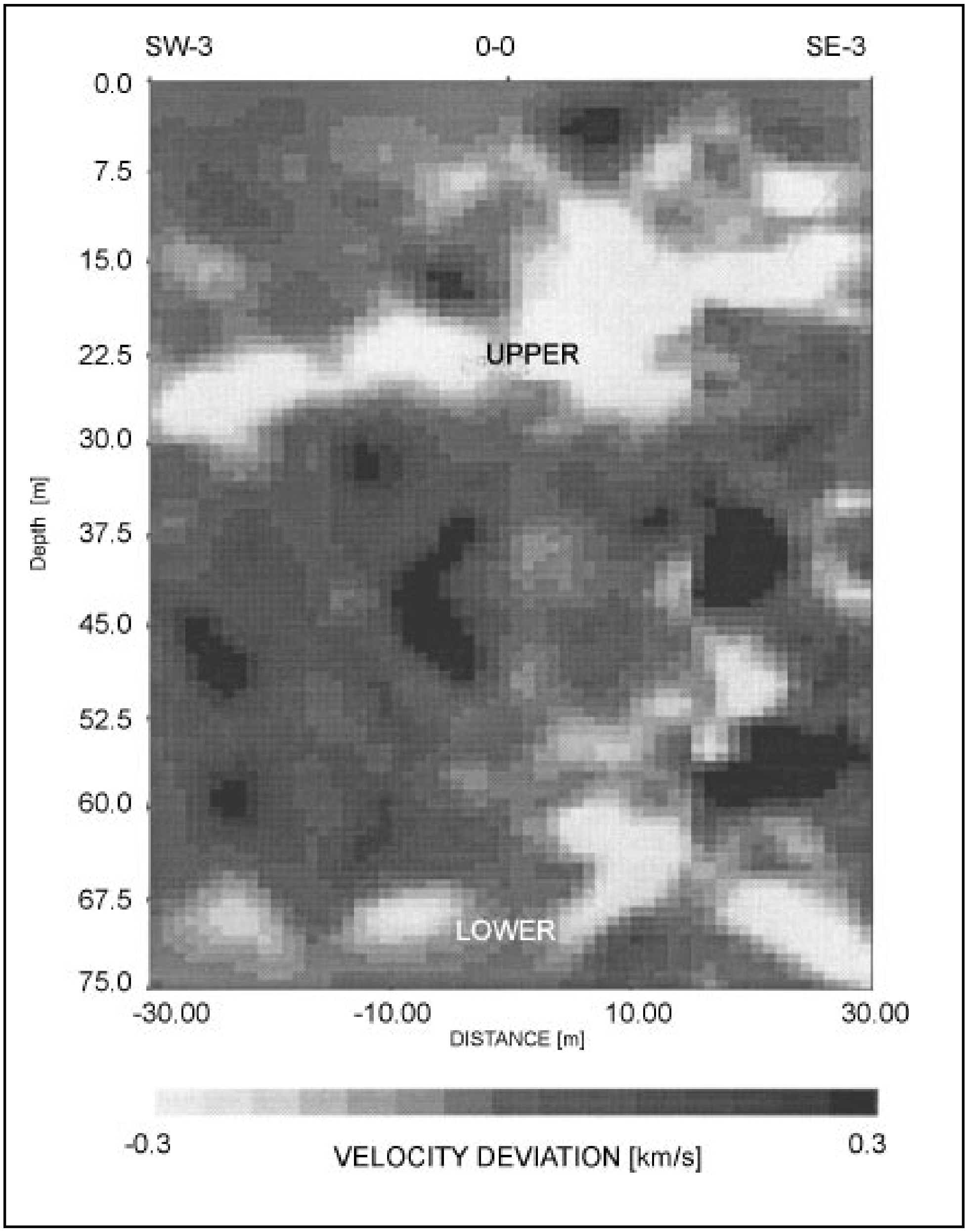

Figure 7. Concatenated seismic velocity tomograms from adjacent well pairs. Image represents cross-section between well SW-3 and SE-3. Negative velocity deviation represents seismic velocity less than mean value. An upper and lower zone is apparent.

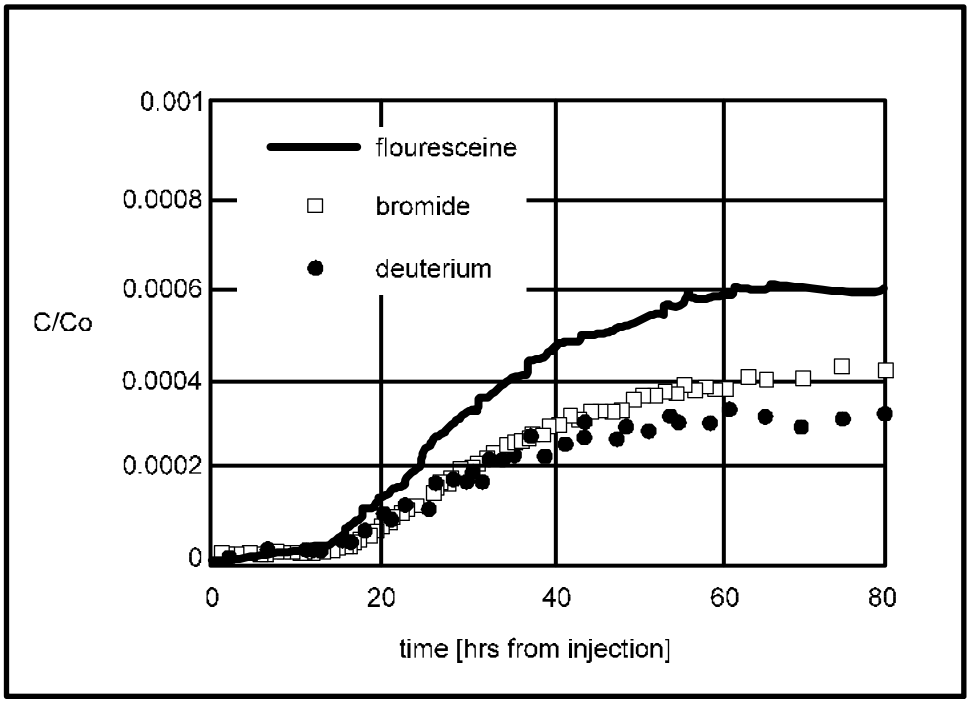

Figure 8. Normalized breakthrough curves of three conservative tracers during radially convergent test.

for later analysis in the laboratory.

Figure 8 shows the breakthrough curves of fluoresceine, bromide, and deuterium normalized to the injection concentration. Microspheres were not detected in the pumped water. It is possible that the microspheres became negatively charged, coalesced and, hence, became stuck within the fracture zone. The background concentration of fluoride was too high for the fluoride concentration result to be meaningful.

The first tracer arrival occurred at about 10 hours after injection. The tracer breakthrough curves did not lie on top of each other, even through the three tracers are presumably *conservative* (Figure 8). The evidence suggests that the most significant factor responsible for this behavior was that effective injection tracer concentrations were different than predicted because of borehole mixing and storage effects. After the mixture of tracers was injected, the tracers may have separated within the injection zone, which was roughly ten times the volume of the injected fluid. Due to its higher density, bromide may have caused the tracer mixture plume to sink to the bottom of the injection zone. The mass of fluoresceine that arrived at the pumping well was calculated to be about 15% of the total mass injected. Almost all of the remaining mass was recovered by pumping out from the injection well. Other contributing factors may include differences in the degree of reaction (or non-reaction) between the tracers. Fluoresceine has been reported elsewhere to react (fluoresce more) with certain minerals in the rock giving increases in apparent mass.

A partial-recirculation injection and recovery tracer test was conducted using both reactive and conservative tracers. The extraction and injection wells were the same as in the previous test. The extraction and reinjection rates were 7.6 and 0.7 L/min, respectively. Bromide and fluoresceine were used as conservative tracers and lithium was used as a sorbing tracer. A specially designed low volume tracer injection system was used to minimize the well bore effects observed in the previous test (Figure 9). The test was halted after 22 days, when the fluoresceine concentration dropped to approximately one tenth of the peak arrival concentration.

There was a significant difference between the recovery of bromide and lithium during the 22 days in which the test was conducted. The percentage of bromide recovered was 80% of the injected mass, and less than 30% of the lithium was recovered. In addition, the breakthrough curve for bromide was much steeper with a peak arrival two days before the peak for lithium. A simple convective-dispersive transport equation was used to determine transport parameters from field data. A linear relationship was assumed to exist between fluid concentration and adsorbed phase, with instantaneous chemical equilibrium. Transport is modeled along a 1-D stream tube between the injection and withdrawal well. This is a reasonable approach for this test since the ratio of fluid injection to discharge is small. A dispersion length of 32 meters was calculated from the best-fit model. As described subsequently, the relevance of this parameter is very questionable.

3 Conclusions and Recommendations

3.1 Surface Fracture Characterization

Observation and measurement of surface geologic features is a standard and usually initial investigative phase in any subsurface characterization effort. A non-intrusive, relatively low cost surface study combined with previously documented geologic studies can provide a means to determine the dominant types and orientations of fracture sets present, as well as their physical properties, spatial distribution, and probable modes of genesis. The relative ease and low cost of performing surface characterization and the pertinent information that it reveals makes it a practical necessity, but it is not a substitute for borehole studies. For example, most of the fractures observable at the surface may not be hydrologically significant. Dominant conductive fractures in the subsurface are not typically observable on the surface, or only limited fractures may be observable at the surface, simply because few bedrock outcrops are present.

3.2 Well Drilling

Air drilling is the most appropriate method for the installation of wells in crystalline bedrock in terms of its relative cost, penetration rate, and potential to yield relevant hydrogeologic information. Observation of drill cuttings, drilling rate, and flow out of the borehole during drilling may be used to infer lithology and the location of transmissive fractures, for example. The rate of penetration offers an obvious cost advantage over other methods, but a greater savings is probably due to the increased information gained concerning fluid-bearing zones. Careful observation during drilling and a descriptive log can provide valuable hydrogeologic information. Of great significance is the fact that the depth of transmissive fractures may be

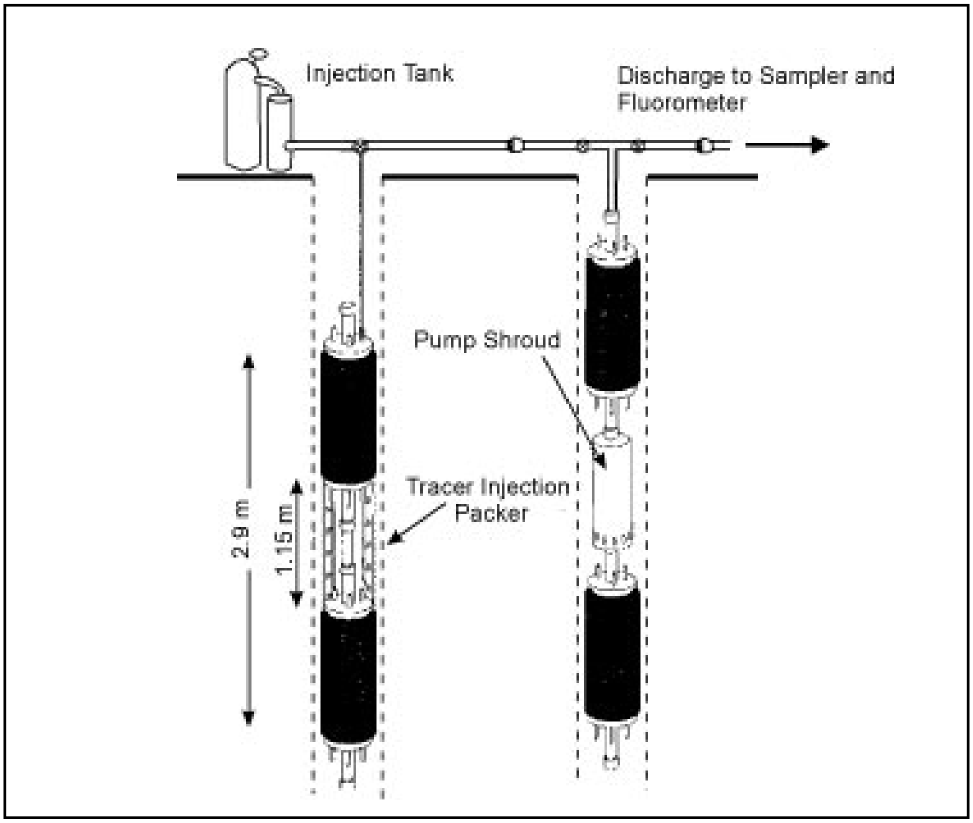

Figure 9. Equipment layout for two well tracer tests with partial recirculation. Tracer is injected into small annulus between borehole wall and injection casing between packers. Tracer exits through several feed-through valves evenly distributed over injection interval. Not to scale.

observable, because water will be brought to the surface with the cuttings when such fractures are encountered. Flow can be measured with a bucket at the surface, and changes in flow with depth may indicate that the drill bit encountered another transmissive fracture or fracture zone. In addition, the flow measured at the total depth may be used as a relative measure of well yield. This information can be used to assess which wells are relatively high yielding and, therefore, are the best candidates for pumping tests or borehole flow profiling tests, for example.

3.3 Pumping Tests

Drawdown transients in different types of fractured formations can behave in a manner describable by the Theis or Cooper-Jacob solutions, but this behavior does not necessarily indicate the aquifer can be considered an equivalent porous medium. Irrelevant parameter values can be derived from analysis of drawdown transients, and analysis of late-time drawdown may be essentially unrelated to the region of the aquifer that is of interest. Well bore storage can mask the effects of important heterogeneities, and semilog analysis of drawdown in the pump well will lead to underestimates of transmissivity. Local transmissivity heterogeneities can produce apparent anisotropic behavior in the drawdown responses in observation wells. The installation of wells can connect previously unconnected fractures and create short-circuit pathways. Pumping of wells can further initiate transport of contaminants to previously uncontaminated areas. In order to maximize the information necessary for characterization and minimize cost and the potentially negative effects of pumping, pumping tests should not be conducted as tests in and of themselves. Other hydrologic tests which are necessary in characterizing a fractured formation yield more valuable information, and can simultaneously provide pressure transients amenable to standard pumping test analysis. For example, impeller-flow meter profiling allows one to determine which fractures are conductive, and pressure transducers can be installed in wells during the test to measure pressure transients. A drilling method that enables observation of fluid emanating from the borehole can provide information regarding which well(s) are best suited for pumping. Pumping of wells during any type of test should be minimized in duration, and efforts should be made to analyze the entire pressure transient rather than resort only to late-time data analysis.

3.4 Detection and Measurement of Subsurface Fractures

The identification and measurement of fractures intersecting boreholes is an absolute necessity. Besides its use in determining the general fracture trends or sets, a database of fracture locations and orientations in boreholes enables one to determine fracture-specific geophysical properties through comparison with standard geophysical and flow logs. The combination of a flowmeter log and an acoustic televiewer log may enable the determination of particular hydraulically conductive fractures. The measured orientation and dip may be used to associate these fractures with fracture sets, and project to intersections with other borehole wells.

Although the digital borehole scanner provides the highest resolution data, it is relatively expensive. However, given the capabilities of the tool and imminent reductions in its cost, it will be the best tool for use in the near future. At present, ATV and television logs used together provide very useful fracture data, especially when coupled with standard geophysical logs. Fractures can be easily mapped from the ATV logs, and television logs can be used to check if particular fractures are altered and/or infilled. The ATV was most useful for identifying the location of fractures and determining their orientation. Measurements of individual fracture properties, such as aperture or roughness are not reliable. The determination of orientation and dip of individual fractures was very useful for later use, when the data was integrated with visualization software and measured fractures were extrapolated to see where they might intersect other boreholes. Most of the information gained from coring is obtainable through the combined data from the ATV, television, and standard geophysical logs, which are more economical and timely.

The large data set resulting from the fracture measurements makes a statistical analysis of spatial properties very tempting. However, because of the effects of drilling on the appearance of individual fractures, and on the fact relatively few of the many fractures detected conduct fluid, statistical descriptions of fracture aperture and spacing (based on ATV data alone) should not be used to estimate general hydrologic properties.

3.5 Borehole Flow Logging

Flow logging is a critical necessity in the characterization study. It provides a means to identify and quantify the transmissivities of only the relatively few fractures or fracture zones which are in fact conductive. This information provides knowledge of the general structure of the aquifer, from which all future remedial planning emanates. Results from flow logging are best when integrated with other geophysical logs.

A necessity of all flowmeters is that pumping or injection of the well-bore is required. Therefore, a flow field may be established in the contaminated field, and contaminants can migrate to previously uncontaminated areas. In order to minimize these effects, profiling should first be conducted in wells under natural conditions. In theory, either the impeller or thermal-pulse flowmeter could be used at this stage, although the lower sensitivity of the latter is probably the better choice since flows are likely to be very low. Vertical borehole flow will probably be greatest soon after drilling when fractures are being connected by the installation of the well and the system is in a highly transient state. After this initial profiling, the method of profiling multiple wells during the pumping of a single well should be implemented. The highest yielding well should be used as the pumping well, and driller's logs can provide this information. Profiling in the pump well with the impeller flowmeter allows determination of transmissivities of intervals adjacent to the well, and by installing pressure transducers in neighboring wells, a multi-well pumping test is effectively conducted. This eliminates the need to perform a separate pumping test. Alternatively, one well can be used for pumping and other wells profiled with a heat-pulse flowmeter, for example. The information gained is somewhat different, but perhaps more informative since one can determine which fractures are transmissive in other wells, although not quantitatively. If the impeller or thermal-pulse is used, it is recommended that a downhole inflatable packer be used around the flow casing to increase the sensitivity and avoid borehole variation and turbulence effects and to reduce the number of calibrations needed.

The use of packer injection tests is not recommended under most situations. The method is expensive and time consuming and creates the greatest non-equilibrium condition in the aquifer. A method like the fluid conductivity logging yields precise locations of transmissive fractures and can be analyzed to determine the transmissivities of these fractures. The packer-injection tests are probably not appropriate as a means to detect flowing fractures but perhaps as a later investigative phase once flowing fractures are found and some quantitative assessment is sought.

3.6 Integration of Geophysical and Hydrologic Logs

Conventional geophysical logs were used in conjunction with flowmeter logs in order to identify the particular hydraulically conductive fractures and/or fractured zones intersecting the boreholes. It was found that by integrating the flowmeter results with the acoustic televiewer, television, 16-inch normal resistivity, caliper, and gamma logs, the particular conductive fracture or fractured zone could be determined. After the conductive fractures were identified, interpolation of properties between wells was made based on similarities in various fracture geophysical properties, and the general hydrologic structure of the aquifer was deduced. The integration of various geophysical logs is an essential component in any characterization effort. All of the conventional geophysical logs collected may be potentially significant for use at other sites. Reference is made in the full report to other works where different tools have been used.

3.7 Computer Visualization

Visualization software is now an affordable reality, and allows one to deduce complexities not possible from traditional 2-D plots of borehole data. One very useful feature of some visualization software routines is their ability to represent spatially distributed data in a true three-dimensional perspective, and which allow real-time manipulation of the viewing perspective. Hypothesis testing via interpolation of fracture properties between wells is extremely beneficial. Visualization should be a commonplace tool for subsurface characterization.

3.8 Interwell Tracer Tests

In general, tracer tests were the most difficult field test to construct and operate, even with the highly sophisticated and expensive equipment used at the Raymond Field Site. Well bore storage and mixing effects in the injection zone severely altered the intended test configuration and rendered the tracer breakthrough curves amenable to arrival time analysis only. Even with the implementation of the special injection system that minimized borehole effects, the usefulness of the test results is very questionable. The theoretical mixing lengths that yielded the best model fit to the data were larger than the well spacing between the injection and withdrawal wells. This result generally points out the shortcomings of using the convection-dispersion equation to model transport in highly heterogeneous fracture rock. Based on the field experience at this site, tracer tests for characterizing fracture formations as part of a remediation program are problematic. Highly controlled and sophisticated and expensive equipment is needed, and even in the best of circumstances there will most likely be considerable ambiguity associated with the derived parameters.

Notice:

The information in this project summary and in the original report is the result of a research project funded jointly by the U.S. Environmental Protection Agency and the U.S. Department of Energy. Neither the original report nor this project summary should be interpreted as official EPA guidance for site characterization at sites located in fractured rock formations.

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The complete report is entitled "Hydrogeologic Characterization of Fractured Rock Formations: A Guide for Groundwater Remediators" and is referenced as **LBL-38142/UC-800** (144 pages, color figures). A limited number of copies of the full report are available from Subsurface Remediation Information Center, P.O. Box 1198, Ada, OK 74821. A digital copy is available on the home page ***http://www.epa.gov/ada/kerrlab.html***

The full report is available to DOE and DOE Contractors from the:
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