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GEOHYDROLOGICAL STUDIES FOR NUCLEAR WASTE ISOLATION AT THE HANFORD RESERVATION

Volume I: Executive Summary

J. Apps, T. Doe, B. Doty, S. Doty, R. Galbraith,
A. Kearns, B. Kohrt, J. Long, A. Monroe,
T. N. Narasimhan, P. Nelson, C. R. Wilson, and
P. A. Witherspoon

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August, 1979

Prepared for the U. S. Department of Energy under Contract No. W-7405-ENG-48 and for Rockwell Hanford Operations—A Department of Energy Prime Contractor—under Memorandum Order No. W8A-SSB-51760.

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I. INTRODUCTION

A study of the hydrology of the Pasco Basin near Richland, Washington, was initiated by Lawrence Berkeley Laboratory for Rockwell Hanford Operations (Rockwell) during Fiscal Year 1978. This work was part of a long-term feasibility study conducted by Rockwell's Basalt Waste Isolation Program for the National Waste Terminal Storage Program of the Department of Energy on the feasibility of nuclear waste disposal in the Columbia River Basalt underlying the Hanford Reservation.

The Hanford Reservation lies within the Pasco Basin near the center of the Columbia River flood basalt physiographic province, which spans parts of Washington, Oregon, and Idaho (Figure 1). The overall feasibility study has been directed to the concept of a mined repository at a depth of about 3000 feet, possibly in the Umtanum Unit, a dense 200 foot thick basalt flow. The feasibility of this concept largely depends on the degree of hydrologic isolation afforded by the basalts. Hydrologic isolation can be determined only by actual field testing and subsequent modeling.

In October 1977 a work plan was formulated which included three hydrologic subtasks: Physical Testing, Geochemical Sampling, and Numerical Modeling. Progress on these three subtasks through September 1978 is reported in this section. In addition to these subtasks an analysis of existing geophysical data is summarized here. Hydrologic work by LBL ceased at the end of FY 1978.

A physical testing program designed to provide hydrologic information for mathematical modeling of the deep basalts in the Pasco Basin was initiated in FY 1978. LBL performed hydrologic testing on several deep drill holes on the Reservation and obtained and analyzed water samples from drill holes and surface water. A technical approach was developed for obtaining and integrating the hydrological, geophysical, and geochemical data required for modeling. A field program oriented toward the collection of needed data was then initiated. A full hydrology testing program was planned for implementation over a period of several years. Included in this program were: pressure measurements to determine hydraulic potential gradients; tracer tests to determine flow direction and velocity; borehole fracture logging to quantify the geometric parameters of the fracture systems; hydraulic fracturing to determine in-situ stress conditions; a wide variety of permeability

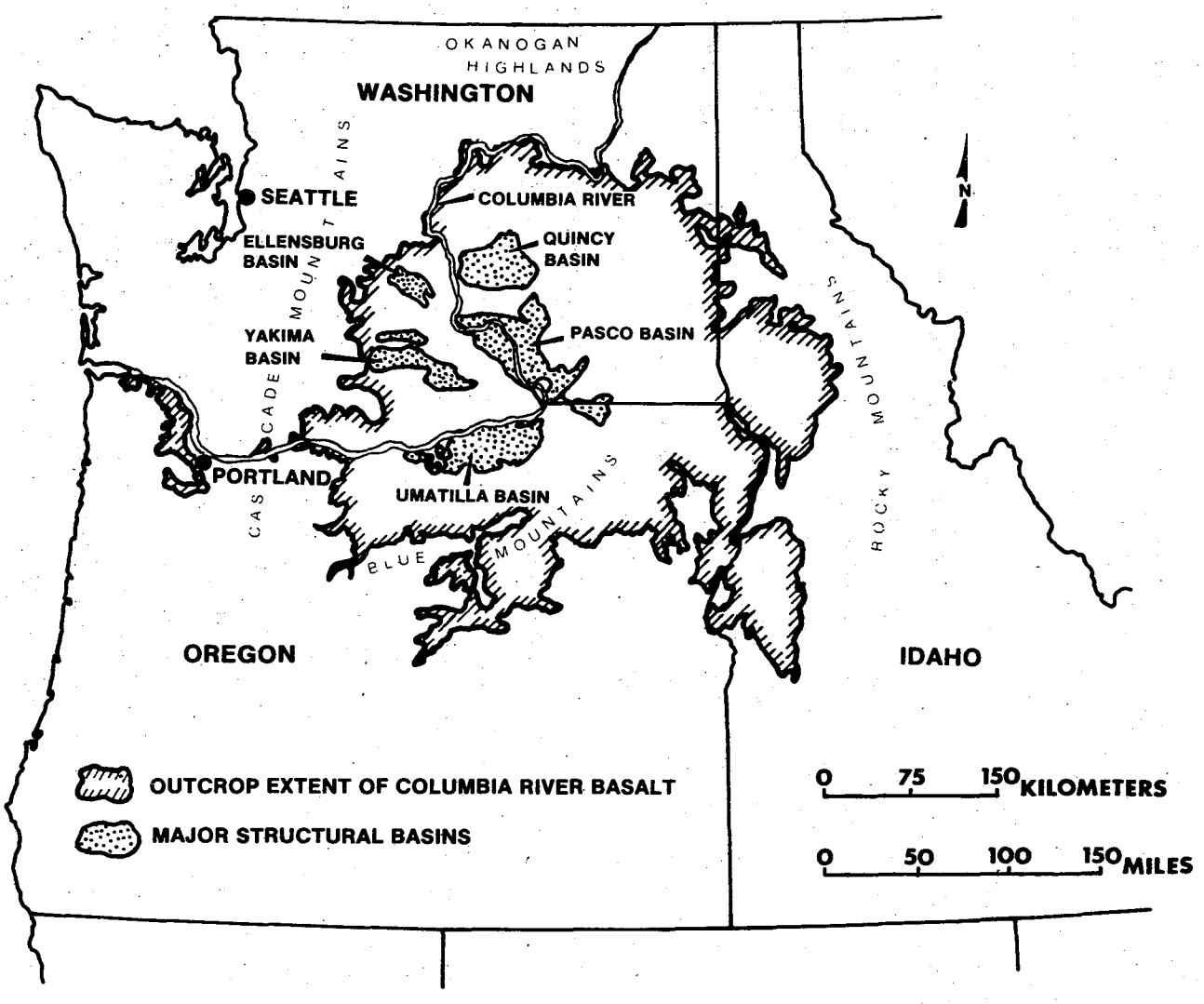

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Figure 1. Location map of the Columbia River Basalt (after Rockwell, 1977).

tests on both multiple and single fractures; and a modular-type long-term monitoring system was recommended for development and installation in selected wells.

II. FY 1978 ACCOMPLISHMENTS

A. Hydrology Field Program

1. Equipment Development

During FY 1978 LBL designed down-hole instrumentation and packer systems for pressure, temperature and permeability testing. Pressure measurements at depths less than 3000 feet were made with a packer-mounted probe containing a single pressure and temperature sensor with no downhole packer release. A second tool was designed to operate at greater depths and do injection tests as well as pressure measurements. This tool included downhole solenoid valves to deflate packers and to bleed the test cavity of pressure pulse due to packer inflation, and an extra pressure transducer for monitoring packer pressure.

2. Field Test Results

Pressure testing was performed in Wells DC-2, DC-6, and DC-8 and permeabilities were estimated from artesian flow in DC-6. Figure 2 shows the location of these wells within the Hanford reservation.

a. Well-DC-2

Well DC-2 is a 3300 foot deep hole drilled about 40 feet from Well DC-1, a 5661 foot hole. Five standpipe piezometers were installed in DC-1 in 1972 and water levels have since been measured periodically.

Pressure measurements were made in 11 zones in DC-2 between depths 2269 feet and 3273 feet. The LBL test data, shown on Figure 3, appear to indicate that the vertical component of hydraulic gradient is sharply downward over the interval tested. Comparison with open hole data, however, showed that a close correlation exists between the falling open hole head and the test zone measurements. This influence is thought to result from either vertical circulation of water through the formation or from residual effects of formation prepressurization which occurred when the well was filled for cleaning prior to testing. The tests were continued until the effects of the packer inflation pulse was essentially dissipated. However, time constraints did not permit the longer-term testing periods that would have been required for

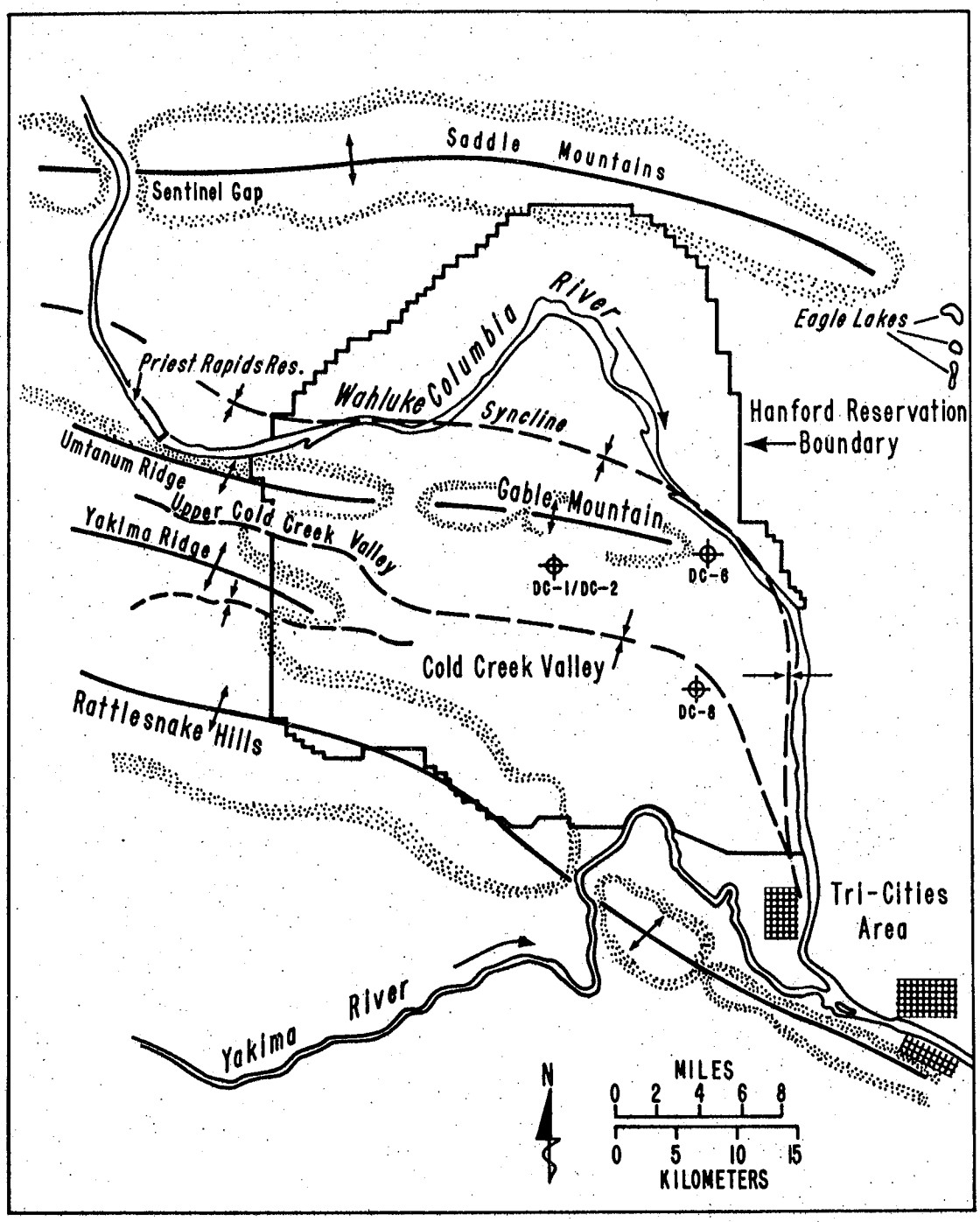

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Figure 2. The Pasco Basin.

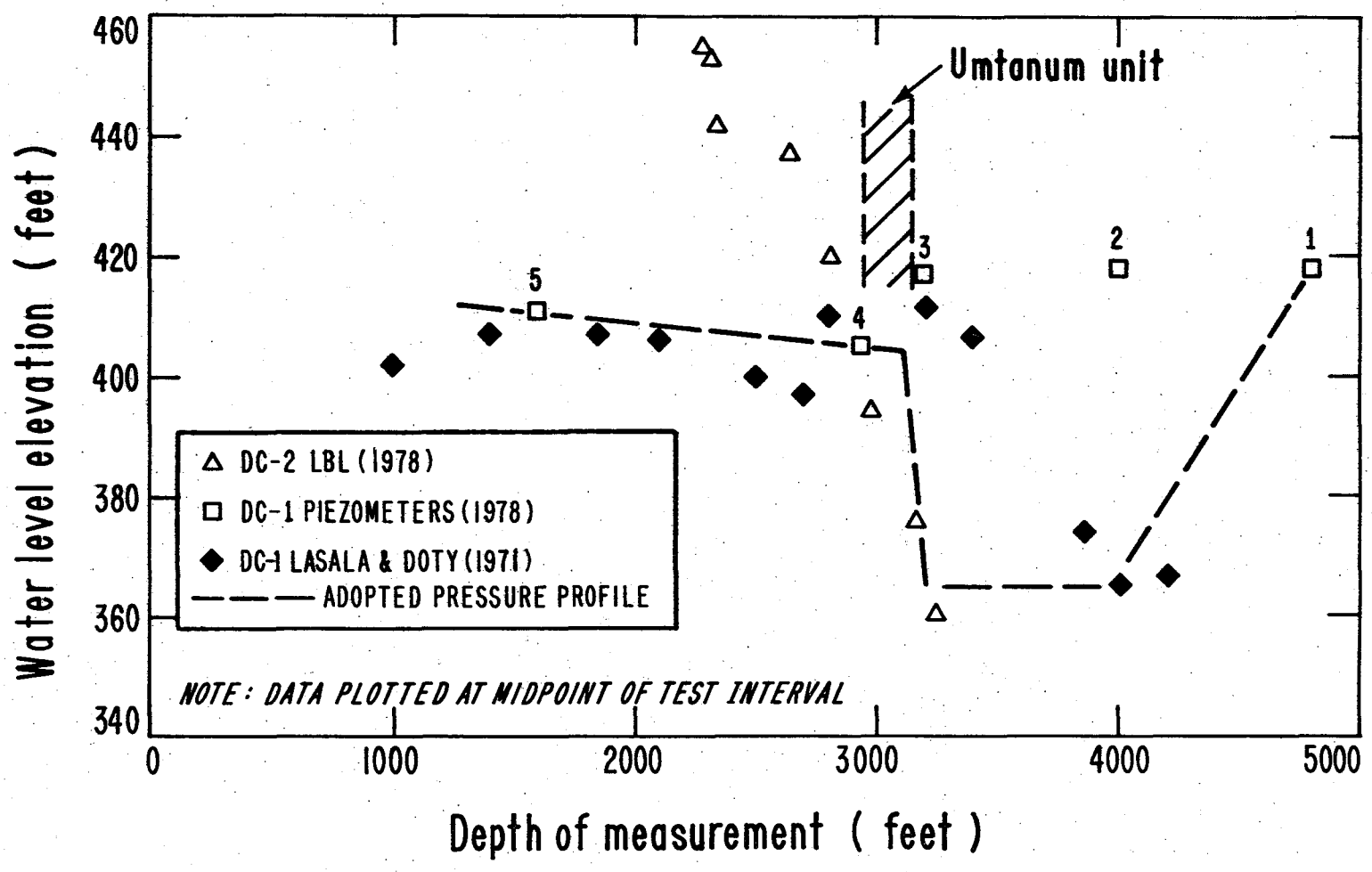

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Figure 3. Pressure measurements in Wells DC-1 and DC-2.

complete dissipation of the overpressure induced by packer inflation and by well cleaning in the lower permeability test zones. Increased testing times and increased sophistication of test equipment will be required to determine the degree to which residual effects of wellbore pressurization and the influence of vertical permeability affect test results in Well DC-2.

The open hole water level in DC-2 fell throughout the test period and was at an elevation of about 360 feet when the tests were concluded. This indicates that: (1) the minimum natural formation head within the open part of DC-2 is equal to or less than 360 feet elevation; and (2) this minimum head probably occurs below the Umtanum Unit. Pressure measurements made by La Sala and Doty in Well DC-1 before the piezometers were installed (1971), and piezometer levels in DC-1 at the time of testing in DC-2 are also shown on Figure 3. Based upon these data and upon observed dynamic changes in DC-1 due to swabbing in DC-2, it may be concluded that:

(1) Piezometer 2 and 3 readings are erroneously high because of vertical flow through leaks in the cement seals in Well DC-1 from a high pressure zone deeper than piezometer 2.

(2) The true formation pressure head elevation at the depth of piezometers 2 and 3 is on the order of 360 feet.

(3) Piezometers 4 and 5 appear to be adequately isolated from the rest of the well.

(4) A downward pressure gradient apparently exists from at least the depth of piezometer 5 (2000 feet) through piezometers 4 and 3 to at least the depth of piezometer 2 (4000 feet), passing through the Umtanum Unit.

(5) An upward pressure gradient apparently exists from at least the depth of piezometer 1 (4800 feet) to approximately the depth of piezometer 2 (4000 feet).

(6) The Umtanum Unit appears to be acting as a partial barrier to vertical flow.

b. Well DC-8

Pressure testing was performed in Well DC-8 at nine zones between depths 1710 feet and 2700 feet with a constant packer interval of 30 feet. Open hole measurements were made immediately prior to packer inflation and subsequent to packer deflation. Filling of the wellbore during testing resulted in considerable variations in open hole water level during the early part of

the testing period. The lowest water elevation recorded during the test period was an open hole head elevation of 413 feet. This measurement indicates that the formation pressure head within some part of the open portion of the well is at least as low as 413 feet. Data collected in DC-8 is shown in Figure 5.

The tests generally appear to be less influenced by open hole pressure than in DC-2, perhaps indicating a lower vertical permeability at Well DC-8. A downward gradient was measured within the depth range 1500 - 2100 feet. Based upon extrapolation of this gradient, the minimum pressure head of 413 feet would occur at a depth of about 2300 feet.

c. Well DC-6

Well DC-6 is artesian and at the time of testing was flowing at a rate of about 17 gallons per minute. The first artesian zone was encountered during drilling in March 1978 between 2300 and 2710 feet, and additional artesian flows were encountered as the hole was deepened.

Water pressures were measured in 15 zones between 2240 and 4336 feet of depth. Artesian discharge from the well was measured in 12 zones between 2483 and 4336 feet, and permeabilities were computed for these zones. The groundwater pressure, flow, and permeability data are shown in Figure 4.

All pressure measurements indicate artesian heads above the elevation of the hole collar, hence all test zones are contributing to the flow from the hole. Between depths of 2240 and 3055 feet the pressure heads average about 450 feet. The scatter in the data does not allow reliable definition of either an upward or a downward gradient. Below 3055 feet heads decline reaching a local minimum elevation of approximately 430 feet in a water producing zone at about 3700 feet of depth. An increase in head below 3700 feet is shown by the head of 466 feet recorded for the zone between 3802 and 4336 feet. There is generally good agreement between the heads measured by Lynes and W. K. Summers Associates in March, 1978 and the values determined by LBL (see Figure 4A).

The most prolific flowing zone yielded about 70% of the total flow and occurs between depths of 3692 feet and 3769 feet as shown on Figure 4B. This zone was logged as a highly altered flow breccia. Flows on the order of one gallon per minute were also measured from similar breccia zones between 3650 feet and 3692 feet.

Permeabilities were estimated using the assumption of steady radial

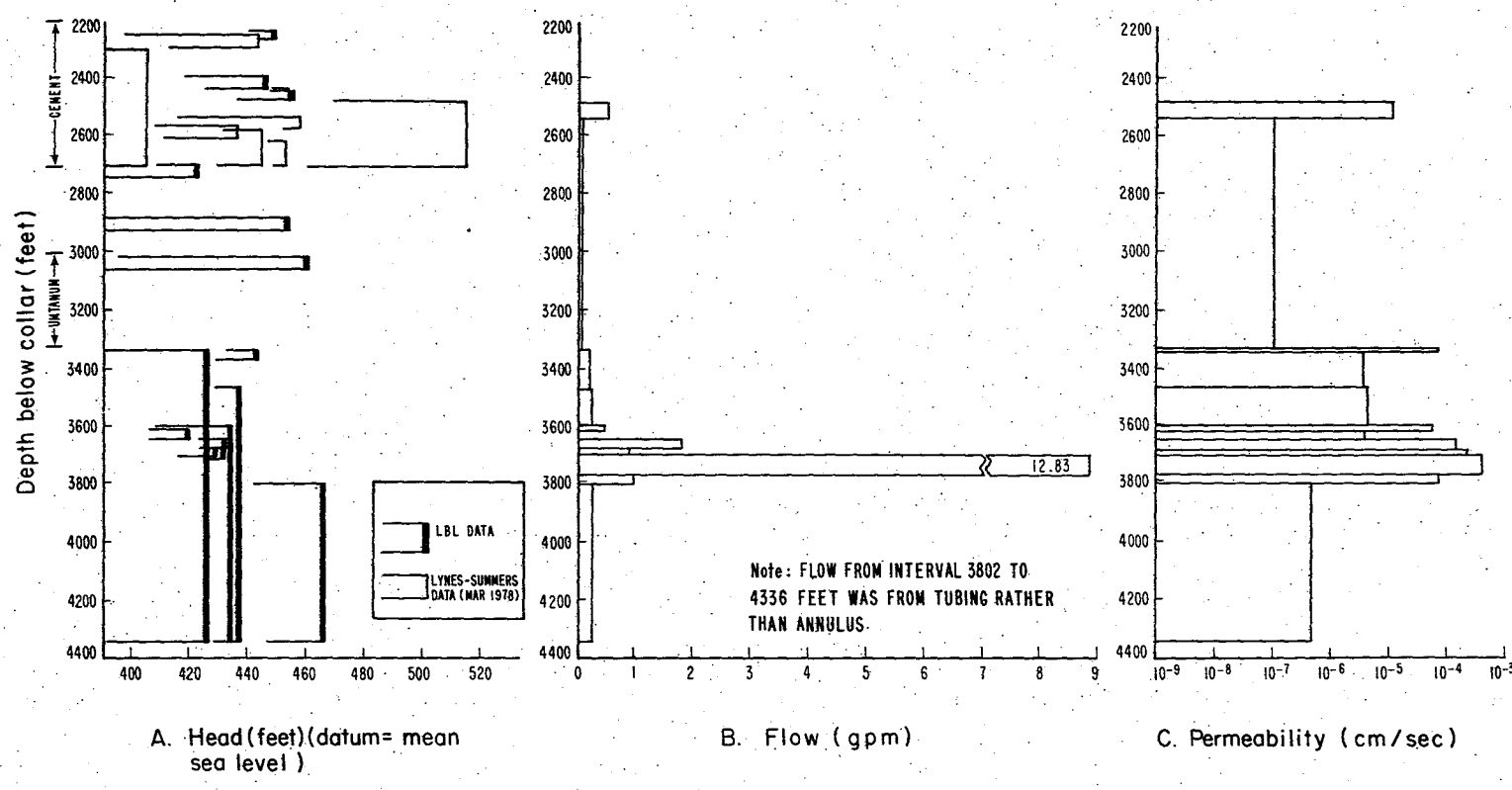

Figure 4. Water heads, flow rates and permeabilities in Well DC-6.

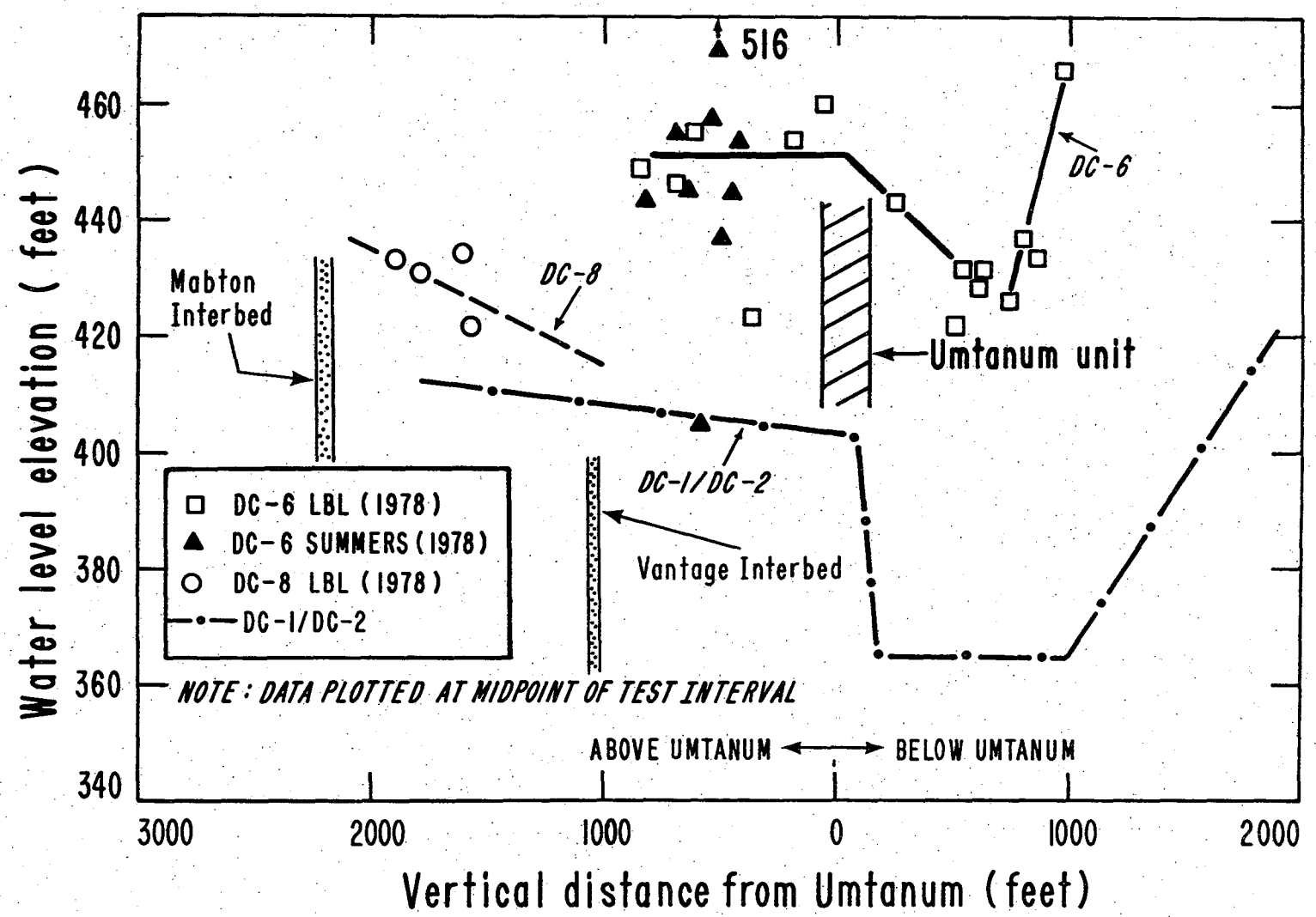

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Figure 5. Summary of pressure measurements.

flow. The results are shown in Figure 4C and represent the average for the zone tested. The largest permeabilities were on the order of 10^{-4} cm/sec, measured in the zone between 3650 and 3800 feet. This zone is about 400 feet below the Umtanum Unit. The lowest average permeabilities were on the order of 10^{-7} cm/sec, measured in and above the Umtanum Unit.

d. Comparison of Pressure Results

The results of pressure measurements in Wells DC-1/DC-2, DC-6, and DC-8 are shown in relation to stratigraphy on Figure 5. These data show a downward gradient between the Vantage interbed and the Umtanum Unit in DC-1/DC-2. The gradient is poorly defined, however, in the same zone in DC-6. DC-8 shows a downward gradient between the Mabton and the Vantage interbeds. Head elevations reach a local minimum in DC-1/DC-2 and DC-6 about 300 feet below the bottom of the Umtanum and there is evidence that gradients may be upward below that depth. The low pressure zone encountered below the Umtanum would act as a drain for any vertical flow converging upon it, thus the recharge and discharge areas of this zone are of great interest.

Pressure data for the zone immediately below the Umtanum is presently available only for Wells DC-1/DC-2 and DC-6. Wells DC-1/DC-2 are in the northern flank of Cold Creek Valley syncline, formed between Gable Mountain anticline to the north and Rattlesnake Hills anticline to the southwest (see Figure 2). The water level elevations measured in and below the Umtanum in DC-1/DC-2 range from 395 to 362 feet. The only part of the Pasco Basin with lower elevations which would serve as a discharge area is the Columbia River bed and adjacent lands from the Tri-Cities area to Wallula Gap. The most likely flow path from DC-1/DC-2 to this discharge area is through Cold Creek Valley.

Pressure head elevations measured in DC-6 in and below the Umtanum range from 421 to 466 feet. The relatively low pressures measured in the deep basalts in Cold Creek Valley and the higher pressures measured in DC-6 suggest higher water tables to the north and east of DC-6. The most likely source of recharge for these high heads is the Columbia River from Sentinel Gap to Priest Rapids Reservoir. The basalt units beneath the Umtanum are at or near the ground surface in this area, and the river is a source of abundant volumes of water. The most likely flowpath to Well DC-6 from this potential recharge area would be along the Wahluke syncline, a structural and topographic valley between the Gable Mountain-Umtanum Ridge anticline and the

Saddle Mountain anticline. Other potential recharge areas, such as the Saddle Mountains or the Eagle Lakes-Scooteney Reservoir area to the northeast of DC-6, are either relatively dry or do not have outcrops of the Umtanum and underlying units. They are therefore less likely to be primary recharge areas.

The pressure data and recharge hypotheses for the deep basalts at DC-6 imply that water pressures throughout the Wahluke syncline are substantially higher than those measured in Cold Creek Valley at Well DC-2. Such a difference would suggest the existence of a barrier to groundwater flow in the general vicinity of the Gable Mountain-Umtanum Ridge anticline. This hypothesis is supported by a lack of likely recharge areas for the Umtanum and underlying units in the vicinity of Cold Creek Valley. Gable Mountain on the north side of the valley is low and provides essentially no recharge. The Yakima Ridge area to the east of the valley and the Rattlesnake Hills to the south rise to elevations of several thousand feet, but like the Saddle Mountains, are relatively dry. Further, the Umtanum Unit is at least 1000 feet deep in all of these areas. Some underflow in the deep basalts may be occurring through structural valleys paralleling Yakima Ridge, but as noted by Newcomb and others (1972, p. 32), the high heads found in a number of deep artesian wells near the western boundary of the Hanford Reservation suggest the presence of a second flow barrier cutting across these structural valleys. The presence of relatively high heads at Juniper Springs and Rattlesnake Spring versus the relatively low heads measured in DC-1/DC-2 supports the assumption of an additional flow barrier. The possible existence of these flow barriers is of significant interest in repository siting and should be further investigated.

e. Comparison of Flow Data

Radioactive tracer and temperature logs in Well DC-1 have indicated three zones of relatively high permeability at depths of 3228 - 3234 feet, 3972 - 3980 feet, and 4824 - 4854 feet. The average permeability of these zones is 9.4×10^{-4} cm/sec. The first two of these zones are 50 feet and 794 feet below the bottom of the Umtanum Unit.

In Well DC-6 the major flowing zone was determined to have a permeability greater than 10^{-4} cm/sec and occurs between depths of 3650 and 3700 feet, which is 442 feet below the Umtanum. There are likely to be, in addition, other zones with permeabilities greater than 10^{-6} cm/sec between the bottom

of the Umtanum and the high permeability zone at 3650 feet, but the large spacing between packer settings in the LBL flow tests did not allow better definition of the exact location of these higher permeability zones.

Comparing the data for the two wells, it is clear that the most permeable zones encountered are below the Umtanum, but these zones do not appear to occur at the same stratigraphic levels relative to the Umtanum Unit in the two wells. The similarity of geochemical stratigraphy for the two holes suggests that these permeable zones may be occurring at different basalt flow contacts. The extent to which these zones may be hydraulically interconnected through a continuous weathered horizon, through faults, or through primary fractures will be important to radionuclide migration from a repository and should be the subject of further studies.

B. Pasco Basin Modeling

The Pasco Basin hydrology modeling effort had three products. The first was a literature survey. The second was a recomendation for a well drilling and testing program. The third was a series of numerical solutions for use in the design of hydrologic field tests such as pump tests and leaky aquifer tests where wellbore storage is significant.

1. Literature Survey for Regional Flow System

The literature survey was undertaken to help define such flow model inputs as boundary conditions, initial conditions, geometry as defined by structural geology, and material properties. The system boundaries are apparently complex and irregular. The groundwater flow system is further complicated by numerous folds and faults and basalt flows of variable continuity. Although primary porosity may be of importance locally, by and large the flow paths are governed by fractures of widely variable pattern (horizontal, columnar, etc.) and spacing. The system is probably characterized by time dependent boundary conditions and a variable, three dimensional distribution of fluid potentials.

Such input data will always be accompanied by uncertainty and hence the simulation results will also be accompanied by significant uncertainties. A limitation of the current LBL models is that they all are intrinsically deterministic. Since the flow system parameters cannot be known with certainty, confidence limits on the potential range of system response must be

provided for the decision-making process. An important capability which would improve the LBL models would therefore be the accomodation of statisistically expressed input parameters and the statistical expression of output parameters indicating the distribution of possible system responses. Further work on the development of such models is recommended to permit adequate risk assessment of repository safety.

2. Recommended Well Drilling and Testing Program

Based on the results of the field work, the literature survey, and the input requirements, a well drilling and testing program was developed for further study of the Pasco Basin. In order to achieve the immediate objective of providing an overview of the regional flow system, six first stage wells, DC-12 through DC-17, were proposed (Figure 6). These wells, when combined with existing wells, are designed to provide sufficient information to indicate on a gross scale the origin, flow paths, velocities, and disposition of groundwater within the basin.

Well DC-12 is in the center of the basin. This well would provide data for determining gradients in several directions within the basin. Well DC-13 is in the "horn" of the Columbia River. This well would help to determine the hydrologic significance of the Saddle Mountains boundary and the influence of the Columbia River on the deep flow system. It would also provide an important data point in the Wahluke Syncline. The role of the Rattlesnake Hills as a recharge zone in the basin needs to be investigated. Well DC-14 would provide information on the extent of this recharge and the possible existence of perched waters. The southwestern boundary of the basin can also be examined.

Well DC-15 examines the extent of recharge from the Sentinel Gap area. The area is important because basalt flows which lie deep under the center of the Basin crop out at Sentinel Gap. This well in conjunction with DC-4 will also help to determine the direction of deep groundwater flow between Cold Creek Valley and the Columbia River Valley. In conjunction with DC-13, this well will enable an examination of deep flow systems along the Wahluke Syncline.

If the rough analysis of groundwater flow patterns seems favorable for siting a repository, these wells will provide a basis for locating second stage wells which may be necessary for a more detailed analysis of the flow system.

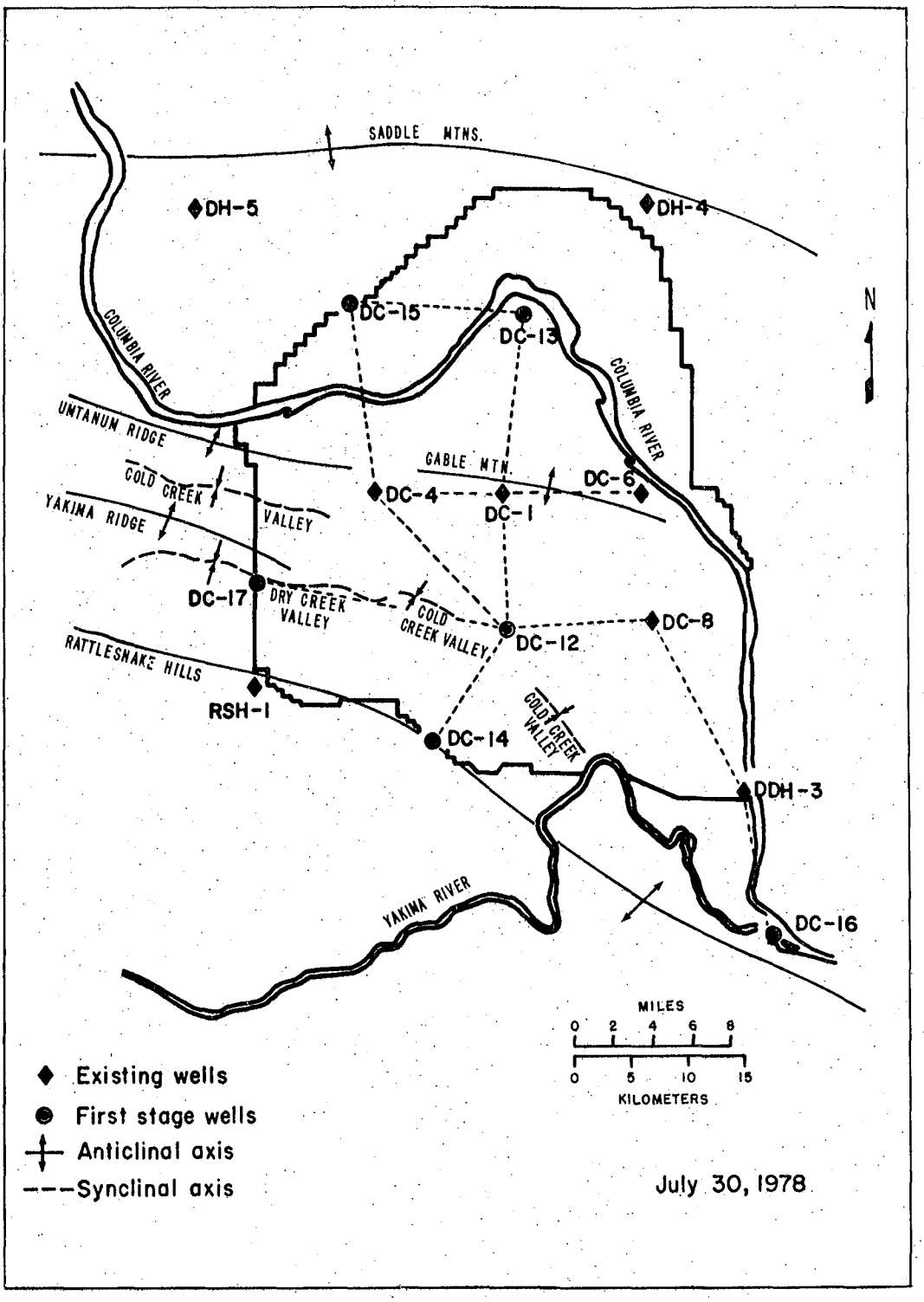

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Figure 6. Proposed first stage wells.

3. Wellbore Storage Effects

Pumping tests were planned for several wells on the Reservation and analyses were made of two anticipated wellbore storage problems. The first problem was to describe the response of an observation well in a pumping test where wellbore storage was significant. The second problem was to see how wellbore storage would affect the data collected in a leaky aquifer test. The LBL groundwater flow program TERZAGHI was used for both problems.

a. Observation well response with wellbore storage

Dimensionless drawdown curves were obtained for values of dimensionless storage parameter, α, of 10^{-1}, 10^{-2}, 10^{-3}, 10^{-4}, and 10^{-5}. A sample is shown in Figure 7. The curves approach the Theis solution with decreases in radius of the well and increase in α. The time necessary to obtain a response in the observation well increases with an increase in wellbore storage effect.

b. Leaky aquifer response with wellbore storage

Fifteen different cases were analyzed for times up to 100 days, comprising three different pumping well radii (.05, .09 and .1125m) and five different values of α(10^{-1}, 10^{-2}, 10^{-3}, 10^{-4}, and 10^{-5}). A sample of results is plotted in Figure 8 showing the ratio of drawdown in the aquitard (s′) to drawdown in the aquifer (s) as a function of wellbore radius. Observation well drawdown with wellbore storage can be as little as half the drawdown predicted without wellbore storage.

Figure 9 shows the time it would take to get a drawdown, s′, in an aquitard 9.0 meters from a pumping well and 0.5 meters from an aquifer. The parameters and geometry used are typical of what might be found in the Pasco Basin. At least 15 days of pumping would be required to get any measurable response in the aquitard for these conditions. This model could be used for well test analysis by developing a set of type curves for any specific well radius and distance to an observation well.

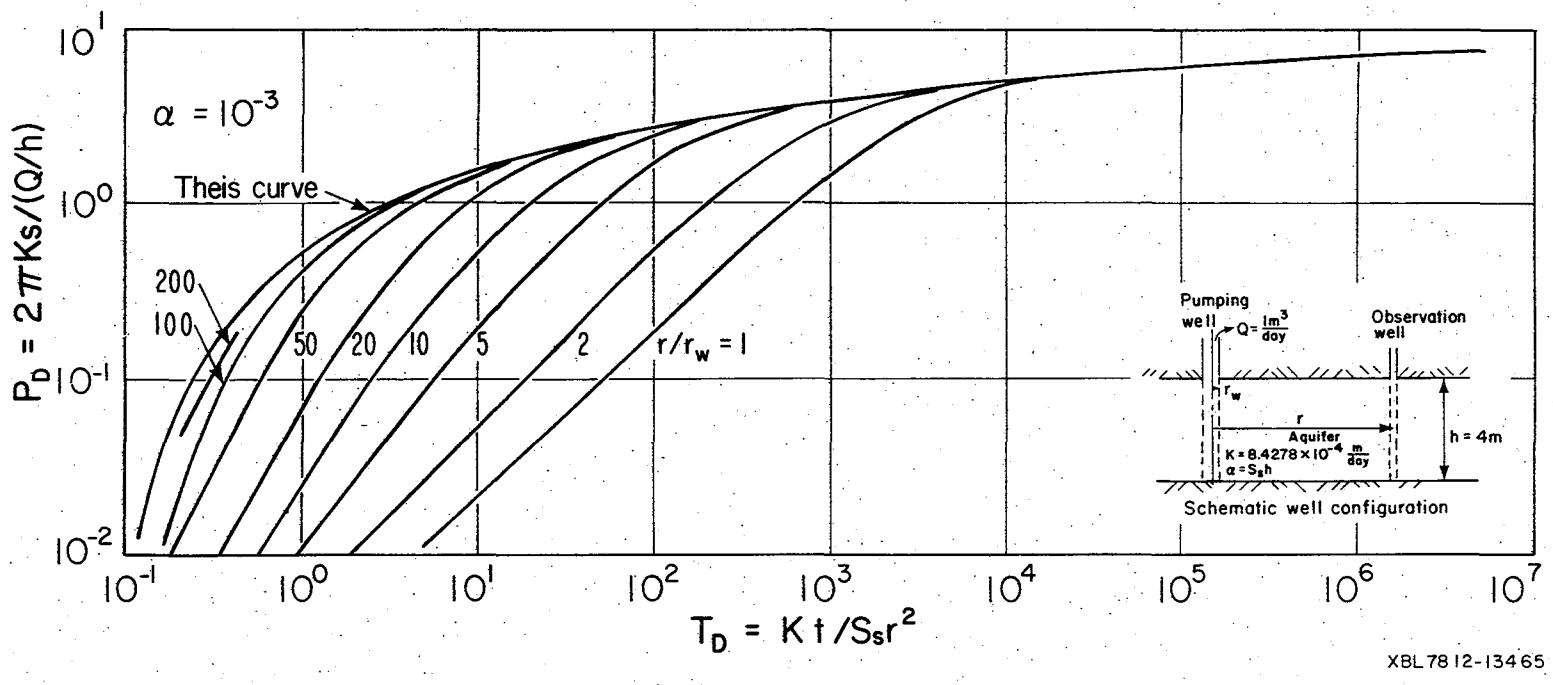

Figure 7. Drawdown in an observation well with wellbore storage in the pumping well, $\alpha = 10^{-3}$.

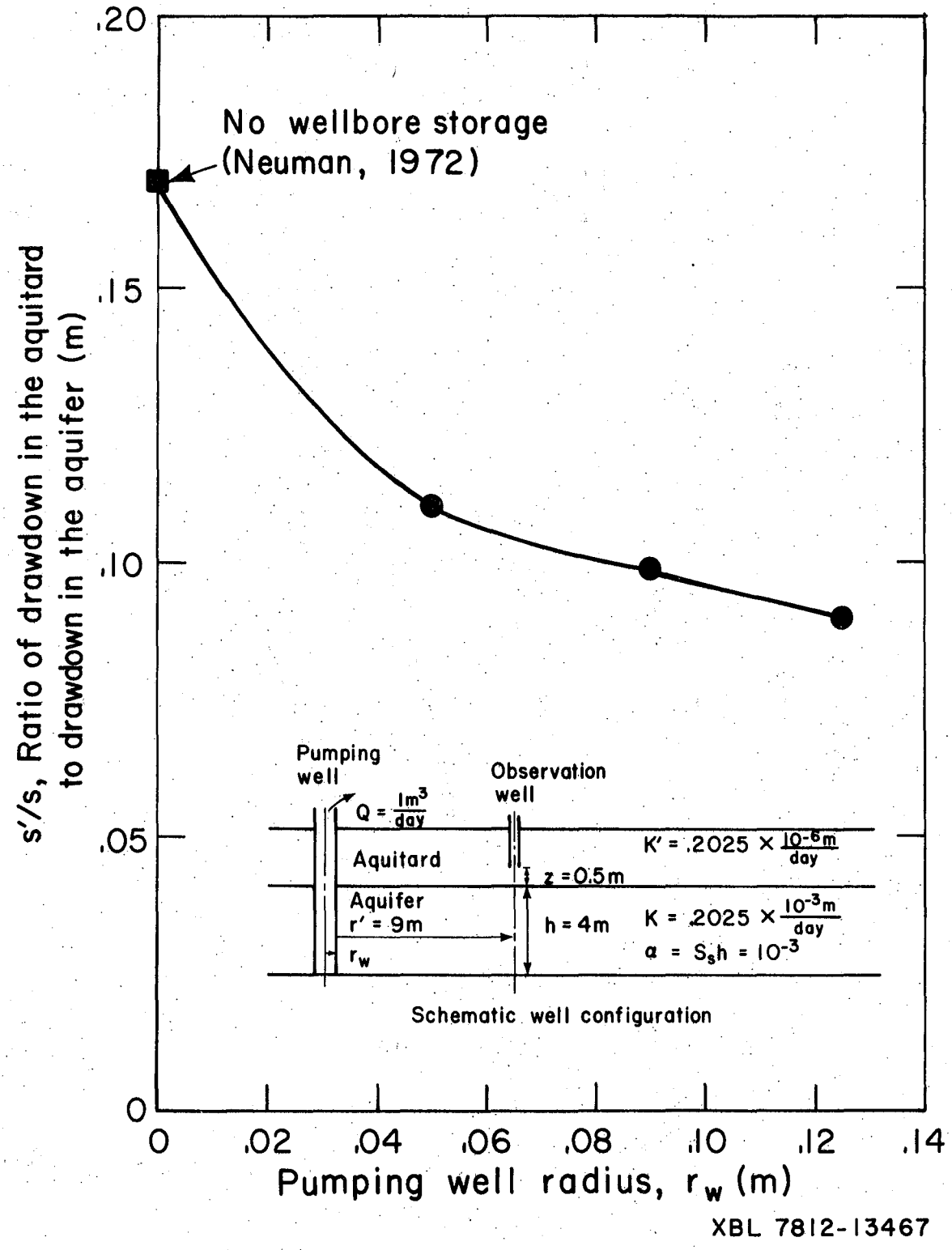

Figure 8. Ratio of drawdown in the aquitard to drawdown in the aquifer, s'/s, at r = 9 m, as a function of pumping well radius at t = 100 days, $\alpha = 10^{-3}$.

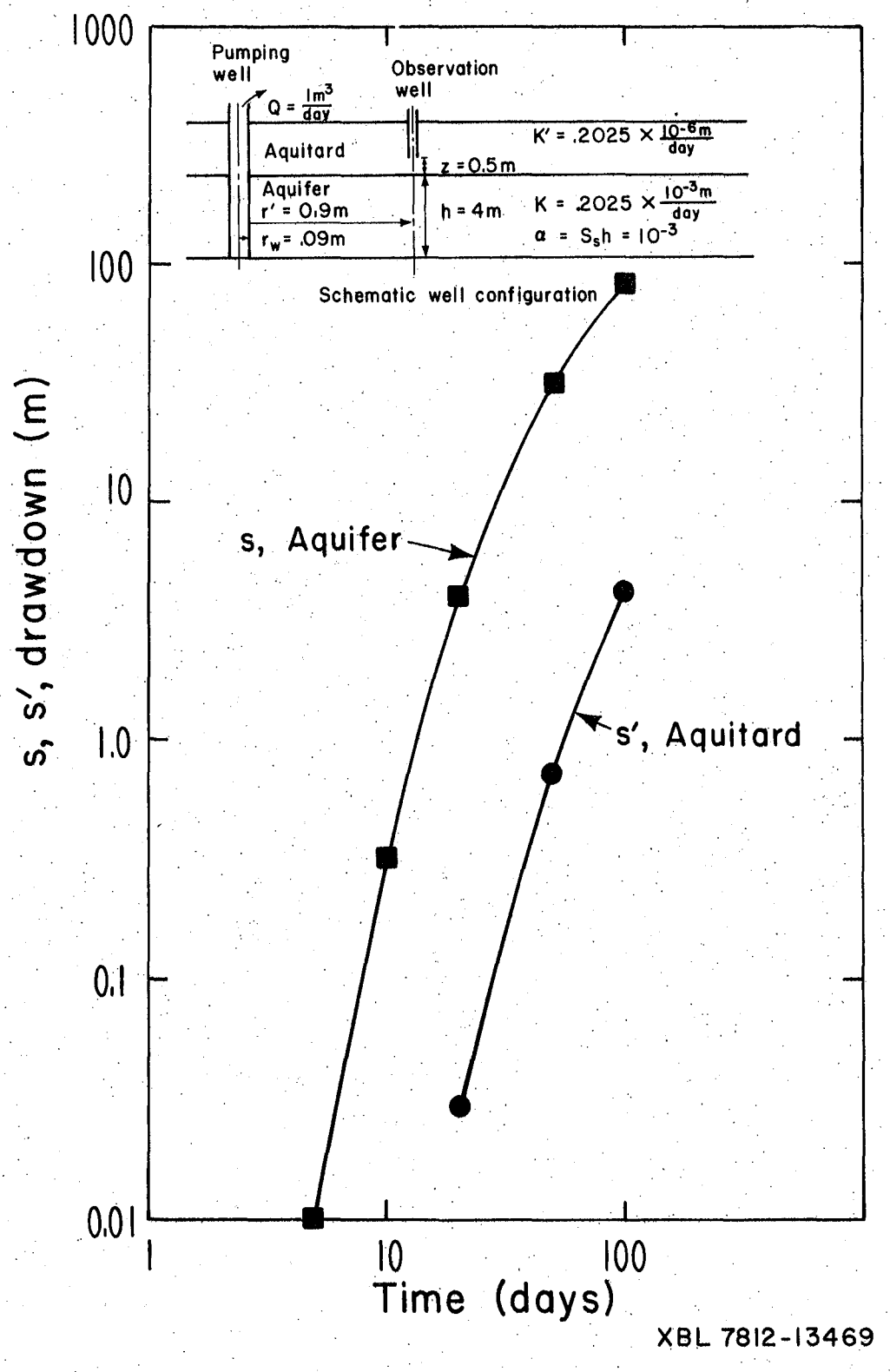

Figure 9. Drawdown as a function of time for $\alpha = 10^{-3}$, $r_w = .09$ m.

C. Groundwater Chemistry Program

1. Introduction

The sampling and analysis of groundwaters for the Pasco Basin was initiated as part of the LBL Hanford Waste Isolation Project. It was planned to perform comprehensive chemical and isotopic analyses of 36 deep well samples, 20 spring samples and 9 duplicates samples. The chemical analyses were to provide information that would permit determination of the source, history, and age of the waters of the Pasco Basin. This information, when used in conjunction with hydrologic data and regional hydrologic simulations of groundwater movement in the Pasco Basin, was expected to provide the basis for predicting the rate and type of chemical evolution of the groundwaters during flow. Such an evaluation is a necessary prerequisite for quantitative predictions of radionuclide migration in the same environment.

2. Previous Groundwater Chemistry Studies

Earlier drilling activities in the Pasco Basin by Fenix and Scisson Inc. indicated a minimum of three zones between 2888 feet and 3392 feet that appeared to justify further investigation as locations for mined caverns. Aquifers adjacent to these zones were therefore considered as the prime target for investigation. Previous studies of groundwater chemistry in the Pasco Basin were few in number. The evidence given by these studies and supported by the chemical analyses is that sampling deep well waters without contamination from extraneous sources would be both difficult and time consuming.

3. 1978 Activities

The chemical analyses planned for the groundwater samples included all major cationic and anionic species as well as trace elements, gas analyses, and on-site measurements of those species or properties that were likely to change during transport. The purpose of these analyses was to allow comparison with the compositions and theromdynamic stabilites of coexisting alteration products, to make internal checks on the validity of the analyses, and to permit estimation of the sources and the relative ages of the groundwaters. Trace elements were to be tested for their value as tracers for given aquifer waters or horizons.

A number of stable and radioisotopic analyses were also planned including those for D/H, $^{18}O/^{16}O$, $^{13}C/^{12}C$, $^{34}S/^{32}S$, ^{3}H, ^{14}C, ^{36}Cl, ^{222}Rn, ^{226}Ra, and $^{234}U/^{238}U$. Each of these isotopic analyses contributes to an interpretation of the source, temperature, history, or age of the groundwater. The

measurement of the age of groundwater is difficult to accomplish or interpret. Consequently, part of the study was directed towards elucidation or clarification of the problem associated with the utilization of ^{36}Cl and $^{234}U/^{238}U$ as tools for dating groundwaters.

LBL staff recognized the need for adequate laboratory services readily accessible from the sampling site, in order to perform analyses for fugitive components, separation procedures for isotopic analyses, and the filtration of samples. A mobile field laboratory was therefore designed and constructed to perform all necessary on site analyses and sample preparation. An 8x20 foot box trailer was leased for this purpose and adequate facilities for two chemists were provided. The mobile laboratory proved to be very satisfactory from the functional standpoint, but the need for a tow truck to move it and lack of intrinsic strength were disadvantages.

The complex sampling requirements for each of the several analytical and isotopic techniques involved in the study necessitated standard operating procedures for Quality Assurance documentation. These procedures became the focal point of organizing and finding the latest and most desirable methods for the sampling, treatment, and packaging of groundwater. Several meetings were held with leading isotope and chemical analysts in order to bridge the gap between analytical expertise and field sampling methodology. These meetings, combined with an exhaustive literature survey of groundwater sampling, resulted in the drafting of Field Operating Procedures for the groundwater chemistry part of the Hanford Waste Isolation Project. This document includes procedures for both well and spring sampling. Improvements were incorporated as field experience was gained.

On January 30, 1978 a meeting was held between the staff of Rockwell Hanford Operations, LBL, and other interested parties, to develop the field program. Between then and June 14, 1978, when swabbing of DC-2 started, isotope and analytical chemists were committed to provide support for the project, Quality Assurance documentation was prepared, and the mobile field laboratory was designed, constructed and equipped. Sampling and refinement of field procedures continued with occasional interruptions until August 16, 1978, when field work was terminated.

Groundwater samples from deep wells were obtained by swabbing, as no other technique had been developed that would permit recovery of large samples from the depths specified in the narrow diameter wells available for

sampling. Only Well DC-2 was sampled, from the zone between 3243 and 3273 feet. In the short time available for sampling, it was not possible to pump sufficient water to obtain a sample free of contamination.

Springs were identified from topographic maps, and chosen following discussion with Rockwell geologists. Only those springs were sampled that issued directly from geologic formations. A total of four springs were sampled in the time available. Access to the spring sites was difficult and required 4-wheel drive vehicles. Three flowing artesian wells (DC-6, Ford and McGee) and the Columbia River were also sampled using similar techniques to those developed for spring samples. Chemical and isotopic analyses were performed on the nine samples collected. The chemical analyses covered most of the elements and aqueous species originally specified. Analyses of some minor components were not performed, primarily because the project was terminated before the work could be completed. However, all major components were analyzed. In many cases different analytical methods were used to measure the same component, thus providing checks on the accuracy of the values obtained. Cation/anion balances were performed on major components of the solutions using the results of a given analytical method for each element that gave the greatest accuracy for that element. In all cases except one, the discrepancy between total cation and anion equivalents was less than 5% of the sum.

The major components and some important minor components in solution were used as input to the distribution of species stage of the FASTPATH code, and checks made on the internal consistency of pH, alkalinity, Eh, sulfide/sulfate and CO_3^{2-}/HCO_3^- pairs. With minor exceptions, results were good. Isotopic analyses for D/H, $^{13}C/^{12}C$, $^{18}O/^{16}O$, and ^{3}H were also determined. However, ^{14}C analyses were not performed owing to initial problems with the procedure used to separate carbonate from solutions.

Analytical development of isotope measurement techniques using the 88-inch cyclotron at LBL demonstrated the feasibility of measuring ^{14}C in CO_2 evolved from one liter samples. The detection of ^{36}Cl was also attempted, and a limit of 10^{-12} for $^{36}Cl/^{35}Cl$ was achieved with possibilities of improvement using a new ion source. Measurement of the $^{234}U/^{238}U$ ratios on the water samples is continuing using a 5 foot radius high-precision mass spectrometer. A precision of about 2% is adequate for the $^{234}U/^{238}U$ ratio and can be achieved.

4. Conclusions and Recommendations

An evaluation of the chemical analyses in terms of their origin, history, and age are not possible owing to the small number of samples taken, the incomplete isotopic analyses, and the diversity of regimes from which the samples were obtained. No spatial relations between samples can be worked out until more samples have been obtained and analyzed, over more horizons, and over a greater areal extent of the Pasco Basin. However, the work done to date leads to the following recommendations.

1. Because of the low concentration of many important components in the deep waters of the Pasco Basin, great care should be taken in avoiding contamination both during and after sampling.
2. Drilling methods that minimize contamination of aquifers should be used.
3. On-site contamination monitoring should be developed using tracers incorporated in the drilling fluids.
4. All sources of contamination should be identified.
5. Downhole sampling devices should be designed and constructed that eliminate contamination from that source.
6. Collection procedures for carbonate samples for ^{14}C analysis should be improved.
7. Improved isotopic techniques requiring smaller samples should continue to be developed; this applies particularly to ^{14}C, ^{36}Cl, ^{81}Kr and $^{234}U/^{238}U$.
8. Discrepancies in species distribution based on alkalinity measurements and chemical analyses should be resolved.
9. More accurate methods of determining oxidation potential in groundwaters from Hanford should be developed.
10. A more sensitive technique for analyzing aluminum in solution should be developed, particularly in the presence of large amounts of fluoride ion.
11. Soluble organic components, and Li, B, NH_4^+, and P_2O_5 should be analyzed to determine their significance.
12. More sensitive gas detection and analytical techniques should be developed.

D. Review of Hanford Well Logs

The work performed in 1978 consisted of a review of pre-existing well log data and data obtained during the year by other Rockwell subcontractors. The well logs at Hanford can be used in several ways to aid the hydrology program:

(1) to examine rock properties, such as porosity, density, and fracture character, on a continuous coverage basis;

(2) to delineate zones of fluid flow;

(3) to correlate geologic units between wells.

Figure 10 demonstrates the response of four standard logs to the basalt in the 2800 - 3400-foot interval in Well DC-1. As porosity increases, all quantities measured by the four sondes deflect to the left. For example, the large deflection from 2950 to 3000 feet is an interbed of much higher porosity than the dense basalt below, from 3000 to 3180 feet. Currently, it is not possible to accurately quantify the porosity because all the sondes are calibrated for sedimentary sequences. Further work with the available logs and core could soon overcome this problem.

Figure 11 shows temperature logs and flow profiles from the entire 5000-foot length of hole DC-1. Breaks in the temperature gradient occur where fluid has left the wellbore and entered the formation, thereby cooling the rock below the temperature dictated by the geothermal gradient. These temperature breaks are confirmed by the flow profiles, which were obtained with the radioactive tracer technique. With this method the downward velocity of the borehole fluid is measured by injecting a tracer into the water column and detecting its transit time past detectors in the sonde. The abrupt drops in velocity occur where fluid leaves the wellbore and enters the formation. The obvious zones in Figure 11 were detected on several logs run at different times, confirming the validity of the methods.

In the course of the review it became clear that the hydrology program would be assisted by a greater effort in well log interpretation and a coordinated program in acquiring new logs. Among the recommendations are:

- routinely obtain flow profiles in all new holes, with the spinner tool appearing to be the preferred method;
- establish a reliable method of quantifying the porosity in the basalt;
- composite the existing well logs and auxiliary data onto base sheets;
- continue to pursue those logs, such as spectral gamma and magnetic susceptibility, which promise correlative geological data among holes.

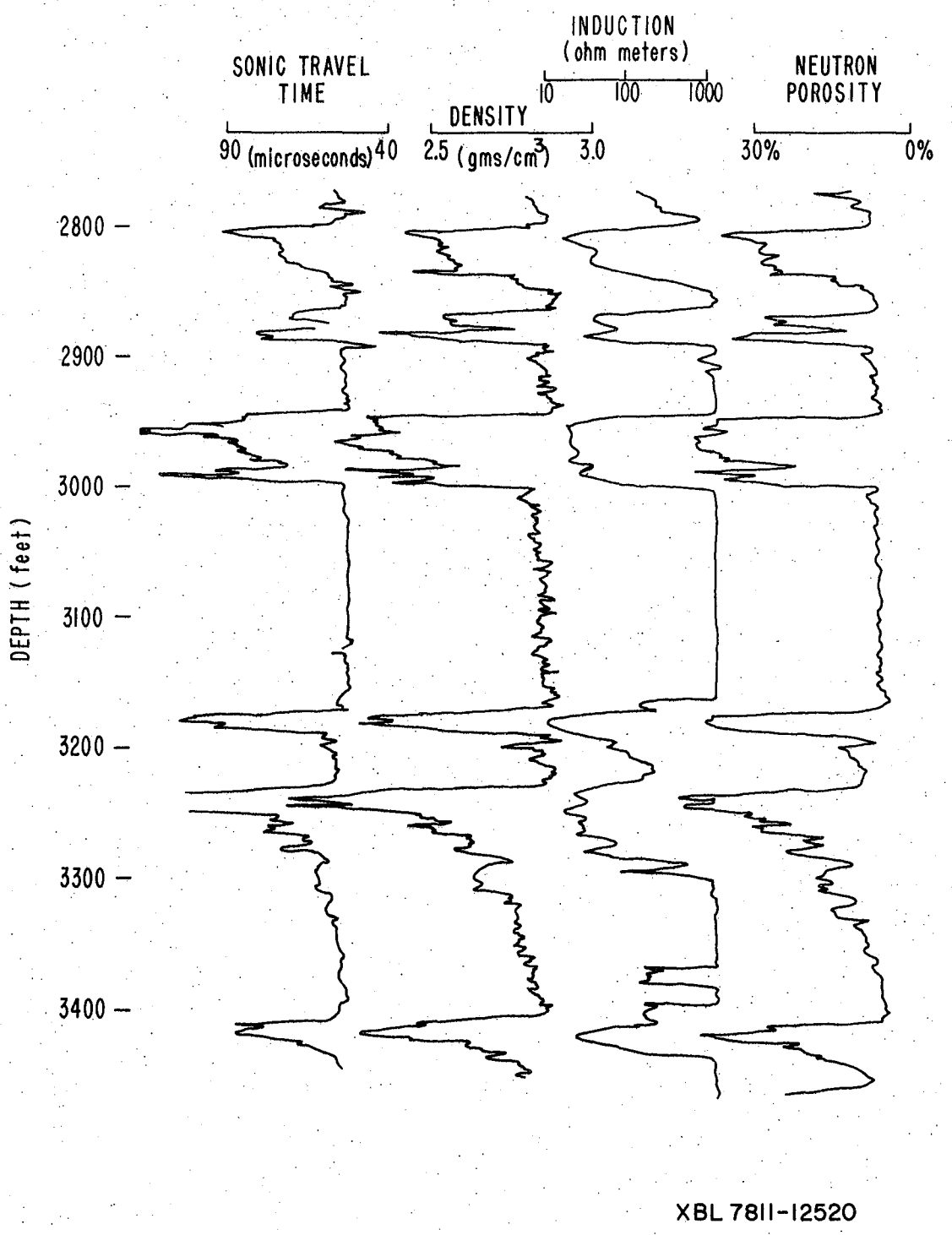

Figure 10. Four porosity-type logs in Well DC-1.

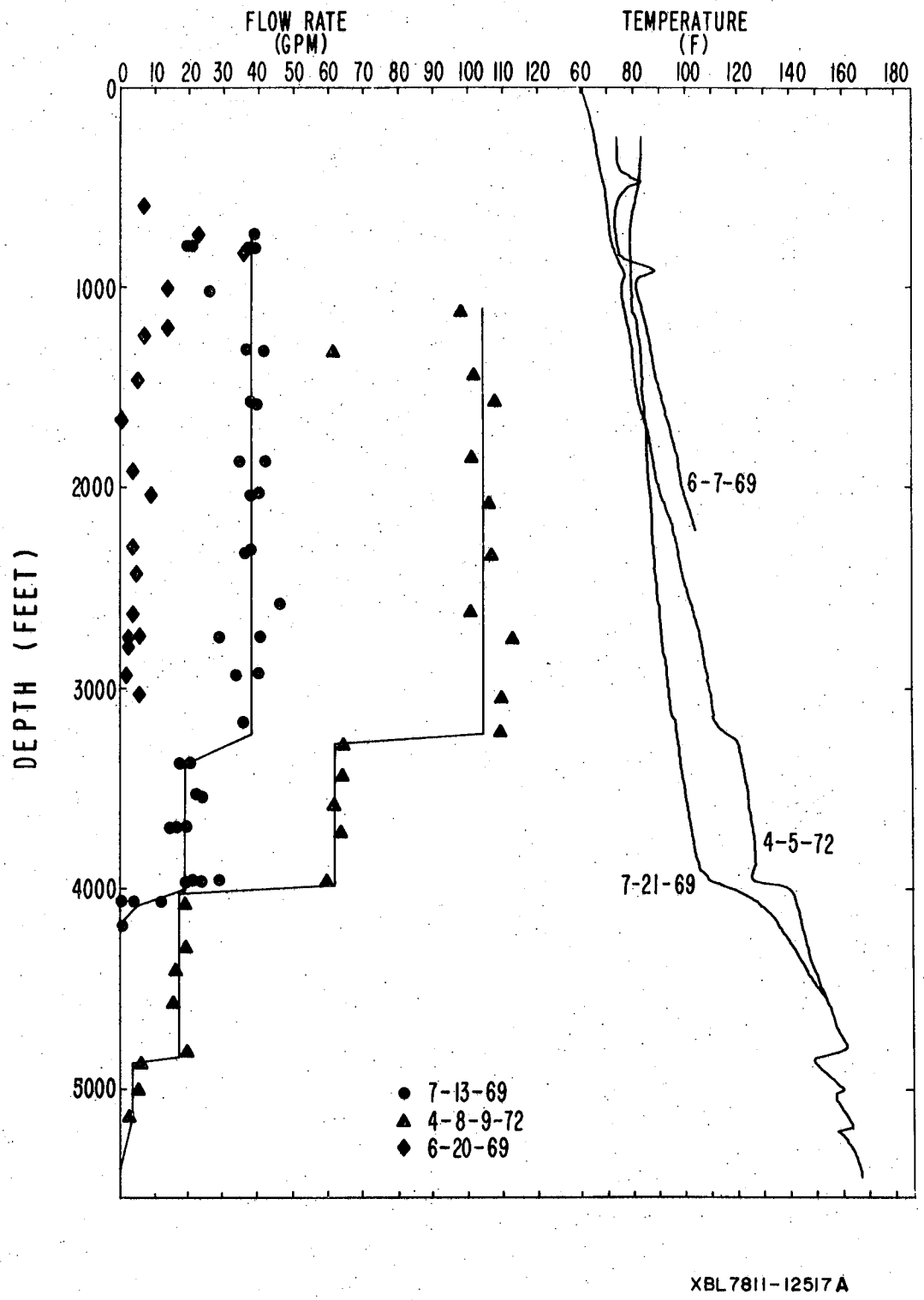

Figure 11. Summary figure of anomalous flow zones in Well DC-1.

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Volume II: Final Report

J. Apps, T. Doe, B. Doty, S. Doty, R. Galbraith,
A. Kearns, B. Kohrt, J. Long, A. Monroe,
T. N. Narasimhan, P. Nelson, C. R. Wilson, and
P. A. Witherspoon

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SUMMARY

A field testing program designed to provide data for mathematical modeling of groundwater flow in the deep basalts of the Pasco Basin near Richland, Washington, was initiated in FY 1978. This study is part of a larger Department of Energy program to evaluate the feasibility of nuclear waste storage in deep mined caverns on the Hanford Reservation. A technical approach for obtaining the required field information was developed based upon the integration of hydrological, geophysical, and geochemical data gathered from a number of deep wells scattered throughout the basin. A full hydrology testing program was planned for implementation over a period of several years. Included in this program were: pressure measurements to determine hydraulic potential gradients; tracer tests to determine flow direction and velocity; borehole fracture logging to quantify the geometric parameters of the fracture systems; hydraulic fracturing to determine in-situ stress conditions, and a wide variety of permeability tests on both multiple and single fractures. Finally, a modular-type long-term monitoring system was recommended for development and installation in selected wells.

Implementation of the testing program began with the design and fabrication of a test probe capable of measuring pressure and permeabilities at depths up to 5000 feet. As an interim measure to expedite initiation of field work, a single-function pressure test probe originally designed by LBL for another project was fabricated and equipped for use in well DC-2 to depths of 3300 feet. An ambitious field program for performing tests in eleven deep wells was laid out in March 1978 based upon drilling schedules provided by Rockwell Hanford Operations earlier in the year.

Delays in the drilling schedule, a delay in the arrival of the support rig and field test equipment, and inadequate funds to provide a second support rig required a curtailment of the planned program. Hydrological tests were performed in wells DC-2, DC-6, and DC-8 between May and October, geochemical sampling was performed in DC-2 and DC-6, and hydrofracturing tests were performed in DC-11. In addition, earlier hydrological and geophysical tests performed by others were reviewed and evaluated in interpretation of test results.

Tests performed in DC-2 and observations of water level response in neighboring DC-1 suggest the possibility of leakage between the three lower

piezometers in DC-1. The conclusions are generally supported by earlier work performed by others in DC-1 and indicate the presence of a downward gradient in the upper basalt layers extending to a depth of about 4000 feet, beneath which there is evidence for an upward gradient. A sharp steepening of the downward gradient in the vicinity of the Umtanum Unit suggest that the Umtanum may be acting as a barrier to vertical flow. Ambiguities in available data immediately below the Umtanum suggest the need for additional testing.

Drilling was suspended for about one week to permit pressure testing in well DC-8, in the basalts above the Vantage sandstone. These tests were performed between 1700 and 2700 feet of depth and indicate a downward gradient within that interval. Water level elevations were found to be higher and downward gradients steeper than in comparative lithologic units in wells DC-1/DC-2.

Well DC-6 was found to be artesian, with a steady-state openhole production rate of about 17 gallons per minute. Single-packer tests showed that about 75 percent of this flow was coming from the depth interval 3650-3800 feet. Pressure tests were performed between 2200 and 4300 feet of depth, and indicate artesian conditions in every zone tested with total heads ranging from 20 to 60 feet above ground surface. Water level elevations measured in the Grand Ronde basalts in DC-6 were higher than water levels measured in the same stratigraphic zones in DC-1/DC-2. As in DC-1/DC-2, there appears to be a local head minimum within 600 feet below the bottom of the Umtanum with higher heads at greater depth.

Comparison of data from the three wells tested indicates that the Gable Mountain anticline may be acting as a flow barrier separating Cold Creek Valley from the Columbia River Valley to the north and east. Recharge to the deep basalts in Cold Creek Valley appears to be small, with drainage probably occurring to the southeast, roughly parallel to the trend of the Cold Creek syncline. The lowest pressure head elevation measured in DC-2 was about 360 feet, which supports earlier contentions by La Sala and Doty (1971) that the deep flow systems in this vicinity may be discharging to the Columbia River, probably at or below the Tri-Cities area. Additional drilling and testing will be required to verify these hypotheses.

The groundwater chemistry program has provided data on four springs, the Columbia River and three flowing artesian wells. The limited number of

samples taken in FY 1978 does not allow any regional interpretation. Data is also presented for DC-2 but the presence of tritium at 20 percent of the Columbia River value indicates contamination of the packed-off zone by drilling fluids. This level of contamination was still present after swabbing approximately 64,000 gallons of water from the packed-off zone over an 8-day period.

A literature review and evaluation of previous groundwater studies at Hanford is presented. The scarcity and uncertainty of this data, combined with the experience of the FY 1978 LBL study, emphasizes that contamination problems must be overcome in deep-drilled wells before representative information can be reliably obtained. Procedures and techniques are recommended for development to aid in the sampling, analysis, and interpretation of groundwaters in this report.

A summary of recommendations is presented for a continued well drilling and testing program at Hanford. Specific drilling and testing schedules for FY 1979, based on completion of a rough model of the deep flow systems by 1980, were presented in Long and Wilson (1978). The program recommends continuation of a basin-wide approach to hydrological studies to permit identification of hydrologically-optimum repository sites. Subsequent second-stage studies are also recommended for refinement of available data.

Recommendations are given for refinement of hydrology testing equipment and procedures based upon experience gained in FY 1978 field operations. The need for the multiple-packer test probe which had been planned for FY 1979 was made evident by FY 1978 field results. Such equipment will allow control of pressure pulses due to packer inflation, and will provide additional checks on the effectiveness of the packer seals. Experience has also indicated that considerably longer testing times, on the order of days or perhaps weeks in tight formations, will be required to obtain accurate pressure data.

Finally, recommendations are made regarding a comprehensive technical approach to the collection and interpretation of data from a deep fractured reservoir. These recommendations include the development of specialized equipment and techniques for in-situ pulse testing of single fractures, for injection and tracer testing of multiple fractures, for downhole identification of the statistical parameters governing fracture system geometry, and for long-term pressure and geochemical monitoring.

I. INTRODUCTION

A study of the hydrology of the Pasco Basin near Richland, Washington, was initiated by Lawrence Berkeley Laboratory for Rockwell Hanford Operations (Rockwell) during Fiscal Year 1978.* This work was part of a long-term feasibility study conducted by Rockwell's Basalt Waste Isolation Program for the National Waste Terminal Storage Program of the Department of Energy on the feasibility of nuclear waste disposal in the Columbia River Basalt underlying the Hanford Reservation.

The Hanford Reservation lies within the Pasco Basin near the center of the Columbia River flood basalt physiographic province, which spans parts of Washington, Oregon, and Idaho (Figure I-1). The generalized basalt stratigraphy within the Pasco Basin is shown on Figure I-2. The overall feasiblity study has been directed to the concept of a mined repository at a depth of about 3000 feet, possibly in the Umtanum Unit, dense, 200-foot thick basalt flow. The feasibility of this concept largely depends on the degree of hydrologic isolation afforded by the basalts. Hydrologic isolation can be determined only by actual field testing and subsequent modeling.

In October 1977 a work plan was formulated which included three hydrologic subtasks: Physical Testing, Geochemical Sampling, and Numerical Modeling. LBL performed hydrologic testing on several deep drill holes on the Reservation and obtained and analyzed water samples from drill holes and surface water. Progress on these three subtasks through September 1978 is presented in this section. In addition to these subtasks an analysis of existing geophysical data and a recommended well drilling and testing program for Hanford are summarized here. Recommendations for further field tests and hydrologic investigations are presented in Appendix A. Hydrologic work by LBL in the project was terminated at the end of FY 1978.

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*Other FY 1978 work by LBL on waste isolation for Rockwell is reported in separate volumes: Benson et al., (1979) and DuBois, et al., (1979).

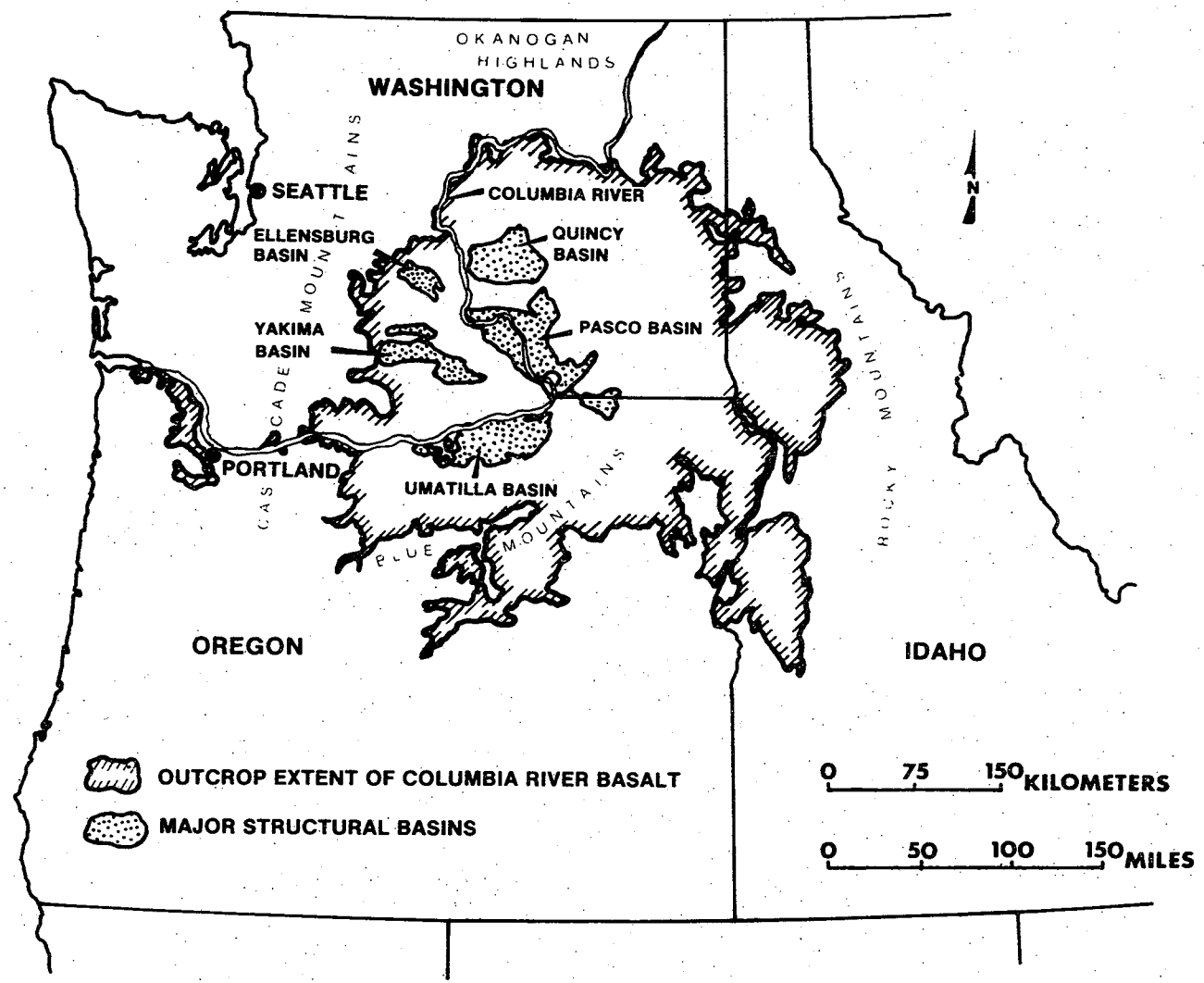

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Figure I-1. Location map of the Columbia River basalt.

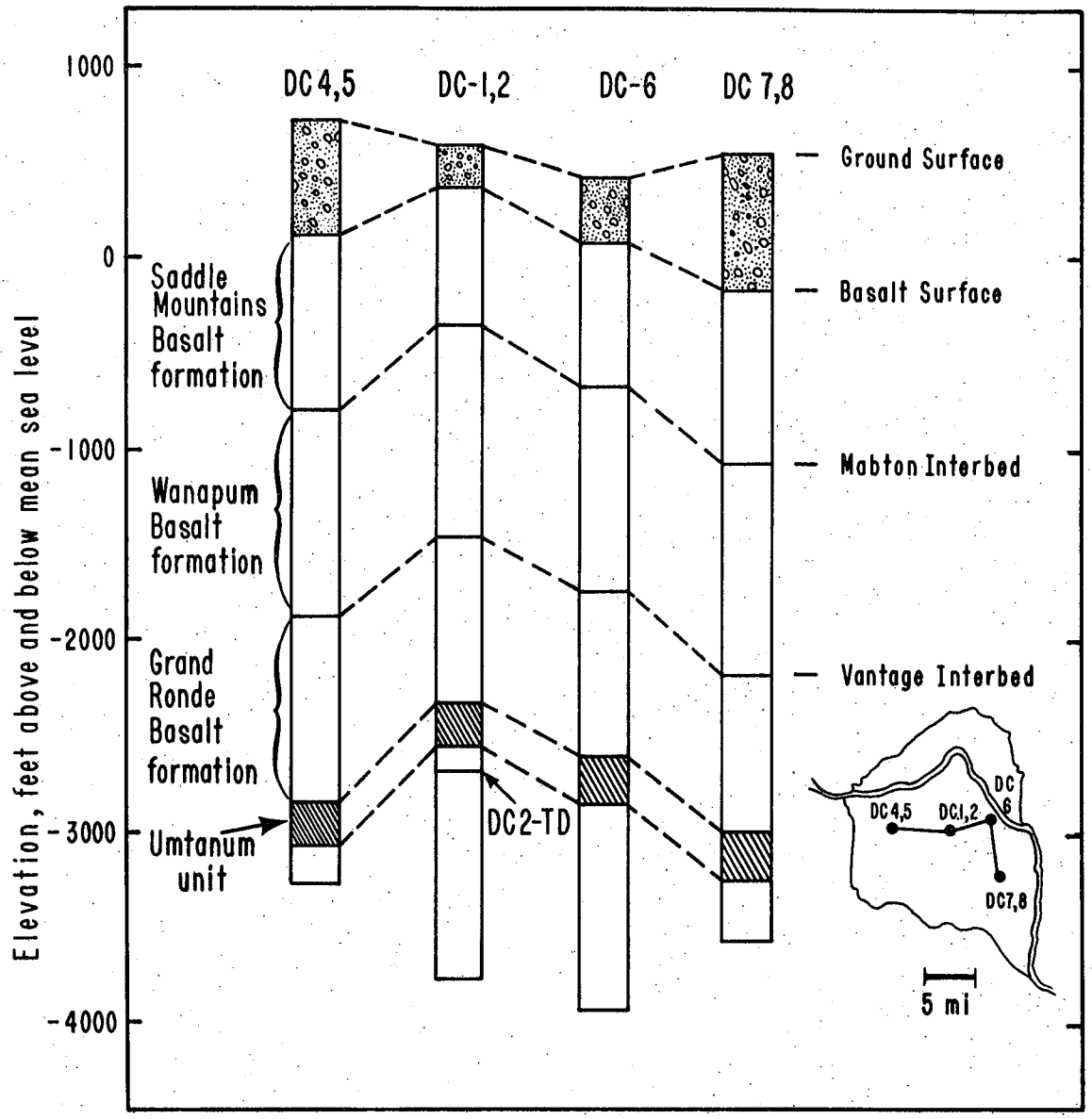

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Figure I-2. Generalized basalt stratigraphy within the Pasco Basin.

II. PHYSICAL TESTING

A. TECHNICAL APPROACH

1. Hydrology Equipment Development

During FY 1978 LBL designed down-hole instrumentation and packer systems for pressure, temperature and permeability testing. The systems assembled include:

a) Packer systems with independent inflation lines.

b) A single pressure transducer formation pressure instrument.

c) A double pressure transducer instrument with downhole valves for packer and test zone pressure relief for use in both injector tests and formation pressure measurements.

d) A pressure tank for constant head injection tests.

a. Packer System

The packer system consisted of two inflatable packers with an inflation line separate from the testing rod. This separate inflation line allows the packers to be reset without removing them from the hole thus saving considerable workover rig time. The original packer choice was the Lynes 2 5/8 inch element modified for use with separate inflation lines. The Lynes element was chosen for its proven durability, its differential inflation pressure in excess of 4000 psi, and its long packer seal length. Tigre Terra NX packers, which are also a steel reinforced inflatable type, were used prior to deliver of the the Lynes packers but they could only withstand a 600 psi pressure differential. In four inch holes, LBL found that NX packers were unusable after approximately four inflations.

b. Pressure Probe 1

A schematic drawing of Pressure Probe 1 is shown on Figure II-1. The downhole electronics consisted of a C.J. Enterprises pressure transducer and a thermistor. A four conductor cable from the probe to the suface allowed continuous monitoring of temperature and pressure. The surface electronics consisted of a power supply for the transducer, a data logger capable of recording all channels at programable time intervals, and a single pen strip chart recorder. A schematic drawing of the entire test setup is shown in

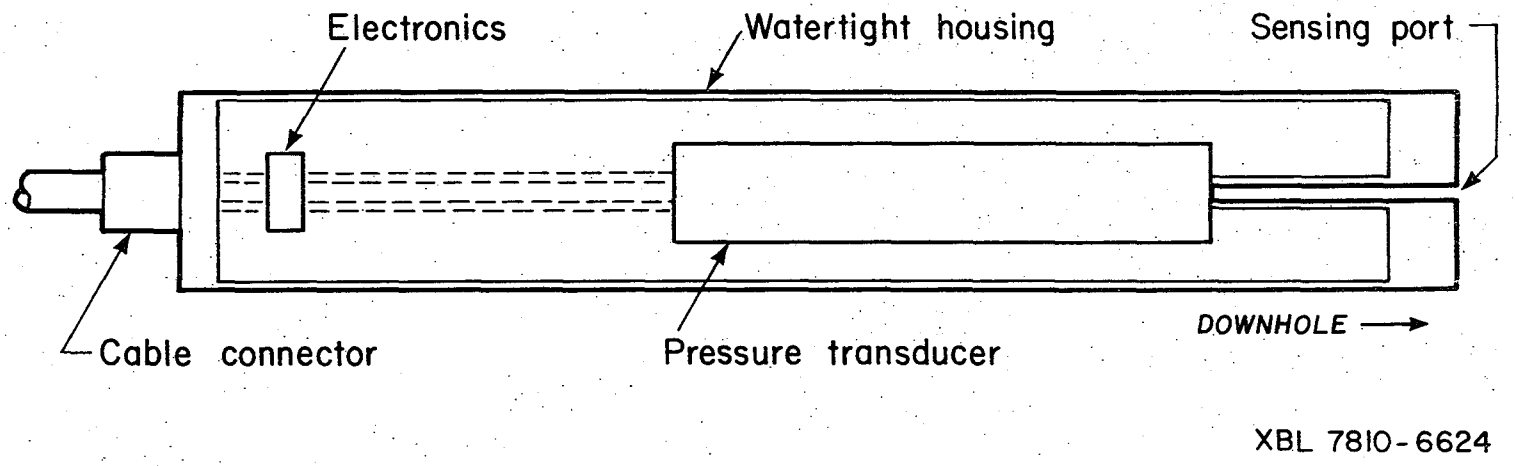


Figure II-1. Schematic drawing of pressure probe no. 1.

Figure II-2. Pressure Probe 1 lacks a downhole packer release, therefore its use is limited to water depths where air can be used for packer inflation.

A typical test consisted of lowering the system to the test zone, inflating the packers, and recording the shut in pressure until it reached a stable value. Since the pressure equilibration depends only on flow into or out of the rock due to the compressibility of water, equilibration is more rapid than in test systems that rely on measurement of a water level in a standpipe.

Figure II-3 shows the typical shape of a pressure test record using Pressure Probe 1. A major factor in the length of time required for the test is the packer inflation pressure pulse. The magnitude of the pressure pulse is a function of rock permeability. This pulse may be avoided by a valve downhole which bleeds the test cavity. This feature was incorporated in the Injection-Pressure Probe discussed below.

c. Injection-Pressure Probe

This probe was designed to perform injection tests as well as pressure tests and is shown schematically on Figure II-4. The major features of the Injection-Pressure Probe are:

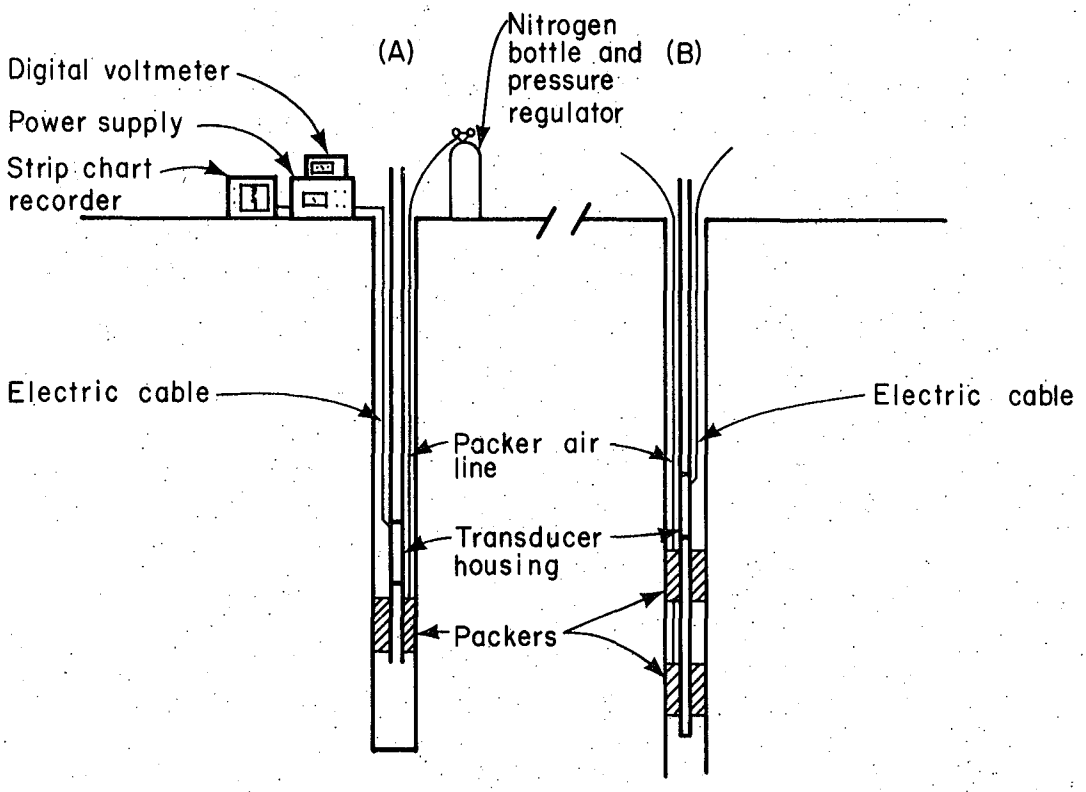
(a) A downhole solenoid valve to deflate water inflated packers.

(b) A downhole solenoid valve to bleed the test cavity.

(c) An extra pressure transducer for monitoring packer pressure, easily adaptable for both pressure measurement and injection permeability tests with a simple change of parts.

The two solenoid valves are manufactured by Circle Seal Corporation of Anaheim, California, and their 1 1/2-inch diameter makes them suitable for use in slim hole probes. The solenoid valve used to deflate the packers downhole is backed up by a Lynes circulating valve which opens at a pressure determined by the strength of a shear pin. Should the solenoid valve fail, the packers can be released by increasing the packer pressure until the pin shears and this Lynes valve opens. With this downhole packer release, the probe can be used with water inflation and is therefore operational to greater depths than Pressure Probe 1. When operated for constant head injection tests, the lines for the pressure bleed are removed.

The electronic control system is designed to supply constant voltage to the pressure transducers and solenoid valves in the probe. The probe also contains a temperature sensitive diode which is read in degrees Kelvin on the



A. Single packer arrangement for bottom hole pressure measurement.

B. Double packer arrangement for pressure measurement in discrete zones.

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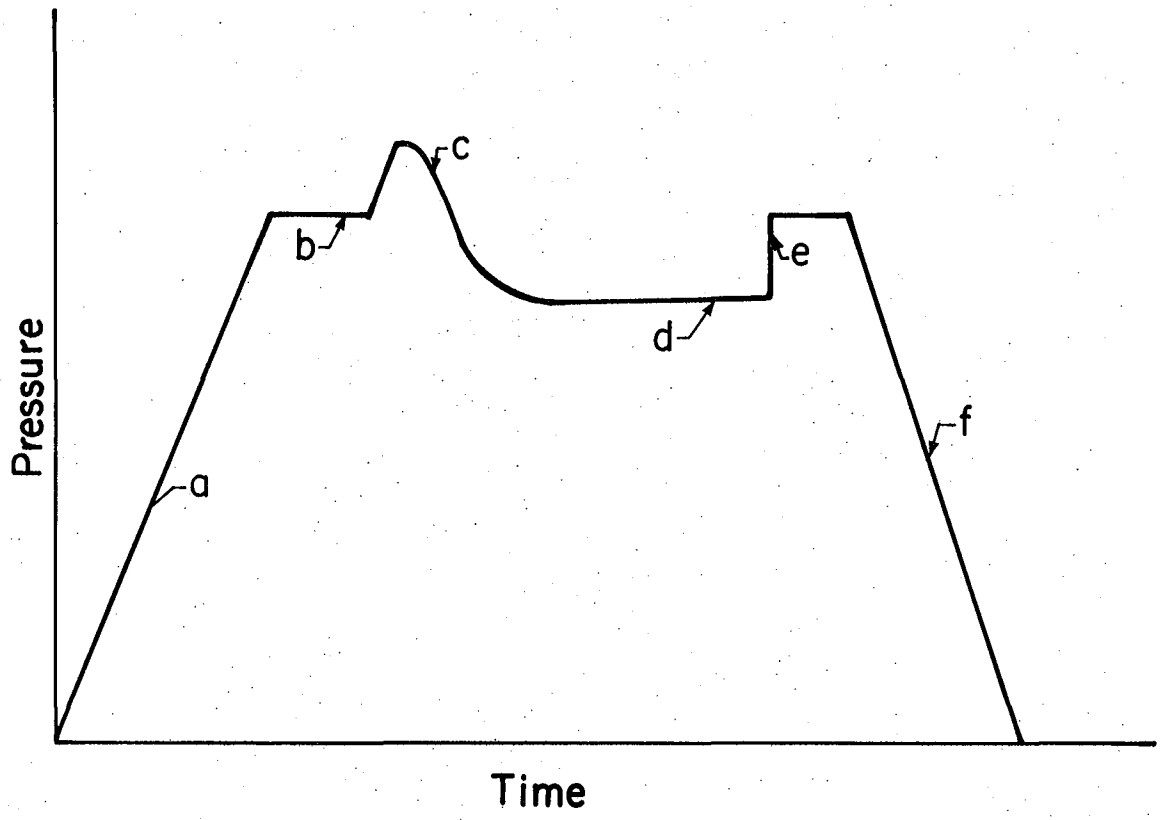
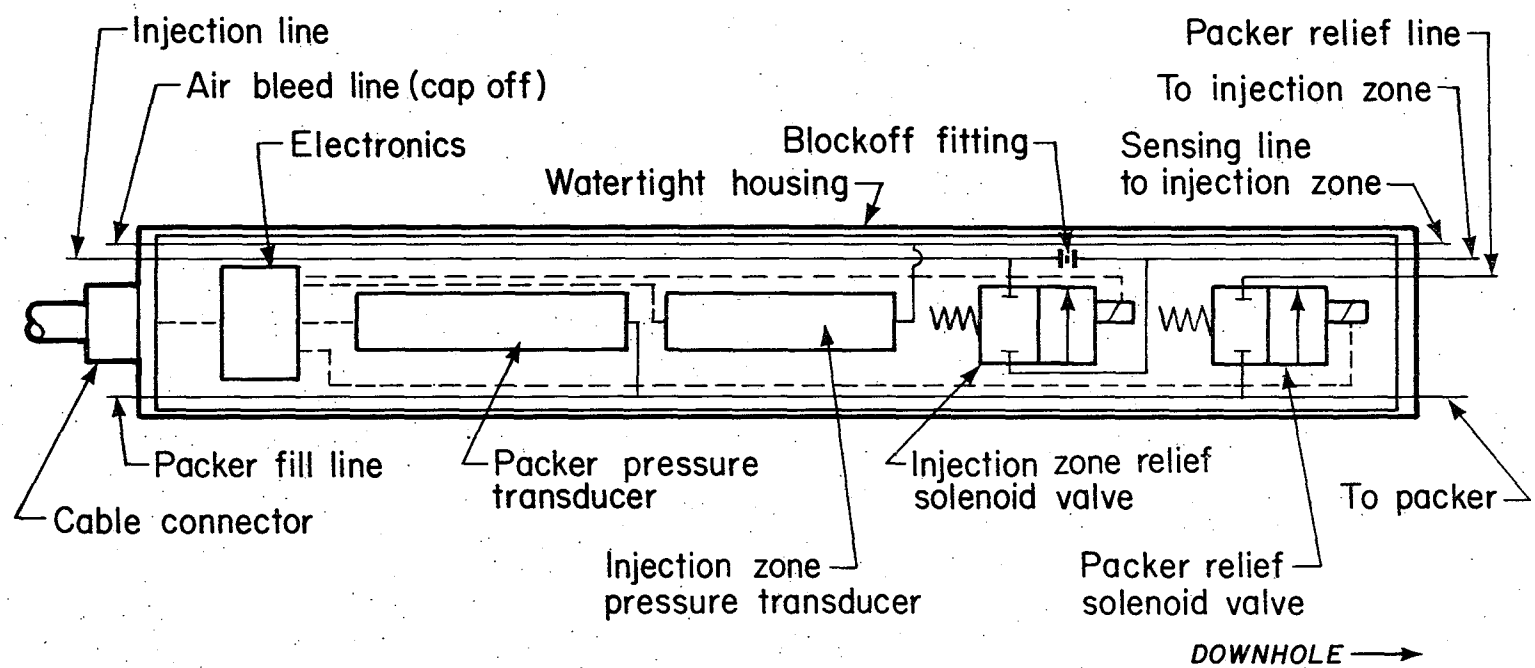
Figure II-2. Schematic drawing of pressure test setup.



XBL788-2628

Figure II-3. Typical shape of pressure test record
a) running into hole
b) reach test zone
c) inflate packers
d) reach stable pressure
e) deflate packers
f) running out of hole



XBL 7810-6625

Figure II-4. Schematic drawing of injection pressure probe.

digital voltmeter mounted in the control box. The uphole electronic controls for this instrument are the same as those of Pressure Probe 1 with the addition of switches for the solenoid valves. The schematic for this injection test system is given in Figure II-5.

d. Injection Pressure Tank

An injection pressure tank has been designed to supply water to constant head injection tests. The driving force for the water is compressed air applied through the top of the tank. The water is supplied without the surges one would get from most pumps, especially at low flow rates. Flow rates can be measured in three ways:

(1) By monitoring the change in the water level in a side mounted standpipe.

(2) Using a differential pressure transducer ported at the top and bottom of the tank.

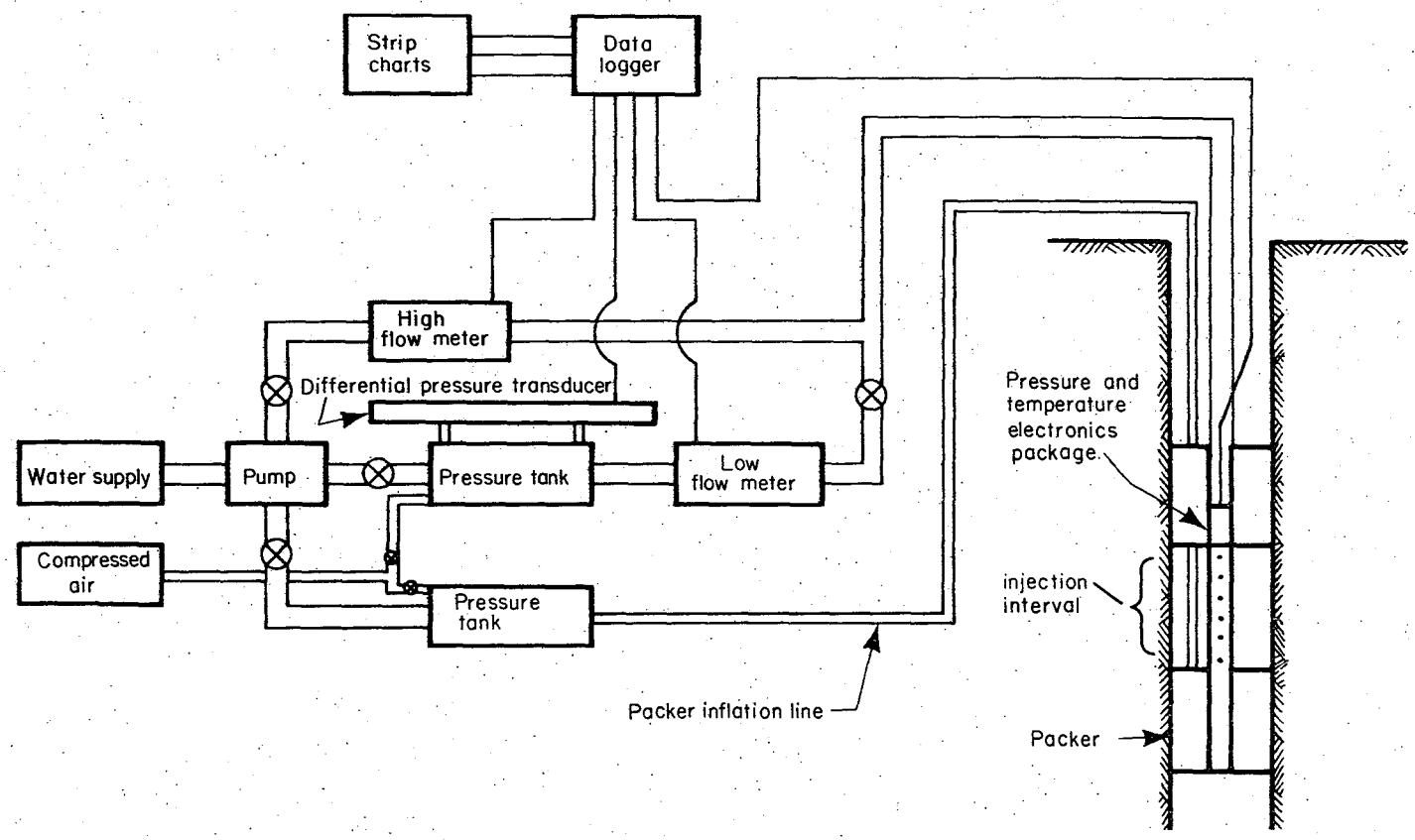
(3) Using electronic flow transducers.

Two electronic flow transducers, manufactured by Flow Technology of Phoenix, Arizona, allow measurement of flow over a range of 0.001 to 20 gallons per minute. The relative location of the injection pressure tank within the injection test system is shown on Figure II-5.

2. FY 1978 Field Activites

Rockwell's proposed drilling schedule for the 1978 fiscal year was received by LBL in January 1978 and is shown on Table II-1. Wells DC-4, DC-5, DC-6, DC-7, and DC-8 were to be completed during the year. Specifically, DC-7 and DC-5 were to be rotary drilled from October 1977 through February 1978, and the remaining wells were to be cable tool and core drilled from December 1977 through August 1978. To complete this drilling program, two core rigs were employed for most of the 1978 fiscal year. Also, one workover rig was to be employed to facilitate the hydrology testing program from May 1st to the end of the fiscal year.

In March 1978 LBL proposed a hydrology testing schedule based on Rockwell's proposed drilling schedule. This schedule is shown on Table II-2 and consisted of pressure tests, geochemical sampling, and/or permeability tests in DH-4, DH-5, DC-2, DC-3, DC-4, DC-5, DC-6, DC-7, DC-8, DC-10, and



XBL 7810-6622

Figure II-5. Schematic drawing of injecting testing equipment.

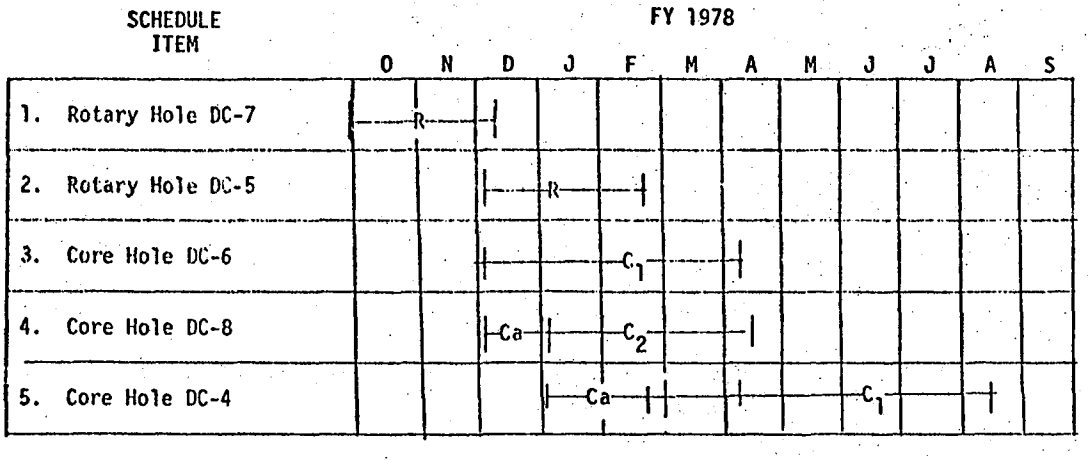
TASK	Drilling and Coring
SUBTASK	Drilling of Core and Rotary Boreholes at Sites 1, 2, and 3 (Figure IV-1)

MILESTONES

FISCAL YEAR 1978

OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP
		▲ 1		▲ 2		▲ 3 4				▲ 5	

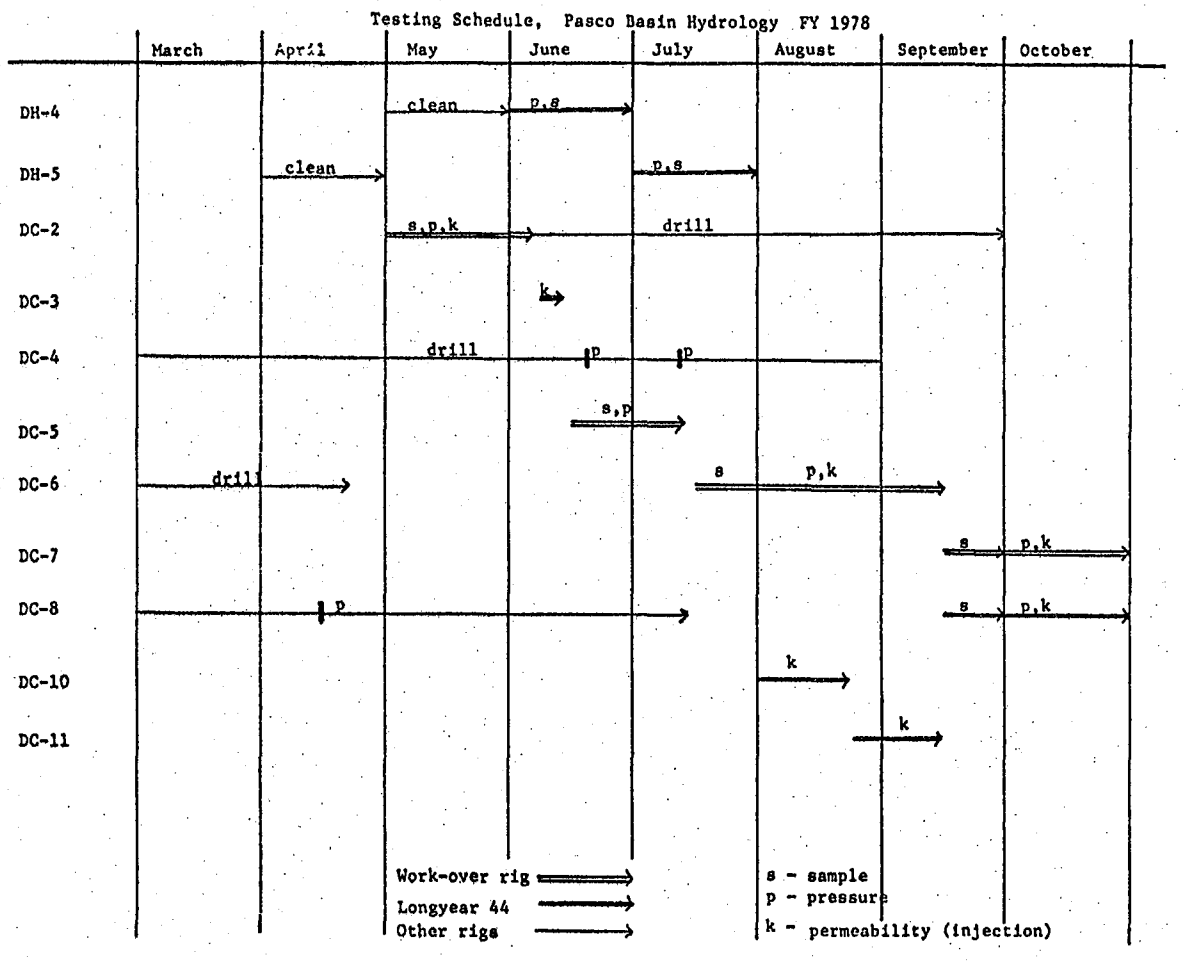
1. DC-7 completed.
2. DC-5 completed.
3. DC-6 completed.
4. DC-8 completed.
5. DC-4 completed.



C_1= CORE RIG 1 Ca = CABLE TOOL R = ROTARY
C_2= CORE RIG 2

XBL 794-9381

Table II-1. Rockwell Hanford Operations, January 1978 Draft drilling program schedule (from RHO-CD-132, 1978, Rough Draft).



XBL 794-9380

Table II-2. Lawrence Berkeley Laboratory March 1978 proposed hydrology testing program.

DC-11. Specifically, DH-4 and DH-5 were to be cleaned in April and May and pressure tested and geochemically sampled in July. DC-10 and DC-11 were to be permeability tested (by injection) in August and September, and the remaining wells were to be variously tested and sampled in sequence from May through October. Three field crews were planned to do this work, and the work-over rig plus one other rig, on a part-time basis, would have been needed to assist them.

The actual FY 1978 work plan was quite different from the proposed FY 1978 work plan and is shown on Table II-3. This difference was caused by delays in the drilling schedule, a delay in the arrival of the work-over rig, insufficient funds to provide a second support rig, and delay in fabrication of test equipment at LBL. The actual field program consisted of pressure testing DC-2, DC-8, and DC-6, geochemical sampling of DC -2 and DC-6, and hydrofracturing of DC-11.

The hydrology field crew arrived in Hanford on May 15th to set up the equipment for the first test. From May 22nd to May 24th, DC-2 was cleaned using a wire brush attached to the drill pipe and by circulating the well with fresh water. Also during this time the pressure test apparatus was assembled and tested. On May 25th, the pressure probe and double packer assembly was lowered downhole to a depth of 1100 feet and tested. At this point a bad electrical connection was found and the assembly was taken back out of the well. On May 26th, the electrical connection was fixed, and the pressure test equipment was run down to the first test interval. During the next week, a total of eleven zones were pressure tested. These zones were mostly flow tops and rubble zones. Pressure testing was completed on June 5th.

The geochemical sampling crew arrived in Hanford on June 1st to set up the geochemical laboratory trailer for testing in DC-2. On June 13th a Lynes production-injection packer system with a 30 foot straddle zone was run into DC-2 on 2 1/16-inch drill pipe to the first sampling interval depth of 3243 - 3273 feet. This packer assembly had to be taken back out of the well when the circulating valve failed to open. In releasing the packers, the bottom packer's rubber element was torn too badly to use again. On June 14th, the shear pins were adjusted on the circulating valve, the packer's rubber element was replaced, and the assembly returned to the sampling interval. The swabbing process was then started, and water samples were taken at

Well	1978							
	March	April	May	June	July	August	September	October
DC-2				p, s				
DC-4	cable tool drilling				core drilling			
DC-6	core drilling						p	
DC-8	core drilling			p	core drilling			
DC-11					h			
Springs						s		

Workover rig ⟹

other rigs ⟶

p - pressure

s - geochemical sampling

h - hydrofracturing

XBL 794-9379

Table II-3. Final Lawrence Berkeley Laboratory FY 1978 hydrology testing program.

regular intervals. These water samples had a pH of 9.8 - 9.9 and appeared to be contaminated with diesel fuel. Water levels were monitored in DC-1 piezometer #3 during the swabbing to obtain a qualitative estimate of the permeability of the test zone. On June 26th, LBL discontinued swabbing at Rockwell's direction so that Science Applications Incorporated (SAI) could begin permeability testing. Ten days of swabbing were insufficient for removing the apparent cutting oil and diesel fuel contamination. Since no time was available for further swabbing, a contaminated sample was taken. In coming out of the hole the lower packer became stuck possibly due to caving of the formation during swabbing. The tubing broke and fishing proceeded for one day with no success.

On June 14th, drilling to the Vantage Member was completed in Well DC-8. On June 15th, the hydrology field crew assembled, tested, and ran the pressure test equipment into the well to the first test interval. It was then discovered that there was an air line leak based on the transducer output and the tank's pressure regulator readings. The equipment was pulled out of the hole to fix the leak, but in the process the air and electrical line slipped along the drill tubing and became tangled around the probe. The resulting damage consisted of a severed electrical line, kinks in the electrical cable, and a few punctures in the air line. On June 16th, the damage was repaired, and the first pressure test was started. There were nine pressure intervals chosen, all of which were flow tops and rubble zones. Both of the packers failed after testing the interval at 2235 - 2265 feet. At this time the equipment was pulled out of the well, replaced, and then run back downhole to test the last two intervals. On June 20th the testing in DC-8 ended.

From July 5th to July 9th the hydrology field crew assisted in hydrofracture testing in DC-11 to acquire field stress data. Dr. B. Haimson of the University of Wisconsin supervised the testing, and Hatch Drilling Company provided the required cable tool rig. The first two days were spent setting up and testing equipment. On July 7th, the double packer assembly was sent downhole and the first two intervals were fractured. On the third test the packers did not deflate due to the water pressure in the inflation line. The packer was freed by filling the hole with water while pressurizing the test interval with air. In subsequent intervals, the problem was eliminated by using two inflation lines, and driving the water out of the packers with air. A total of six intervals were pressurized at depths of 55, 144,

172, 194, 200, and 226 feet. Caving of the hole in the Selah bed prevented deeper tests from being performed. Impressions of the hydrofractures were then made; these were oriented using a gyrocompass survey tool operated by an engineer from Sperry Sun.

From July 21st to August 13th the geochemical sampling field crew collected spring samples from locations in and surrounding the Pasco Basin. Specifically these samples were collected from:

(a) DC-6 (artesian flow) on July 21st.

(b) The Columbia River at the "Old Hanford Townsite" on July 25th.

(c) Juniper Spring at Umtanum Ridge on July 23rd.

(d) Rattlesnake Springs at Dry Creek by Battelle's radioecology field station on July 31st.

(e) Benson Spring at Rattlesnake Hills on August 1st.

(f) Bennett Spring at Rattlesnake Ridge on August 3rd.

(g) Ford Well (artesian flow) at Cold Creek Valley on August 11th.

(h) McGee Well (artesian flow) at Cold Creek Valley on August 13th.

Sample treatment and field analysis was then done in the geochemical laboratory trailer.

From July 10th to August 15th no hydrological testing was done due to the unavailability of the workover rig. On July 13 a packer was set at 30 feet depth in Well DC-6 and a flow meter installed. Artesian flow from DC-6 was thus monitored until August 11th.

On August 5th the workover rig arrived at DC-6 and a wellhead was installed to control flow. On August 15th the hydrology crew assembled, tested and ran a single Lynes packer to 2240 feet. An air line leak was then detected by observing the N_2 tank pressure drop and the air lift of water from the well. While bringing the equipment back out of the well, the air line was snagged by sharp edges on the casing, and the packer broke off and dropped to the bottom of the well. The casing was then inspected and found to be badly worn. The next two weeks were spent replacing worn casing to a depth of 1110 feet. On August 29th pressure testing was resumed. Test intervals were chosen because they were either:

(a) Flow tops.

(b) Rubble zones.

(c) Poker chip zones (disced zones of numerous closely spaced, horizontal fractures).

(d) Zones noted for lost circulation or water outflow in the drillers' logs.

On August 29th four intervals were pressure tested. A fifth test was in progress when the tool failed due to a short circuit in the cable head. The tool was pulled out and the two transducer tool was run in to continue the pressure tests. On August 31st this tool also failed due to a leak. The cable head was replaced and the single transducer tool run into the hole on September 5th and 6th. The lower packer failed during inflation. This was replaced and pressure tests resumed with the single transducer tool on September 7th. Between September 7th and 11th five additional pressure tests were run. The lowest of these was at 3343 feet which, due to the length of the electric cable, was the maximum depth attainable with the single transducer tool.

On September 12th and 13th five flow tests using a single packer were run. Pressure and flow from the artesian well were measured from the zone below the packer. Only flow was measured from the zone above the packer.

From September 18th to 20th pressure/flow tests were run using the two transducer tool and a 30-foot straddle pipe between packers. Four pressure measurements were made followed by flow tests. The last test was completed by noon on the 20th. The tools were then pulled from DC-6 and the service rig released by LBL. This completed the FY 1978 field testing program.

B. DATA ANALYSIS

1. Hydrologic Field Testing

a. Introduction

Pressure tests are used to determine distribution of hydraulic potential in a groundwater system from measurements of groundwater pressure in isolated zones of boreholes. The pressure test consists of lowering a double packer, single transducer probe to a specified depth in a well, inflating the packers to about 300 psi over the water pressure in the hole, and then measuring the pressure in the isolated interval between the two packers. When the packers inflate, the water in the test interval is compressed, producing a pressure pulse which must decay before the pressure transducer measures the in-situ pressure. Detailed test procedures and equipment are discussed in Appendixes A and C. Pressure testing was performed in Wells DC-2 and DC-8 between

May 15, and June 20, 1978, and in Well DC-6 between August 15 and September 20, 1978. Well DC-6 was found to be artesian, and in addition to pressure tests, flow tests were also run on this well. The flow tests were run with both single and double packers, and the average permeabilities of the zones producing the artesian flow could be estimated by assuming steady state conditions.

b. Data Analysis

In analyzing test data, it is necessary to correct for the elongation of the drill tubing under its own weight, the location of the air-water interface within the probe, transducer calibration shift, the effects of temperature upon the transducer, and barometric pressure changes. Artesian flow in Well DC-6 permitted some procedural variations in data analysis which are discussed in the presentation of results from that well.

The depth of the probe was initially estimated by measuring the length of tubing as it lay on the ground to an accuracy of $\pm$ 0.01 feet. These depth data were then corrected for buoyant elastic stretching under the weight of the tubing in water. Hydril tubing with a 1.315 inch outside diameter, an 0.179 inch wall thickness, and a unit weight of 2.25 pounds per foot was used in all pressure tests. The steel is specified as N80, which has a modulus of elasticity of approximately 30×10^6 psi. For the range of depths covered in these tests, the correction for elastic stretching ranges from 0.12 feet to 0.42 feet. The magnitude of this correction becomes large enough to be significant only in those tests made with water-filled drill tubing. This correction was therefore only applied to certain tests in Wells DC-6 and DC-8.

The packer mandrel and lines leading to the pressure transducer from the test zone are unvented above the uppermost perforation in the straddle pipe, resulting in a volume of air being trapped below the transducer when the probe is lowered into the well. Assuming that the trapped air behaves as an ideal gas, it is possible to solve for the location of the air-water interface knowing the initial pressure and temperature, the geometry of the conduit leading to the transducer, the downhole pressure, and the downhole temperature. The magnitude of this correction ranges from 0.66 feet to 0.91 feet.

A correction for transducer calibration shift was required in the reduction of DC-2 data. Testing was performed as a single trip operation in this hole, and calibrations could only be performed at the start at the end of the test series. The calibrations were separated in time by 12 days and varied in slope by 3 psi per volt. This slope variation corresponds to ± 7 psi at 1000 psi and ± 9 psi at some of the higher pressures encountered. This means that water levels computed using both calibrations may vary by as much as 40 feet in extreme cases. For the analysis of the DC-2 data, a linear variation in time between the two calibrations was used. Only one calibration was made during the testing of DC-8, and this calibration was used on all the DC-8 data. Calibrations for DC-6 were made by measuring the constant open-hole pressure prior to each test.

The effect of temperature changes on the transducer calibration was investigated in the field. Temperatures in the range of 25° C to 65° C were imposed on the transducer, producing a seemingly random variation in transducer output which corresponded to ± 1 psi at both zero and full scale pressure. This, in turn, corresponds to a variation of about ±2.31 feet of water. Because of the random nature of the variation, no temperature corrections, except for determination of the air-water interface, were made.

The effects of barometric pressure changes were relatively minor. Barometric pressures measured daily at 12:00 noon, Pacific Standard Time, were obtained from Battelle Northwest Laboratory in Richland, Washington. Barometric pressure change for the period in question was typically 0.14 inches of mercury and the extreme change was 0.45 inches. These correspond to changes of 0.16 feet of water and 0.51 feet of water, respectively, and were not included in the data analysis because insufficient data were available to determine barometric efficiency.

A summary of the various corrections considered in analysis of pressure data is presented below. From these data an overall accuracy of about ± 3 feet of water may be inferred.

SUMMARY OF CONSIDERATIONS IN DATA ANALYSIS

Cause	Effects on Water Levels
Transducer Calibration:	Changes water level by 0 to 40 feet
Drill String Stretch :	Lowers water level by 0.12 to 0.42 feet
Air Pocket :	Lowers water level by 0.66 to 0.91 feet
Temperature :	Random variation of ± 2.31 feet (no correction)
Barometric Changes :	Random variation of ± 0.25 feet (no correction)

c. Discussion of Results for Well DC-2

Well DC-2 is a 3300-foot deep NX borehole located in the NE 1/4 sec 35 T13N R26E. The reference surface elevation of the wellhead is 572 feet. The well is cased to a depth of 2260 feet and is open for the remainder of the hole. Well DC-1 is a 5661 foot deep hole drilled about 40 feet northeast of the site of DC-2. Stratigraphic correlation between the two wells is good, and much of the geophysical information for DC-1 has been directly applied to DC-2. Well DC-2 has not been surveyed as of this writing and the distance between the two wells at depth is not known. Five standpipe piezometers were installed in DC-1 in 1972 and water levels have since been measured periodically.

The basic data for pressure test results in Well DC-2 are presented in Table II-4. Testing was performed during the period from May 25, 1978 through June 5, 1978 at 11 zones between depths 2269 feet and 3273 feet. The tests were performed sequentially from uppermost zone to lowermost zone with a constant interval of 30 feet. Test durations ranged from 1.88 to 93.45 hours, depending upon the rate at which equilibrium conditions were reached. In three of the zones tested (2306 - 2336, 2745 - 2775, and 2860 - 2890) decay of the pressure pulse was very slow and pressure readings were still anomalously high when the tests were terminated because of time constraints.

TABLE II-4

DC-2 PRESSURE DATA

Depth Interval of Test Zone (feet)(2)	Test Starting Date	Test Duration (Hours)	Water Elevation(1) Open-Hole Before Test (feet)	Test Zone (feet)	Open-Hole After Test (feet)	80% Pulse Decay Time (Minutes)	Permeability Relative to Other Test Zones in Well (3)	Estimated % of Permeable Rock in Test Zone(4)	Zone Lithology(4)
2269 - 2299	5/25/78	14.51	456	470	453	2	High	50%	Vertical Fracturing.
2306 - 2336	5/26/78	93.45	453	505(5)	453	>5600	Low	33%	Flow top; highly vesicular.
2340 - 2370	5/30/78	1.88	441	443	441	1	High	70%	Flow top; highly vesicular.
2625 - 2655	5/30/78	19.78	434	438	433	5	High	67%	Flow top; highly vesicular.
2745 - 2775	5/31/78	23.63	426	1116(5)	416	>1400	Low	50%	Highly vesicular.
2795 -2825	6/1/78	14.98	416	421	415	38	Medium	67%	3 highly vesicular zones; vertical fracturing.
2798 - 2828	6/2/78	4.95	413	(6)	414	(6)	(6)	67%	3 highly vesicular zones; vertical fracturing.
2860 - 2890	6/2/78	63.40	409	525	410	>3800	Low	67%	Flow top; highly vesicular.
2960 - 2990	6/5/78	2.13	393	395	391	2	High	100%	Rubble zone.
3160 - 3190	6/5/78	2.28	375	377	373	6	High	55%	Rubble zone.
3243 -3273(7)	6/5/78	15.28	366	362	360	1	High	100%	Flow top; highly vesicular.

(1)Surface reference elevation is 572 feet above mean sea level.

(2)A 30 foot interval was used in all tests.

(3)As inferred from pressure pulse decay times.

(4)As inferred from core photographs.

(5)Anomously high reading; equilibrium pressure not established.

(6)Test terminated early; results essentially same as for zone 2795 - 2825.

(7)Zone swabbed for geochemical sample upon conclusion of pressure testing.

Data from these zones were not used in the analysis of this well.

The test in zone 2795 - 2825 was partially repeated in zone 2798 - 2828 because it was felt that vertical fractures observed in core photographs may have been causing leakage around the top packer. When the assembly was moved down 3 feet, essentially the same pulse, rate of decay, and transducer outputs were observed as had been recorded in the higher zone, and the lower test was terminated before equilibrium pressure was established.

Open hole and test zone water heads for zones in which tests were not terminated early are shown on Figure II-6. The open hole pressures are the pressures before packer inflation and after packer deflation; any difference between the two is caused by a change in water level in the well during the test. The test zone measurement is the stable pressure reached while the packers were inflated.

The test zone data, shown as solid bars on Figure II-6, appear to indicate that the vertical component of hydraulic gradient is downward over the interval tested. Comparison with open hole data, however, shows that a close correlation exists between open hole and the test zone measurements. The entire wellbore was filled to ground surface for cleaning operations prior to pressure testing and in so doing, the formation pressures immediately surrounding the wellbore were increased. Upon completion of cleaning, no further water was added to or pumped from the well, and the open hole water level steadily declined during testing to as low as 360 feet elevation as water flowed from wellbore storage into the formations.

The close correlation observed between open hole pressure and test zone pressure in every zone in which equilibrium is thought to have been reached indicates a strong influence of open hole pressure upon the test results. Such an influence can result from vertical circulation of water around the packers, either through the formation or through an incomplete packer seal, or from residual effects of formation prepressurization when the well was filled for cleaning.

Packer seals were checked following each test by increasing the differential packer inflation pressure by 100 psi and noting any changes in equilibrium water pressure within the zone. Other indications of a good seal are a clear pressure pulse in the zone when the packers are inflated, and long term maintenance of a differential pressure between the zone and the open hole. A lack of open communication between the test zone and open hole

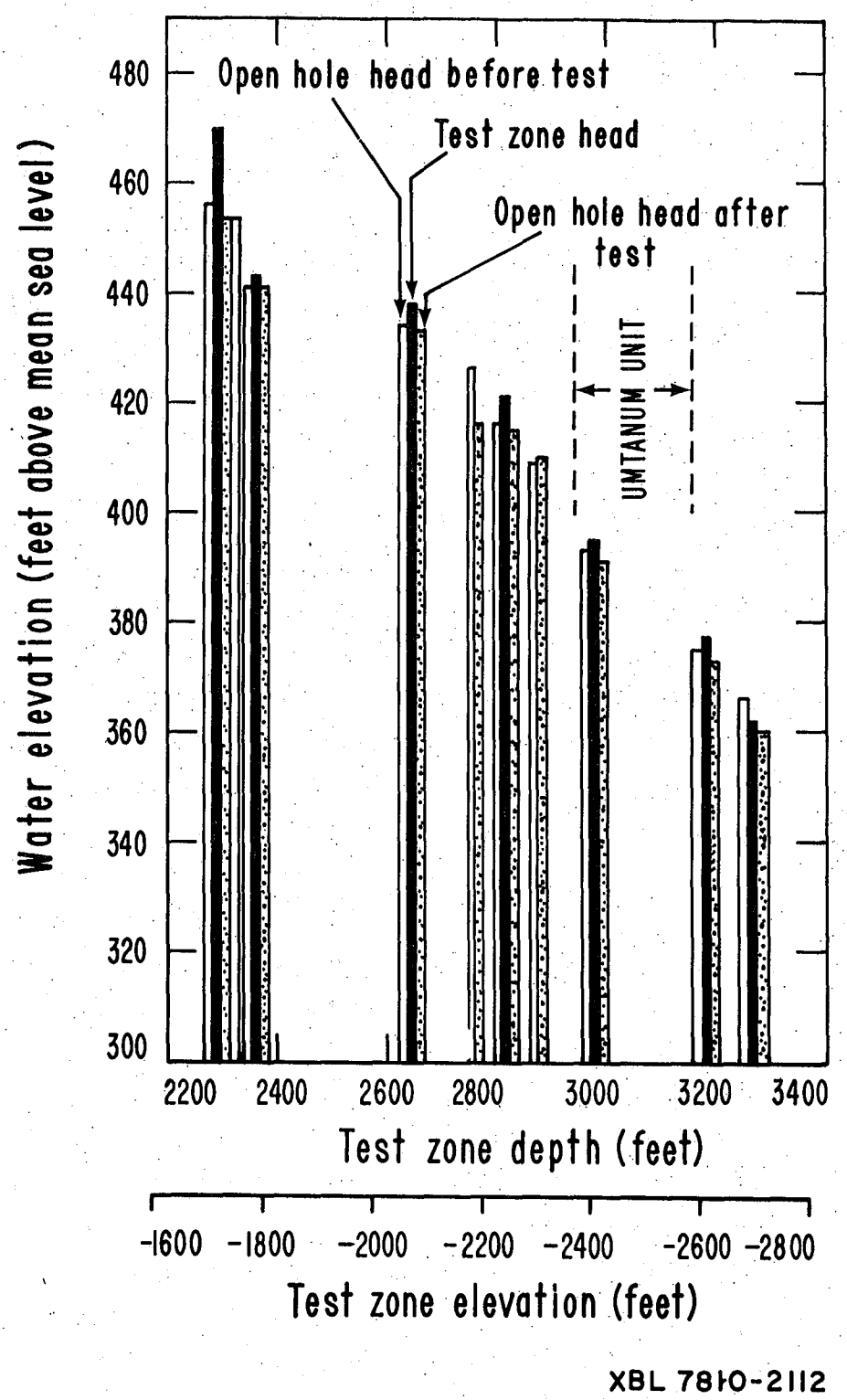


Figure II-6. Water heads in well DC-2.

may be demonstrated by these checking procedures, and a good packer seal was indicated in virtually every test. An alternative method of checking for a poor seal, at least for the upper packer, is to fill the hole with water and watch for pressure changes in the test zone. This method was not used in DC-2 because any unnecessary disturbance of the wellbore pressure was felt to be undesirable.

In view of the foregoing evidence that systematic packer leakage was not occuring, vertical circulation of water around the packers through the formation must be considered as a possibility in at least some of the tests. All of the test intervals straddle either rubble zones, highly vesicular flow tops, or zones in which vertical fracturing is evident in the drill core. The packers, however, were always carefully positioned in unfractured materials outside of these zones where vertical circulation of water would be minimized. Such vertical movement of water implies that vertical permeabilities in the vicinity of the zones tested may be significant. The magnitude of such permeabilities should be carefully analyzed in future testing programs.

Residual effects of formation prepressurization may also be responsible for the close correlation observed between open hole pressure and test zone pressure, expecially in the less permeable zones tested. The tests were generally continued until the effects of the packer inflation pulse were essentially dissipated, however time constraints did not permit the longer-term testing periods that would have been required for complete dissipation of the overpressure induced by well cleaning in the lower permeability test zones. Significantly increased testing times and increased sophistication of test equipment will be required to resolve the degree to which residual effects of wellbore pressurization and the influence of vertical permeability affect test results in Well DC-2.

The rate at which the pressure pulse induced by packer inflation decays is indicative, in a qualitative manner, of the relative permeabilities of the various zones. The decay time for 80 percent of the pressure pulse is shown on Table II-4 and may be seen to fall into three distinct categories: six tests had decay times of 6 minutes or less, and are considered to indicate high permeabilities relative to the other zones tested; one test had a decay time of 38 minutes and is considered to indicate an intermediate permeability; and three tests had decay times in excess of 1000 minutes and are considered to indicate relatively low permeabilities. Only those test zones

with low or medium permeabilities came to equilibrium within allowable time constraints.

A number of interesting conclusions may be drawn from analysis of DC-2 data and from comparison with piezometric data from Well DC-1. The observation that the open hole water level in DC-2 fell throughout the test period and was at an elevation of about 360 feet when the tests were concluded indicate that: (1) the minimum natural formation head within the open part of DC-2 is equal to or less than 360 feet elevation, and (2) this minimum head probably occurs below the Umtanum Unit.

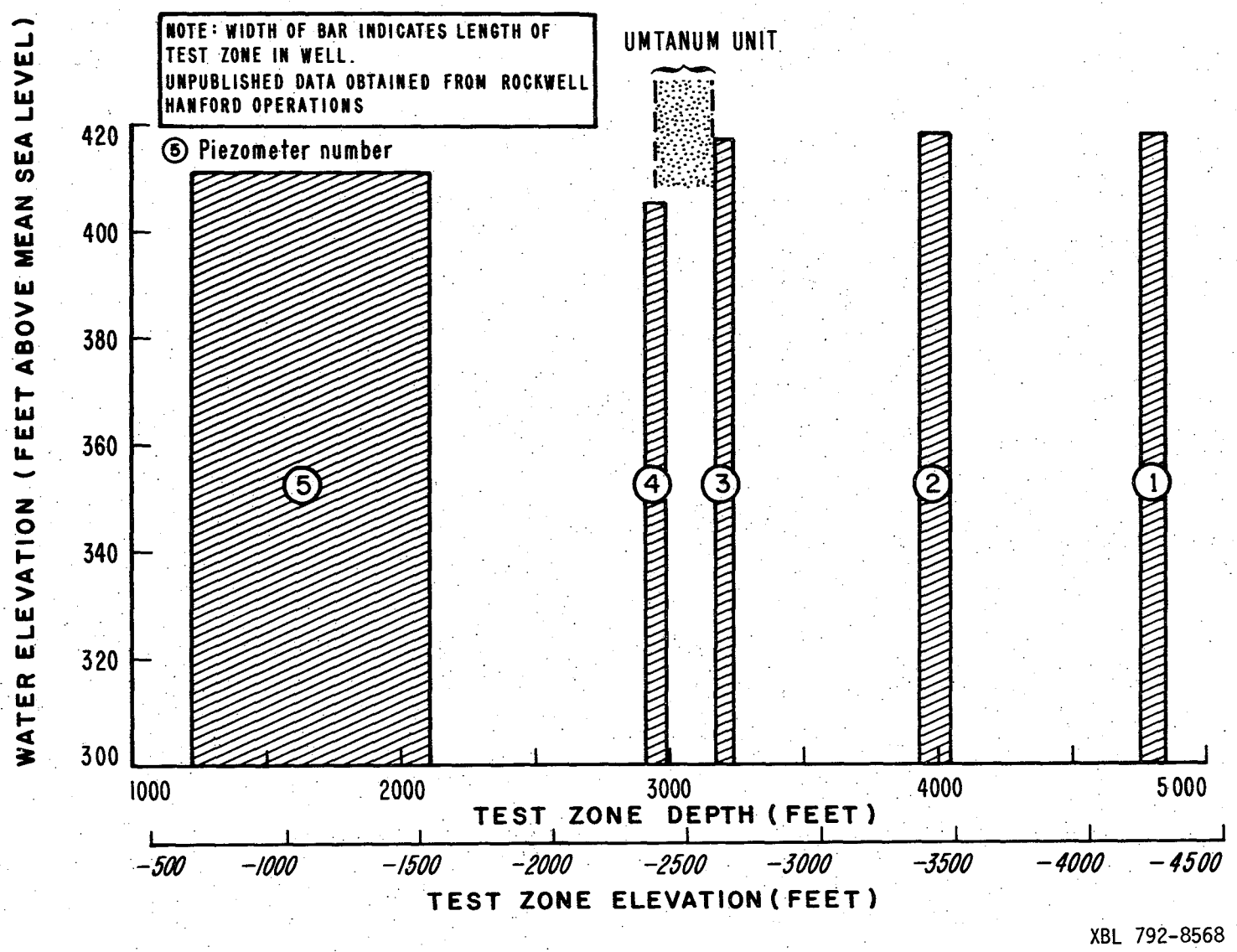
Water level elevations for the five piezometers in Well DC-1 were obtained from the files of the Basalt Waste Isolation Program Library, Richland, Washington, and are shown on Figure II-7. These data were taken on March 27, 1978 and represent conditions before cleaning and testing began in Well DC-2. Only piezometers 3 and 4 fall within the range of depths tested in DC-2. Prior to June 1978 the piezometric readings are reasonably stable with time, as shown on Figure II-8, and are compared with equivalent zones in DC-2 in the following tabulation:

COMPARISON OF WATER HEAD ELEVATIONS

	Well DC-1 (March 27, 1978)		Well DC-2 (June 5, 1978)	
Piezometer Number	Test Zone Depth (feet)	Water Head Elevation (feet)	Test Zone Depth (feet)	Water Head Elevation (feet)
3	3177-3242	417	3160-3190	377
			3243-3273	362
4	2913-2987	405	2960-2990	395

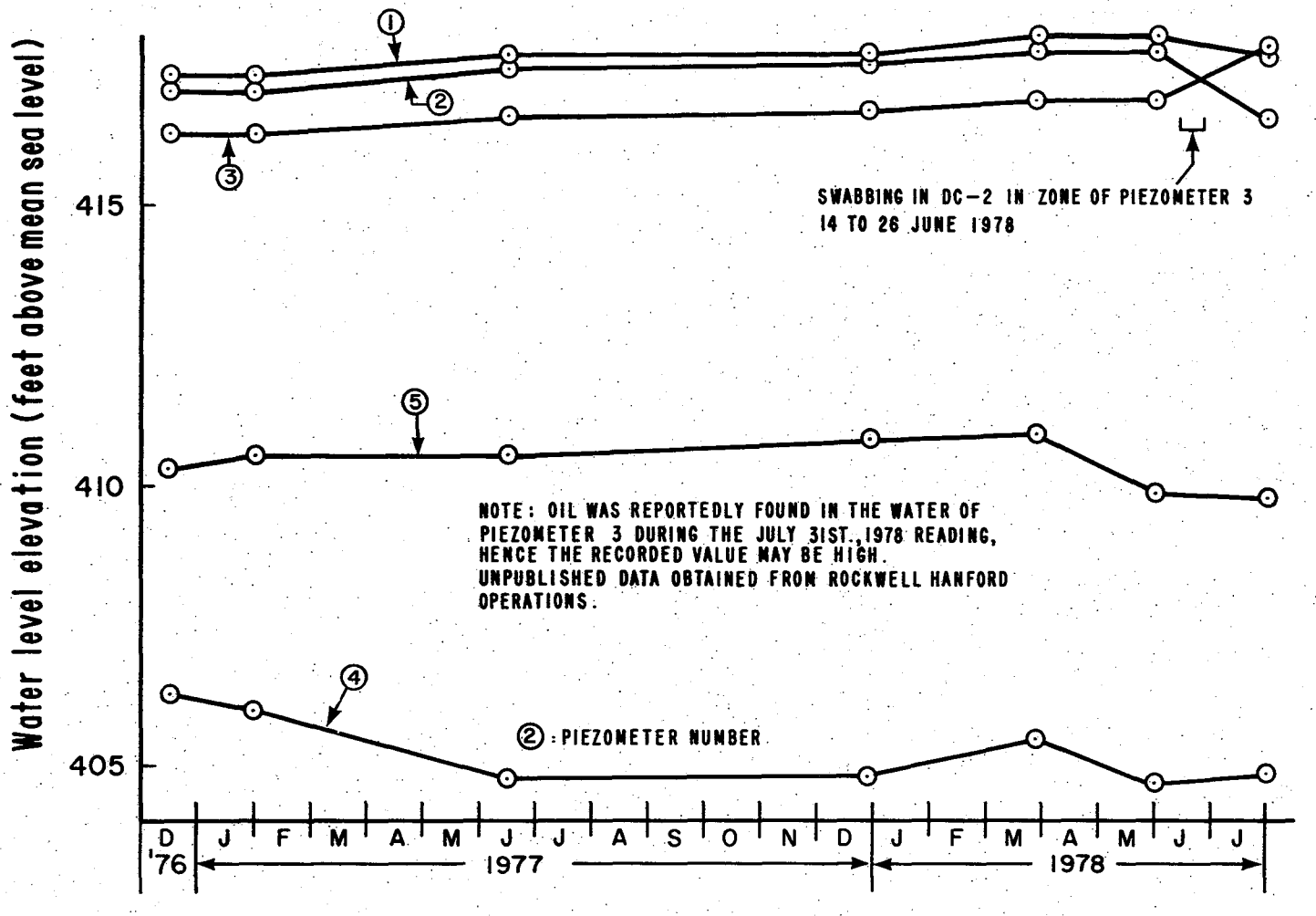
Water heads at the depth of piezometer 4 are within about ten feet of one another in the two wells, while those at the depth of piezometer 3 differ by 40 to 50 feet. The tests in DC-2 thus tend to substantiate piezometer 4 readings, but cast significant doubt on piezometer 3 readings.

Well DC-1 piezometer water elevations are plotted as a function of time on Figure II-8. Water levels may be seen to be reasonably stable with time until June and July, 1978, during which water levels in the three lower piezometers, 1, 2, and 3, changed relatively abruptly. This time period coincides with initiation of swabbing in the zone 3243 - 3273 in Well DC-2



XBL 792-8568

Figure II-7. Piezometric water elevations in well DC-1 on 27 March 1978.



XBL 792-7373

Figure II-8. Variation of piezometric water elevations in well DC-1 with time.

for the purpose of obtaining geochemical samples. A total of about 64,000 gallons is estimated to have been swabbed from this zone. The swabbed zone corresponds closely with the depth of piezometer 3 in Well DC-1, and the water level in that piezometer was observed by LBL to rapidly rise and fall about 45 feet with each swab in Well DC-2. Although changes in water level in piezometers 2 and 4, which bracket piezometer 3, were not observed by LBL when DC-2 was swabbed, measurements in all piezometers made by Rockwell on July 31, 1978 showed that water levels in piezometers 2 and 3 had changed significantly from the March measurement, that piezometer 1 had been slightly affected, and that piezometers 4 and 5 had not been affected.

This evidence indicates that there is hydraulic continuity between piezometers 2 and 3, and possibly between all three lower piezometers. Indeed, a review of earlier data indicate that these three piezometers have behaved essentially as a unit since they were first installed in 1972, while piezometers 4 and 5 have behaved much more independently (Atlantic Richfield Hanford Company, 1976, p. 92).

These conclusions are generally supported by pressure measurements made by La Sala and Doty in Well DC-1 before the piezometers were installed (1971). Their data indicates that a general downward gradient exists from 3300 feet, which is the bottom of DC-2, to at least 4000 feet where a pressure head elevation of 365 feet was measured. Considering that minor pressure fluctuations should be expected with time, this value compares favorably with the elevation of 362 feet measured at the 3243 - 3273 foot depth interval in DC-2. These conclusions are further supported by tracer tests made in DC-1 in July 1969 which indicate significant natural downward hydraulic gradients and water losses at depth intervals 3228 - 3234 (within the test zone of piezometer 3) and 3972 -3980 (within the test zone of piezometer 2). Logs of these tests are shown on Figure II-16.

Pressure data from La Sala and Doty, from DC-1 piezometers, and from LBL's testing program may be compared on Figure II-9. The LBL data, as previously mentioned, may have been influenced by open hole water levels and is at variance with the other data above the Umtanum Unit. Measurements by La Sala and Doty are largely in agreement with piezometer data above the Umtanum and these results are considered to be generally accurate. Below the Umtanum, both LBL and La Sala and Doty measurements show a similar pressure drops, although there is a disagreement as to the depth at which the drop

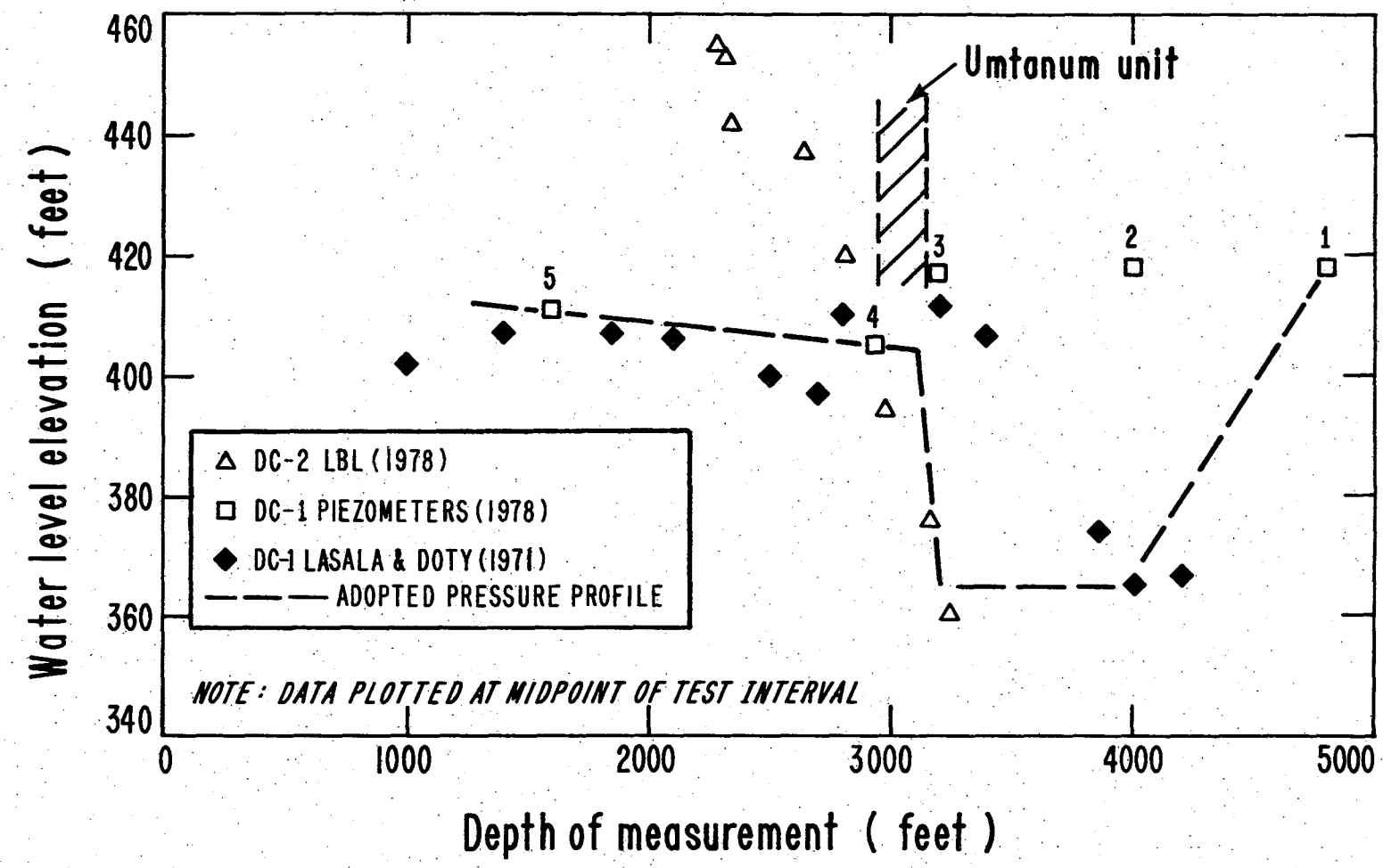


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Figure II-9. Comparison of pressure data for wells DC-1 and DC-2.

occurs. Water levels in piezometers 2 and 3 are higher than those derived from pressure measurements at corresponding depths, and indicate gradients opposite to those demonstrated by the tracer tests. The indications of leakage between the three lower piezometers suggests that piezometers 2 and 3 readings are erroneously high and are being influenced by a higher pressure zone intersecting DC-1 at some point deeper than piezometer 2. The dashed line drawn on Figure II-9 indicates a subsurface pressure distribution which maximizes conformance with all available information. A sharp decline in head is evident in the vicinity of the Umtanum, indicating that the unit may be acting as a partial barrier to vertical flow. Further testing will be required to more precisely identify the distribution of pressure in this vicinity.

In summarizing the foregoing data, it is concluded that:

(1) Piezometer 2 and 3 readings are erroneously high because of vertical flow through leaks in the cement seals in Well DC-1 from a high pressure zone deeper than piezometer 2.

(2) The true formation pressure head elevation at the depth of piezometers 2 and 3 is on the order of 360 feet.

(3) The seal between piezometers 3 and 4 is apparently tight.

(4) The seal between piezometers 4 and 5 is apparently tight.

(5) The accuracy of piezometer 4 measurements is generally substantiated.

(6) A downward pressure gradient apparently exists from at least the depth of piezometer 5 (2000 feet) through piezometers 4 and 3 to at least the depth of piezometer 2 (4000 feet), passing through the Umtanum Unit.

(7) An upward pressure gradient apparently exists from at least the depth of piezometer 1 (4800 feet) to approximately the elevation of piezometer 2 (4000 feet).

(8) The Umtanum Unit appears to be acting as a partial barrier to vertical flow.

d. Discussion of Results for Well DC-8

Well DC-8 is an NC oversize corehole located in the SE1/4 sec 36 T11N R27E. The reference surface elevation of the wellhead is 545 feet. At the time of pressure testing the well had been drilled to a depth of 2734 feet, which is about the depth of the Vantage Sandstone. Well DC-7 had been

previously drilled about 40 feet south of DC-8, to a total depth of about 4100 feet. At the time of testing, DC-8 had not been extensively surveyed, and the distance between the two wells at depth is not known. A geophysical survey of DC-7 was performed during pressure testing in DC-8, but that well was not otherwise disturbed.

The basic data for pressure test results in Well DC-8 are presented in Table II-5. Testing was performed during the period from 16 to 20 June 1978 at nine zones between depths 1710 feet and 2700 feet. The tests were performed sequentially from uppermost to lowermost zone, although variations in this sequence did occur within individual days. A constant packer interval of 30 feet was maintained throughout the test program.

It was necessary to suspend drilling during the testing program, and an effort was made to test only the most permeable zones to keep testing times short and interrupt the drilling program for as short a time as possible. With the exception of one 63-hour test, the maximum test duration is 2.6 hours. Two tests (zones 2630 - 2660 and 2670 - 2700) were terminated early because insufficient time was available to reach equilibrium. Data from three additional tests (1900 - 1930, 2235 - 2265, and 2290 - 2320) were unstable due to packer seal and/or air leakage and could not be used.

Open hole water heads and test zone water heads for zones which were not terminated early are shown on Figure II-10. The open hole measurements were made immediately prior to packer inflation and subsequent to packer deflation. The wellbore was filled with water twice during the series of tests, once on June 14, 1978 before testing commenced and again on June 16, 1978 immediately prior to testing in zone 1810 - 1840. This filling has resulted in considerable variations in open hole water level during the early part of the testing period, and was done to check instrument calibration. The lowest water elevation recorded during the test period was an open hole head elevation of 413 feet. This measurement indicates that the formation pressure head within some part of the open portion of the well is at least as low as 413 feet.

The test zone measurements were made after packers has been inflated and equilibrium was reached. Zone 1710 - 1740 is considered to be of medium permeability relative to the other zones in the well, based upon the pressure pulse decay rate, and was allowed to run over a weekend to assess the long term stability of the test system. In that test the pressure reached what is

TABLE II-5

DC-8 PRESSURE DATA

Depth Interval of Test Zone (feet)(2)	Test Starting Date	Test Duration (Hours)	Water Elevation(1) Open-Hole Before Test (feet)	Water Elevation(1) Test Zone (feet)	Water Elevation(1) Open-Hole After Test (feet)	80% Pulse Decay Time (Minutes)	Permeability Relative to Other Test Zones in Well (3)	Estimated % of Permeable Rock in Test Zone(4)	Zone Lithology(4)
1710 - 1740	6/16/78	63.30	447	433	430	10	Medium	55%	Flow top; highly vesicular.
1810 - 1840	6/16/78	0.35	548	431	483	0(7)	High	100%	Flow breccia.
1900 - 1930	6/16/78	0.50	469	653(8)	459	>30	Low	10%	Fractured zone.
1990 - 2020	6/19/78	2.60	429	435	427	52	Medium	50%	Ash interbed.
2033 - 2063	6/19/78	0.50	428	422	428	6	High	60%	Flow breccia.
2235 - 2265	6/19/78	1.57	427	(8)	434	(8)	(8)	67%	Flow top; highly vesicular.
2290 - 2320	6/19/78	1.67	434	(6)	433	(6)	(6)	87%	Flow top; highly vesicular
2630 - 2660	6/20/78	2.10	413	724(5)	413	>126	Low	20%	Poker chip (disced) core.
2670 - 2700	6/20/78	1.65	413	584(5)	412	>99	Low	8%	Vantage: Lithic tuff

(1)Surface reference elevation is 545 feet above mean sea level.

(2)A 30 foot interval was used in all tests.

(3)As inferred from pressure pulse decay times.

(4)As inferred from drill core photographs.

(5)Anomously high reading; equilibrium pressure not established.

(6)Test terminated due to packer air leak. No data available

(7)Hole filled with water imeediately prior to test. Negative pressure pulse observed when packers inflated.

(8)Pressure data unstable. Suspected packer seal and/or air leak.

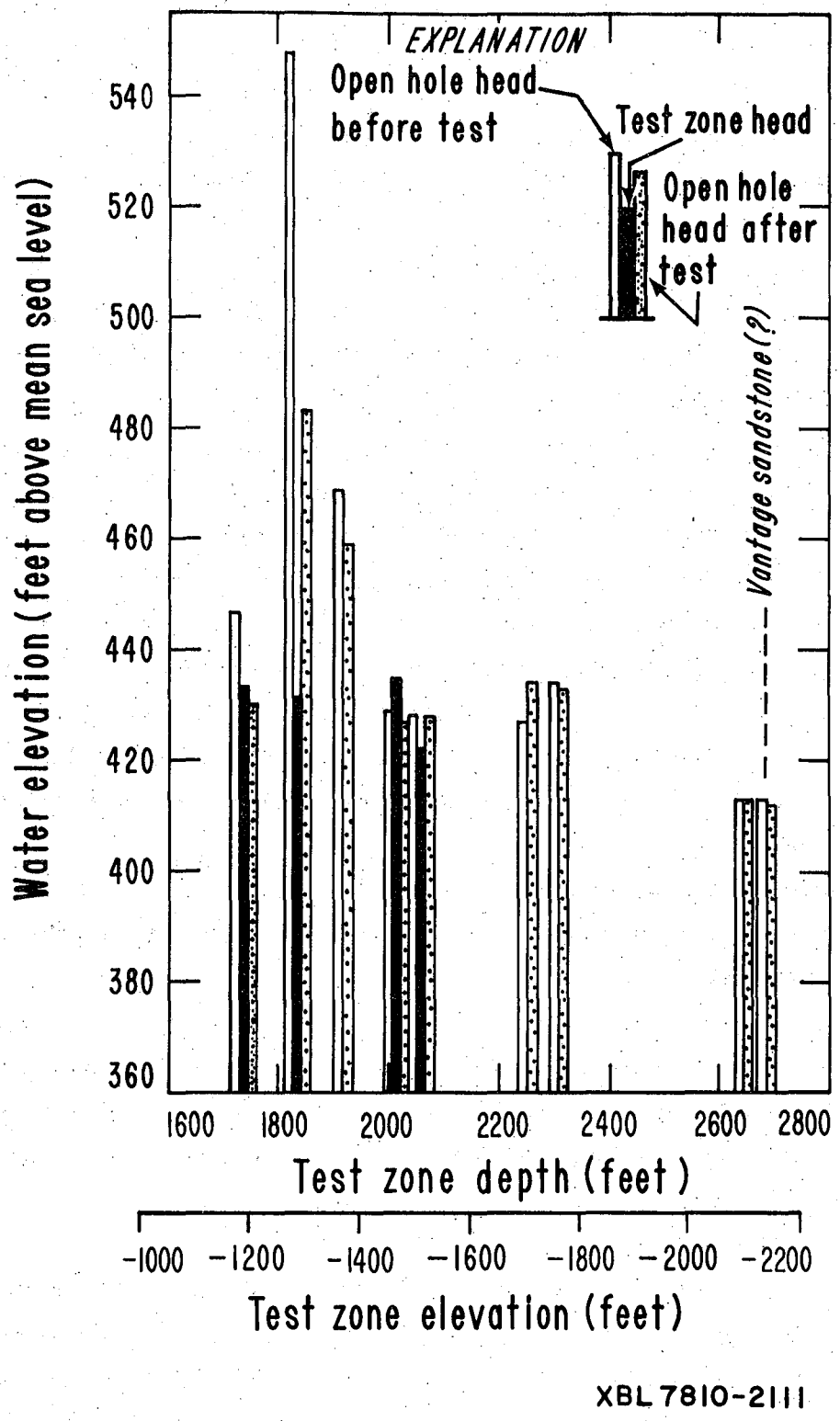

Figure II-10. Water heads in well DC-8.

considered the final equilibrium value after 29 hours and thereafter transducer output drifted over a range of about ± 1.2 millivolts for the balance of the test period. This range is equivalent to about ± 0.5 feet of water. By the end of the test period the open hole pressure had become less than the equilibrium pressure of the test zone and less than the minimum pressure recorded during the test. These results indicate both a good packer seal and low vertical permeability.

An indication of low vertical permeability was also obtained from the test in zone 1810 - 1840. The wellbore was filled with water immediately prior to packer inflation to a head of about 548 feet. Upon inflation the pressure head dropped and stablized at a value of 431 feet. Although this test was quite short, the achievement of an equilibrium value considerably lower than the open hole head indicates no substantial vertical hydraulic communication through either the packer seal or the formation.

Zone 1990 - 2020 appears to be of medium permeability, relative to the other zones in the well, and the test had to be terminated before full equilibrium conditions were established. The measured zone pressure head of 434 feet may, therefore, be slightly high. The measured pressure in zone 2033 - 2063 was less than the open hole pressure recorded both before and after the test. This test result may therefore be given a relatively high degree of confidence.

In summary, it may be concluded that:

(1) A downward gradient appears to occur within the depth range 1500 - 2100 feet.

(2) The minimum formation pressure head elevation in the open part of the well at the time of testing is equal to or less than 413 feet, and based upon extrapolation of the downward gradient, this formation pressure probably occurs at or below a depth of 2300 feet.

e. Discussion of Results for Well DC-6

Well DC-6 is located off the east end of Gable Mountain near the old Hanford townsite in NE 1/4 Sec 26 T13N R27E. The reference surface elevation of the wellhead is 402 feet. The total depth of the well at the time of testing was 4336 feet. Artesian flow was encountered while drilling in March 1978 between 2300 and 2710 feet of depth. That zone was cemented by the drillers when it was feared the well might cave. Pressure measurements and permeability tests were run by Lynes Tool Company and W. K. Summers

Associates before cementing was done. At that time the flow was thought to be due to pressurization from the drilling; however, additional artesian flows were encountered as the hole was deepened. After completion of the hole LBL, using a single packer at the top of the well, measured a flow at the surface of 10.3 gpm at 12.5 psi with a water temperature of 42°C. This flow was somewhat lower than that coming from the open hole due to pressure losses in the packer and flowmeter.

Nine zones between depths of 2240 and 3373 feet were pressure tested by LBL with the single transducer Pressure Probe 1 using packer spacings of 30 feet. Four tests were run using only a single packer set at depths between 3341 and 3802 feet to isolate the zones producing water. For each test the flow rates from above and beneath the set packer were recorded, and the well was shut in to obtain a pressure measurement. These readings were recorded at the surface with a Paroscientific pressure transducer.

Five pressure tests were done using 30-foot straddle zones set between 3620 and 3799 feet to further isolate the main zone of outflow. The Injection-Pressure Probe was used for these tests in its injection test configuration with pressure readings obtained both uphole and downhole using pressure transducers. Packers were inflated with nitrogen over water, and the packers were deflated using the downhole solenoid valve. As in the previous test, flow rates from above the packers and between the packers were recorded.

The groundwater pressure data expressed as head above mean sea level are shown in Table II-6 and in Figure II-11A. All measurements indicate heads above the elevation of the hole collar, hence all test zones are contributing to the artesian flow from the hole. Whereas the open hole is lower in pressure than any of the individual zones, all flow is essentially radial to the hole and no significant cross flow should be occurring through the hole between lithologic units. Between depths 2240 and 3055 feet the pressure heads average about 450 feet. The scatter in the data does not allow reliable definition of either an upward or a downward gradient. Below 3055 feet heads decline reaching a local minimum of approximately 430 feet in a water producing zone at about 3700 feet of depth. An increase in head below 3700 feet is shown by the value of 466 feet recorded for the zone between 3802 and 4336 feet. There is generally good agreement between the heads measured by Lynes and Summers and the values determined by LBL (Figure II-11A).

Flow data were recorded whenever possible both for the zone above the

TABLE II-6

DC-6 PRESSURE DATA

Depth Interval of Test Zone(1) (feet)	Test Starting Date	Test Duration (minutes)	Water Elevation(1) Open Hole (feet)	Water Elevation(1) Test Zone (feet)	Type of Equipment
2240 - 2270	8/29/78	74	402	450	Pressure Probe 1
2400 - 2430	8/29/78	37	402	447	" " "
2454 - 2484	8/29/78	32	402	456	" " "
2483 - 2513	8/29/78	15	402	(2)	" " "
2538 - 2568	8/29/78	1128	402	(2)	" " "
2708 - 2738	9/8/78	48	402	423	" " "
2896 - 2926	9/8/78	16	402	454	" " "
3025 - 3055	9/8/78	26	402	460	" " "
3343 - 3373	9/8/78	24	402	443	" " "
3620 - 3650	9/14/78	32	402	421	Injection-Pressure Probe
3650 - 3680	9/19/78	33	402	432	" " "
3683 - 3713	9/20/78	88	402	429	" " "
3692 - 3722	9/14/78	976	402	432	" " "
3769 - 3799	9/18/78	205	402	(2)	" " "
3341 - 4336	9/12/78	180	402	426	Transducer at surface
3477 - 4336	9/12/78	1020	402	437	" " "
3601 - 4336	9/13/78	180	402	434	" " "
3802 - 4336	9/13/78	1020	402	466	" " "

(1) Reference surface elevation is 402 feet above mean sea level.

(2) Anomalously high reading; equilibrium pressure not established.

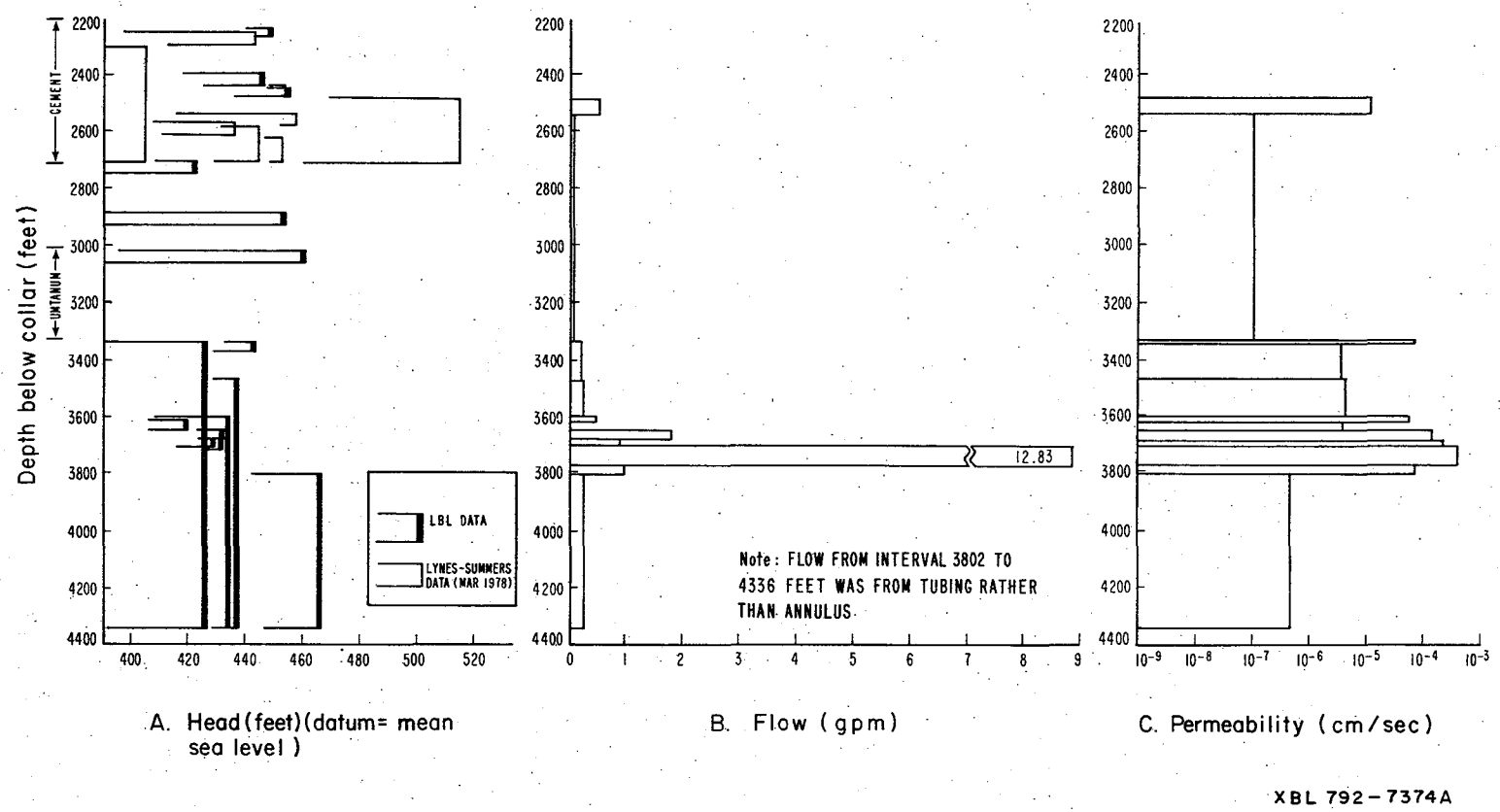

Figure II-11. Water heads, flow rates, and permeabilities in well DC-6.

packers and the zones beneath or between the packers. Pressure losses in the 1 3/8 inch tubing appeared to inhibit flow from beneath or between the packers, hence the flow rates given in Table II-7 and Figure II-11B are based only on the flow from above the packers except for the deepest zone. The flowrate for each zone is equal to the incremental increase in total flow above the top packer for successively deeper packer settings. The zone between depths of 3692 and 3769 feet produced 70% of the total flow. Core from this zone was logged as a highly altered flow breccia. Significant flows also came from similar breccia zones between 3650 and 3692 feet.

Hydraulic conductivities were estimated using the following equation for radial steady flow (Zeigler, 1976):

$$K = \frac{Q}{LH} \frac{1}{2\pi} \ln \frac{R_o}{r}$$

where:

K = hydraulic conductivity (L/T)

Q = flowrate (L^3/T)

L = test zone length (L)

H = hydraulic head (L)

R_o = radius of influence (L)

r = well radius (L)

The hydraulic head is the head in feet above mean sea level computed from the pressure tests minus the elevation of the hole. The radius of the well was 0.038m, and the radius of influence was taken as 30 meters. This last term is the most uncertain; however, the computed hydraulic conductivity varies with the natural log of R_o/r, hence the solution is relatively insensitive to this term.

The hydraulic conductivities are shown in Table II-7 and Figure II-11C. Note that no correction was made for frictional pressure losses between the wellbore and the tubing; this correction would only be significant for the highest flow rates and would tend to raise the conductivity values slightly. The highest values were recorded between 3650 feet and 3769 feet and are between 1.5×10^{-4} and 3.8×10^{-4} cm/s. The lowest permeability was 1.1×10^{-7} measured between 2538 feet and 3341 feet. The conductivity of the entire open hole (i.e., the Grand Ronde Formation to 4336 feet of depth) can be calculated from the total flow from the hole and is 1.2×10^{-6} cm/s for a flowrate of 17.6 gpm and a head of 48 feet.

TABLE II-7

DC-6 FLOW AND HYDRAULIC CONDUCTIVITY VALUES

Depth Interval of Test Zone(1) (feet)	Flowrate (gpm)	Head (cm)	Hydraulic Conductivity (cm/s)
2240 - 2483	(2)	-	-
2483 - 2538	0.53	1630	1.3×10^{-5}
2538 - 3341	0.05	1260	1.1×10^{-7}
3341 - 3343	0.08	1260	7.0×10^{-5}
3343 - 3472	0.22	1080	3.5×10^{-6}
3472 - 3601	0.25	980	4.4×10^{-6}
3601 - 3620	0.49	980	5.8×10^{-5}
3620 - 3650	0.05	930	4.0×10^{-6}
3650 - 3683	1.82	840	1.5×10^{-4}
3683 - 3692	0.80	910	2.1×10^{-4}
3692 - 3769	12.83	920	3.8×10^{-4}
3769 - 3802	.98	920	7.1×10^{-5}
3802 - 4336	.28	1950	2.7×10^{-7}

(1) Reference surface elevation is 402 feet above mean sea level.

(2) Not measurable.

The zones for which conductivities are calculated include both permeable rubble zones and flow tops as well as less permeable collonade and entablature zones. The conductivity values reported above, therefore, include neither the high nor the low extremes. More detailed testing using smaller packer spacings will be required for better definition of variation of hydraulic conductivity in the hole.

Comparison of Pressure Results

The results of pressure measurements in Wells DC-1/DC-2, DC-6 and DC-8 are shown in relation to stratigraphy on Figure II-12. These data show a downward gradient between the Vantage interbed and the Umtanum Unit in DC-1/DC-2. A downward gradient was found in DC-8 between the Mabton and the Vantage interbeds. Head elevations reach a local minimum in both DC-1/DC-2 and DC-6 about 300 feet below the bottom of the Umtanum and there is evidence that gradients may be upward below that depth. The low pressure zone encountered below the Umtanum would act as a drain for any vertical flow converging upon it, thus the rechange and discharge areas of this zone are of great interest.

Pressure data for the zone immediately below the Umtanum are presently available only for Wells DC-1/DC-2 and DC-6. Wells DC-1/DC-2 are in the northern flank of Cold Creek Valley syncline, formed between Gable Mountain anticline to the north and Rattlesnake Hills anticline to the southwest (see Figure II-13). The water level elevations measured in and below the Umtanum in DC-1/DC-2 range from 395 to 362 feet. The only part of the Pasco Basin with lower elevations which would serve as a discharge area is the Columbia River bed and adjacent lands from the Tri-Cities area to Wallula Gap. The most likely flow path from DC-1/DC-2 to this discharge area is through Cold Creek Valley.

Pressure head elevations measured in DC-6 in and below the Umtanum range from 421 to 466 feet. The relatively low pressures measured in the deep basalts in Cold Creek Valley and the higher pressures measured in DC-6 suggest higher water tables to the north and east of DC-6. The most likely recharge areas for these high heads are the Columbia River from Sentinel Gap to Priest Rapids Reservoir, and to a lesser extent the lakes area to the northeast of DC-6, and Saddle Mountain. Sentinel Gap and Priest Rapids Reservoir at 480 to 500 feet elevation are sources of abundant volumes of

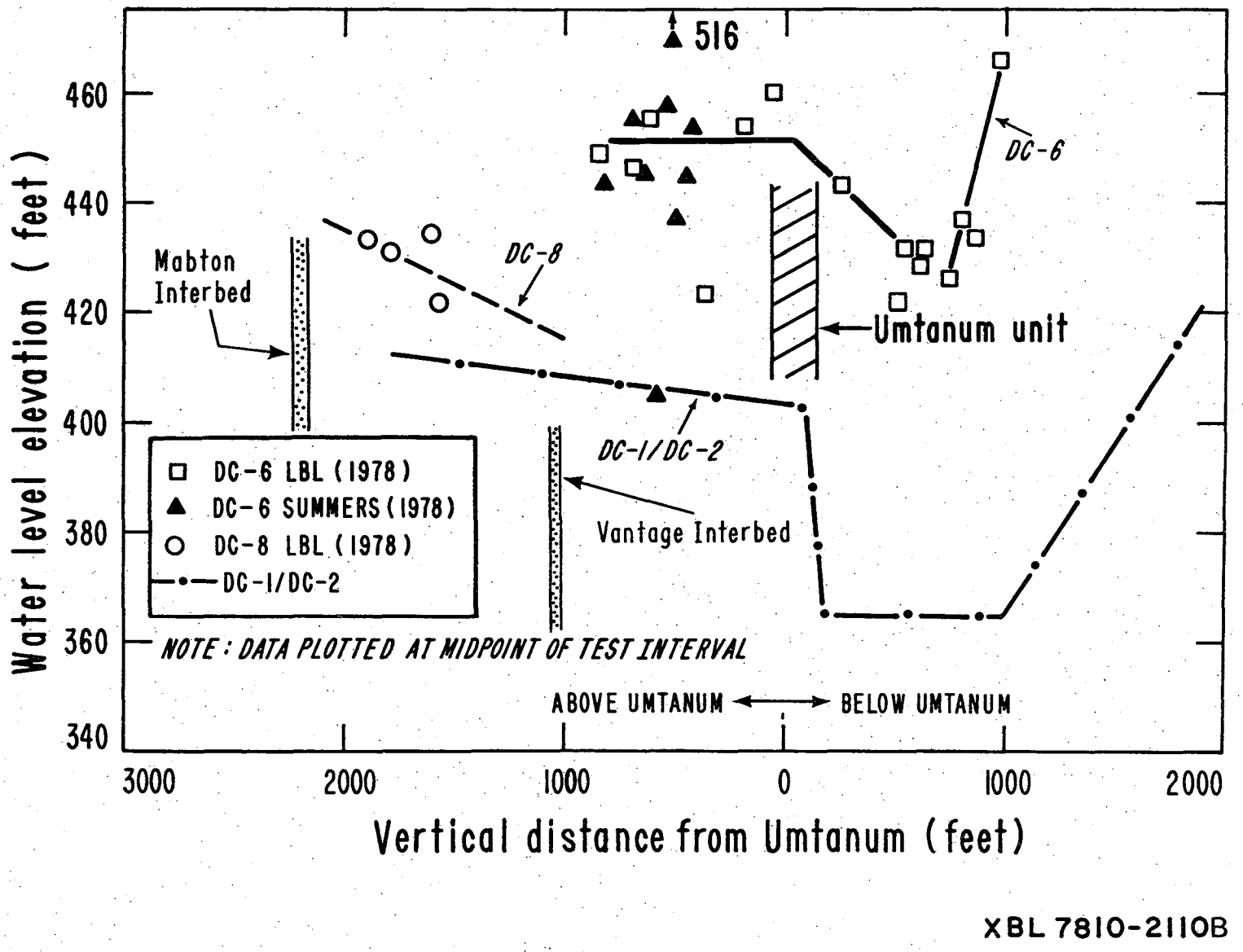

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Figure II-12. Summary of pressure data vs. stratigraphy.

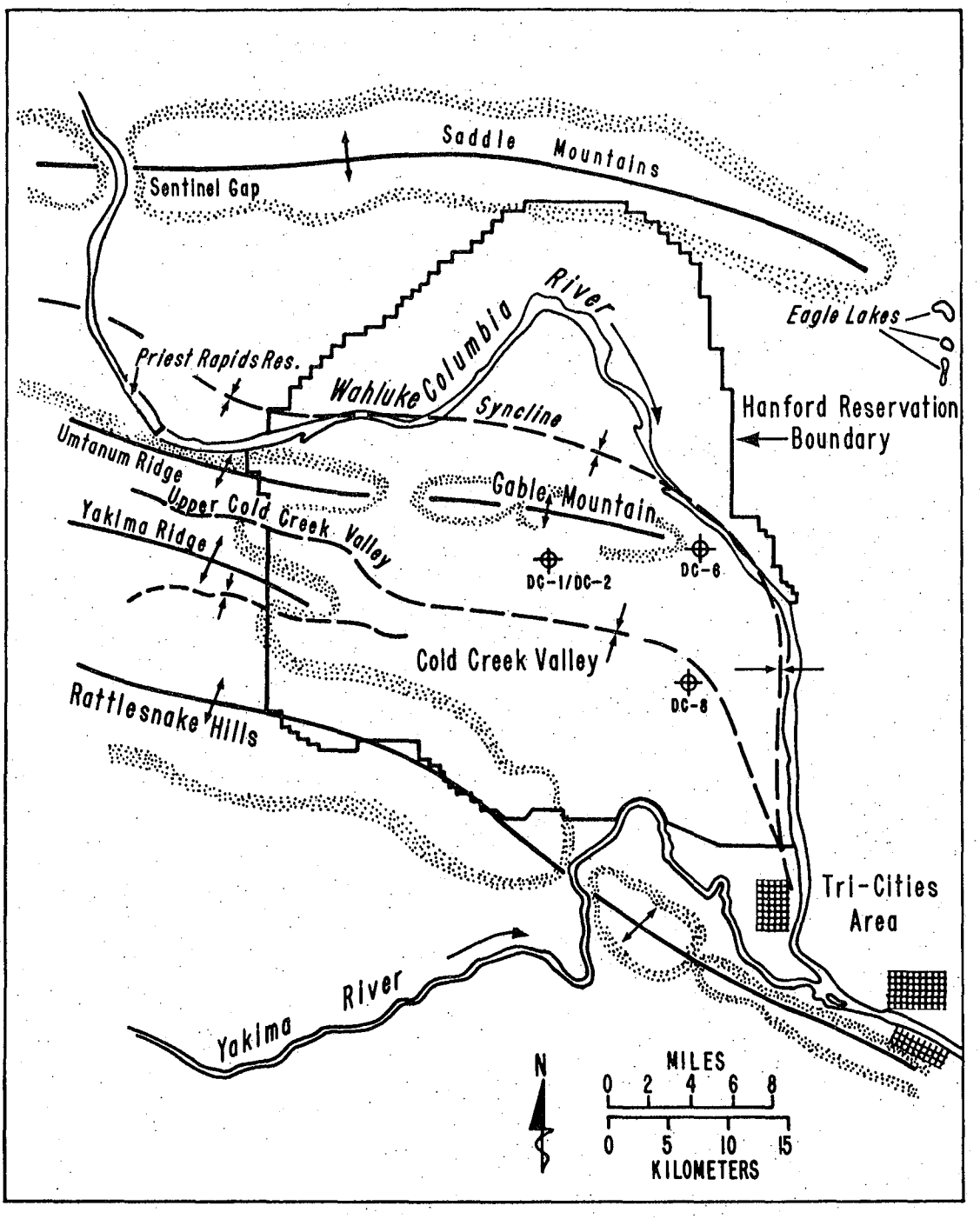

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Figure II-13. Structural features in Pasco Basin area.

water and are in areas where the basalt units beneath the Umtanum are at or near the ground surface. The most likely flowpath to Well DC-6 from this potential recharge area would be along the Wahluke syncline, a structural and topographic valley between Gable Mountain-Umtanum Ridge anticline and the Saddle Mountain anticline. The Eagle Lakes-Scooteney Reservoir area to the northeast of DC-6 is at about 900 feet elevation and has relatively abundant surface water, but is in an area where the Umtanum Unit is about 1000 feet beneath the surface. The Saddle Mountains are relatively dry but the Umtanum and the basalt units beneath it either outcrop or are near the surface.

The pressure data and recharge hypotheses for the deep basalts at DC-6 imply that water pressures throughout the Wahluke syncline are substantially higher than those measured in Cold Creek Valley at Well DC-2. Such a difference would suggest the existence of a barrier to groundwater flow in the general vicinity of the Gable Mountain-Umtanum Ridge anticline. This hypothesis is supported by a lack of likely recharge areas for the Umtanum and underlying units in the vicinity of Cold Creek Valley. Gable Mountain on the north side of the valley is low and provides essentially no recharge. The Yakima Ridge area to the east of the valley and the Rattlesnake Hills to the south rise to elevations of several thousand feet, but like the Saddle Mountains, are relatively dry. Further, the Umtanum Unit was estimated to be at least least 1000 feet deep in all of these areas. Some underflow in the deep basalts may be occuring through structural valleys paralleling Yakima Ridge, but as noted by Newcomb and others (1972, p. 32), the high heads found in a number of deep artesian wells near the western boundary of the Hanford Reservation suggest the presence of a second flow barrier cutting across these structural valleys. The presence of relatively high heads at Juniper Springs and Rattlesnake Spring versus the relatively low heads measured in DC-1/DC-2 supports the assumption of an additional flow barrier.

The possible existence of these flow barriers is of significant interest in repository siting and should be further investigated. Recommendations for future field programs are presented in Section IIC1 of this report as well as in Appendix A.

g. Comparison of Flow Data

Radioactive tracer and temperature logs in Well DC-1 are discussed in Section IIB2 of this report and have indicated three zones of relatively high

hydraulic conductivity at depths of 3228 - 3234 feet, 3972-3980 feet, and 4824 - 4854 feet. The average conductivity of these zones is 9.4×10^{-4} cm/sec. The first two of these zones are 32 feet and 812 feet below the bottom of the Umtanum Unit.

In Well DC-6 the major flowing zone was determined to have a hydraulic conductivity greater than 10^{-4} cm/sec and occurs between depths of 3650 and 3700 feet which is 392 feet below the Umtanum. There are likely to be other zones with conductivities greater than 10^{-6} between the bottom of the Umtanum and the high conductivity zone at 3650 feet; the large spacing between packer settings in the LBL flow tests did not allow better definition of the exact location of these higher conductivity zones.

Comparing the data for the two wells, it is clear that the most conductive zones encountered are below the Umtanum, but these zones do not appear to occur at the same stratigraphic levels relative to the Umtanum Unit in the two wells. The similarity of geochemical stratigraphy for the two holes suggests that these conductive zones may be occuring at different basalt flow contacts. This raises an important question -- are these zones discontinuous and of relatively finite areal extent, or are they hydraulically interconnected through a continuous weathered horizon, through faults, or through primary features such as lava tubes which cut across several flows? Future hydrologic work should be directed toward answering these questions.

2. Geophysical Data Analysis

a. Well Logs from DC-1

Over the four year period 1969-1972 almost 100 well logs were run in Well DC-1. A large portion of these logs, such as temperature, caliper, and tracer, were run repeatedly to check specific conditions encountered as the drilling progressed. A list of the logs in graphical and tabular form, giving the depth, date, log type and supplier is given in Appendix B. For purposes of this discussion, these logs are divided into three categories: "open hole" logs; speciality logs; and logs indicating permeable zones.

Most of the logs are commonly run in petroleum fields as indicators of rock type and porosity and are often referred to as "open hole" logs. These

include the electrical induction, formation density, neutron, and sonic travel time logs. These logs span the entire depth of the hole but were acquired in sections as drilling progressed. Both Birdwell and Schlumberger logs were run in the well, but the Schlumberger coverage is more complete, so that a consistent suite of logs exists from 300 to 4450 feet. These logs are the temperature, borehole compensated sonic, borehole compensated density, dual induction laterolog, gamma ray, caliper, and the sidewall neutron porosity logs. A composite of these logs at an approximate scale of 1 inch per 100 feet exists in the files at Rockwell-Hanford and at LBL.

The second category consists of a miscellaneous collection of DC-1 logs apparently run on an experimental basis, usually over only a limited portion of the well. Included in this group are the televiewer, microlaterolog, sonic waveform, and various computed logs. This group includes some of the more interesting and promising logs from the standpoint of designing future logging programs at Hanford.

Thirdly, we discuss the radioactive tracer and temperature logs which provide information on the location and relative magnitude of permeable zones in the well. The temperature logs are run after the injection of surface waters, either from the drilling operation or for some other reason. Where the injected water enters the formation it is usually at some temperature different from the formation temperature and hence creates a temperature anomaly in the borehole which decays slowly with time. Such applications are common in oilfield practice and are discussed by Smith and Steffensen (1970), among others. The radioactive tracer technique is applied within a borehole (not between boreholes) as a means of measuring the flow velocity and is often referred to as "flow profiling." Another method of flow profiling is the spinner tool, but it has not been applied at Hanford.

Besides the large number and variety of logs which were run in DC-1, continuous core and core photographs from the adjacent borehole DC-2 are also available. As a consequence, the DC-1 data provides an ideal starting point for examining the usefulness of the various log types in the basalt. To the authors' knowledge no extensive examination of the Hanford well logs exists, although some logs are displayed as composites by Atlantic Richfield Hanford (1976) and apparently were used in the hydrology study by La Sala and Doty (1971). The observations which follow are the outcome of a first-pass examination of the available data. Much more could be done, both qualitatively

and quantitatively, to assess the well log response and to estimate pertinent physical parameters (see recommendations).

Open Hole Logs in DC-1

The four porosity logs -- sonic, density, induction, and neutron -- are controlled primarily by the void space of the rock, and secondarily by other factors depending upon the method. In each case a semi-empirical equation relates the tool response to the porosity of the rock, although in the case of the neutron tool, the porosity is scaled directly (there are problems with this as discussed below). Detailed discussions of the response of these tools can be found in any of the documents issued by the well logging service companies; for example, see Schlumberger (1972).

Figure II-14 displays the four Schlumberger porosity logs over the 600-foot interval, 2800-3400 feet, in DC-1. The logs are plotted so porosity increases to the left. A number of features are obvious:

(a) The logs exhibit dramatic fluctuations in total porosity, reflecting the vesicular nature of the basalt and the high porosity of the interflow zones.

(b) All four logs respond in much the same way. Any one of the four could be used to describe the porosity character of the basalt, certainly as far as gross features are concerned.

(c) The neutron and the density logs give more detail (fine structure) than do the sonic or electrical induction logs.

(d) The electrical induction log operates very near to its high resistivity limit (1000 ohm-m) in the dense basalt. In fact, many times the induction log is off-scale and hence cannot give information in the high resistivity zones.

(e) In the interval 3250-3400 feet, the porosity decreases monotonically with depth. This effect is attributed to the decreasing vesicle population towards the bottom of the flow. The trend is apparent to some extent in almost all the flow units.

Figure II-15 (in four parts) displays four logs over the 300-4400 foot interval of DC-1, with 100 feet of overlap at the top and bottom of consecutive sheets. The sidewall neutron porosity (SNP) scale is taken directly from the log; it must be regarded as only a crude estimate because the correction factor applied to the data is for a limestone matrix. Due to

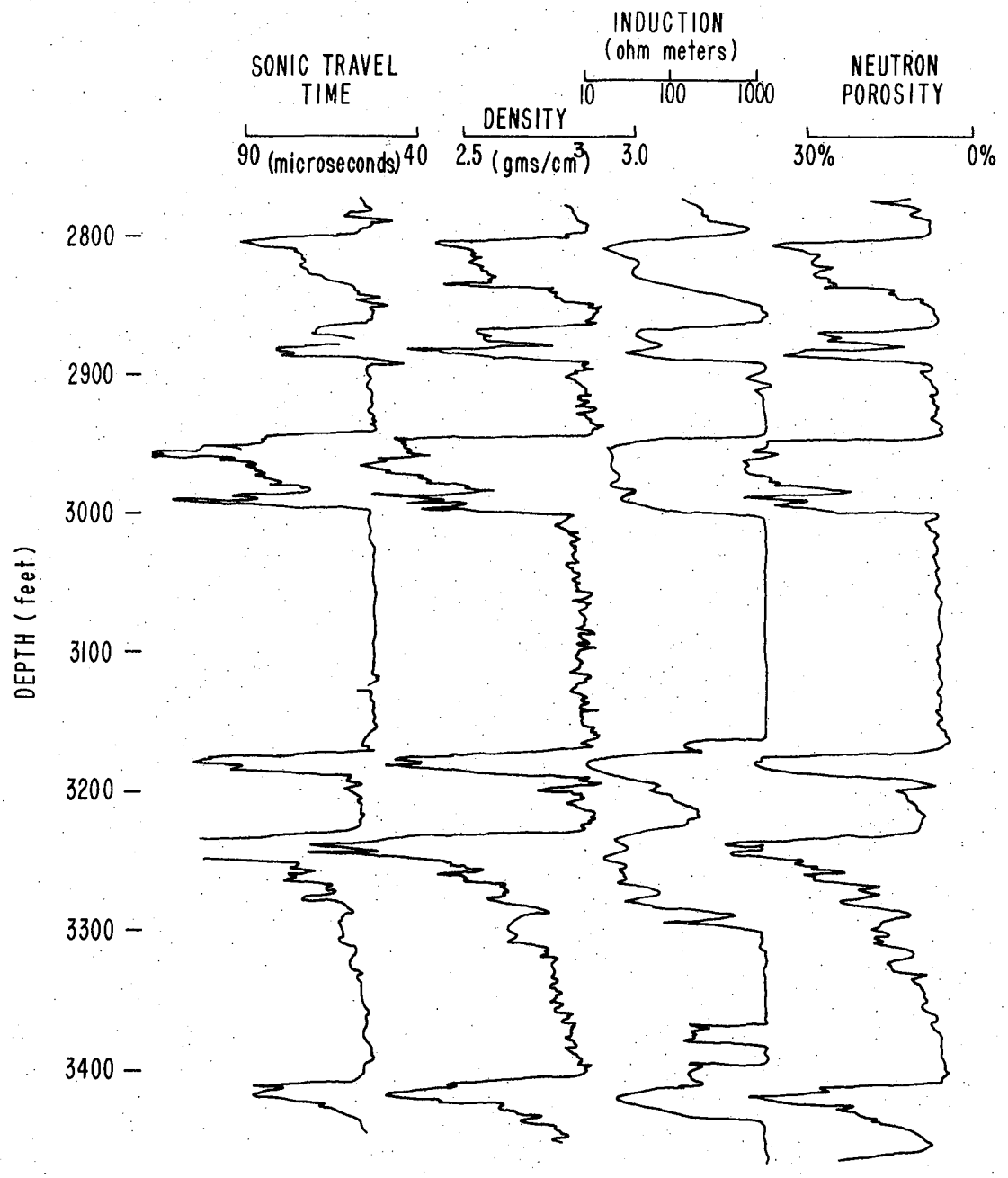

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Figure II-14. Four Schlumberger porosity logs in well DC-1 over the depth interval 2800-3400 feet. The Umtanum lies in the interval 3000-3180 feet. All logs deflect to the left as porosity increases.

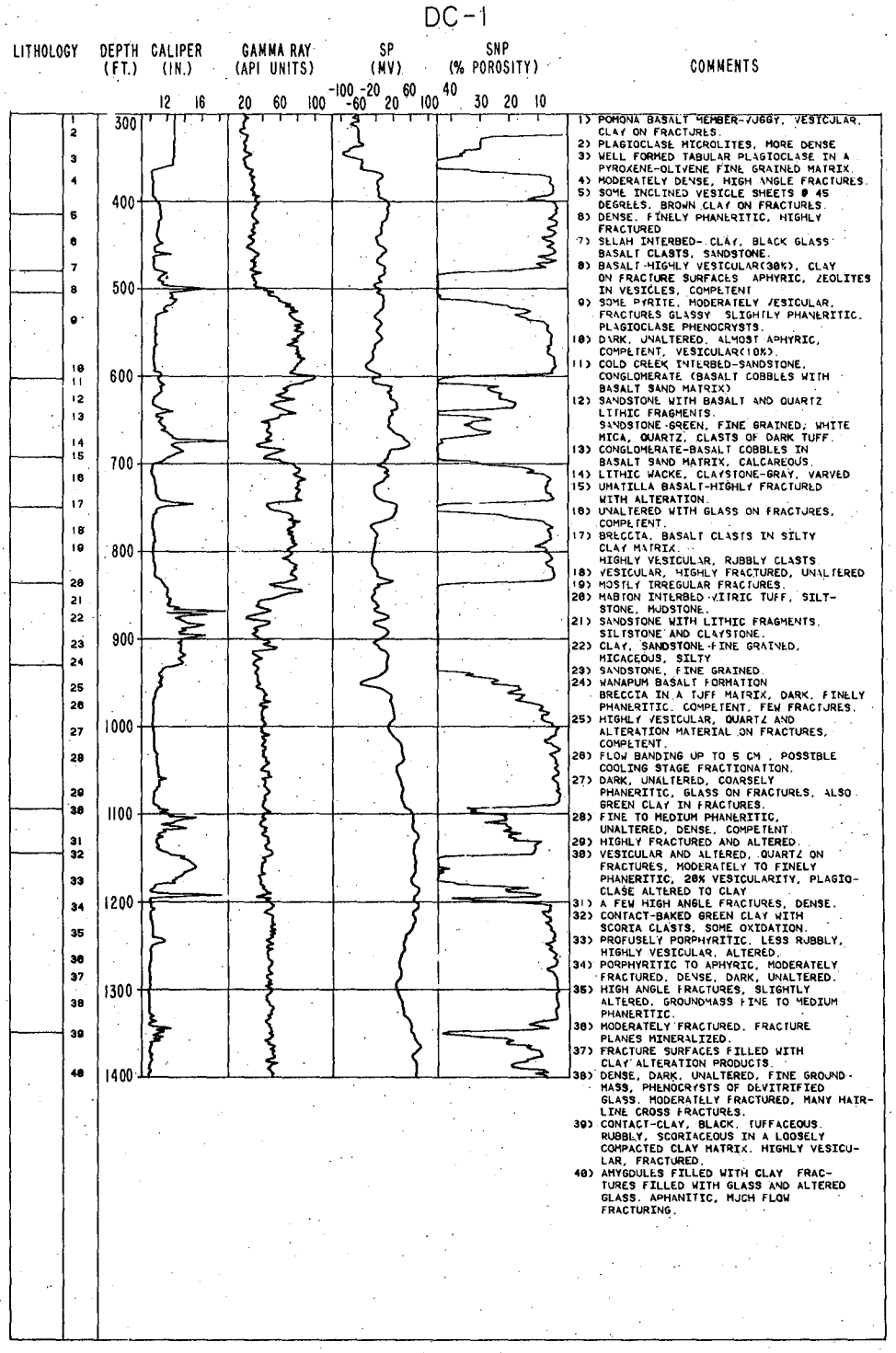

Figure II-15. Composite of geophysical logs with geological description in well DC-1.

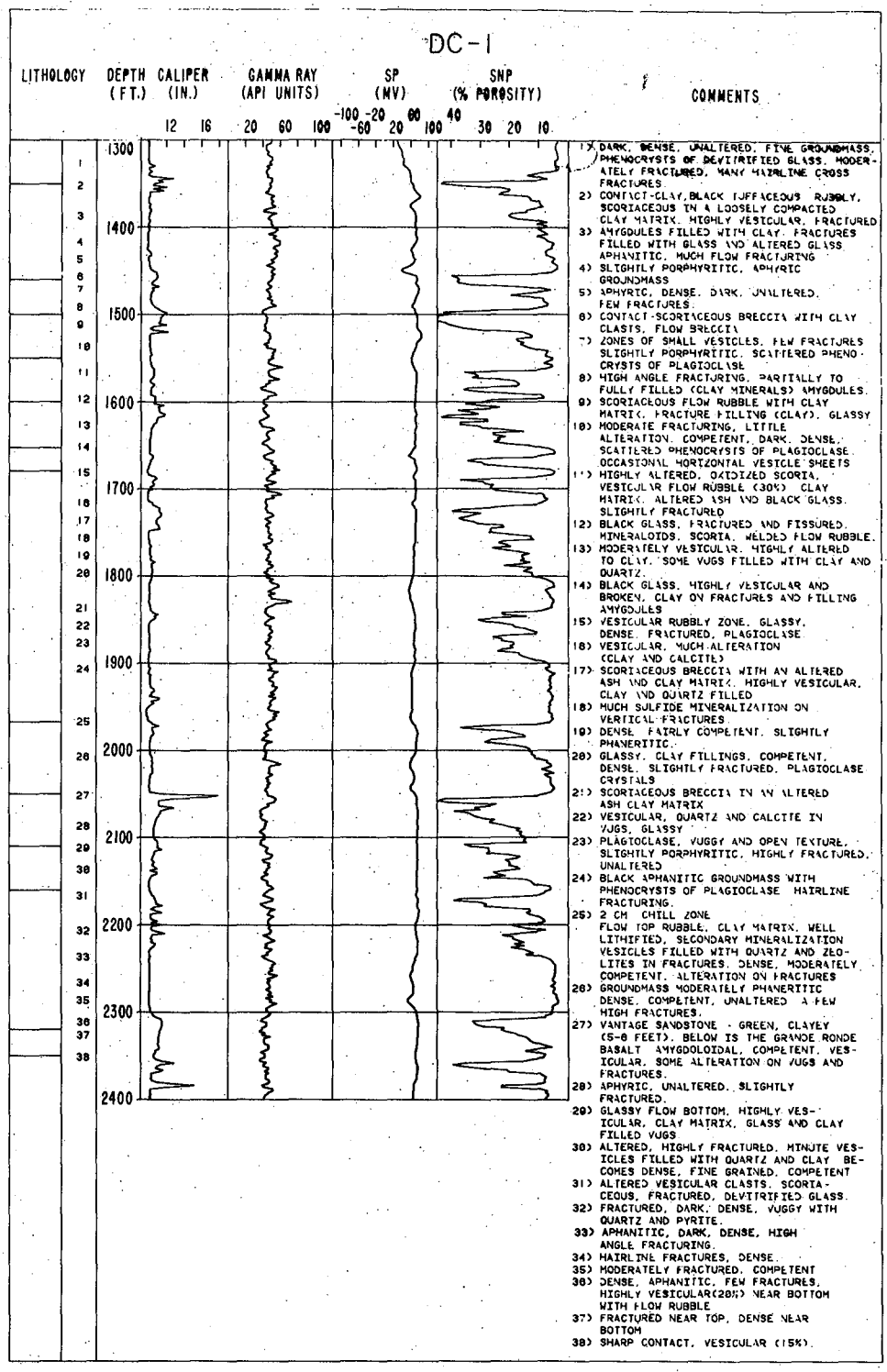

Figure II-15. Cont.

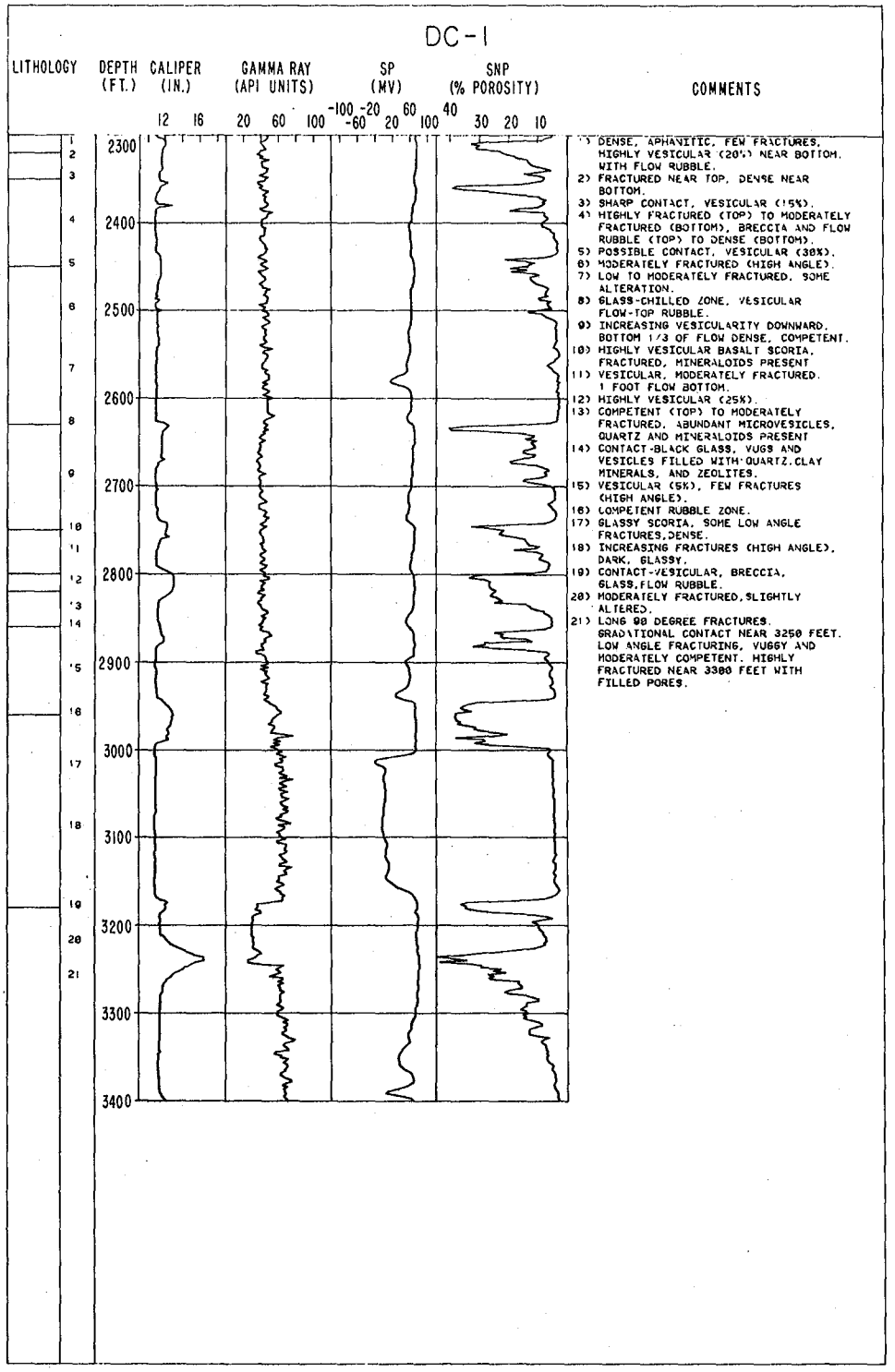

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Figure II-15. Cont.

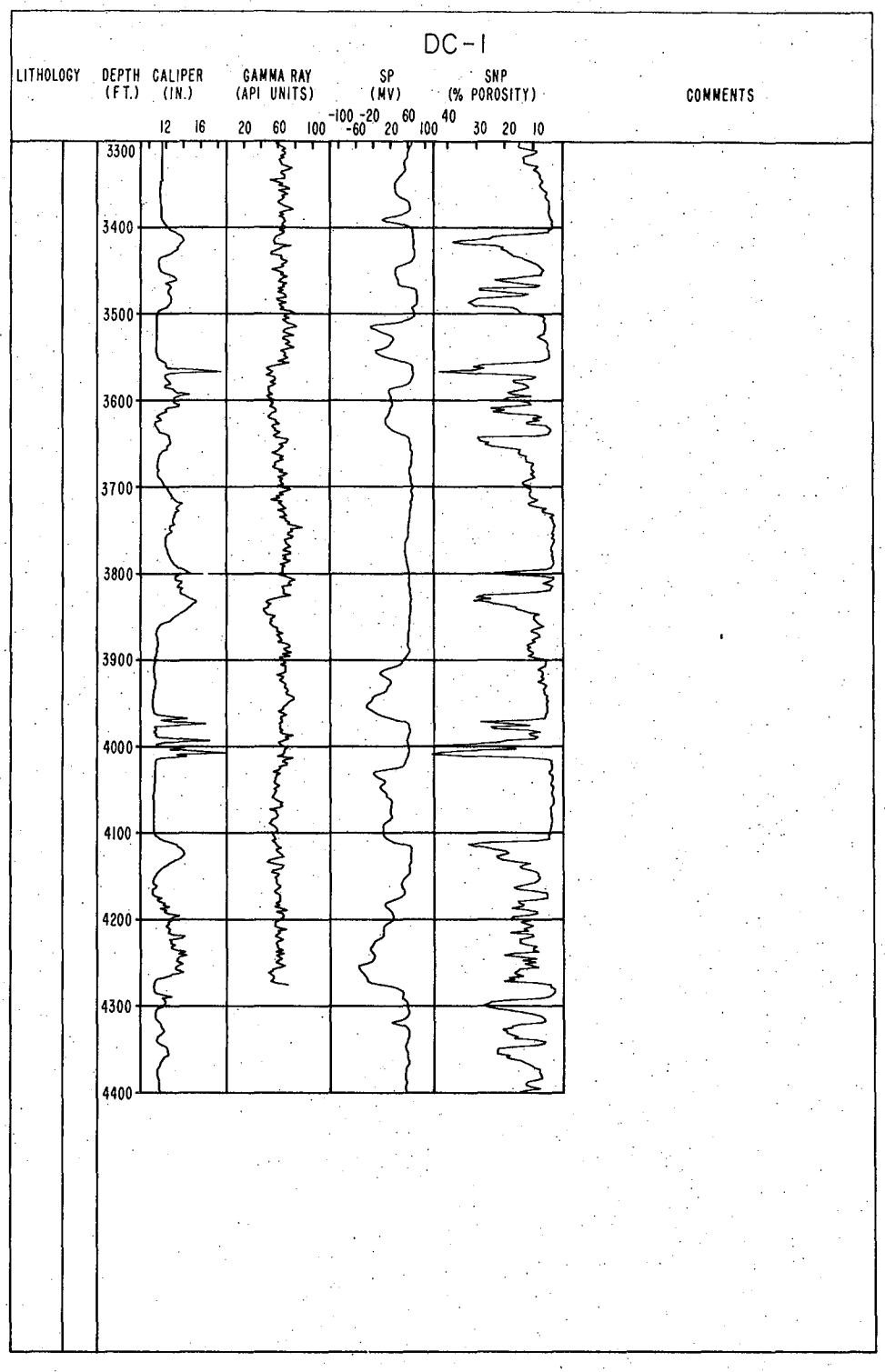

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Figure II-15. Cont.

the complexity of matrix effects, it is not possible to apply a correct porosity scale except by calibration with cores. (Alternatively, cross-plot analysis of the existing logs could be done to refine the estimate.) It should be noted that the SNP log porosity value will vary by about 4 volume percent at the 10 to 20 percent porosity level, depending upon whether the rock is a limestone or dolomite (Tittman, et al., 1966). Even greater differences can be expected in the basalts with their mafic mineralogy. Another example of the neutron scaling problem is discussed below under the section on correlation.

Despite the uncertainty in the SNP scale, the general porosity character of the basalt flow sequence is reliably portrayed in the SNP log. Dense basalt intervals are low porosity; good examples occur at 2510 to 2630 feet, 3000 to 3160 feet (the Umtanum) and 4020 to 4110 feet. Vesicular zones and rubble zones are high porosity, indicated by the abrupt and irregular swings to the left. Examples occur throughout the hole. The comments in the right-hand column, taken from the geological examination of the core from the adjacent hole DC-2, can be examined to demonstrate the reliability of the porosity log. Another especially instructive exercise is to lay out side by side the color photographs of core from DC-2 and the SNP (or any porosity log) from DC-1.

The caliper log in the left-hand column of Figure II-15 shows diametral excursions of up to 6 inches in several places and frequent cases of borehole enlargement of a few inches. With few exceptions these enlargements occur at the intervals where the porosity is high, as expected, since the rock is less competent in the rubble zones and in the highly vesicular zones. One might suspect that the borehole enlargements have in fact contributed to the anomalous porosity indications, but the tools are designed to minimize these errors and the necessary corrections are applied automatically as the log is run.

In oil-field exploration the SP and gamma ray logs are regarded as lithology indicators and in a sand-shale sequence give traces which are very similar in appearance. In the basalt the SP log might be expected to indicate zones where mud invasion occured during drilling. However, inspection of the SP log in conjunction with the other logs revealed no explanations for its behavior.

The gamma ray log, on the other hand, must respond to the combined gamma ray contributions from potassium, uranium, and thorium, and it might be expected that there would be systematic variations in the content of these three elements from flow to flow so the gamma ray log could be used to correlate flows aross the basin. However, Figure II-15 shows very little change in the gamma ray signature except between 500 and 900 feet and between 2950 and 3250 feet. Bowman, et al., (1973), shows that uranium content in the Columbia River basalts ranges from 0.3 to 2.0 ppm, thorium from 1 to 8 ppm, and K_2O from 0.5 to 3.0%. These ranges indicate that each of the three sources may be contributing more or less equally to the total count rate. Hence, significant correlatable change in one of the three sources could be masked by irregular fluctuations in one of the others. For this reason a spectral gamma ray log is worth running on a trial basis to see if discernible features can be mapped. Other considerations on gamma ray correlation are considered below.

Specialty Logs in DC-1

The outstanding log in this category is the televiewer log run by Schlumberger in 1969. Unfortunately this log was only run over the limited interval, 1139-2226 feet. The log provides an excellent visual display of the vesicles and fractures on the borehole wall. (The tool sends out high frequency acoustic energy from a rotating scanner and receives the pulse reflected from the borehole wall.) The resulting image is transmitted to the surface and photographed from the oscilloscope display. Details of the tool operation are given by Zemanek, et al. (1970). Because of the complex nature of openings in basalt, the televiewer pictures would be quite valuable if they were generally available for inspection wherever hydrological tests are carried out and particularly where permeable zones exist (see subsequent section on flow profiling). Hence it is recommended that televiewer logs be routinely obtained in wells where hydrological testing is planned.

Several "3-D" or "variable density" sonic logs were run in DC-1 with different source-receiver separations. Of these, the most interesting is the Schlumberger log of July 21, 1969 using a three foot separation, the closest spacing which was run. Both compressional and shear amplitudes and their transit times are displayed as traces, as well as the variable density waveform display. This data is of interest because of the greater wealth of

fine detail displayed in the dense basalt than appears on the other logs. It is diffucult to comment further without more detailed knowledge of the tool operation, but the short-spaced sonic tool does merit further consideration in terms of detailed examination of the dense basalt.

The pad-type electrical tools - microlaterolog, microinverse and micronormal - also show more detail than the larger tools, but this advantage is offset by the trace being off-scale over significant portions of the log. This occurs in the resistive dense basalt where the resistivity often exceeds 2000 ohm-meters.

Logs Indicating Permeable zones

The Birdwell temperature log of April 5, 1972 (0 - 5550 feet) and the Birdwell radioactive tracer log under dynamic conditions of April 8 - 9, 1972 (1060 - 5582 feet) were run during the reentry sequence carried out during February through April 1972 (Fenix & Scisson, 1972a). During the reentry operations the hole, which had been lost previously, was successfully reentered in the vicinity of 935 feet. The recovered hole was then cased with 10-3/4 inch casing to 1219 feet. About six days were then spent retrieving a packer which had been left in the hole during previous operations. Following this, April 2 - 4 were spent cleaning the hole with a 9-7/8 inch bit. With both rig pumps running, water loss was approximately 150 gallons per minute as cleaning progressed from 2171 to 5582 feet. At 5582 feet junk and solid fill were encountered. At this point water was circulated for a two hour period - presumably with the 150 gallon per minute loss continuing - and the drill string was pulled out of the hole. Washington State University commenced logging on April 4 and finished on April 5. Birdwell commenced logging on April 5 and completed logging on April 9.

Hence, the Birdwell temperature log was run one day after cleaning and circulation of the hole were completed. The total volume of water loss was not estimated nor do we know the temperature of the injection fluid. Another imperfection in the Birdwell temperature log is possible disturbance of the water column due to the logging operations of Washington State University during the intervening one day period. Otherwise, the Birdwell log appears to be quite adequate. The repeat section from the interval 5150 to 5550 feet duplicated all the recognizable features. Repeatability was within 1/2 degree F.

With this information on the injection history, some comments on the features of the temperature log of April 1972 are now in order. One temperature maximum occurs at 930 feet within the casing (see Figure II-16). This is undoubtedly a residual heating effect from the extensive cementing done at that depth which was completed 20 days before the log was run. The other anomalies occur below the bottom of casing and all are negative, that is, they represent cooling due to the flow of the cleaning/circulation fluid which left the wellbore and entered the formation. Seventeen discernable anomalies occur between 1219 feet and total depth. All 17 of these anomalies occur at zones of high porosity as indicated on the well logs, that is, within either the interbeds or the vesicular basalt.

Twelve of the 17 cooling features are quite small, about 1/2 degree F or less, and are not discernable on the temperature log in Figure II-16 which is plotted at a fairly coarse scale. However, they can be examined on the original log and are also located schematically in Figure II-17. These 12 anomalous features are centered at depths of 1360, 1490, 1612, 1735, 2060, 2320, 2530, 2950, 3562, 4120, 4700, and 5390 feet. It appears quite likely that these minor features indicate zones which are more permeable than the dense basalt, but much less permeable than the major features discussed below.

Five temperature anomalies are quite pronounced and stand out clearly in Figure II-17, centered at depths of 3180, 3965, 4860, 5055, 5195 feet. In these zones the temperature deviates from the gradient by 3 to 9 degrees Fahrenheit. The geometry of the injection method was such that cooler surface waters were introduced at the bottom of the hole. Hence, permeable zones near the bottom are emphasized more than those higher up because the temperature contrasts are greater. Because of this and other factors it is not possible to rank the anomalous features with regard to their permeability. These five pronounced features are indicated as major anomalies in Figure II-17. Most of the fluid lost during the cleaning operation exited the well at these locations.

The temperature log of April 5, 1978, can also be used to give a crude estimate of the geothermal gradient in the basalts. The estimate is crude due to the prior injection of surface water. The gradient in the 2000-5000 foot depth zone is 2.8 ± 0.2^{o} per 100 feet, equivalent to $51^{o}C$ per km. This estimate is higher than the data presented by Sass, et al.

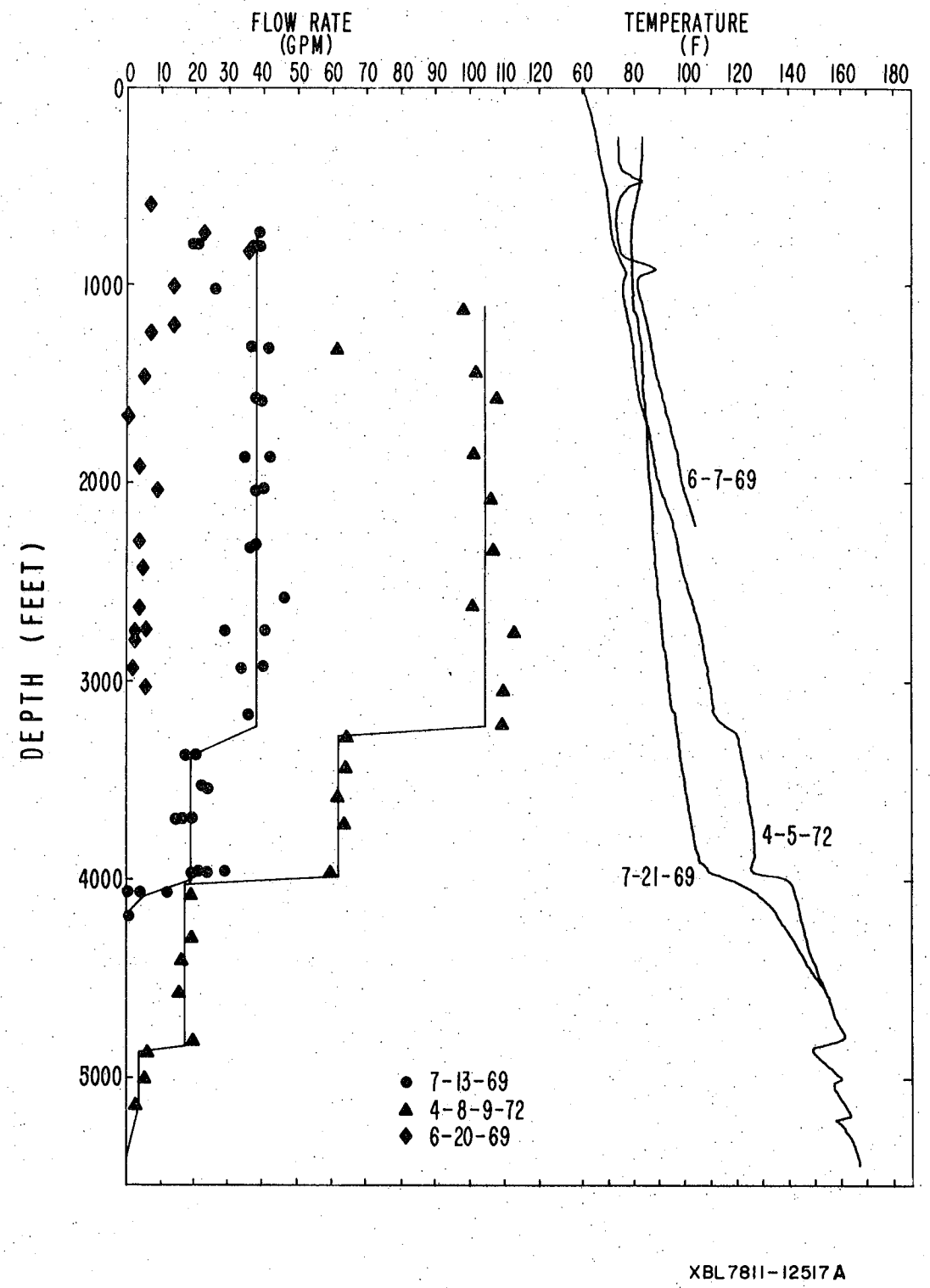

Figure II-16. Three radioactive tracer flow profiles and three temperature logs in DC-1.

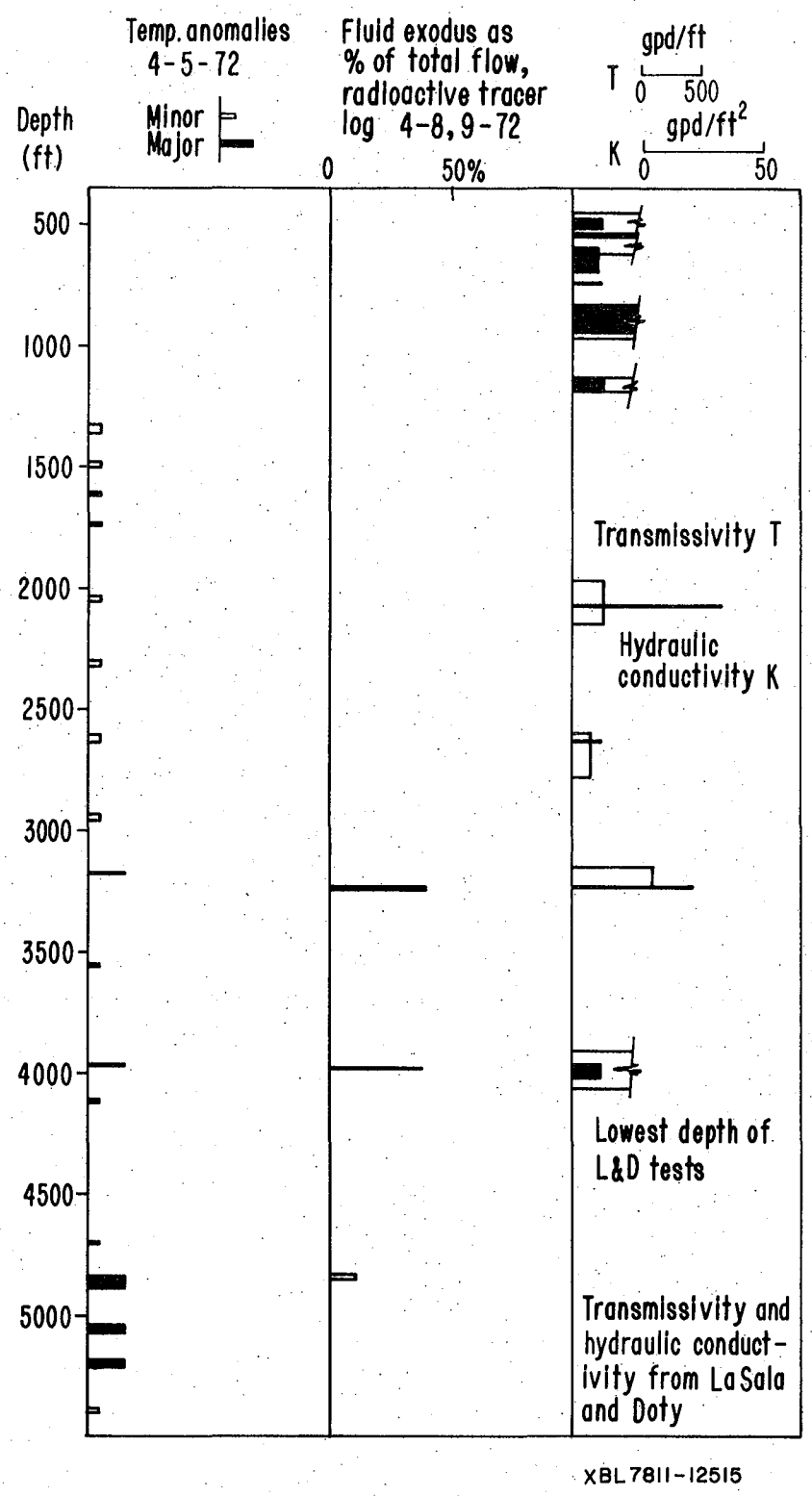

Figure II-17.

Summary figure of anomalous flow zones in well DC-1 shown by the temperature and radioactive tracer logs of April, 1972. Minor temperature anomalies represent fluctuations of ½° F or less. Also shown are hydrological data from La Sala and Doty (1972).

(1971). Their measurements in four wells close to Hanford (RS-1, RS-2, DH-3, and DH-1) range from 28 to 39°C/km, with errors estimated to be less than 1°C/km. Since the data by Sass must be the better estimate of the geothermal gradient, either the DC-1 gradient has been greatly increased by the drilling injection history, or else the DC-1 gradient is anomalous compared to that immediately ouside the basin. Good temperature estimates will be important to repository design, and the issue should be settled by careful measurements in some of the DC holes after the holes have stabilized thermally.

A radioactive tracer log under dynamic well conditions was run by Birdwell on April 8 and 9, 1972. The survey used radioactive iodine-131. Water was injected into the hole during the survey at a 105 gallon per minute rate. Cumulative injection during the 7-hour test was 46,100 gallons. No information is readily available on the pressure maintained during the test. Fenix and Scisson (1972a) report simply: "Logging hole with Birdwell equipment. While running dynamic tracer log, ran water in hole at 105 gpm." We surmise that no pumps were used and that the hole was kept full of water. Since the static head was around 156 feet (47.5 m) below ground level, this implies an applied differential pressure of about 47 m of water during the test.

Measurements were carried out by ejecting a slug of iodine at a certain depth, then subsequently pulling the tool through the zone of interest at time intervals of about one minute. From 3 to 12 passes were made at each depth over intervals ranging from 20 to 240 feet depending upon the velocity of the water and the dispersion of the iodine tracer. The iodine concentration was detected with a gamma ray detector and recorded on chart paper as a function of depth. An example of the resulting record is shown in Figure II-18. Note the increased dispersion of the tracer as the slug migrates down the borehole.

The caliper correction is a major source of error in computing the volumetric rate because it depends upon the square of the diameter. The percent of error in the caliper correction is:

$$\text{Error } (\%) = 100\ [(d'/d)^2 - 1]$$

where d' is the measured diameter and d the true diameter. Hence, a one inch error in the measurement of a 10 inch diameter borehole can cause a 20% error in the flow rate calculation. Assigning a representative diameter

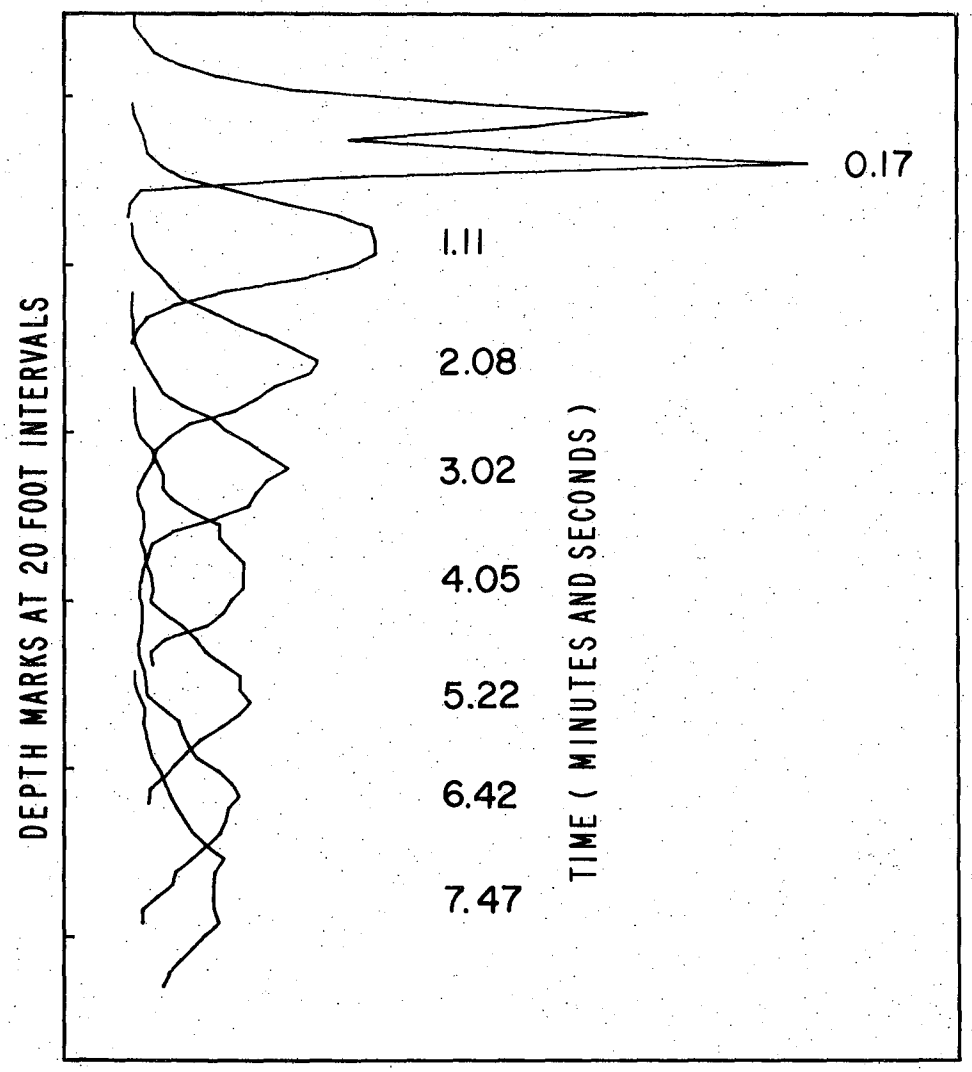

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Figure II-18.

Example of radioactive tracer data in well DC-1. Radioactive tracer log run by Birdwell, April 8 & 9, 1972. Each individual peak represents a single measurement run in the borehole after the tracer was ejected. Time of run given in minutes and seconds. Water injection at time of log was approximately 105 gmm. Depth marks are at 20-foot intervals.

in a rough borehole contributes as much error as the caliper measurement itself; that is, the caliper contributes both absolute and relative errors. Generally the tracer log results were within ± 10% on an individual ejection run, except in cases where large borehole washouts were present. In these cases the deviations could be as much as 40%. The scatter in the averaged data is usually about 10% as can be seen in Figure II-16.

The Birdwell analyst noted three major zones of water loss at 3228-3234, 3972-3980, and 4824-4854. Inspection of Figure II-16 indicates that these three zones account for 40%, 38%, and 12% of the loss, respectively. As nearly as it can be estimated with the tracer log, the total vertical footage of the loss zones, z, is 44 feet (13 m). Using the injection rate of 105 gallons per minute (6620 cc/sec) and an injection head, H, of 47.5 m, we can use the radial flow equation to estimate the average hydraulic conductivity. With a radius of influence of 30 m and a well radius of 12.7 cm, we can compute:

$$K(\text{cm/sec}) = \frac{1}{2 \times 10^4} \frac{Q(\text{cc/sec}) \times \ln(r_b/r_a)}{\pi\, Z(\text{m}) \times H(\text{m})}$$

$$= \frac{1}{2 \times 10^4} \frac{6620 \times \ln(3000/12.7)}{3.14 \times 13 \times 47.5}$$

$$= 9.4 \times 10^{-4} \text{ cm/sec}$$

La Sala and Doty (1971) estimated conductivities of 5.6×10^{-4} and 2.4×10^{-3} cm/s (11.8 and 50.8 gpd/ft^2) in two of the three zones delineated by the tracer log (see Figure II-17), the third zone being inaccessible to La Sala and Doty at that time. Hence, the tracer log is roughly consistent with the only existing hydraulic conductivity data. The estimate obtained above is only an order-of-magnitude-estimate due to such factors as the assumption of static radial flow in what was probably a transient condition. Other uncertainties are the lack of compensation for temperature-dependent viscosity and the estimate of the factor $\ln(r_b/r_a)$.

In summary, the radioactive tracer log clearly and unambiguously delineated three zones of fluid exodus in DC-1, as shown in Figures II-16 and II-17. These same zones were also delineated as the upper three major temperature anomalies on the temperature log. According to the tracer log, the lower two temperature anomalies were taking only a few percent of the total flow.

Figure II-16 shows two radioactive tracer and two temperature logs run in DC-1 during the 1969 drilling operations (Fenix and Scisson, 1969) as well as the tracer and temperature from 1972 which we have just discussed. Because they contribute only confirmatory evidence for the reliability of the 1972 data, we will discuss them only briefly here.

The temperature log of 6/7/69 extends to 2230 feet. At the time the log was made the casing extended to 362 feet. The two prominent heating anomalies resulted from the emplacement of cement plugs two to four days prior to logging. Below the lower heating anomaly there are no heating or cooling anomalies, and hence no interpretable zones of fluid loss.

The temperature log of 7/21/69 extends to 4605 feet. Temperature anomalies at 3210 and 3990 feet correspond to those registered on the 1972 log. In addition a 1° cooling feature occurs at 1180 feet. This probable flow zone was behind casing when the 1972 temperature log was run so that no temperature anomaly was then observed.

Both the radioactive tracer logs of 6/20/69 and 7/13/69 were run under static hole conditions, that is, without injecting surface water while the log was being run. It should be noted that these logs were not run under the same hydraulic conditions as the April 1972 log discussed earlier. Neither the Mabton (835 to 931 feet) nor the Vantage (2046-2050 feet) interbeds were cased when these logs were run but both had been cemented and the cement drilled through. Both logs show that some 20 to 40 gallons per minute of water were entering the hole from somewhere in the interval 590 to 785 feet. The tracer log of 6/20/69 indicates two loss zones, one between 825 and 990 feet and another between 1194 and 1231 feet. Below 1233 feet the flow rate is about 5 gallons per minute and the data scatter is too great to resolve any other zones of exodus. At this time the hole had been drilled to 3103 feet (Fenix and Scisson, 1969). The lowermost tracer shot was at 3013 feet.

Drilling continued to 4282 feet when the tracer log of 7/13/69 was run. There is no indication of any modification to the wellbore in the depth zone above 1300 feet, or anywhere in the well for that matter, yet the flow regime in the upper portion of the well changed between the execution of the logs. The data quality above 1300 feet does not allow a detailed analysis of the flow regime there, but it is clear that the zone between 1194 and 1231 feet is no longer taking fluid and instead may be producing it. Below 1300

feet the flow is more or less uniform in the 35 to 40 gpm range down to 3154 feet. The lower portion of the log shows the same two zones taking fluid as are indicated in the log of 1972, although with less depth definition because fewer tracer shots were taken.

It is noteworthy that both the static logs examined here show downward fluid motion in the well. Transient, rather than steady-state conditions prevailed in both cases as both logs were run soon after the cessation of drilling.

b. Well Logs From DC-3

Because no hydrology tests were conducted in Well DC-3, the logs were only briefly examined. At the present time, DC-3 has a more complete suite of logs than any of the other wells, with the obvious exception of DC-1. The logs are listed in Appendix B.

Figure II-19 is a replica of several log segments from DC-3 plotted at the original scale of 20 feet per inch. It confirms many of the features displayed in Figure II-14 and already discussed above. Particularly obvious is the strong correlation among the density, neutron and sonic logs and the monotonic porosity decrease with depth in an individual basalt flow.

Two dipmeter curves are included in Figure II-19. The dipmeter tool is designed to map the strike and dip of thin beds and other correlatable features. Four arms, equipped with a microresistivity probe on a pad pressed against the borehole wall, obtain detailed and independent resistivity logs at 90° separation around the borewall. Except for optical methods and the televiewer, the vertical resolution exceeds that of any other existing tool. Some of the very thin features in Figure II-19 correlate between the two arms; others appear to be uncorrelated. Because of the potential of this tool to resolve and map fractures, a detailed study to examine its usefulness in the basalt is warranted. Such a study would require independent information, preferably from cores, for confirmation.

c. Well Logs From DC-5

Well DC-5 was cased to the Vantage sandstone before the suite of logs was run by Welex in August 1978 over the interval 2630-3960 feet. Wells DC-5 and DC-7 were both drilled, cased and logged in much the same fashion. In DC-5 the neutron log extends up to the top of the fluid column at 340

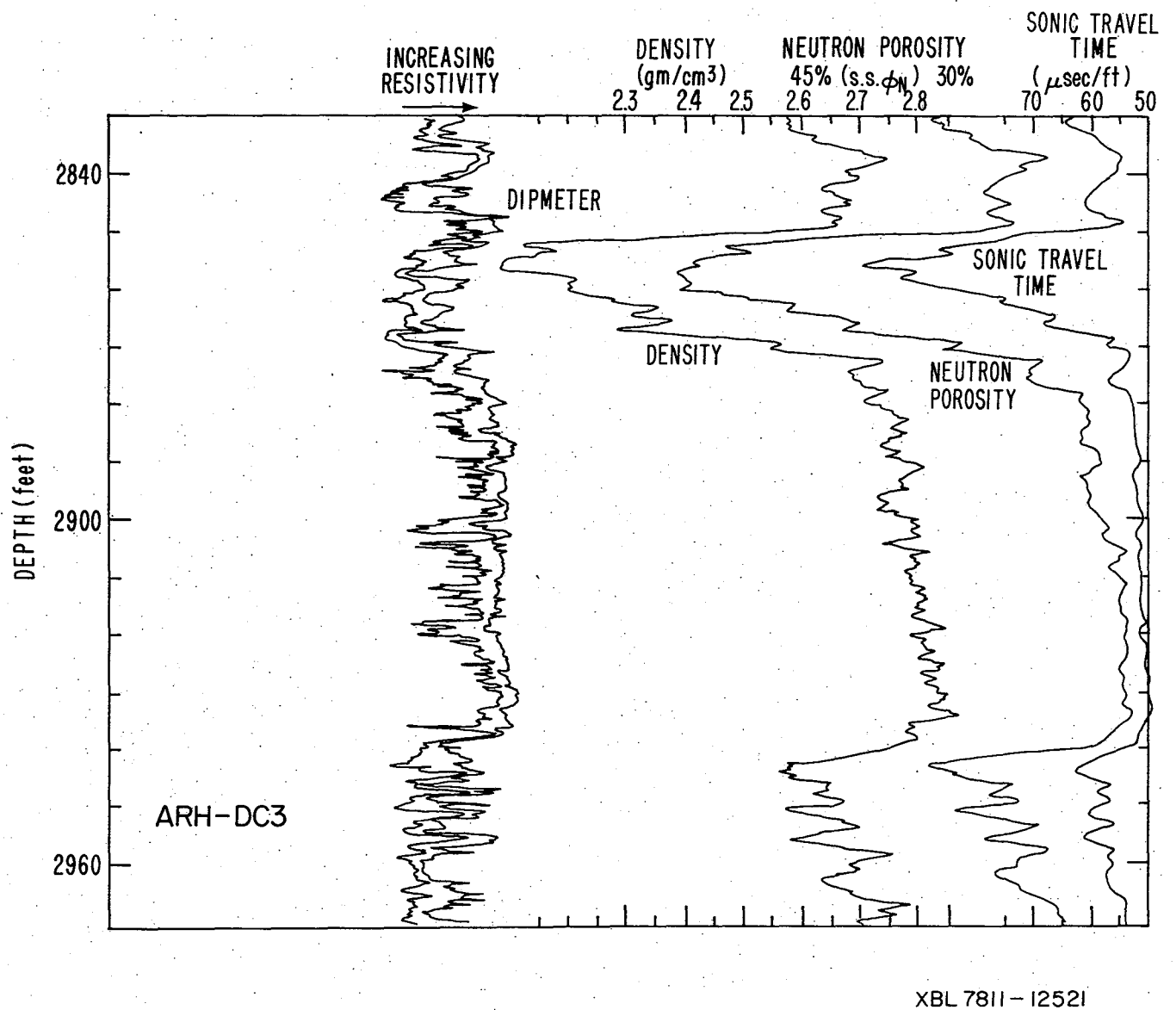

Figure II-19. Four logs from 2830-2970 foot interval in well DC-3.

feet (Figure II-20) and the gamma ray log extends to surface (Figure II-21).

The DC-5 logs have been inspected briefly and have not been composited. The four "porosity" logs - neutron, density, acoustic velocity, and electrical resistivity - generally behave as previously described, that is, they correlate well and map the porous zones quite well.

The density log in DC-5 often exhibits sharp spikes indicating low density. These features do not appear to be real. They correlate with sharp caliper openings and may be due to poor compensation on the tool. The areas around 3100 and 3300 feet exhibit this effect.

d. Well Logs From DC-6

Well DC-6 was logged by Washington State University in May 1978. A variety of slim-hole logs were run (see Appendix B) but they are not scaled, nor are any details of tool calibration presented on the logs. Before the logs will be readily usable, they must be scaled, aligned, and composited, along with the geological log that was drawn up during the drilling.

A unique feature of the coring in DC-6 is the prevalence of long intervals of "poker-chip" core, called "pringling" in the geological core log. This term refers to the wafer-like discs, often as many as 20 to 40 per foot, which have wavy surfaces causing the wafers to nest with one another. The logs correlate well with the pringled zones, showing higher density and lower porosity at these intercepts.

Also of interest is the temperature log of 31 May 78. Below 3780 the temperature gradient increases dramatically, with a disturbed zone at 3665-3780 feet. This includes the interval which flowed 90°F water at a 12 gallons per minute rate during the drilling operation. Another, smaller heating anomaly occurs at 3360 feet where fluid was lost during drilling at a 11 gallon per minute rate. Two cooling anomalies occur at 2740 and 2900 feet. The geologic log indicates drilling fluid loss just above the former, but nothing at 2900 feet.

The caliper log does not appear to be valid and shows very few individual features. It is recommended that another caliper tool be run before any hydrological tests are carried out.

e. Well Logs From DC-7

Well DC-7 was cased to the Vantage sandstone and a suite of logs were

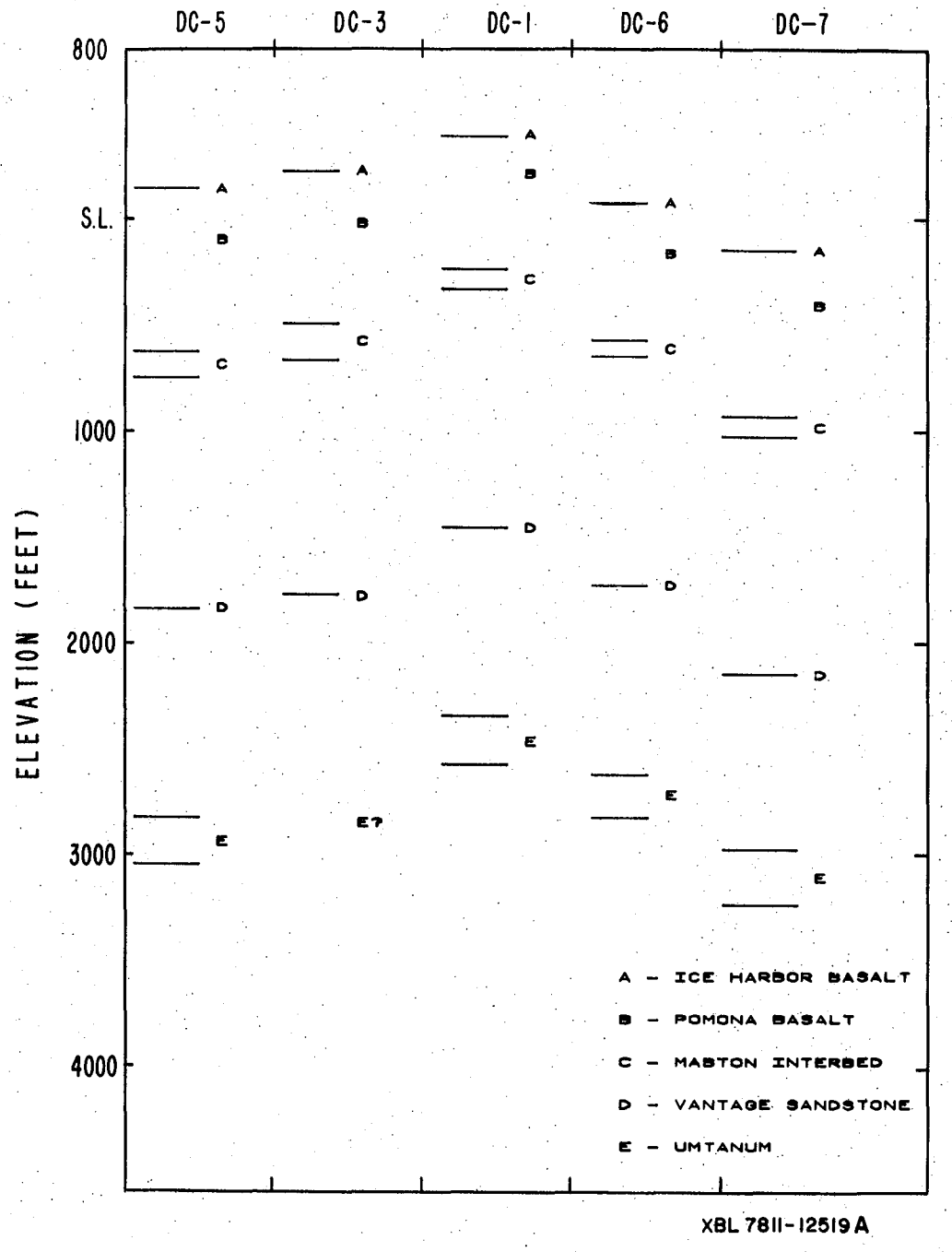

Figure II-20a. Geologic units and correlations for Figures II-20 and II-21.

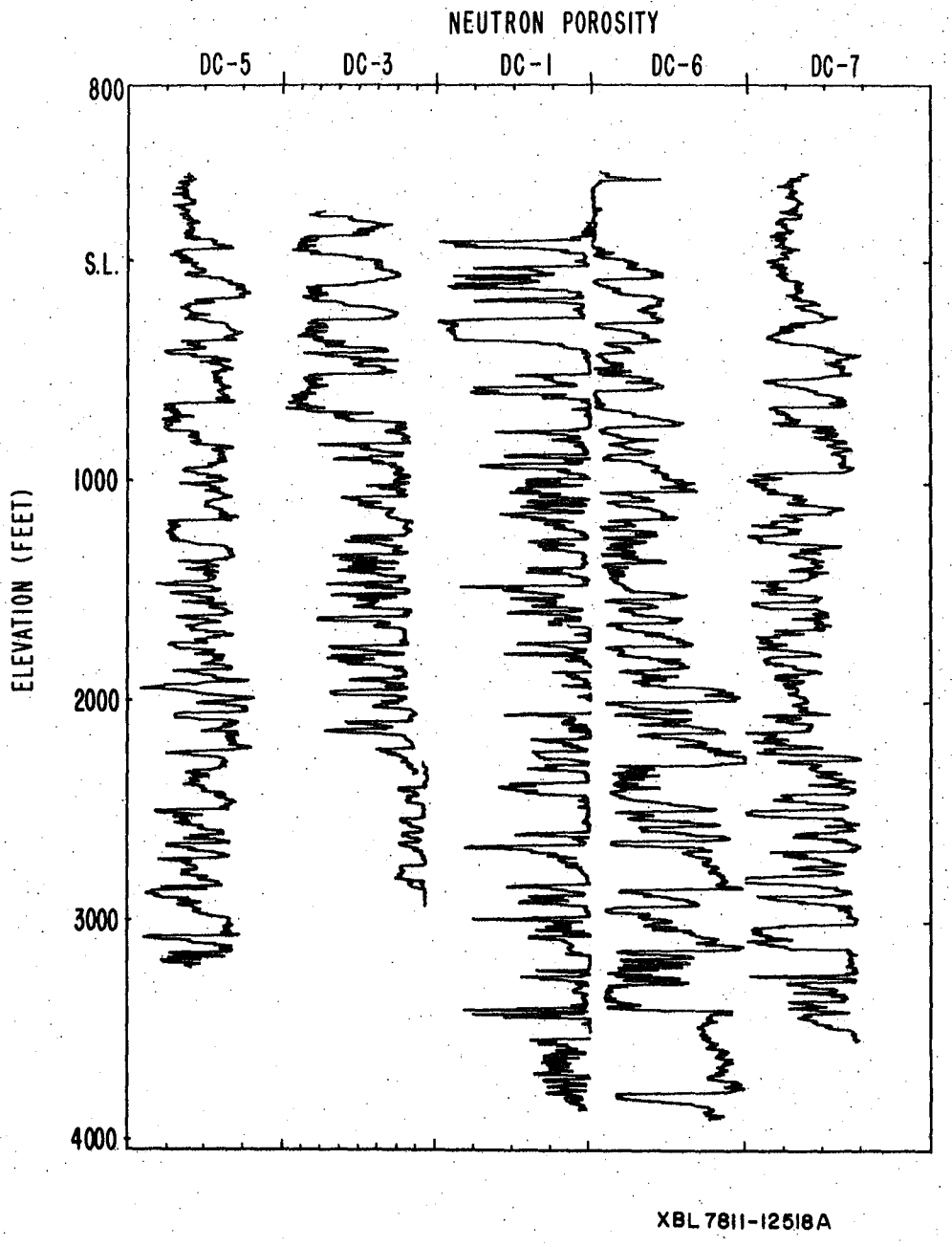

Figure II-20. Neutron porosity logs from wells DC-5, DC-3, DC-1, DC-6, and DC-7.

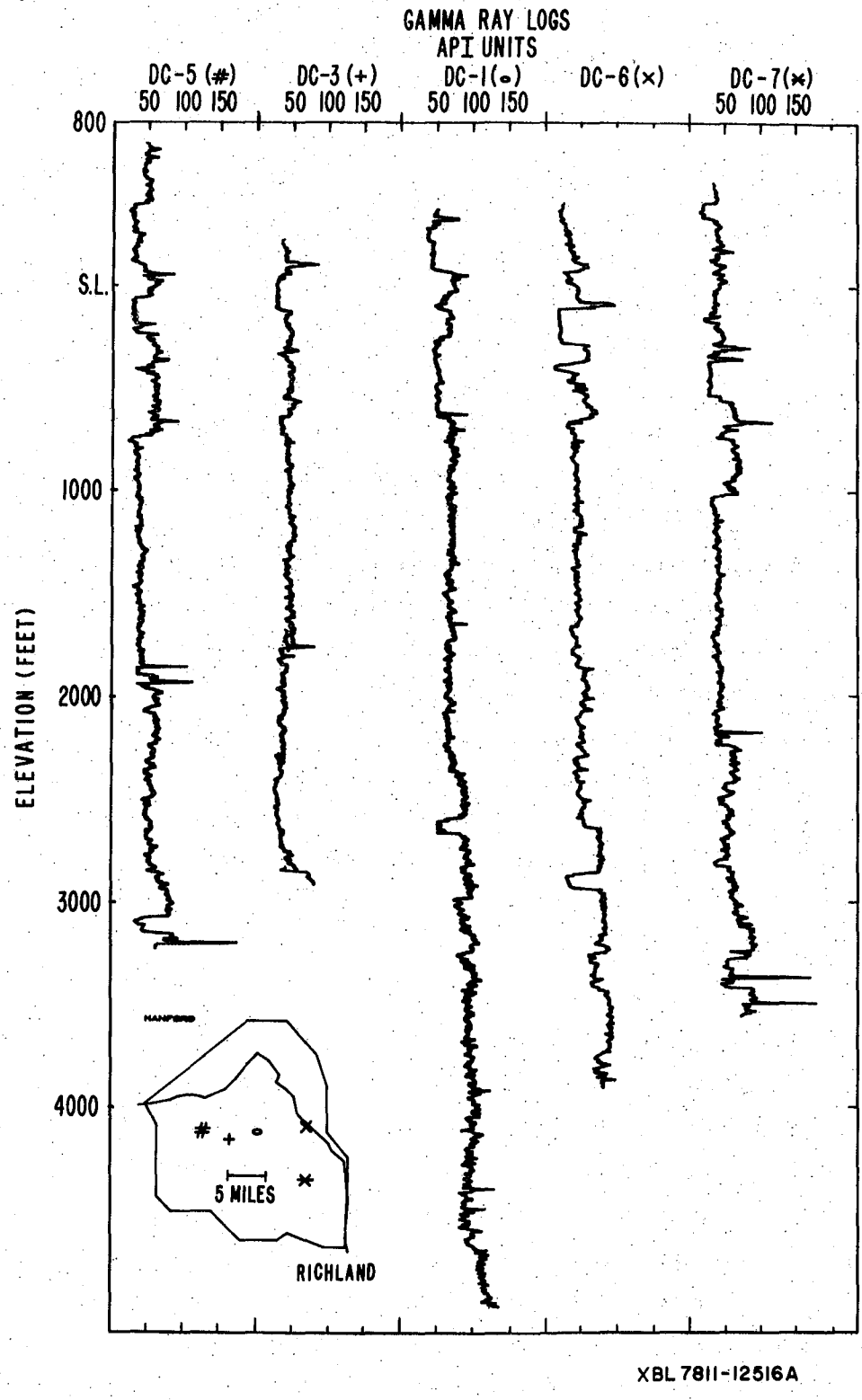

Figure II-21. Gamma ray logs from wells DC-5, DC-3, DC-1, DC-6, and DC-7. Logs adjusted to common elevations to remove topographic effects.

run by Welex in August 1978, over the interval 2780-4095 feet (see Appendix B). Exceptions are the neutron which was run up to water level at 150 feet (see Figure II-20) and the gamma ray which was run up to the surface (see Figure II-21).

The logs have not been composited and only a brief visual inspection has been performed. The four "porosity" logs behave as described previously, that is, they are well correlated and map the porous zones quite well. An important exception is the compensated acoustic velocity log below the depth of 3755 feet. Below 3755, the velocity (transit time) log is erratic, does not track the other logs very well, and often records unrealistically low (< 45 μsec/ft) transit time. Such erratic character might not have been apparent had it occurred only in a porous zone, but the log is off-scale over the lower portion of the dense Umtanum Unit as well. A possible explanation (other than a temporary malfunction) is that excessive mud cake somehow caused an exceptionally noisy environment causing short apparent transit time. The caliper log seems to indicate mud buildup in the bottom of the hole. If this is the case, extra care should be exercised in cleaning the hole before commencing hydrological tests.

The neutron, density, and gamma ray logs indicate that the top and bottom of the Umtanum occur at 3670 and 3820 feet, respectively. These estimates compare with footage of 3561 and 3801 based upon core recovery. Hence in DC-7 the logs apparently do not respond to the upper 90 feet of the Umtanum flow unit.

f. Well Logs From DC-8

Logs in DC-8 were obtained in July 1978 by Edcon. DC-8 is an NX core hole, necessitating the use of slim-hole logging tools. Available at the time of this writing is the first set of logs from the interval 1600 to 2720 feet (see Figure II-22). Two log types previously untried at Hanford were run in DC-8, the magnetic susceptibility and induced polarization logs.

The magnetic susceptibility measurement responds mainly to the magnetite content of rock. The purpose of running the log was to determine its usefulness for correlation purposes. Since the log has so far been operated in only one hole, correlation cannot yet be checked. However, the log does appear valid and signal level and the variations are both adequate to determine the utility of the log as soon as a second hole is logged. It

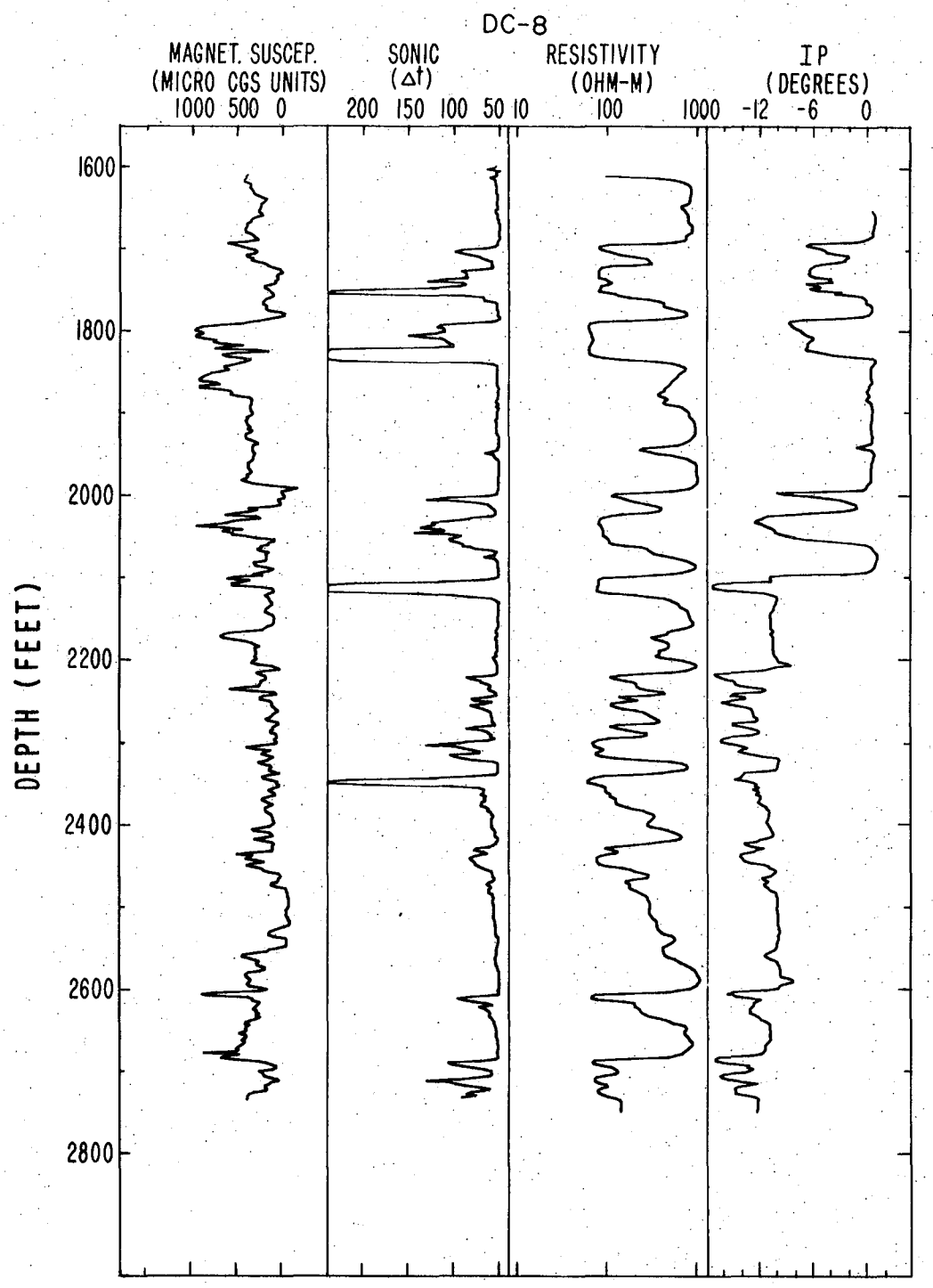

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Figure II-22. Magnetic susceptibility, sonic travel time, resistivity, and induced polarization logs in well DC-8.

is recommmended that the logs be acquired on a more sensitive scale on subsequent operations, however.

The induced polarization measurement responds to the sulphide and clay content of rock, in particular to the sulphides and clays exposed to the pore fluids where electrical conduction takes place. A possible application of this tool, then, is to indicate clay content of the basalts. This is of particular interest from the waste repository standpoint because of the desirability for the retention of radionuclide migration by the rock mass. Clay materials in the basalt would afford one such barrier because of their high cation exchange capacity. Unfortunately there appear to be some questions about the log shown in Figure II-22. The sudden transition to high phase values at 2100 feet has no obvious geological explanation and the values of -12° are much too high to be realistic. Another question is the apparent control of the induced polarization trace by the apparent resistivity. While some correlation is expected and may be quite valid in this circumstance, it can also be an indication of measurement problems. Careful study of the measurement and validation of its effectiveness through core studies are required before the method can be recommended for routine use in the basalts.

g. Correlation Between Holes Using Well Logs

Figures II-20 and II-21 summarize our examination of the existing well logs to correlate basalt flows among the DC series of holes. The overlay of Figure II-20a aids in examining the relationships between the basalt geology and the well logs. In Figure II-21, the Umtanum can always be recognized by its characteristic increase in gamma ray activity, with an unusually low gamma ray interval just below it. In three of the five holes, the Vantage sandstone is marked by the presence of a large spike increase in the gamma ray count rate, but unfortunately this feature is inconspicuous in Wells DC-1 and DC-6 because the Vantage is thin in these two holes. Higher in the holes, the Mabton interbed is characterized by a small peak and a decline in the gamma ray logs. Hence there are three units which can usually, but not always, be picked from the total count gamma ray logs. Disappointing is the lack of apparent features in the interval between the Umtanum and the Vantage, and again between the Vantage and the Mabton. As mentioned elsewhere, there is some chance that a spectral gamma ray log might exhibit

enough character in one of its components to allow correlation among these flows (see recommendations).

The neutron porosity logs (Figure II-20) are much less encouraging with respect to the possibility of correlating among the various holes. Visually it is very difficult to correlate individual features even between a pair of holes. Attempts to correlate using the expanded scales of the original logs were equally frustrating. No detailed work was done with any of the other logs. However, Rockwell Hanford Operations (1977, their Figure 10) reports success in correlating the compensated sonic logs between DC-3 and DC-1. Hence, an attempt should be made to examine the porosity correlations more closely. It may be worthwhile to use existing computer codes which cross-correlate data series of the well log type, with provision for dropping sections as well as stretching and sliding of data sections.

Figure II-20 also illustrates the problem of the neutron log scale which was alluded to earlier. The gross mismatch in the two segments of the log at the bottom of DC-3 accurately reflects the mismatch in the originals. The upper segment, from 500 to 2582 feet subsurface (above ~ 2300 feet below sea level), is a Schlumberger compensated neutron log recorded with compensation for a sandstone matrix, with the porosity values ranging from 9 to 60%. The lower segment, from 3000 to 3572 feet subsurface (below ~2300 feet below sea level), is a Birdwell compensated neutron log compensated for a limestone matrix, with values ranging from 4 to 18%. This illustrates the problem which arises when different suppliers and different specifications are used in the same area. A consistent porosity log can be pieced together from the existing data only with a great deal of care and attention to detail.

Also mentioned above in the section dealing with Well DC-8 are the results of the magnetic susceptibility log which displayed enough character to warrant running the tool in other holes of the DC series. This log would provide a closer tie to the chemical properties now relied upon for correlation (Atlantic Richfield, 1976) than any of the other logging methods.

h. Summary

1) Three major permeable flow zones exist at depth in Well DC-1. They lie at 3228-3234 feet (just below the Umtanum unit), 3972-3980 feet, and 4824-4854 feet subsurface. The units are clearly defined on radioactive

tracer flow profiles made in 1969 and 1972 as well as on a 1972 temperature log. The flow profiles indicate that the magnitude of the average permeability in the three zones is on the order of 10^{-3} cm/sec ($\sim$ 1 m/day). All three zones lie in high porosity intervals, as defined by the well logs which respond to rock porosity.

2) A large library of well logs exists detailing the basalts in the Hanford area. Most of them were collected in one well (DC-1), which in conjunction with the core from the neighboring Well DC-2, makes it ideal as a study case. However, the log collection suffers because different holes were logged by different suppliers using different tools, because no records of log analysis exist, and because no core studies have been coordinated with analysis of the logs.

3) The four logs which respond to rock porosity - density, neutron, sonic, and electrical resistivity - all do an excellent (and highly correlated) job of delineating porous zones. However, the porosity cannot yet be evaluated quantitatively from the logs because the tools are not calibrated for operation in basalt. This shortcoming can be overcome by study of existing logs in conjunction with the requisite core data, but such a study has not yet been done.

4) Previous open hole logging suites have been overemphasized, in the sense that redundant information was acquired for the identification of lithology. One or two of the traditional porosity logs can be eliminated from the suite, preferably the electrical combination because it provides no detail in the massive zones where the resistivity is often greater than the measurement capability of the tool.

3. Stress Measurements

a. Introduction

In situ stress data is essential to understanding the behavior of underground openings, both in the Near Surface Test Facility in Gable Mountain and in an eventual repository at great depth. Hydraulic fracturing is the only extensively used method of obtaining stress data at depth without having an underground excavation. Reliable stress measurements can only be made with hydraulic fractures in rock free of preexisting open fractures. Healed fractures may or may not cause problems depending on the nature of the

fracture filling and the fracture orientation. Stress measurements require fracture free borehole intervals of at least 0.5 m. A series of tests were run in DC-11 to serve the two purposes of checking applicability of hydraulic fracturing to basalts prior to attempts on deep holes, and to obtain stress data for the Near Surface Test Facility. Professor Bezalel C. Haimson of the University of Wisconsin conducted the tests with the aid of LBL field personnel. A complete discussion of test results is presented by DuBois, et al., (1979).

b. Procedures

Hydraulic fracturing measures in situ stresses by employing the following elastic solution:

$$P_F = (3\sigma_{Hmin} - \sigma_{Hmax}) + T_h - P_o$$

where:

P_F = Breakdown pressure

σ_{Hmin} = Minimum horizontal stress

σ_{Hmax} = Maximum horizontal stress

T_h = Hydrofracture tensile strength

P_o = Pore pressure

Assuming that one principal stress is coaxial with the borehole, a hydraulic fracture will propogate in the direction of σ_{Hmax} and normal to σ_{Hmin}. σ_{Hmin} is equal to the shut in pressure after fracture generation; σ_{Hmax} is then calculated using the results of laboratory tensile tests of the core from the zone tested.

The first step in hydrofracturing is the generation of the fractures. Sections of hole free of open fractures are chosen, and straddle packers are set in those zones. Water is then injected at increasing pressures up to the strength of the rock. After fractures are generated, the orientations are recorded using impression packers. While the impression packer is set, its orientation is determined using a gyroscopic orienting tool.

c. Experiment

Six primary test zones with alternates were selected between 55 and 340 feet of depth in Well DC-11. All zones were at least two feet long and free from open fractures. It was not possible to avoid healed fractures, but since hydrofractures are commonly vertical, zones were selected which

were free of vertical healed fractures. The deepest three zones were inaccessible due to caving of the Selah bed at about 280 feet; however, it was still possible to fracture zones in the Pomona flow where the shallow heater test is planned. Six fractures were generated at the following depths: 55, 144, 172, 196, 200, and 227 feet.

d. Results

The magnitudes of the breakdown pressures varied between 750 and 1625 psi. Since the tensile strength of the basalt is between 2300 and 4350 psi, this suggests a difference of about 10 times between the maximum and minimum horizontal stresses. All principal stress magnitudes were found to increase with depth: the vertical stress from 65 psi at 55 feet depth to 280 psi at 277 feet depth; the minimum horizontal stress from 115 psi to 275 psi; and the maximum horizontal stress from 2120 psi to 3525 psi.

Good impressions were obtained for fractures in five of the six tests and all showed vertical fractures averaging N61°W, parallel to the axis of Gable Mountain. Thus a large stress appears to act parallel to the Gable Mountain fold axis and a very low stress normal to it. Such orientation and magnitudes are undoubtedly due to topographic causes, hence it is not possible to infer the regional stress state in the Pasco Basin at potential repository depths.

e. Inference of Stress State from "Poker Chip" Core

Information on the state of stress at depth on the Hanford Reservation may be inferred from the "poker chip" zones encountered in DC-6 and other holes. Obert and Durvall (1967, p. 426) refer to this kind of fracturing as "core discing" and consider the cause to be stress relief of the cored rock during drilling. They show that the horizontal stress at the disced horizon is:

$$S_h \geq k_1 + k_2 \gamma h$$

where k_1 and k_2 are determined from laboratory tests, S_h is the horizontal stress and γh is the vertical stress calculated from the product of the unit weight of the rock and the depth. Calculation of the in situ stresses from core discing should be included in any future stress measurement program at Hanford.

C. RECOMMENDATIONS

1. Well Drilling and Testing Program

Based on both the results of a literature survey and the input requirements of a basin model, LBL has made the following recommendations for new well drilling and testing in the Pasco Basin. In order to achieve the immediate objective of providing an overview of the regional flow system, six first stage wells (DC-12 through DC-17) were proposed (Figure II-23). These wells, when combined with existing wells, are designed to provide sufficient information to indicate on a gross scale the origin, flow paths, velocities, and disposition of groundwater within the basin.

Well DC-12 is in the center of the basin. This well would provide data for determining gradients in several directions within the basin.

Well DC-13 is in the "horn" of the Columbia River. This well will help to determine the hydrologic significance of the Saddle Mountains boundary and the influence of the Columbia River on the deep flow system. It would also provide an important data point in the Wahluke syncline.

The role of the Rattlesnake Hills as a recharge zone in the basin needs to be investigated. Well DC-14 would provide information on the extent of this recharge and the possible existence of perched waters. The southwestern boundary of the basin can also be examined.

Well DC-15 examines the extent of recharge from the Sentinel Gap area. The area is important because basalt flows which lie deep under the center of the basin crop out at Sentinel Gap. This well in conjunction with DC-4 will also help to determine the direction of deep groundwater flow between Cold Creek Valley and the Columbia River Valley. In conjunction with DC-13, this well will enable an examination of deep flow systems along the Wahluke syncline.

If the rough analysis of groundwater flow patterns seems favorable for siting a repository, these wells will provide a basis for locating second stage wells which may be necessary for a more detailed analysis of the flow system. Each of the first six wells will also have particular use in detailed analysis for determining pressure distribution, material properties, geology, geochemistry, and boundary conditions for mathematical models. Until the feasibility of resealing exploratory boreholes is established, the final locations of the recommended test wells must be selected such that

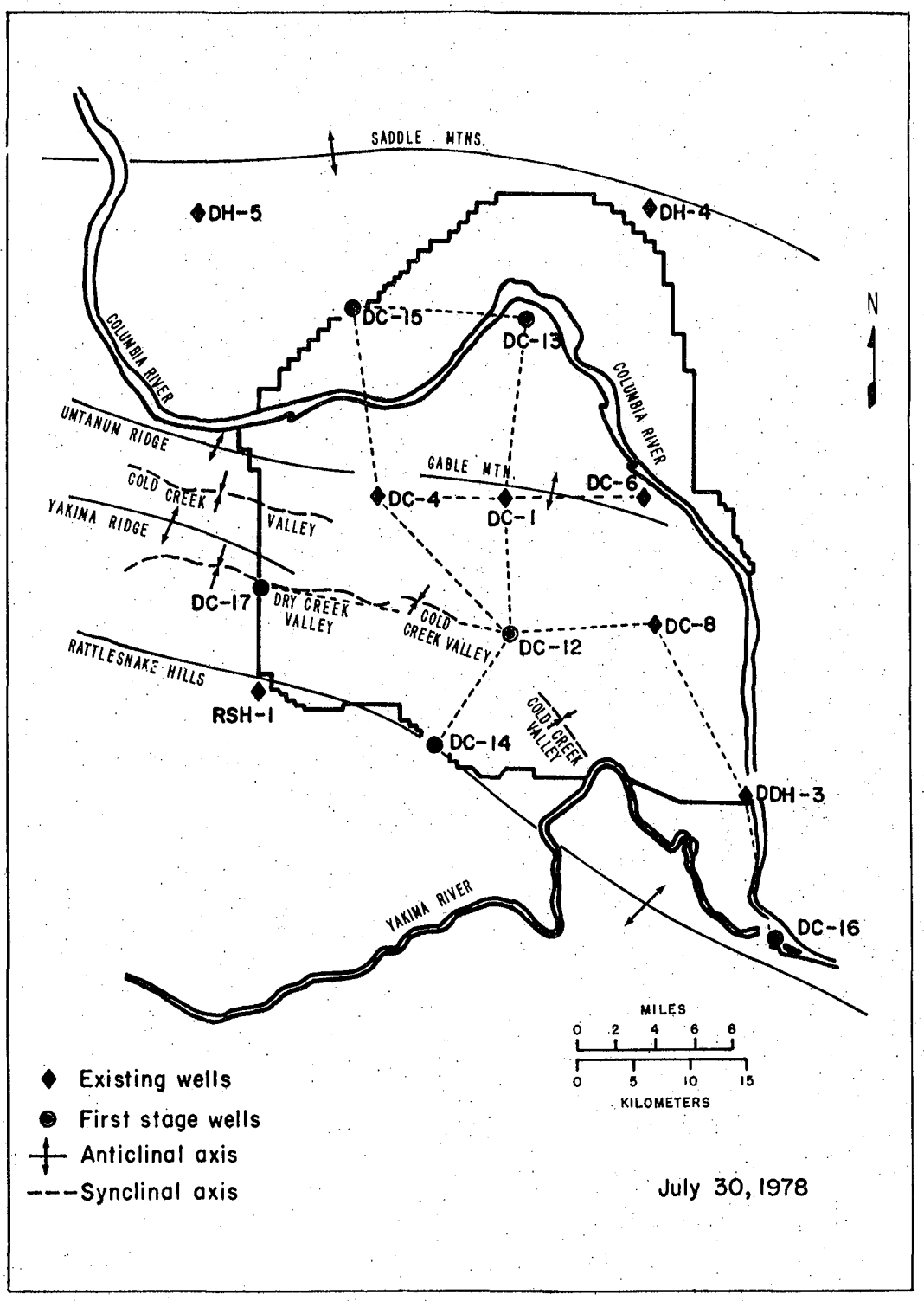

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Figure II-23. Proposed first stage wells.

possible adverse effects upon a future repository are minimized. A more detailed discussion of the recommended well drilling program may be found in Long and Wilson (1978).

2. Equipment Development

a. Four Packer Test System

A major source of test uncertainty is the integrity of the packer seal. LBL procedures called for using two inflation pressures in each test as a check for packer seal. However, these do not absolutely guarantee its integrity. An alternative method is to fill the borehole to produce a pressure transient. This procedure does test the upper packer, however, it disturbs the hole for pressure measurement.

LBL suggests using a four packer system of three isolated cavities - a central test zone and upper and lower guard zones. Pressures should be monitored continuously in each zone and leakage can be detected through pressure response of the guard zones to testing in the central cavity. Guard zones should be fitted with solenoid valves or some other pressure release system to bleed any pressure that might build due to packer inflation.

b. Monitoring System

A system for monitoring pressure in a large number of isolated zones will be essential to obtaining reliable hydraulic potential data. As DC-2 test showed, effects of drilling or artifically altering the heads in a well can affect the pressure for long periods of time. Further discussion of monitoring systems is in Appendix A.

3. Hydrologic Testing

a. Pressure Testing Procedures

Pressure data can best be obtained by pulsing the test zone both in injection and withdrawal. This procedure was used by La Sala and Doty (1971) for standpipe piezometers, and can be done possibly more effectively with the injection-pressure probe. The procedure would be to fill the drill rod with water, and after the packers are set, quickly open the solenoid valve to put a positive pressure pulse on the system. After allowing this

pulse to decay, water should be removed from the drill rod by swabbing and the procedure repeated; this time with a negative pulse. The injection and withdrawal pulses can be used for pressure values by taking the mean of the final pressure values. Furthermore, the decay data can be used to calculate permeability. Test procedures should include measurement with electric tape of the water level in the hole for each test as a check on the transducer calibration.

b. Need for Vertical Permeability Tests

The data from DC-2 also suggests vertical permeability. As a result, tests for vertical permeability are critical. These can take the form of pump tests interpreted using leaky aquifer curves, ratio tests, or tests in inclined holes. The deviated parts of DC-2 may be used, but since these holes are inclined only 30° from vertical, care must be taken that only vertical fractures are isolated.

c. Pressure Tests During Drilling

Water pressures within a given horizon may change rapidly after drilling penetration due to heads induced by drill water and cross flow between aquifers. Time should be allowed during drilling to run pressure tests at frequent intervals as various rock units are penetrated.

4. Geophysical Testing

a. Flow profiling techniques have been used quite effectively to delineate permeable zones in the Hanford basalts. We recommend that flow profiles be obtained in all wells as they become available, and that a detailed program of flow profiling be undertaken in conjunction with the hydrological testing. Although the radioactive tracer method has been used successfully in the past, the spinner method may be more appropriate at Hanford.

b. Using the existing data base, establish a reliable method of quantifying the porosity in the basalt. The study would be based upon the logs and core from DC-1 and DC-2, with emphasis on the neutron and density logs. Extension of the results to other holes will be complicated by the diversity of tools which have been used at Hanford (for example, five different neutron tools by four different suppliers have been run in the DC series of holes).

c. Composite the existing data on base plots at a scale of 100 feet per inch. The plates should contain:

- o the best (or all) of the porosity-type logs.
- o temperature and tracer logs where appropriate.
- o drilling information.
- o geological information where available.
- o interpretative comments.

Figure II-15 of this report is a modest start in this effort. With such composites all of the information on individual holes is readily available for both field and office use. Comparisons and correlations can be made quickly and data is easily made available to all users. Some composites such as for DC-5 can be constructed fairly quickly. Others such as for DC-6 will require more effort to sort out problems with scaling and data quality.

d. Continue to pursue methods of correlating betwen holes using logging methods. The magnetic susceptibility log, currently available in DC-8, should be run in DC-7 and DC-6. The spectral gamma ray log, a refinement of the total count gamma ray log, should be run in two holes. In addition, further examination of existing data may uncover data or methods which are not now obvious.

e. It is highly desirable that the same log type from the same commerical supplier be used in the entire drilling and logging program. Additionally, it is useful to have a knowledgeable person working with the supplier on specific logs, particularly since the basalt geology and the waste isolation requirements are unusual in the logging industry.

f. At some stage, pursue methods of studying the fine detail in the dense basalts. From the existing data base it appears that the televiewer, a short spacing sonic tool with waveform display and shear amplitude, and the electrical resistivity dipmeter are the most promising tools which are currently available. Detailed logging in the near surface test facility now under construction may be a practical way to pursue some of these studies.

g. We recommend the following basic approach for the specification of well logs at Hanford:

- o The minimal logging suite in a new hole should be:
  - i) gamma ray, or spectral gamma ray, depending upon the outcome of recommendation (d)
  - ii) neutron or density or both, depending upon the outcome of recommendation (b)

iii) caliper, preferably a four-arm or six-arm caliper.

iv) temperature

v) televiewer

vi) magnetic susceptibility, if the outcome of recommendation (d) is positive

- In addition, the minimal suite should be complemented with the following consideratons in mind:

  i) a sonic tool with transit time and waveform recording is quite desirable although not mandatory. The compensated sonic tool may be replaced by a short spacing tool, depending on the outcome of (f)

  ii) the electrical methods are not as useful as other tools, primarily because of the high resistivity limitation. Nor do the self-potential or induced polarization measurements appear worthwhile at this time. The dipmeter, however, should be definitely considered further (see (f)).

- The flow profiling program should be pursued as outlined in (a). Because of its flexibility and sensitivity, the Schlumberger "full-bore spinner", or its equivalent, is recommended as the best candidate tool for this purpose.

- Depending upon the scope and nature of subsequent hydrological programs, a captive wireline capability may be warranted. Such a facility would be operated according to the needs of the hydrological investigations. Minimum capability would be a caliper, temperature, water sampler, and one lithology probe.

III. GROUNDWATER CHEMISTRY

A. INTRODUCTION

The sampling and analysis of groundwaters from the Pasco Basin was initiated in FY 1978 as "Part 2 - Geochemical Testing," a complementary part of "Task 1 - Pasco Basin Hydrology" in LBL's Hanford Waste Isolation Project. It was planned that 36 deep well samples, 20 spring samples and 9 duplicates would be collected in the Pasco Basin near Richland, Washington.

The chemical and isotopic composition of a groundwater provides much information that can elucidate the origin, age, and subsequent history of the water. To get this information successfully requires that a number of samples be taken from various parts of the aquifer system. In addition, the groundwater hydrology, including the direction of flow, expected flow rate, and magnitude of flow should be known.

Chemical analyses of groundwater in the aquifers can be used to:

- Estimate the temperature of the water at its point of origin.
- Identify trace elements characterizing specific horizons.
- Infer mixing between aquifers.
- Determine if the water has been subjected to higher temperatures.
- Establish whether there is equilibrium with the country rock matrix or the coexisting alteration products.
- Determine the nature of chemical reactions likely to proceed between the groundwater and the country rock, thereby providing support for interpreting isotopic data for age determinations.

Isotopic analyses of selected elements in groundwaters can be used to:

- Estimate the apparent age of the water.
- Determine the source of the water.
- Estimate the origin of the water in terms of temperature, contact or reaction with organic materials, geographic location, and climate.
- Interpret the extent that chemical reactions and/or mixing have occurred during transit through the aquifers and identify some of the reactions that may have taken place.
- Establish relative ages.
- Identify boiling or vapor phase separation.

The information obtained from a careful evaluation of the groundwater chemistry and isotopic ratios of selected elements, when used in conjunction with hydrologic models of regional or local groundwater flow, serves as the basis for predicting the rate and type of chemical evolution of groundwaters during flow. Such an evaluation is a necessary prerequisite for quantitative predictions of radionuclide migration in the same environment.

Aquifers associated with basalt flows that could be considered as candidates for the siting of a waste repository, were of particular interest in the groundwater chemistry program. The original drilling report on the exploratory hole ARH-DC-1 (Fenix and Scisson, Inc., 1969) states that "a minimum of three zones have been identified between 2888 feet and 3392 feet which appear to justify further investigation as possible locations for mined caverns." This region also includes a water-bearing zone immediately below the Umtanum, between 3243 feet and 3273 feet in DC-2, as identified by LBL (see Part IIB1 of this report).

Deju et al. (1977) state:

> Groundwater movement does occur along some zones within the basalts. However, that portion of the basalt under consideration for the storage of radioactive waste is the dense, thick, central volume of certain flows having little, if any, known hydraulic contact with the regional aquifers. Most investigators conclude that groundwater does move in the horizontal plane along the interflow zones and not in the dense central volume of the flow. Any vertical flow occuring through fractures is quite limited, having been determined in one area to be less than 10^{-7} meters per day.

As the objectives of the groundwater chemistry program were to evaluate the aquifers associated with these basalt flows, further studies of this particular zone were considered desirable.

On January 30, 1978 a meeting was held between LBL, Rockwell Hanford Operations (Rockwell), and other interested parties at Richland, Washington, to develop the field program on the Hanford Reservation. An integrated testing and sampling schedule was drawn up that centered around the deployment and availability of drilling and workover rigs. Samples as large as 150 liters would have to be collected from depths greater than 2000 feet in three inch boreholes. It was decided to use swabbing under a closed gas atmosphere, as no commerically available downhole pumps were found were to be suitable for the task in hand.

Within these constraints a program was developed to minimize and quantify contamination of groundwaters so that representative formation water could be sampled and analyzed. In addition, artesian wells and springs were also to be sampled where they might contribute to an understanding of groundwater flow in the region. The program was established and operated as a research project to study the groundwater evolution of the Pasco Basin with particular regard to the age, source, and history of groundwaters and the interaction between host rock and water

B. PREVIOUS STUDIES

Very little groundwater chemistry has been done on the aquifers* in the Grande Ronde Basalt beneath the Hanford Reservation (see fig. I-2). Before this study commenced, the only available data from aquifers associated with basalt zones deep enough to be of interest for a waste repository on the Reservation were contained in the USGS open-file report by La Sala and Doty (1971). Those authors make a number of references to contamination of their samples by the drilling process, indicated by tritium values, detergent levels, and the possibility of cement hydrolysis affecting the groundwater composition. Most zones were swabbed for about 24 hours (Fenix and Scisson, Inc., 1969), which according to LBL calculations would be inadequate to remove the invaded volume of drilling fluid (see appendix A to this report). Confirmatory evidence that at least ten times the volume of fluid injected must be removed before the sample shows no contamination is provided by the experiences of Marine (1976) in recovering groundwater from a deep well at the Savannah River Plant.

La Sala and Doty report data from eighteen zones in Well DC-1 between depths of 362 feet and 4283 feet. Four zones between 362 feet and 2242 feet were sampled from the discharge of a submersible pump. The remaining fourteen zones between 362 feet and 4283 feet were sampled by swabbing from zones isolated by packers. Of these fourteen zones, five were noted as being contaminated by drilling fluid, including three of the six zones sampled between 2600 feet and 4283 feet. The three uncontaminated zones which were sampled (3146 - 3236, 3166 - 3196, 3206 - 3246) straddle the Umtanum basalt flow and partially include the zone sampled (3243 - 3273) in the LBL FY 1978 study of the companion well, DC-2.

*Aquifers, according to Todd (1959, p. 15) are "formations having structures that permit appreciable water to move through them under ordinary field conditions."

The La Sala and Doty paper is cited in the "Preliminary Feasibility Study on Storage of Radioactive Wastes in Columbia River Basalts" by Atlantic Richfield Hanford Company (1976), but no mention is made of the probable contamination of the samples from which the data was derived. No further geochemical field work was conducted for this feasibility study and it provided no further groundwater chemistry data on Grande Ronde Basalt beneath the reservation.

The unconfined and uppermost confined aquifers of Pasco Basin are much better characterized. An active sampling and analysis program is under way by Rockwell Research Engineering and Hydrology. However, the primary purpose of the program is to monitor the progress of radionuclide movement away from the 200 Areas (U. S. Energy Research and Development Administration, 1975). Therefore, this study offers no further information on the hydrogeochemistry of deep basalt flows.

More information has appeared on groundwater chemistry of Columbia River basalt in the region as a whole and in the Pasco Basin and vicinity (Newcomb, 1972; La Sala et al., 1973). However, information is lacking on aquifers in the vicinity of the Umtanum basalt flow. This is included in the zone of present interest for testing, sampling, and repository site selection because Deju et al., (1977) report that: "Deep core drilling within the central Pasco Basin has indicated that, at approximately 900 meters, there exists a basalt flow with a thick, dense interior."

Groundwater samples taken from a deep hole in the Rattlesnake Hills (RSH-1) which penetrates the Umtanum have been analyzed (Basalt Waste Isolation Program Library, data from U. S. Testing Co.), but these samples appear to have been contaminated. Trace element contents, particularly zinc, suggest gross contamination during sampling. Values for pH, sodium, and silica do not follow the general characteristics of basalt groundwater (La Sala and Doty, 1971; La Sala et al., 1973). These analyses provide the only other information from the Umtanum level, besides those from DC-1, that were available before the LBL FY 1978 study started.

C. SCOPE OF ANALYTICAL WORK PLANNED

In view of the scanty earlier work on groundwaters in the Pasco Basin, and of the need to determine what potential exists for interpreting the resulting chemical analyses, it was decided at the outset that the initial chemical and isotopic analyses would be comprehensive. A list of elements and isotopes that were to have been analyzed is given below. Not all

listed were eventually analyzed, and reasons for not having done so are given in the discussion section of this report.

1. Chemical Analyses

Chemical analyses of groundwaters were planned using the following techniques to measure concentrations of the constituents listed:

(1) Neutron Activation Analysis

Na, Cl, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, As, Se, Br, Rb, Sr, Mo, Ag, In, Sn, Sb, Cs, Ba, La, Ce, Nd, Sm, Eu, Tb, Dy, Yb, Lu, Hf, Ta, W, Ir, Au, U, Th.

(2) Soft X-Ray Fluorescence

Na, Mg, Al, Si, K, Ca, Ti, Mn, Fe, Cr, Br, S, Cl

(3) Hard X-Ray Fluorescence

Ti, Mn, Fe, Ni, Cu, Zn, Ga, Ge, As, Se, Br, Rb, Sr, Y, Zr, Pb, Pd, Ag, Cd, In, Sn, Sb, Te, I, Cs, Ba, La, Ce, V, Cr, Hg, U, Th, Co

(4) Zeeman Atomic Absorption

Ag, Cd, Cu, Pb

(5) Carbon Rod Atomic Absorption

Cd, Cu, Ni, Pb, Zn

(6) Wet Chemical Methods

HCO_3, CO_3^{2-} by titration and combustion.

SO_4^{2-}, Fe^{3+}/Fe^{2+}, P_2O_5

(7) Gas analyses (by mass spectrometry)

All gases present except Ne which is used as an internal standard.

(8) Measured at the sampling site:

pH, Eh, CO_2, H_2S, O_2, alkalinity, electrical conductance, and temperature.

Major components and some minor components can be used to compare with the compositions and thermodynamic stabilities of the coexisting alteration products. These include the cations Na, Mg, Al, Si, K, Ca, Fe(II), Fe(III), Mn, the anions HCO_3^-, CO_3^{2-}, SO_4^{2-}, Cl^-, F^-, HS^-, and neutral species, H_2S and H_2CO_3.

Oxidation potentials calculated from SO_4^{2-}/H_2S, CO_2/CH_4, H_2/H_2O, and N_2/NH_3 ratios can be used to test for internal equilibrium, and comparison

with measured Eh. The rare gases can be used to estimate the temperature of groundwater at its last point of equilibrium with the atmosphere. Helium (which consists primarily of ^{4}He, a fission product of uranium) can be used as a dating tool, if the amount of uranium in the aquifer host rocks is known. Deviations in the ratio of argon with respect to other rare gases are due to the build up of argon in solution as a result of the decay of ^{40}K. This effect could be used to assign relative ages to groundwaters. All other elements may be tested for their value as tracers for given aquifer waters or horizons.

2. Isotopic Analyses

Isotopic analyses consist of the following:

Stable Isotopes

D/H	$^{18}O/^{16}O$
$^{13}C/^{12}C$	$^{34}S/^{32}S$

Radioactive isotopes:

^{3}H	^{222}Rn
^{14}C	^{226}Ra
^{36}Cl	$^{234}U/^{238}U$

The principles behind the various isotope measurements are outlined below:

a. Stable Isotopes

Deuterium/Hydrogen Ratio. This ratio is established during the precipitation of water from the atmosphere. Because rocks contain little hydrogen, the ratio remains essentially fixed, unless subsurface boiling or phase separation occurs. Variations in D/H from present day surface values can be ascribed to temperature differences due to climate or altitude.

Carbon-13/Carbon-12 Ratio. Carbon isotope ratios can be modified extensively by organic reactions, and to a lesser extent by temperature. Comparisons of $^{13}C/^{12}C$ of carbon species in groundwater with coexisting calcium carbonates in the host rock can, under certain circumstances, indicate the nature of the carbon source, the effect of isotopic exchange, and the origin of carbon in carbonates found in basalts.

Oxygen-18/Oxygen-16 Ratio. The initial oxygen isotope ratios are established during the precipitation of water from the atmosphere. Subsequent isotopic exchange with host rock minerals leads to a progressive shift in isotope ratio, thereby permitting assignment of relative ages to groundwaters

under favorable circumstances. $^{18}O/^{16}O$ ratios ($\delta^{18}O_{SMOW}$) are often used in connection with Deuterium/Hydrogen ratios (δD_{SMOW}).

Sulfur-34/Sulfur-32 Ratio. Sulfur isotopes can be extensively fractionated by biological processes. A study of the sulfur isotope ratios in dissolved sulfate and sulfide species in solution, and in coexisting sulfates and sulfides in host rocks can, under favorable circumstances, lead to interpretation of the origin and subsequent history of the groundwater and the source of the sulfur. $^{34}S/^{32}S$ ratios in sulfides and coexisting sulfate ions in equilibrium in the groundwater can also provide an independent check on pH and oxidation potential if the system is at equilibrium.

b. Radioactive Isotopes

Tritium. This isotope of hydrogen is generated in the atmosphere by cosmic rays and by the atmospheric thermonuclear explosions begun in the 1940's. It has a half life of 12.3 years. Measurement of tritium in groundwaters permits ages up to 25 years to be determined. A new method employing the 88-inch cyclotron at LBL could allow dating as far back as 100 years B.P. The use of tritium for dating will thus apply only to groundwaters of relatively recent age. A tritium tracer might identify "short circuits" in the aquifer, due to rapid water movement along faults. Tritium may be used to measure the amounts of contamination of groundwater caused by drilling fluids.

Carbon-14. ^{14}C is produced in the atmosphere through cosmic ray bombardment. The half life of ^{14}C is 5730 ± 40 years. Conventional counting techniques permit age determinations of up to 40,000 years using 1-10 g of carbon and counting times of 1.5 to 15 hours. However, ages of up to 100,000 B.P. might be determined by using the 88-inch cyclotron at Berkeley. There are several technical problems associated with the latter method which require resolution before it can be used routinely for age dating.

Chlorine-36. This isotope of chlorine is produced in the atmosphere by cosmic ray bombardment. It is a long lived isotope with a half-life of 3.08×10^5 years. It is potentially useful for measuring ancient groundwaters, since it is relatively free of interference and is resistant to removal from solution by precipitation or adsorption. A potential problem with the use of ^{36}Cl is the subsurface formation of this isotope by the neutron activation of chloride from neutrons released by the natural fission of uranium and thorium. However, techniques for ^{36}Cl measurement are still in their infancy. Measurement of the $^{36}Cl/^{35}Cl$ ratio can be accomplished through use of the 88-inch cyclotron of LBL. Subject to the elimination of

interferences, and there being sufficient ^{36}Cl in surface water, this method could permit measurement of apparent ages to about 2×10^6 years.

Radon-222. ^{222}Rn enters groundwater through the decay of ^{226}Ra, a product of ^{238}U decay. The resulting concentration is a measure of a number of factors including the fracture surface area of the host rocks, the surface area to volume ratio of the groundwater, and the distribution of radium within the rock matrix and as coatings on fracture surfaces.

Radium-226. This isotope is part of the decay chain of ^{238}U. Its behavior during its 1620-year half-life is a measure of the distribution of its parent, the host rock chemistry, and the rate of groundwater movement. Information on this isotope should be used in conjunction with the data on ^{222}Rn above and the uranium distribution in the host rocks.

Uranium-234/Uranium-238. ^{234}U in surface waters is sometimes found to be enriched up to ten times over the concentration predicted to be in secular equilibrium with respect to its parent, ^{238}U. The usual explanation of the lack of equilibrium is that in the decay of ^{238}U through 26 day ^{234}Th to ^{234}U, the finally resulting ^{234}U product would be left in a nonequilibrium lattice position in the host rock and be subsequently more easily leached by slightly complexing groundwaters, leaving the residual rock depleted in ^{234}U and, of course, the waters enriched. Later, weathering of the depleted rock could give rise to waters depleted in ^{234}U. Although this leaching mechanism can account for the small enrichments and depletions observed in near-surface and surface waters, one is hard pressed to explain the extreme enrichments (greater than a factor of 5) sometimes encountered in subsurface waters. Such enrichments may be due to direct recoil of the ^{234}Th into the water phase from near the surface of the uranium bearing rock, and subsequent decay to ^{234}U in the solution.

In flowing aquifers, once reducing conditions are encountered, uranium is reduced, often in a short distance, from the +6 to the +4 valence state. Because the +4 state is considerably less soluble in typical groundwaters, this results in local precipitation of uranium on aquifer rock surfaces. Subsequent migration of the reducing barrier updip can now result in water highly depleted in uranium contacting the previously precipitated uranium. The latter can now serve to inject, by recoil, relatively large amounts of ^{234}Th, leading to very high enrichments of ^{234}U downdip.

Once the uranium is out of equilibrium, the reapproach to equilibrium can be used as a "clock" to determine the age of the water, provided one knows enough about the initial conditions and the environment in which the

water finds itself. These initial environmental conditions can vary for each site and create uncertainties with this and most other dating methods since the "clock" radionuclide is not isolated in a completely closed system during the decay but is subject to continuous interactions with its environment, some of which could disturb the clear interpretation ofthe decay data.

The half-life of ^{234}U is 2.44×10^5 years, so it might be feasible to date groundwaters as old as 5×10^5 years by this method. Many questions on the behavior of uranium isotopes in groundwaters remain unanswered. Further research is required to eliminate these problems.

D. SAMPLING AND ANALYTICAL PROCEDURES

The need for careful and systematic sampling procedures, on-site chemical analyses, and sample preparation and packaging for shipment resulted in the design and construction of a mobile field laboratory. In addition, field operating procedures were prepared for the purpose of ensuring consistent quality of the samples. A discussion follows regarding these two topics and specific sampling procedures adopted for wells and springs.

1. Mobile Field Laboratory

The expected volume and quality of sampling and field analysis and the initial difficulty in arranging adequate laboratory services and space brought about the need for a mobile laboratory. An 8 ft x 20 ft box trailer was leased and modified at LBL specifically for groundwater sampling. Basic considerations were to provide adequate facilities for the field analysis of chemical components of water samples that were most likely to change during shipment. Sufficient workspace for two chemists had to be provided during the anticipated rush of downhole sampling.

Features include adequate bench and storage space, a wet bench with raised edges and a waterproof surface for carbonate extractions, an analytical area for titrations and instrumentation, a sample packaging and equipment repair area, gas bottle racks and chains, protective electrical fixtures above the wet bench, a constant voltage transformer to ensure reliable instrumentation readings, a forced-draft filtration box that provides filtered air over a clean bench, a sampling manifold system constructed of PVC capable of carrying water from the well head into three carboys under a closed atmosphere of argon; and restraining devices to stop drawers and cupboards from sliding open during transit. The trailer was also designed

to include desk and drawer space. Some unused and uncommitted space was available for future work assignments.

Installed equipment and instrumentation included an Orion specific ion meter with electrodes for pH, redox, sulfide and CO_2; a Turner fluorometer with flowthrough cuvette; Masterflex sampling pumps and a selection of pump heads; dissolved oxygen and conductivity meters; filtration apparatus; CO_2 evolution and precipitation apparatus; burettes and scaffolding; hot plates; water bath; magnetic stirrer; chart recorder; spectrophotometer; refrigerator; and a wide range of glassware, fixtures, tubing and reagents.

Operationally, the mobile laboratory was very satisfactory and the segregation of certain analytical or preparative tasks at specific locations allowed two persons to work efficiently and comfortably. A recognizable problem was the semimobile nature of the trailer, necessitating a tow truck that was not always available when required for movement from one site to another. A self-propelled mobile unit would overcome the problem of having to rely on available transport. The frame of the box trailer was supported on a single axle and a front-end hoist, but this appeared inadequate to support the weight. At least six jacks, heavy timbers or cinder blocks were necessary to support and stabilize the trailer to avoid recurring flat tires. Experience also proved that a functioning air-conditioning unit is essential for effective operation and a stabilized analytical environment, particularly during the summer months at Hanford.

2. Field Operating Procedures

A set of standard operating procedures for Quality Assurance documentation was prepared. These procedures became a focal point of organization in finding the latest and most desirable methods for sampling, treatment, and packaging of groundwater. Leading isotope and chemical analysts were brought together in a series of meetings aimed at bridging the gap between analytical expertise and field sampling methodology. Field sampling is an underestimated and often unidentified source of error and uncertainty behind reported groundwater data. This source of error may be even further masked by the validity assigned to chemical data from interlaboratory comparisons and statistical analyses.

These meetings, combined with an exhaustive literature survey of groundwater sampling, resulted in the drafting of the Field Operating Procedures (appendix D, vol. II, this report), an evolving document with the provision for incorporating changes as experience or new information required.

Sampling, analytical, and treatment techniques used at the well-head and spring sites are specified in the Field Operating Procedures. Nuclepore filter papers (0.2 micron pores, 142 mm diameter) were placed in a Lucite filtration unit in the mobile field laboratory under forced-draft filtered air using teflon-tipped tweezers before going to the spring site. A back-up unit was prepared and carried in case the pores became clogged and another filter paper was needed. About 250 ml was passed through the filter and discarded, then the three one-liter bottles for neutron activation, the one liter bottle for atomic absorption and the 500 ml bottle for uranium isotopes were filled in that order. All bottles were immediately sealed with plastic tape. As a result of initial field experience, improvements in analytical methods and sampling techniques were written into a revised version of these procedures. These include sample bottle preparation, the carbonate extraction system, alkalinity titrations, contamination monitoring, and filtration procedures.

3. Sampling Schedule

April 1 - 15 was originally scheduled for the beginning of sampling on DC-2. Following a series of delays, swabbing began on June 14, 1978. The schedule was organized around the availability of rigs and sampling was limited by contracts issued to other testing organizations who had fixed dates to commence work. The schedule allowed little flexibility for equipment failure and other complications, or at what rate aquifers could be swabbed to an acceptably clean level. Two field chemists were required for well and spring sampling with the assistance of a field engineer for geotechnical downhole applications. Although a great deal of effort went into planning and establishing this program, only DC-2 (3243 - 3273 feet), the free flowing DC-6, two artesian wells from the upper aquifers, four springs and the Columbia River were sampled before the termination of the field program on August 6, 1978. Details regarding the locations of the sampling sites are given in Table III-1.

4. Sampling

a. Well-Head Sampling

A continuous closed gas system from the packed-off zone to the sample vessel was designed and constructed for sampling using the swabbing technique. Nitrogen was used to prevent access of atmospheric oxygen to the borehole above the water. Argon was used to flush the carboys and the sampling manifold in the trailer, but was not allowed to pass back along the polyethylene

Table III-1. Location of USGS coordinates of sampling sites.

Sampling site	Location	Coordinates *
DC-2 (3243-3273 ft)	N of 200 E Separation Area	13N/26E-35H
Juniper Spring	Umtanum Ridge	13N/24E-14G
Rattlesnake Springs	Dry Creek Battelle Field Station	12N/25E-29B
Benson Springs	Rattlesnake Hills	11N/25E-11N
Bennett Springs	Rattlesnake Hills	11N/24E-14F
DC-6	Old Hanford Townsite	13N/27E-26E
Ford Well	Cold Creek Valley	13N/24E-25E
McGee Well	Cold Creek Valley	13N/25E-30G
Columbia River	Old Hanford Townsite	13N/27E-20
Columbia River	Richland Townsite	9N/28E

* Township, range, section number, and sector letter (see Newcomb et al., 1972 for description of sector lettering system).

pipe to the dissolved gas sampling port. A pressure gauge was clearly visible for the rig operator to monitor the speed of the swab pull. An overpressure of 10 to 15 psi nitrogen provided an adequate water flow through the sampling system for ease of rig operation and sampling.

In Well DC-2, the sample was withdrawn from the zone at 3243 to 3273 feet of depth. A swab cup lasted 15 to 16 pulls at an average efficiency of approximately 60 per cent of the maximum amount of water that could be recovered with a new cup. The average withdrawal rate was 250 gallons per swab pull. A swab pull was possible every 15 minutes because of rapid recharge of the borehole, thus an average of about 8000 gallons per day could be removed. No further experience concerning swabbing was gained as this was the only packed-off zone in a deep well to be sampled in FY 1978. Further experience may have suggested other improvements. The technique developed seems to be a satisfactory means of maintaining a closed gas system during swabbing and sampling.

At DC-2, discrete samples were taken every fourth swab pull and checked for temperature, conductivity, and pH. These remained constant although a persistent diesel oil and bacterial breakdown odor as well as turbidity suggested the presence of nonformation water. The fluorescence of diesel oil

was used as a monitoring parameter when it was found that the traditional assessment parameters of constant conductivity, temperature, and pH were inadequate for determining the degree of contamination by drilling fluids.

b. Spring Sampling

Springs were identified from topographic maps and chosen following discussion with Rockwell geologists who had visited some of these sites. Although 120 springs were noted from the topographic maps of the Pasco Basin, many were dry or no more than creek beds with intermittent resurfacing streams that appeared to be springs. A spring was sampled where it issued directly from a geological formation that suggested it had travelled some distance beneath the ground, as opposed to being located in a dry creek bed. Some spring sites required access by 4-wheel drive vehicles and walking. As some chemical parameters are inherently unstable, field analyses for pH, Eh, and temperature were carried out at the spring sites and samples for sulfide and sulfate were fixed as outlined in the Field Operating Procedures. Where possible, all samples were collected from a single site at the same time.

Spring sites required no prior preparation. Acid-cleaned silicone tubing was attached to a 500 ml polyethylene bottle filled with water; this acted as a weight to permit careful positioning of the intake tube in the flow away from turbid sediments. The tubing was connected through a one liter/minute peristaltic pump head (Masterflex Portable Sampling Pump), and attached to a filtration assembly. This portable unit allowed spring water to be collected and passed through Nuclepore filters into specially cleaned sample vessels without any contact with contaminating surfaces.

c. Artesian Well Sampling

The artesian wells (DC-6, Ford and McGee) were sampled in the same manner as the springs. The intake tube, connected to the portable sampling pump and filtration unit, was placed inside the outlet pipe of the artesian well. This allowed water to be sampled which had not come into contact with the atmosphere. A one-inch diameter polyethylene tube was placed inside the outlet pipe and used to siphon large volumes into gas-flushed carboys.

d. The Columbia River

The Columbia River was sampled from the old Hanford townsite shoreline with the intake tube placed one foot below the air-water interface but above the sediments. The Columbia River was also sampled at the Richland townsite for a tritium analysis.

E. RESULTS OF FIELD AND LABORATORY ANALYTICAL AND ISOTOPIC MEASUREMENTS

1. Chemical and Isotopic Analyses

The results of the chemical analyses performed in the field and on samples returned to the Lawrence Berkeley Laboratory, are given in Tables III-2 and III-3. Isotopic analyses are summarized in Table III-4.

a. Analyses not performed

Field analyses. Measurements in the field were to have included potentiometric measurements of dissolved CO_2 and H_2S concentrations. However, these were not done during the short period samples were being collected, due to insufficient time to calibrate the electrodes beforehand. Oxygen measurements were made only when monitoring the discharge from DC2 prior to sampling. This was done primarily to check for the level of contamination due to atmospheric oxygen. Oxygen concentration measurements were not made at springs or artesian wells although this would have been desirable.

Laboratory analyses. Chemical analyses by low energy XRF were not made for Al, Ti, Mn, Fe, and Cr. Aluminum was found to be below the limit of sensitivity for the instrument, and Ti, Mn, Fe, and Cr concentrations were not calculated because the computer code used to convert x-ray intensities to concentrations did not have the capability of handling these elements at the time of analysis.

Chemical analyses by hard x-ray fluorescence were not made for Pd, Ag, In, Sn, Sb, Te, I, Cs, La, and Ce because the instrument did not possess the analytical capability for these elements at the time the measurements were made.

Wet chemical analyses of Fe^{3+}, Fe^{2+} and P_2O_5 were not made because the project terminated and funding was no longer available before they could be done. Sulfate analyses were calculated from low energy XRF analyses for sulfur. Oxidation potential measurements in the field indicated that in most cases, the dissolved iron was present in the ferrous state, thereby rendering unnecessary the analysis of Fe^{3+}. Based on earlier measurements by La Sala and Doty (1971) the P_2O_5 contents of the water sampled were not expected to be sufficient to affect the bulk composition of the groundwater within analytical error.

In addition to the systematic ommissions of certain elements by given techniques, several techniques were not applied to all samples because the project was terminated before the analyses could be completed.

Isotopic Analyses. Isotopic analyses for ^{14}C, ^{226}Ra, and $^{234}U/^{238}U$ are not presented in this report. Difficulties were experienced collecting sufficient carbonate precipitate from the groundwater samples to perform ^{14}C analyses. ^{226}Ra analyses were not performed because the analytical method planned did not prove to be sufficiently sensitive for the concentrations expected in groundwaters from basaltic terrains. $^{234}U/^{238}U$ analyses by means of spectrometry are currently under way, but results will not be available before this report goes to press.

b. Analyses not originally scheduled

Fluoride. Previous analyses of groundwater from deeply buried aquifers in the basalts at Hanford (La Sala and Doty, 1971; U. S. Testing Co.) reveal concentrations of fluoride ion as large as 20 ppm. Accordingly, analyses for fluoride ion were carried out on the samples collected using a fluoride ion sensitive electrode.

Aluminum. Because aluminum was not detected by low energy XRF, an attempt was made to determine aluminum levels by a modified Aluminon (aurin tricarboxylic acid) colorimetric method. All samples contained significant fluoride ion concentrations (up to 40 ppm). The interference by fluoride ion is well recognized, therefore all samples were acidified and run through Dowex 1-X8 anion exchange resin in the chloride form to remove the fluoride ion. The bed volume was calculated so that the anion exchange capacity greatly exceeded the known fluoride levels in solution. All aluminum levels were found to be below the level of detection (0.05 ppm Al) for this method and sample preparation.

c. Duplicate analysis

Because of the short time available before completion of the study, it was decided that several samples would be taken during the swabbing of DC-2, and that these samples would be used to compare the changes in chemical composition as decontamination proceeded, by examining the composition trends of various elements. Random fluctuations in concentrations of a given element would be taken as an indication of poor analytical reproducibility. Three samples from DC-2 were taken and analyzed, and these show good agreement among themselves for most elements. Noticeable and possibly significant trends with time were observed in the elements Fe(down), Cd(down), and Pb(down). Almost all other elements appear to be constant to within analytical error.*

* See Table III-5, Sample Collection Techniques, for the consistency of NAA analyses.

Table III-2. Chemical analyses of groundwaters.

Constituent	Unit	Method[a]	DC-2 (3243-3273 feet) 6/21/78	6/22/78	6/26/78	Juniper Spring 7/28/78	Rattle-snake Springs 7/31/78	Benson Springs 8/1/78	Bennett Springs 8/3/78	DC-6 (artesian flow) 7/21/78	Ford Well 8/11/78	McGee Well 8/13/78	Columbia River (Hanford Townsite) 7/25/78
A. Field Measurements													
Collection temperature	°C	thermo.	37.4	35.8	36.4	20.0	16.0	13.5	13.0	46.0	22.8	26.8	22.2
pH		electrode	9.8	9.9	9.9	8.3	7.7	7.3	7.5	10.1	8.0	8.0	8.7
E_{NHE}	mV	electrode	+89	+14	-46	+404	+427	+413	+429	-32	+152	+90	+303
conductance	$\mu.cm^{-2}$	electrode	750	750	840	260	275	200	230	1060	300	300	115
Total alkalinity HCO_3^-	ppm	color t[b]	--	--	--	191	166	111	108	199	188	179	67
CO_3^{2-}	ppm	c	--	--	--	N.P.	N.P.	N.P.	N.P.	127	N.P.	N.P.	1
HCO_3^-	ppm	d	--	--	--	186	162	85	104	51	176	173	61
B. Laboratory Measurements													
pH			--	--	9.8	8.3	7.7	7.3	--	10.1	--	--	8.7
Total inorganic carbon, C	ppm	comb	--	--	20.0	36.0	31.0	21.0	--	8.0	--	--	8.6
CO_3^{2-}	ppm	e	--	--	26.93	1.52	0.52	N.P..	--	17.28	--	--	0.97
HCO_3^-	ppm	e	--	--	73.47	176.43	147.44	93.46	--	22.99	--	--	41.88
CO_2	ppm	e	--	--	N.P.	1.46	5.13	8.43	--	N.P.	--	--	0.11
F	ppm	electrode	21	21	21	0.50	0.36	0.28	0.27	41	0.62	0.80	0.46
Na	ppm	NAA	181±4	178±4	181±4	19.6±0.45	12.0±0.28	6.09±0.15	7.10±0.21	233±7	26.0±0.72	29.5±0.72	1.25±0.04
		SXRF	--	--	182	21	11	6	5	242	15	28	1.3
Mg	ppm	NAA	<29	<36	<42	10.3±2.3	8.0±2.0	4.3±1.4	8.2±1.0	<470	6.3±1.9	8.5±2.3	< 9.3
		SXRF	--	--	<1	13	10	8	7	2	9	7	--
		AA	--	--	--	--	--	--	--	--	--	--	3.7
Al	ppb	color s	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50
SiO_2	ppm	SXRF	152	154	153	50	45	39	46	115	53	56	2
		color s	153	152	152	--	--	--	--	--	--	--	--
Sulfide	ppm	color t	--	--	--	--	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
		gravim.	--	--	6.2	--	--	--	--	--	--	--	--

Total S as SO_4^{2-}	ppm	SXRF	30	29	26	18	14	11	10	96	< 2	< 2	7
		gravim.	--	--	17.4	16.5	12.3	9	5.4	85.2	--	--	8.1
Cl	ppm	NAA	90±3	88±3	95±3	4.67±0.15	3.85±0.12	3.12±0.08	5.87±0.11	125±6	4.87±0.14	4.82±0.16	6.6±0.5
		SXRF	--	--	107	6	4	3	6	148	4	4	<1
K	ppm	NAA	<26	<25	<18	5.6±1.0	3.3±0.7	2.7±0.5	2.3±0.6	<44	4.2±1.1	8.3±1.2	0.47±0.19
		SXRF	3.1	3.3	3.2	5.2	3.0	1.5	1.6	3.2	5.6	7.5	0.3
		HXRF[f]	1.04	1.04	1.45	3.33	1.87	1.15	1.00	1.51	3.18	3.48	0.407
Ca	ppm	NAA	--	--	--	24 ± 3	34±2	20±2	22±1	--	17±2	15±2	19±2
		SXRF	0.39	0.35	0.26	23.6	28.5	22.83	22.8	1.3	17.6	16.5	15
		HXRF[f]	0.25	0.25	0.22	15.4	19.9	22.7	19.5	0.43	10.6	7.8	13.5
Sc	ppt	NAA	<4.2	<6.1	<4.5	<3.0	<2.8	<3.0	2.5±1.4	<10.4	<2.3	<2.1	1.9±0.7
Ti	ppb	NAA	<710	<1200	<1100	<150	<150	<100	<90	<6200	<140	<160	<100
		HXRF	18±8	22±7	14±4	< 11	< 12	<7	<10	<28	<11	<10	<1.3
V	ppb	NAA	<27	<38	<61	<20	25±6	<16	11±2	<2600	<5.9	<9.0	<40
		HXRF	<12	14±5	7±4	< 5	<9.4	3.6±1.1	5.5±1.5	<14	<2	<2	<0.8
Cr	ppb	NAA	<0.61	<0.25	<0.22	<0.22	0.76±0.06	0.43±0.035	0.22±0.051	<0.42	<0.074	<0.091	0.098±0.02
		HXRF	<7	6±3	5±2	<2	<2	1.1±0.7	<2	<11	<2	<2	<0.4
Mn	ppb	NAA	<8	<17	<4.3	<1.6	4.4±0.3	<0.6	<1	<17	47.9±0.6	43.6±0.6	2.74±0.14
		HXRF	<5	3±2	4±2	<2	3.5±1	<1	<1	< 9	38±2	36±2	2.2±0.3
Fe	ppb	NAA	<30	<22	<22	<14.3	<15.8	<8.3	<9.2	<37	45.6±6.2	41.6±6.0	10.3±2.1
		HXRF	26±3	20±3	17±2	16±1.6	6.2±0.8	5.0±0.7	3.3±0.6	15±3	50±3	33.8±1.6	6.47±0.34
Co	ppt	NAA	<23	18±7	<17	13.6±3.9	26.3±5.5	<8.8	31.5±5.2	47±16	10.7±3.9	10.7±3.7	10.7±3.4
		HXRF	<23,000	<19,000	<22,000	<3,000	<2,000	<2,000	<2,000	<14,000	<3,000	<3,000	<300
Ni	ppb	NAA	<2.0	<1.2	<1.7	0.36±0.17	0.39±0.13	0.32±0.09	0.63±0.13	3.08±0.55	<0.40	<0.59	0.60±0.09
		HXRF	<3	<3	<3	0.96±0.3	0.82±0.08	0.94±0.25	0.90±0.3	1.5±0.9			1.05±0.07
		AA	0.08	0.05	0.07	0.04	0.06	<0.03	0.03	--	<0.03	0.04	0.20
Cu	ppb	HXRF	<3	<3	<3	2.3±0.5	0.70±0.23	1.15±0.29	0.80±0.30	2±1	1.3±0.3	0.89±0.31	1.3±0.2
		AA	0.25	0.26	0.24	0.02	0.07	0.02	0.03	0.06	<0.01	0.13	0.63
		ZAA	0.065	0.050	0.050	--	--	--	--	--	--	--	--
Zn	ppb	NAA	<2	<3	<2	<0.80	<0.73	<15	<2.7	<6	<0.83	<0.93	<1.3
		HXRF	2±1	<3	<2	2.1±0.5	0.98±0.23	1.48±0.36	2.5±0.5	11±3	1.01±0.27	1.6±0.3	1.13±0.07
		AA	0.19[g]	0.25	0.26	0.89	0.11[g]	0.21	1.82	0.24[g]	0.09	0.32	0.39

Table III-2. Chemical analyses of groundwaters. (continued)

Constituent	Unit	Method[a]	DC-2 (3243-3273 feet) 6/21/78	DC-2 (3243-3273 feet) 6/22/78	DC-2 (3243-3273 feet) 6/26/78	Juniper Spring 7/28/78	Rattle-snake Springs 7/31/78	Benson Springs 8/1/78	Bennett Springs 8/3/78	DC-6 (artesian flow) 7/21/78	Ford Well 8/11/78	McGee Well 8/13/78	Columbia River (Hanford Townsite) 7/25/78
Ga	ppb	NAA	<320	<310	<200	<47	<20	<19	<22	<640	<39	<41	<5.0
		HXRF	< 2	< 2	< 2	<0.5	<0.5	<0.5	<0.5	<3	<0.5	<0.5	<0.1
Ge	ppb	HXRF	12±1	13±1	14±1	0.6±0.3	<0.4	<0.4	<0.5	2.6±1.0	0.74±0.26	0.67±0.26	<0.08
As	ppb	NAA	<6.6	<8.0	<6.2	<1.7	2.6±0.5	<1.4	2.0±0.37	<10	<1.6	<1.9	1.8±0.14
		HXRF	<1	<2	<2	<0.5	2.7±0.5	1.6±0.4	2.2±0.5	11±3	<0.5	0.3±0.2	1.5±0.1
Se	ppb	NAA	<0.70	<0.84	<0.86	<0.14	<0.67	<0.70	<0.54	<0.81	<0.10	<0.8	<0.9
		HXRF	<1	<1	<1	<0.5	0.3±0.1	0.43±0.14	0.25±0.15	<1.5	<0.5	<0.5	<1
Br	ppb	NAA	191±4	187±3	201±3	53±1	39±1	36±1	50±1	285±7	53±1	52±1	4.2±0.2
Rb	ppb	NAA	12.8±0.6	13.5±0.5	13.0±0.5	11.3±0.5	2.0±0.2	1.9±0.1	3.2±0.2	13.8±0.8	13.4±0.5	17.4±0.7	0.73±0.08
		HXRF	12.8±1.8	13.7±1.4	13.1±1.0	10.6±1.6	1.6±0.4	1.8±0.4	2.5±0.5	11±3	13.8±1.1	17.7±1.0	0.63±0.13
Sr	ppb	NAA	<640	<630	<400	<93	100±20	58±13	110±20	<1100	<130	<140	63±8
		HXRD	11±2	12±2	12±1	88.0±4.2	129±6	119±5	122±6	3.4±1.7	77.4±3.2	69.7±2.6	85.3±4.0
Y	ppb	HXRF	7±2	6±2	6±1	<1	<1	<1	<1	<3	<1	<1	<0.1
Zr	ppb	HXRF	27±7	26±6	29±4	<5	<4	<4	<2	<11	<2	<2	<2.1
Mo	ppb	NAA[h]	250±20	260±10	270±10	1.0±0.2	1.6±0.2	1.0±0.2	0.5±0.2	310±20	<0.6	0.7±0.2	0.35±0.06
Ag	ppb	NAA	<0.083	<0.120	<0.110	<0.035	<0.024	<0.017	<0.320	<0.120	<0.027	<0.033	<0.015
		ZAA	<0.010	<0.010	<0.010	--	--	--	--	--	--	--	--
Cd	ppb	AA	0.010	0.008	0.007	0.006	0.033	0.017	0.016	0.089	0.002	0.001	0.044
		ZAA	0.089	0.047	0.025	--	--	--	--	--	--	--	--
In	ppb	NAA	<0.50	<0.90	<0.32	<0.08	<0.04	<0.06	<0.04	<1.0	<0.06	<0.16	<0.01
Sn	ppb	NAA	<105	<330	<170	<11	<12	<8	<6	<120	<10	<11	<27
Sb	ppt	NAA[i]	89±15	89±15	86±11	15±5	44±8	29±5	77±9	92±22	<13	<17	129±10
				40±11									
Cs	ppt	NAA[i]	426±14	522±16	363±14	153±5	65±4	78±4	257±7	1450±30	204±8	196±6	234±6
				351±13	309±13								
Ba	ppb	NAA	134±6	146±6	150±6	<21	30±4	<6	12±3	<112	14±4	20±5	256±15
		HXRF[f]	82±23	58±18	73±13	<26.5	19.5	<14.4	<25	<57	<21.2	<20.8	16.8
La	ppb	NAA	<1.5	<2.2	<1.7	<0.55	<0.28	<0.20	<0.22	<4.5	<0.30	<0.32	<0.081

Ce	ppb	NAA	<0.79	<0.67	<0.87	<0.25	<0.41	<0.25	<0.18	<2.03	<0.18	<0.11	<0.1
Nd	ppb	NAA	<4.3	<4.4	<4.5	<1.4	<1.2	<0.84	<1.1	<10	<12	<1.2	<0.37
Sm	ppt	NAA	<16	<16	<16	<4.0	<6.1	<4.0	<1.8	<29	<3.4	<3.3	<3.2
Eu	ppt	NAA	<15	<13	<17	<5.2	<5.5	<5.9	<6.2	<24	<2.3	<2.6	<2.2
Tb	ppt	NAA	<9.7	<9.6	<10	<2.9	<2.6	<1.9	<2.3	<14	<2.5	<3.1	<1.4
Dy	ppt	NAA	<1.6	<1.1	<1.0	<0.1	<0.06	<0.06	<0.06	<2.2	<0.17	<0.21	<0.01
Yb	ppt	NAA	<41	<41	<64	<12	<12	<8.0	<8.7	<68	<6.2	<6.7	<5.4
Lu	ppt	NAA	<49	<37	<38	<13	<12	<6.6	<11	<109	<13	<11	<5.1
Hf	ppt	NAA	<69	<89	<75	<22	<23	<23	<16	<180	<10	<10	<17
Ta	ppt	NAA	<5.1	<8.0	<8.1	<1.5	<1.3	<1.0	<1.2	<20	<0.37	<0.70	<0.58
W	ppb	NAA	70±5	69±4	67±4	<0.59	<0.44	<0.30	<0.36	101±11	0.70±0.24	0.71±0.26	<0.12
Ir	ppt	NAA	<1.6	<1.3	<1.0	<1.5	<0.24	<0.23	<0.27	<1.5	<0.23	<0.23	<0.16
Au	ppt	NAA	<25	<60	<34	<14	<6	<8.4	<6.3	<52	<12	<6.2	<2.5
		AA	1.33	0.76	0.60	0.01	0.02	0.02	0.02	0.03	0.02	0.04	0.05
Pb	ppb	ZAA	<1	<1	<1	--	--	--	--	--	--	--	--
		HXRF	<5	<4	<4	1.22±0.85	1.17±0.59	1.12±0.54	0.95±0.60	6.3±2.9	1.01±0.64	0.73±0.47	0.34±0.21
Th	ppt	NAA	<19	<12	<11	<4.8	<4.0	<3.3	<4.0	<25	<3.3	<4.9	<3.7
		HXRF	<500	3000±2000	4000±2000	<2000	<2000	<1000	<1000	<6000	<1000	<1000	<400
U	ppt	NAA	<105	<81	<100	<29	493±8	140±5	290±6	<180	<27	<14	214±3
		HXRF	<8000	6000±4000	4000±3000	<2000	<2000	<2000	<2000	<9000	<2000	<2000	<800

Notes

ppm parts per million
ppb parts per billion
ppt parts per trillion
< below detection limit for method
-- no sample collected or analysis not performed
N.P. not present

a Methods

NAA	neutron activation analysis. Limits given are 2σ where σ is the counting error. All values are relative to Standard Pottery.
SXRF	low energy x-ray fluorescence
HXRF	high energy x-ray fluorescence
AA	atomic absorption spectrophotometry
ZAA	Zeeman atomic absorption spectrophotometry
color s	colorimetric spectrophotometry
color t	colorimetric titration
electrode	specific ion electrode
gravim.	gravimetric assay
thermo.	thermometer reading
E_{NHE}	oxidation-reduction potential relative to normal hydrogen electrode
comb	total inorganic carbon by combustion

b. from pH of sample to pH 4.5, including noncarbonate species
c. pH to 8.3; DC-6 value has $SiO(OH)_3^-$ interference, see discussion
d. (pH 8.3 to pH 4.5) - (pH to 8.3) - (pH 4.5 to 8.3)
e. species by calculation but not corrected for ionic strength of each sample (using pH, pK only). Samples were filtered through 0.2 micron papers and analyzed at least one month following sampling.
f. K, Ca, Ba values by HXRF are likely to be low by a factor of 2 to 3, due to particle size effects.
g. single replicate value
h. Mo corrected for U fission
i. Cs and Sb values in duplicate DC-2 samples indicate a problem in sampling or sample handling during preparation for analysis.

Table III-3. Analyses of dissolved gases in groundwater

Species	DC-2[a] (3243-3273 ft) 6/26/78	Juniper Spring 7/28/78	DC-6[a] (artesian flow) 7/21/78	DC-6 (artesian flow) 8/16/78	Ford Well 8/11/78	McGee Well 8/13/78
	Concentration, ppm moles gas per mole water					
^4He	--	0.00035	--	--	0.00027	0.00052
H_2	0.74	0.21	0.013	--	0.004	<0.00002
O_2	<0.02	0.32	0.014	0.015	0.11	12
N_2	192[a]	55	11	18	12	57
Ar	1.4	0.75	0.23	0.17	0.28	0.77
CO_2	0.0054	1.1	<0.016	0.43	1.5	1.6
CH_4	48	0.061	0.13	0.14	7.1	7.3
C_2H_6	0.01	--	--	--	--	--
higher hydrocarbons	<0.001	--	--	--	--	--

a Neon internal standard and helium buffer gas. All others used helium-3/krypton internal standard and CF_4 buffer gas.
b DC-2 flushed with nitrogen during swabbing and sampling.

Table III-4 Isotopic analyses of selected elements in groundwater.

Species	DC-2 (3243-3273 ft) 6/26/78	Juniper[a] Spring 7/28/78	Rattlesnake Springs 7/31/78	Benson Springs 8/1/78	Bennett Springs 8/3/78	DC-6 (artesian flow) 7/21/78	DC-6 (artesian flow) 8/16/78	Ford Well 8/11/78	McGee Well 8/13/78	Columbia River (Hanford Townsite) 7/25/78	Columbia River (Richland Townsite) 8/16/78
A. Radioactive isotopes											
Tritium, T.U.±1σ	16.40±0.50	0.15±0.04	0.47±0.06	3.17±0.24	0.37±0.06	0.08±0.04	-0.02±0.05	0.15±0.04	-0.03±0.04	78.30±2.40	82.80±2.30
Radon-222 pCi/l	104±2	0±1	94±3	324±4	56±2	471±8	--	95±1	140±4	-1±1	--
B. Stable isotopes											
δD_{SMOW}, ‰	-132.50	-132.7	-128.5	-126.2	-121.1	-124.60	--	-136.2	-139.2	-128.1	--
$\delta^{13}C$, ‰	-10.47	--	--	--	-5.70	-19.20	--	-6.31	-14.51	*	--
$\delta^{18}O_{SMOW}$, ‰	-16.35	-16.75	-16.40	-16.40	-15.75	-15.00	--	-18.00	-18.05	-16.60	--
$\delta^{34}S(SO_4)$, ‰	+1.96	+8.67	-1.64	-1.49	-0.47	-2.12	--	*	*	+2.73	--
$\delta^{34}S(SH)$, ‰	+3.24	*	*	*	*	*	--	*	*	*	--

* Insufficient material for analysis.
-- No sample collected, or analysis not performed.
a A sample from Juniper Spring was obtained on 8/14/78 for $\delta^{13}C$ analysis but the amount of material collected was insufficient.

Although the three samples of DC-2 water were not in the true sense duplicates, they do give confidence that the analytical techniques used give reproducible results. The shifts in Fe, Cd, and Pb may be real or may reflect contamination effects. Further study would have to be undertaken to clarify this ambiguity.

Replicate analyses. Replicate analyses of many of the elements were performed as a natural consequence of the broad applicability of the instrumental methods used. The elements Ni, Cu, and Pb were analyzed by three independent methods. The elements Na, Mg, Cl, K, Ca, Ti, V, Cr, Fe, Co, Ga, As, Rb, Sr, Cd, Th, and U were analyzed by two independent methods. Such an approach permits identification of computational and measurement errors as well as contamination during sample preparation. In most cases, however, the sensitivity of different analytical methods varies for different elements, and for many elements, only the lower limit of detection can be cited. This information, while useful, is no substitute for a quantitative value by a more sensitive analytical method.

Neutron activation analysis is a particularly powerful technique for testing the internal consistency of the values presented. The data from NAA of three samples from DC-2 were checked by one or more of six methods, thus:

1. The same gamma rays were measured:
   a. with the same equipment at different times
   b. with different equipment.
2. Different gamma rays of the same isotope were measured:
   a. in the same counting period
   b. in different counting periods with the same equipment
   c. with different equipment.
3. Gamma rays of different isotopes of the same element in different counting periods were measured:
   a. with the same gamma ray detector system
   b. with different gamma ray detector systems.
4. The gamma rays measured in two different reaction irradiations were:
   a. identical
   b. different gamma rays of the same isotope
   c. gamma rays of different isotopes of the same element.
5. Duplicate samples were measured from the same sample collection.
6. Samples collected at different times were measured.

It is possible to distinguish between measurement errors, sample preparation errors and sample collection errors as shown in Table III-5.

Table III-5 Quality assurance methods used in NAA work.

Element	Method	Typical Difference, %	Typical Counting Error, %	Conclusion: (NAA technique)
A. Measurement technique checks (all samples)				
Na	2b	2	2	excellent
Cl	2b	10	5	adequate
Ba	2c	16	13	excellent
Cs	2a	8	7	excellent
B. Sample preparation techniques (DC-2; 6/22/78 and 6/26/78)				
Na	5	1	1	excellent
Cl	5	6	3	adequate or excellent
Br	5	4	3	excellent
Mo	5	1	2	excellent
Ba	5	14	7	adequate
W	5	8	6	excellent
Cs	5	20	3	poor
Sb	5	30	15	poor
Rb	5	4	5	excellent
C. Sample collection techniques (DC-2; 6/21/78, 6/22/78, 6/26/78)				
Na	6	0.2	1	excellent
Cl	6	3	3	excellent
Br	6	3	3	excellent
Mo	6	7	10	excellent
Ba	6	6	7	excellent
W	6	4	6	excellent
Cs	6	14	4	poor[a]
Sb	6	14	12	poor[a]
Rb	6	3	4	excellent

a Variation may be due to sample preparation techniques.

The measurement techniques for the four detected elements which could be checked were excellent or adequate. The sample preparation techniques for all elements above the one part per billion (ppb) level were excellent or adequate. Two elements, Cs and Sb, which were less than 1 ppb in abundance showed variations of 40% in between two duplicate samples which were not due to measurement error. Thus the adequacy of the sample preparation techniques for these elements at their abundance level is questionable. The sample collection techniques appear excellent. Variations for Cs may be due to sample preparation techniques.

Periodic replicate analyses of samples were also made by other analysts to check the validity of their own data.

Discrepancies between analytical techniques for some elements at very low concentrations (ppb - ppt (parts per trillion)) may be attributed to different sample preparation techniques, or to differences in what was actually analyzed. For example, analyses by NAA and XRF tend to yield higher values than by AA. This is because the former methods will analyze for both dissolved and colloidal species. Similarly, AA normally reports lower values than ZAA because the former method involved a preliminary extraction technique that "sees" only dissolved species.

Results determined for K, Ca, and Ba by HXRF are low due to x-ray absorption as particle size effects are a problem. HXRF analyses are determined by calibration with the bromine analysis by NAA. This means that any error by HXRF or NAA will be propagated through all analyses. The overall consistency of replicate analyses is very good, however.

d. Internal consistency of the analyses

A number of checks can be made to test the internal consistency of the analyses. These include a test for electrical neutrality, reconciliation of alkalinity titrations with CO_2 measurements and with pH, Eh measurements with redox pairs (e.g., S^{2-}/SO_4^{2-}, CH_4/CO_2, NH_4^+/N_2, Fe^{2+}/Fe^{3+}), etc.

Table III-6 summarizes selected analytical data relevant to tests for electrical neutrality. Only those elements or components were included that were present in concentrations of greater than 0.01 milliequivalents/liter. The calculated discrepancy between anions and cations, is in all but one case less than 5% of the sum. When considering the relatively low concentrations of total dissolved solids in the samples analyzed, the level of agreement can be considered satisfactory.

Table III-6 Cation/anion balance

Ion	Method	mg/l-meq/l factor	DC-2 (3243-3273 ft) 6/26/78	Juniper Spring 7/28/78	Rattlesnake Springs 7/31/78	Benson Springs 8/1/78	Bennett Springs 8/3/78	DC-6 (artesian flow) 7/21/78	Ford Well 8/11/78	McGee Well 8/13/78	Columbia River (Hanford Twns.) 7/25/78
			Concentration[a], meq/l								
Cations											
Na^+	NAA	0.0435	7.87±0.17	0.85±0.02	0.52±0.01	0.26±0.01	0.31±0.01	10.14±0.30	1.13±0.03	1.28±0.03	0.05
K^+	SXRF	0.0256	0.08	0.13	0.08	0.04	0.04	0.08	0.14	0.19	0.01
Mg^{2+}	SXRF	0.0823	0.0	1.07	0.82	0.66	0.57	0.16	0.74	0.57	0.30[d]
Ca^{2+}	NAA	0.0499	0.01[c]	1.20±0.15	1.70±0.1	1.00±0.1	1.00±0.05	0.06[c]	0.85±0.10	0.75±0.10	0.95±0.1
Sr^{2+}	HXRF	0.0228	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
Anions											
$H_3SiO_4^-$[f]	SXRF	0.0105	1.56	0.03	0.0	0.0	0.0	1.36	0.01	0.01	0.0
Cl^-	NAA	0.0282	2.68±0.08	0.13±0.00	0.11±0.00	0.09±0.00	0.17±0.00	3.53±0.17	0.14±0.00	0.14±0.00	0.30[c]
SH^-	grav	0.0303	0.19	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SO_4^{2-}	SXRF	0.0208	0.20	0.37	0.29	0.23	0.21	1.77[e]	0.04	0.04	0.15
CO_3^{2-}	color t	0.0333	0.90[b]	0.0	0.0	0.0	0.0	1.15[b]	0.0	0.0	0.0
HCO^-	color t	0.1639	1.20[b]	3.05	2.66	1.39	1.70	0.84	2.88	2.83	1.00
F^-	electrode	0.0526	1.11	0.03	0.02	0.01	0.01	2.16	0.03	0.04	0.02
OH^-	electrode	0.0588	0.08	0.0	0.0	0.0	0.0	0.13	0.0	0.0	0.0
Total cations			7.96	3.25	3.12	1.96	2.02	10.44	2.86	2.79	1.33
Total anions			7.92	3.61	3.08	1.72	2.09	10.94	3.10	3.06	1.47
% error			+0.25	-5.25	+0.65	+6.52	-1.70	-2.34	-4.03	-4.62	-5.00

a limit: 0.01 meq/l.
b carbonate equilibrium
c SXRF value
d AA value
e gravimetric value
f calculated from SXRF data using the first dissociation constant for H_4SiO_4

In order to test for consistency between alkalinity, CO_2 measurements and pH, and Eh and redox pairs, the selected analytical data given in Table III-6 was augmented with low concentration though important elements relevant to the thermodynamic stability of associated mineral phases (e.g., Fe, and Al), and the concentrations of the aqueous species present determined through the use of the distribution step of the FASTPATH code. This code uses a data bank of dissociation or solubility constants originally compiled by Helgeson (1969) with some additional data supplied by Kharaka and Barnes (1975) of the U.S. Geological Survey. Distributions were made using dissociation constants for 25°C in all cases except for the analysis of water from DC-6, where a temperature of 60°C was used. Electrical neutrality was forced on the analyses by addition or removal of a balancing component. CO_3^{2-} was chosen for all analyses except those of DC-2 and DC-6 where Na^+ was used. The balancing component was selected primarily on the basis of its predominance over other components in solution. The oxidation potential was, in all cases except for the DC-2 analysis, held at the value measured in the field.

The results of the distribution are summarized in Table III-7. The distributions show that sulfur is present entirely in the SO_4^{2-} state as verified by field analyses. The only exception is in the sample from DC-2 where sulfide sulfur was observed, and where it appears that the oxidation potential should be lower than actually measured. In all samples, the iron is shown to be in the ferrous state. However, this appears unlikely in the Columbia River, which is exposed to atmospheric oxygen. The reason for this inconsistency probably lies in the questionable reading of Eh, that may have been affected by the potential due to the Pt/PtO pair on the platinum electrode (Benson, 1978).

The most important need for making a comparison between carbonate species distribution based on alkalinity measurements, and those determined by the distribution of species from chemical analyses occurs when the pH of the sampled water exceeds 9.0. At pH = 9.0 or greater, a significant fraction of the carbonate species is present as carbonate ions, CO_3^{2-}, and $H_3SiO_4^-$ begins to appear. Both species affect alkalinity measurements and must be taken into account when making comparisons between species distributions based on alkalinity measurements or chemical analyses. Table III-8 summarizes the distributions based on data obtained for water from DC-6. A comparison is not made for water from DC-2, because alkalinity measurements were not made on samples from this source.

Table III-7. Concentration of aqueous species.

Species	DC-2 (3243-3273 ft) 6/26/78		Juniper Spring 7/28/78		Rattlesnake Springs 7/31/78		Benson Springs 8/1/78		Bennett Springs 8/3/78		DC-6 (artesian flow) 7/21/78		Ford Well 8/11/78		McGee Well 8/13/78		Columbia River (Hanford Townsite) 7/25/78	
	Concentration, mol/kg water[a]																	
E^-	0.179	-39	0.215	-53	0.877	-54	0.151	-53	0.811	-54	0.443	-46	0.391	-49	0.437	-48	0.109	-51
H^+	0.137	- 9	0.534	- 8	0.213	- 7	0.529	- 7	0.334	- 7	0.884	-10	0.106	- 7	0.106	- 7	0.209	- 8
HSO_4^-	-		0.647	-10	0.198	- 9	0.421	- 9	0.241	- 9	-		0.148	-10	0.151	-10	0.112	-10
HS^-	0.671	- 3							-		-		-		-		-	
H_2S	0.745	- 6							-		-		-		-		-	
HCO_3^-	0.104	- 2	0.252	- 2	0.262	- 2	0.161	- 2	0.161	- 2	0.418	- 3	0.255	- 2	0.249	- 2	0.102	- 2
H_2CO_3	0.266	- 6	0.263	- 4	0.109	- 3	0.170	- 3	0.107	- 3	0.612	- 7	0.536	- 4	0.523	- 4	0.433	- 5
Na^+	0.845	- 2	0.851	- 3	0.522	- 3	0.265	- 3	0.309	- 3	0.120	- 1	0.113	- 2	0.128	- 2	0.543	- 4
$NaCO_3^-$	0.566	- 4	0.356	- 6	0.569	- 7	0.714	- 8	0.132	- 7	0.425	- 3	0.241	- 6	0.267	- 6	0.236	- 7
$NaSO_4^-$	0.614	- 5	0.120	- 5	0.566	- 6	0.246	- 6	0.261	- 6	0.152	- 3	0.185	- 6	0.214	- 6	0.342	- 7
K^+	0.818	- 4	0.133	- 3	0.767	- 4	0.383	- 4	0.409	- 4	0.814	- 4	0.143	- 3	0.192	- 3	0.767	- 5
KSO_4^-	0.358	- 7	0.113	- 6	0.502	- 7	0.215	- 7	0.208	- 7	0.408	- 6	0.141	- 7	0.193	- 7	0.291	- 8
Mg^{2+}	0.246	- 4	0.491	- 3	0.392	- 3	0.318	- 3	0.279	- 3	0.357	- 3	0.355	- 3	0.277	- 3	0.142	- 3
$MgCO_3$	0.155	- 4	0.213	- 4	0.433	- 5	0.931	- 6	0.129	- 5	0.206	- 4	0.802	- 5	0.613	- 5	0.690	- 5
$MgHCO_3^+$	0.143	- 6	0.756	- 5	0.627	- 5	0.327	- 5	0.285	- 5	0.575	- 6	0.566	- 5	0.432	- 5	0.955	- 6
$MgSO_4$	0.273	- 6	0.116	- 4	0.715	- 5	0.521	- 5	0.413	- 5	0.453	- 5	0.995	- 6	0.794	- 6	0.163	- 5
$MgOH^+$	0.575	- 6	0.309	- 6	0.618	- 7	0.207	- 7	0.286	- 7	0.196	- 4	0.114	- 6	0.887	- 7	0.237	- 6
MgF^+	0.793	- 7	0.329	- 5	0.202	- 5	0.145	- 5	0.115	- 5	0.145	- 5	0.279	- 6	0.223	- 6	0.449	- 6
Ca^{2+}	0.530	- 5	0.554	- 3	0.802	- 3	0.481	- 3	0.529	- 3	0.183	- 4	0.403	- 3	0.356	- 3	0.449	- 3
$CaCO_3$	0.207	- 5	0.150	- 4	0.566	- 5	0.881	- 6	0.153	- 5	0.118	- 4	0.569	- 5	0.494	- 5	0.139	- 4
$CaHCO_3^+$	0.688	- 7	0.193	- 4	0.291	- 4	0.112	- 4	0.123	- 4	0.300	- 6	0.146	- 4	0.126	- 4	0.688	- 5
$CaSO_4$	0.469	- 7	0.106	- 4	0.118	- 4	0.634	- 5	0.632	- 5	0.157	- 5	0.910	- 6	0.824	- 6	0.415	- 5
$CaOH^+$	0.546	- 8	0.155	- 7	0.562	- 8	0.139	- 8	0.242	- 8	0.382	- 6	0.573	- 8	0.508	- 8	0.335	- 7
Fe^{2+}	0.219	- 8	0.241	-11	0.223	-10	0.450	- 9	0.384	-10	0.851	-16	0.393	- 6	0.403	- 6	0.297	-10
$FeOH^+$	0.650	- 7	-		-		0.376	-10	-		-		0.161	- 6	0.166	- 6	0.640	-10
Sr^{2+}	0.115	- 6	0.946	- 6	0.140	- 5	0.131	- 5	0.135	- 5	0.305	- 7	0.846	- 6	0.763	- 6	0.940	- 5
$SrCO_3$	0.198	- 7	0.114	- 7	0.440	- 8	0.107	- 8	0.174	- 8	0.615	- 8	0.531	- 8	0.470	- 8	0.128	- 6
$SrHCO_3^+$	0.148	- 8	0.329	- 7	0.507	- 7	0.306	- 7	0.313	- 7	0.342	- 9	0.305	- 7	0.269	- 7	0.144	- 6
$SrSO_4$	0.781	- 9	0.140	- 7	0.159	- 7	0.134	- 7	0.125	- 7	0.159	- 8	0.148	- 8	0.137	- 8	0.673	- 7

Table III-7. Concentration of aqueous species (continued).

Species	DC-2 (3243-3273 ft) 6/26/78		Juniper Spring 7/28/78		Rattlesnake Springs 7/31/78		Benson Springs 8/1/78		Bennett Springs 8/3/78		DC-6 (artesian flow) 7/21/78		Ford Well 8/11/78		McGee Well 8/13/78		Columbia River (Hanford Townsite) 7/25/78	
	Concentration, mol/kg water[a]																	
Al^{3+}			-		-		-		-		-		-		-		-	
$Al(OH)_2^+$	0.120	- 9	0.172	- 6	0.114	- 5	0.168	- 5	0.148	- 5	0.106	-10	0.536	- 6	0.536	- 6	0.295	- 7
$Al(OH)_4^-$	0.185	- 5	0.168	- 5	0.706	- 6	0.164	- 6	0.365	- 6	0.185	- 5	0.132	- 5	0.132	- 5	0.182	- 5
$Al(OH)^{2+}$			0.345	- 10	0.915	- 9	0.325	- 8	0.181	- 8	-		0.211	- 9	0.210	- 9	-	
AlF_2^+			-		0.163	- 9	0.958	- 9	0.325	- 9	-		0.710	-10	0.119	- 9	-	
AlF^{2+}			-		0.299	-10	0.213	- 9	0.735	- 10	-		-		-		-	
AlF_3			-		0.269	-10	0.127	- 9	0.423	- 10	-		0.226	-10	0.494	-10	-	
Fe_3^+	0.280	-28	0.226	- 17	0.513	-16	0.565	-15	0.902	- 16	0.196	-23	0.197	-16	0.180	-17	0.494	-18
$Fe(OH)_2^+$			0.409	- 8	0.586	- 8	0.111	- 7	0.444	- 8	0.179	- 8	0.931	- 8	0.858	- 9	0.653	- 8
$Fe(OH)_3$			0.282	- 6	0.102	- 6	0.779	- 7	0.492	- 7	0.267	- 6	0.324	- 6	0.299	- 7	0.116	- 5
$Si(OH)_4$	0.860	- 3	0.795	- 3	0.741	- 3	0.647	- 3	0.761	- 3	0.192	- 3	0.863	- 3	0.912	- 3	0.298	- 4
$H_3SiO_4^-$	0.169	- 2	0.381	- 4	0.893	- 5	0.306	- 5	0.571	- 5	0.172	- 2	0.206	- 4	0.217	- 4	0.351	- 5
S^{2-}	0.895	- 7	0.517	-105	0.194	-103	0.214	-98	0.334	-102	0.161	-103	0.185	-69	0.459	-61	0.708	-95
SO_4^{2-}	0.945	- 4	0.164	- 3	0.126	- 3	0.102	- 3	0.931	- 4	0.725	- 3	0.185	- 4	0.187	- 4	0.668	- 4
CO_3^{2-}	0.531	- 3	0.297	- 4	0.775	- 5	0.182	- 5	0.289	- 5	0.538	- 3	0.148	- 4	0.144	- 4	0.283	- 4
OH^-	0.880	- 4	0.214	- 5	0.539	- 6	0.212	- 6	0.336	- 6	0.134	- 2	0.107	- 5	0.107	- 5	0.527	- 5
F^-	0.111	- 2	0.230	- 4	0.169	- 4	0.133	- 4	0.131	- 4	0.216	- 2	0.323	- 4	0.419	- 4	0.238	- 4
Cl^-	0.268	- 2	0.132	- 3	0.109	- 3	0.880	- 4	0.166	- 3	0.353	- 2	0.137	- 3	0.136	- 3	0.282	- 4
Balancing Components	Na^+		CO_3^{2-}		CO_3^{2-}		CO_3^{2-}		CO_3^{2-}		Na^+		CO_3^{2-}		CO_3^{2-}		CO_3^{2-}	
Total Initial	0.788	- 2	0.287	- 2	0.268	- 2	0.139	- 2	0.166	- 2	0.101	- 1	0.276	- 2	0.270	- 2	0.947	- 3
Total Final	0.851	- 2	0.264	- 2	0.279	- 2	0.180	- 2	0.174	- 2	0.126	- 1	0.266	- 2	0.249	- 2	0.108	- 2
Ionic Strength	0.925	- 2	0.435	- 2	0.436	- 2	0.283	- 2	0.289	- 2	0.136	- 1	0.361	- 2	0.343	- 2	0.197	- 2

a The approximation that mol/l ≈ mol/kg H_2O was used to calculate the distribution of species.

Table III-8. Comparison of measured and calculated concentration of aqueous species from a sample drawn from DC-6.

Concentrations of aqueous species, mol/l

	Measured (alkalinity titration)	Calculated (distribution of species based on chemical analysis)	
Temperature	46°C	25°C	60°C
pH	10.1	10.1	10.1
SiO_2	0.19×10^{-2}	--	--
$Si(OH)_4$	--	0.461×10^{-3}	0.192×10^{-3}
$H_3SiO_4^-$	--	0.145×10^{-2}	0.172×10^{-2}
CO_3^{2-}	0.212×10^{-2}*	0.593×10^{-3}	0.538×10^{-3}
HCO_3^-	0.836×10^{-3}	0.707×10^{-3}	0.418×10^{-3}

* Reported value expressed as CO_3^{2-}, but includes $H_3SiO_4^-$.

2. Analytical Development

a. Mass spectrometry using the 88-inch Cyclotron.

The measurement of isotopic ratios using the 88-inch cyclotron at LBL was investigated by R. Muller, with the purpose of establishing the feasibility of counting ^{14}C in groundwater with CO_2 derived from a one liter sample (Muller, et al., 1978; Stephenson, et al., 1978). This would avoid the need for 100 liter samples and their subsequent extractions (which proved unsuccessful in FY 1978) and allow the use of discrete downhole samplers. No Pasco Basin samples were run on the LBL cyclotron as there are still some contamination problems to be overcome in the cyclotron. A new external ion source is presently under construction; this would allow samples to be run at a cost economically comparable to standard beta decay counting techniques.

Muller also investigated the detection of ^{36}Cl; using the 88-inch cyclotron. A limit of 10^{-12} for the $^{36}Cl/^{35}Cl$ ratio was achieved with possibilities of improvement using the new external ion source.* As chloride ion is generally soluble in groundwater and is probably only slightly adsorbed by host rock minerals, this promises to be a very useful technique for age dating and groundwater hydrology, particularly as it is remembered that ^{36}Cl has

*The Rochester tandem Van de Graaf accelerator has been used to measure the $^{36}Cl/^{35}Cl$ ratio in six natural waters from Arizona. Samples of one to five liters of water had ranges from 1.12×10^{-13} to 2×10^{-12} with a background level below 3×10^{-15} (Elmore et al., 1978).

a half-life of 308,000 years. Once ^{36}Cl formation in the atmosphere and underground is better understood, this age dating technique may be valuable in deep aquifer systems as found in the Pasco Basin at Hanford.

b. Measurement of $^{234}U/^{238}U$

Measurement of this ratio in the water samples collected is being undertaken by M. C. Michel using the 5 foot radius, high precision mass spectrometer at LBL. There are numerous problems associated with measuring ages of Pasco Basin aquifer waters by this method. Basalts in the Pasco Basin may contain two to a few tens ppm uranium, which may complicate interpretation.

The $^{234}U/^{238}U$ disequilibrium measurements are being made mass spectrometrically on aliquots of approximately 500 ml samples, acidified with HCl in the field and sealed. The chosen aliquot is "spiked" with a known amount of pure ^{233}U to allow determination of the total uranium concentration at the same time that the $^{234}U/^{238}U$ isotope ratio is measured.

Chemical separation from other elements is done by anion exchange techniques involving a minimum of handling to reduce contamination by natural (equilibrium) uranium. Mass spectrometric measurements are made by sequential rapid scanning of the uranium mass region and direct ion counting. The instrument being used will allow the $^{234}U/^{238}U$ ratio to be measured to an accuracy limited primarily by statistics (approximately 2% is adequate), since background at the 234 mass position due to scattering of the ^{238}U ion beam is well below the ^{234}U ion intensity.

Interpretation of the data requires information on the uranium concentration and distribution in the aquifer rocks. This can be obtained from drillcores. Information is also required on the hydrologic properties of the aquifer under study.

c. Dissolved Gases

An analytical system was developed by A. S. Newton and S. P. Lubic at LBL to determine the level of dissolved gases, particularly helium, in groundwater. Helium-4 is a candidate for age dating groundwaters. A number of one liter stainless steel sample containers and associated valves and fittings were tested for vacuum tightness. After evacuating the sample containers, 20.0 torr of an internal standard gas mixture was added to each sample container. The gas mixture consisted of ^{3}He, Kr and CF_4. The ^{3}He was used as an internal standard for the measurement of ^{4}He dissolved in the water. Kr was used to measure the efficiency of gas recovery from the water

and sample container, and CF_4 acted as a carrier for gas transfer in the vacuum system and provided a suitable expansion volume for the water in the sample container. Atmospheric contamination of the sample was prevented by alternately evacuating and purging the sample line with CF_4 before the water samples were aspirated into the sample containers.

The samples were transferred to the vacuum system by means of stainless steel lines connected to a two-liter collection flask fitted with a large cold finger to prevent water contamination of the vacuum system. The traps and two-liter vessel were evacuated prior to sample introduction. The water was allowed to flow into the collection flask and then degassed. Evolved gases were collected in a series of traps. After degassing was complete the traps were isolated from the collection flask and vacuum manifold, connected to a Teopler pump, allowed to warm and the evolved gases transferred to a thermostated gas buret. The gases were then transferred by mercury displacement from the gas buret into evacuated demountable sample bulbs and analyzed with a CDC model 21-103 mass spectrometer. Gas standards were run to determine mass fragmentation patterns and sensitivities. Analyses of various gas fractions were performed and the water basis determined.

F. DISCUSSION AND RECOMMENDATIONS

1. Contamination of water from deep wells

Limited experience was gained collecting samples from deep wells. However, what was done emphasized the need to develop sampling techniques that both minimized contamination and permitted the level of contamination to be measured.

Only three samples were collected in DC-2 during swabbing. Although temperature, pH, and conductivity were constant, the presence of tritium in the last sample (16.40 ± 0.50 T.U.; 6/26/78) suggests contamination of the aquifer by drilling fluids. Columbia River water (78.30 ± 2.40 T.U.) is the most likely source of the tritium as this water was used during the drilling and cleaning of DC-2. Approximately 64,000 gallons were swabbed from DC-2 before the last sample (6/26/78) was taken, thus emphasizing the need to consider the potential for contamination of aquifers before drilling commences.

This contamination may have been due to the presence of a lost hole that was open in the adjacent DC-1 from August, 1969 until March, 1972. Due to unstable conditions in the interbeds of the Mabton Formation (830 to 940 ft)

and to problems with a Lynes retrievable bridge plug which had become wedged at 1224 feet, the original 9 7/8" diameter hole was plugged with cement above the packers. Attempts to reenter the original hole were unsuccessful resulting in "...the hole being sidetracked and ultimately lost." (Fenix and Scisson, Inc., 1969)*.

This hole remained open between 1264 ft, where the Lynes packer was subsequently relocated in 1976, and 5661 ft; except between 2045 ft and 2171 ft where cement had apparently moved from the 1969 sidetracked hole into the original hole (Fenix and Scisson, 1972). The successful recovery of the original hole was followed by the installation of the presently functioning DC-1 piezometers. The recovery and completion report (Fenix and Scisson, Inc., 1972) mentions losses of "approximately 150 gallons water per minute" between 2963 and 5350 ft. The possibility of mixing of waters from the various aquifers should be evaluated in considering the present hydrogeochemical data obtained in the LBL FY 1978 study.

On-site evaluation of groundwater contamination of drilling fluids is a major sampling problem. Conventional use of conductivity, pH or temperature were not found to be adequate means for judging representative formation water. Tritium levels and total organic carbon levels give after-the-fact information on mixing of aquifers with drilling fluids and detergent or polymeric "mud" contamination respectively. The rare earth elements detected by neutron activation analysis may also be used to indicate the presence of bentonitic drilling muds.

The only reliable means of on-site detection of contamination is to include a tracer compound in the drilling fluids at the time of drilling. This compound must be chemically stable, inert, nonadsorptive, nonpartitioning from the aqueous phase, capable of easy extraction and detection, and nontoxic at the levels of application. Conventional hydrological tracers, such as fluorescent dyes, satisfy some of these criteria. A more satisfactory class of compounds would be fluorocarbons detected by electron capture gas chromatography or by Fourier transform infrared spectroscopy for the highly specific C-F bond.

Complementary to the need to develop monitoring systems to assess the presence of formation water is the need to evaluate and quantify the source and level of contamination. An outline for laboratory studies to examine the leaching of contaminants from materials associated with the drilling process

*This Fenix and Scisson report incorrectly refers to the Mabton Interbeds as the Vantage Formation, and the Selah Interbed as the Mabton Formation.

and the downhole environment was developed (Dubois et al., 1979, appendix A). Contaminination of groundwaters from the drilling and sampling process is a difficult and serious problem that needs to be overcome before hydrogeochemical data, and its interpretation, can be regarded as representative and reliable.

The scarcity and uncertainty of available data from Hanford emphasizes the importance of overcoming the contamination problems inherent in drilling deep wells. In this regard, Maxwell (1976) states:

> It is trite to say that an analysis is no better than the sample that it represents, but it is a fact of life that is too often either not fully appreciated, or completely ignored. Much time and labor is expended on samples which are not worthy of the effort: an attempt is then made to justify this unneccessary work by drawing conclusions from the data that, unfortunately, may be misleading or incorrect because of the nature of the sample.

This publication provides an excellent general background on methods for overcoming problems of sample contamination. Further useful background information on container preparation is provided by Robertson (1968), Moody and Lindstrom (1977), and Bowditch et al. (1976). A useful literature survey on sampling, handling and storage of water for analysis is presented by Maienthal and Becker (1976).

Often useful information is mostly derived from marine and aquatic chemistry studies where the prime interest is in nutrient and trace element levels. Because these levels are often extremely low, contamination from sample containers may be higher than the levels in seawater. Workers in the marine and aquatic chemistry fields have therefore been forced to develop sampling tools and techniques to a high level of sophistication. This development provides a very useful precedent for workers in hydrogeochemistry; problems brought about by drilling, limitations on downhole tool size and the nature of the downhole environment make contamination the major obstacle in data collection.

While the potential for contamination of groundwaters should be evident, there are few references that express concern or understanding of the magnitude of the problem or ways to alleviate it (GAIN, 1978). Both Brinkmann (1974) and Marine (1976) address the problem of drilling fluid infiltration. Marine states that "it is absolutely essential to know the history of fluid injection and removal before the assumption can be made that a particular sample is representative of the native water." He goes on to say that: "The

history of each well and the probability of contamination must be considered before using these data to interpret the geohydrologic history of the area."

To deal with drilling fluid contamination it may be necessary to change the drilling technique. In regard to the Savannah River region, Marine suggests that:

> Because of the difficulties experienced in obtaining reliable water samples when water was used as a drilling fluid, air was used as a drilling fluid on all wells drilled from 1967 through 1971. Although using compressed air as a drilling fluid eliminated contamination of the formation with foreign fluids, it thoroughly aerated any water samples collected during the drilling process. The saturation of the water specimens with air probably caused an alteration of pH and perhaps other values. However, samples taken from air-drilled wells are considered more representative than samples taken from the water-drilled wells. The most reliable samples are those that were later pumped or drawn from a well that was drilled with air.

However, it should be recognized that there are possible problems associated with the use of air. Air invasion into formations of interest often is not easily dissipated, and therefore can greatly affect the hydraulic properties of the formation. Since research wells are usually drilled both for the acquisition of the hydraulic properties of an aquifer, as well as for groundwater chemistry, this detraction should be considered.

Possibilities for alternate techniques and their economic and technical evaluation are given by Campbell and Lehr (1973). The most relevant comments for drilling on the Hanford Reservation may be that:

> "Experience on ARH-DC-1 shows that mud is required as the circulating medium when drilling geological holes. Water and/or air should be used as the circulating medium on hydrological test holes, therefore, it is not practical to obtain optimum geological and hydrological data from one hole." (Fenix and Scisson, Inc., 1969).

As a result of the experience gained sampling well DC-2, four areas were clearly recognized where existing technology or knowledge was inadequate to ensure reliable groundwater samples. Further research and development is needed as suggested below:

(a) Drilling technology: A preferred method of drilling that minimizes contamination of aquifers with drilling fluids by limiting the invasion volume is needed. This could include the evaluation of integrating sampling with drilling, so that as an aquifer is breached it could be sampled before the invasion of drilling fluid becomes significant. Holes could be drilled with air as suggested by Marine, but in this case, the holes would probably

have to be restricted to geochemical purposes. Contamination of the groundwater with oxygen would have to be assessed and the impact of oxygen on subsequent chemical analyses determined.

(b) Contamination monitoring: Methods exploiting chemical or physical differences between contaminated and uncontaminated water cannot be trusted to provide the degree of precision needed to estimate the level of contamination remaining in the water being sampled. Promising tracers such as fluorocarbons should be mixed with drilling fluids at the time of drilling. New tracer detection methods should be tested and developed for continuous monitoring of fluids in the field at the time of sampling. New tracers should be developed that would be most suitable for contamination monitoring.

(c) Sources of contamination: Although the drilling fluid is the most obvious source; casings, grout, interbed aquifer flow, drill cuttings, and sampling devices may also cause unanticipated contamination. These need to be evaluated and their significance established so that appropriate action may be taken.

(d) Downhole sampling devices: Formation water samples must be obtained directly from the horizon selected for investigation and should be isolated in a sampler that will not contaminate the sample. Such a sampler should be capable of recovering discrete one to two liter samples. Alternatively, a downhole pump should be developed that is capable of delivering contamination-free samples of similar size at the surface in a reasonable length of time.

Samplers should also be available for specialized purposes such as dissolved gas samplers capable of being heat baked, evacuated, and filled with an internal standard, or trace element samplers made of or coated with teflon.

2. Sample preparation and analysis

The original intent of the project was to evaluate and interpret the chemical and isotopic data from the collected solution samples in terms of the applications specified in the introduction to this section. However, both the number of samples collected and their distribution does not permit such an ambitious effort at this time, and funds are not available for such an effort. More samples must be collected, analyzed, and compared before useful conclusions can be drawn. Furthermore, not all of the chemical or isotopic analyses originally planned for this study were made. This was partly due to the collection and sampling techniques not having been wholly suitable for solutions of the compositions actually encountered in the field,

and partly due to some of the elements in solution being below the limits of detection for the method used, and partly due to termination of the project prior to completion of the analyses. Modifications in sampling techniques were incorporated in the Field Operating Procedures as a result of the experience gained.

The short duration of the field program did not allow springs, artesian wells, or the Columbia River sites to be sampled a second time. An extended period of swabbing and a contractual deadline limited the sampling time on DC-2 so that only one complete sample was taken. DC-6 was to be extensively sampled, with duplicates and "blind" samples, when the program was terminated. Furthermore, analytical results were returned after the termination of the program and did not allow this experience to be included in the sampling system.

The most serious problem encountered in the field, following the contamination of aquifers by the drilling process which is discussed elsewhere in this report, was the carbonate extraction system for isotopic analyses of carbon. The field system involved the acidification of 100 liters of groundwater under a closed nitrogen atmosphere, with purging of evolved carbon dioxide by nitrogen bubbled through the carboys and into carbonate-free sodium hydroxide traps. The precipitated sodium carbonate was sent to the analyst in the sodium hydroxide solution for subsequent carbon dioxide evolution and counting.

There was some difficulty maintaining a leak-proof plumbing system between the carboys and the traps. This was partly from excess acid destroying the sealing material around the fixtures and from back-pressure build-up caused by the precipitation of sodium carbonate on the aerators in the traps. These difficulties were overcome and four subsequent extractions produced roughly a half-inch deep precipitate in the bottom of a 3-inch diameter cylinder. Assuming a pulp density of 10% and a specific gravity of 2.710 for calcite, this represents approximately 15 grams of precipitate. This precipitate proved inadequate for carbon-14 analysis although the extraction procedure appeared to be working efficiently and groundwaters contained enough material for analysis. Hence no carbon-14 data is reported. It would seem that careful barium hydroxide precipitation under a closed gas atmosphere without acidification may be a more practical extraction procedure.

Over the longer run, techniques using much smaller sample volumes are recommended for ^{14}C determinations. The promising developments at LBL using the 88-inch cyclotron in which samples as small as one liter are required,

should be investigated further. Not only are lengthy field extractions avoided, but the possibility of contamination is markedly decreased. The latter consideration becomes particularly important when ancient (>20,000 yr) groundwaters require dating by this technique.

In an on-going field sampling program the rapid turnaround of analytical results is essential for making decisions and adjustments in the field sampling and analysis procedures. The data presented represents the first stage in the development of a thorough groundwater chemistry program. Interpretation of this preliminary data is not possible at this stage, but some comments can be made as a result of the evaluation of the analytical data.

The DC-6 carbonate value from the field alkalinity titration (127 mg/l CO_3^{2-}), when corrected by equilibrium calculation at 46°C for the presence of the titratable species, $H_3SiO_4^-$, yields a value of 84 mg/l CO_3^{2-}. This CO_3^{2-} value is too high to be in equilibrium with HCO_3^- (51 mg/l) from the same titration, but should approach 35 mg/l CO_3^{2-}, assuming the HCO_3^- value is correct.

This carbonate-bicarbonate anomaly is also observed in analyses reported by La Sala and Doty (1971) in DC-1 in a number of deep zones, one of which closely approximates the 3243 - 3273 foot zone in DC-2. These authors state that "the proportion of carbonate to bicarbonate increases as the pH increases, until at a pH of about 10, essentially only carbonate is present." While this trend is observable in their data it does not follow from carbonate equilibria. A more likely explanation is the uncorrected interference from the $H_3SiO_4^-$ ion which is present in amounts equivalent to that of the carbonate ion because of the high pH of these groundwaters.

Although the $H_3SiO_4^-$ ion interference has been corrected for DC-6 data, a large discrepancy with carbonate equilibria still remains. An error in titration seems unlikely when the same pattern appears in the La Sala and Doty data. Further interference from an unknown ion is a possiblity that requires more investigation. This enigma needs to be resolved for a proper understanding of the groundwater chemistry of high pH, deep waters in basalts of the Pasco Basin.

Measurement and evaluation of stable redox potentials in the field needs further development. The low concentration of components poising the oxidation potential makes such measurement of Eh using the platinum electrode both difficult and unreliable. Further thought should be given to indirect measurement through evaluation of the distribution of dissolved gases and sulfate/sulfide ratios.

Measurement and evaluation of stable redox potentials in the field needs further development. The low concentration of components poising the oxidation potential makes such measurement of Eh using the platinum electrode both difficult and unreliable. Further thought should be given to indirect measurement through evaluation of the distribution of dissolved gases and sulfate/sulfide ratios.

Because of its importance in thermodynamic calculations, the concentration of aluminum should be determined quantitatively. Distributions of species calculations indicate that the actual concentration of aluminum present probably ranges from a high of ≈0.05 ppm Al in DC-6 to a low of 0.00025 ppm Al in Rattlesnake Springs. Because of the large fluoride content in most samples obtained so far, it will be necessary to develop alternative methods for measuring the concentration of aluminum in groundwaters from the Pasco Basin.

Analyses not carried out in this program but which require some examination for their potential importance include soluble organics such as humic and fulvic acids, Li, B, NH_4^+ and P_2O_5.

The concentrations of dissolved Cd, Cu, Ni, Pb, and Zn in the Pasco Basin water samples as analyzed by atomic absorption spectrophotometry and presented in Table III-2, were examined by D. Girvin who made the following observations.

> Trace metal concentrations in the Columbia River sample can be compared to concentrations recorded in seven samples obtained from the Sacramento-San Joaquin Delta over a period of 1 1/2 years (Girvin et al., 1977). Average trace metal concentrations in the Delta samples were 0.011 μg Cd/l, 1.77 μg Cu/l, 0.80 μg Ni/l, 0.07 μg Pb/l, and 0.30 μg Zn/l. Columbia River and Delta Pb and Zn values are comparable, while Columbia River Cu and Ni values are 3-4 times lower than the respective Delta values. The Cd concentration in the Columbia River sample, on the other hand, is four times higher than the average Delta concentration. Since only one Columbia River sample was analyzed, no significance can be ascribed to these variations; however, they may reflect real differences in the mineralogies of the drainage basins.
>
> Well DC-2 was sampled over a period of six days during which time approximately 8000 gallons per day of water was withdrawn from 3243-3272 feet by the swabbing technique. Only Pb concentrations decreased during this period while concentrations of the other elements remained quite constant. Comparison of Well DC-2 with Well DC-6, which had a deep artesian flow of more than 15,000 gallons per day for several months, shows that Cu and Pb concentrations were substantially lower in the flowing well. Zinc levels in the two wells were equivalent, while the Cd concentration in Well DC-6 was unexplainably higher.

Dissolved Cu, Ni, and Pb levels in the four spring samples were uniformly low. The source of variability in the Cd and Zn levels is not readily apparent; however, the high Zn concentration in Bennett Spring probably derived from a galvanized pipe used to channelize the flow for livestock watering.

Trace metal concentrations in the two artesian wells, Ford and McGee, which have been flowing since the 1920's, were also low and generally equivalent to the spring values. The higher Cu and Zn levels in McGee Well may have been due to the large cast (bronze?) head affixed to this well.

Mass spectrometric techniques for the analysis of rare gases and other gases dissolved in the water samples did not attain the sensitivity needed for the interpretive studies originally planned. Future work will require that greater levels of sensitivity be achieved if the rare gases are to be used for the estimation of the temperatures of the waters at the time they were last exposed to the atmosphere, or if ^{4}He and Ar measurements are to be used in interpreting relative ages of different waters. The concentrations of other gases present in groundwaters, but not always detected in this study such as H_2 and C_2H_6 should also be determined quantitatively.

New age dating techniques in which such isotopes as ^{36}Cl, ^{81}Kr, and $^{234}U/^{238}U$ can be used to estimate the apparent age of groundwater, should be developed further and the sample size required for analysis should be reduced to more manageable proportions. In this regard, the use of the cyclotron as an extremely sensitive mass spectrometer for ^{36}Cl and ^{81}Kr should be considered seriously.

As a result of the initial experience gained in the sampling of groundwaters at Hanford, the following recommendations are made:

(a) The collection of carbonate samples for ^{14}C analyses should be improved so that contamination-free samples of sufficient size for analysis can be obtained.

(b) New methods for ^{14}C analysis should be investigated that require smaller-sized samples.

(c) Discrepancies between species distributions based on alkalinity measurements and those obtained from chemical analyses must be resolved. The presence of as yet unidentified species in solution should be investigated, especially for waters from deep holes such as DC-2.

(d) The accurate evaluation of oxidation potential in groundwater should be investigated further. Direct measurements using a platinum electrode should be reconciled with calculated values based on species

electrode should be reconciled with calculated values based on species distributions, or satisfactory explanations should be obtained for the discrepancies.

(e) An improved analytical method of measuring low aluminum concentrations ($\approx$0.00025 - 0.05 ppm Al) in the presence of fluoride ion concentrations as high as 40 ppm should be developed.

(f) Soluble organic components such as humic and fulvic acids, Li, B, NH_4^+ and P_2O_5 should be analyzed in groundwater samples to determine whether these species are significant.

(g) A more sensitive analytical technique is required for the measurement of rare and other dissolved gases than was used in the present study.

(h) Support for research in new age-dating techniques through the measurement of ^{36}Cl, ^{81}Kr, or $^{234}U/^{238}U$ should continue.

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IV. PASCO BASIN MODELING

A. INTRODUCTION

Mathematical modeling can be usefully employed in two areas of the Pasco Basin study. The first is understanding the disposition of the regional groundwater system, with emphasis on determining the feasibility of selecting a suitable site for a deep repository in basalt. The second is to help in the design of certain hydrologic field tests and the interpretation of data forthcoming from these. The first task, basin modeling, is a long-term one. During FY 1978 basin modeling was limited to a thorough review of existing geologic and hydrologic data for the Pasco Basin and development of conceptual mathematical models that would best be capable of simulating the known field conditions. Well test simulations were conducted of drawdown tests in low permeability formations such as those likely in the deep basalt system in order that meaningful data could be gathered and interpreted.

B. THE CONCEPTUAL MODEL

The purpose of basin modeling is to simulate the regional hydrogeology of the Pasco basin with special reference to the deep basaltic system. In order to develop the model, it is first necessary to study the hydrology of the Pasco Basin in terms relevant to mathematical modeling. Based on this study the utility of existing models for simulating the required field problem would be evaluated and improved models would be developed if necessary.

In general, mathematical simulation of the regional groundwater system requires four categories of information. These are:

a) Geometry: Areal extent, limits and shape of the flow region; nature of layering.

b) Material Properties: Permeability; heterogeneity; anisotropy; storativity; porous, fractured, or fractured-porous disposition of the materials; porosity.

c) Boundary Conditions: Disposition of surrounding groundwater divides interaction of deep system with the shallow sedimentary system and the Columbia and Yakima Rivers; interaction of the Pasco Basin with neighboring hydrologic basins.

d) Initial conditions: The distribution of fluid potentials over the Pasco Basin and the distribution of fluid fluxes within the basin at the present time.

Data from deep groundwater systems is generally scanty and hence considerable judgement has to be exercised in interpolating or extrapolating from known, generally sparse field data. The degree of uncertainty is a very important attribute of field data and has to be considered in the simulation task.

1. Present State of Knowledge of Pasco Basin Hydrology

In a broad sense, the Pasco Basin groundwater system can be divided into two parts: the shallow sedimentary system comprising the Ringold formation and the post-Ringold glaciofluviatile and alluvial materials, and the bedrock system comprising the basalts of the Columbia River Basalt group ranging in age from Late Miocene to Middle Pliocene (Atlantic Richfield Hanford Company, 1976). The deep groundwater system in the Pasco Basin, which is of particular concern in this study, is loosely defined to constitute formations below the Mabton interbed. The upper boundary of the deep system thus communicates through the Saddle Mountain basalts with the shallow, unconfined groundwater system. The lower boundary of the deep basaltic system is much harder to define. Although it may be reasonable at this time to consider formations within 1,000 to 2,000 feet below the Umtanum, the actual definition of the lower limit will have to be governed by deep hydrologic data that will be forthcoming with new exploration activities. The lateral limits of the groundwater system in the Pasco Basin are also not clearly defined. The reason for this is that there may exist several groundwater systems within the basin at varying depths. Each of these systems may span different recharge-discharge areas and, as Toth (1963) points out, deeper systems tend to encompass much larger areas than shallow systems. Since very little data is at present available below the Umtanum, it is only possible to estimate how far to expand the basin area in order to realistically model the deep groundwater system.

2. Previous Studies on Hydrology of Deep Basalts in the Hanford Region for Evaluation of Radioactive Waste Disposal Feasibility

Unconfined flow in the sedimentary deposits has been studied and numerically modeled at Hanford; however, a model of flow in the deep basalt has yet to be developed (Deju, 1974; Atlantic Richfield Hanford Company,

1976). Groundwater movement in basalt aquifers to the north and east has been modeled numerically based on data from water-supply wells, few of which, however, are deeper than 1,500 feet (Luzier and Skrivan, 1975; Macnish and Barker, 1976; Tanaka et al., 1974).

Several deep holes have been drilled and studies undertaken in an effort to make a preliminary determination of the favorability of the geologic and hydrologic regime at depth since the National Academy of Sciences (NAS, 1966) made its recommendations that the feasibility of defense waste storage in basalt on the Reservation be evaluated. A 10,655-foot exploration well in the Rattlesnake Hills was re-entered (Raymond and Tillson, 1968) and a new test hole, ARH-DC-1, was drilled to 5661 feet beneath the 200 East Areas (Fenix and Scisson, 1969 and 1972a). Permeability and pressure tests and other information from ARH-DC-1 were described by La Sala and Doty (1971) and La Sala, Doty, and Pearson (1973). Piezometer readings collected intermittently are available for DDH-3, DH-4 and DH-5, drilled in 1970-72 (La Sala, 1976). The only other wells on the reservation deeper than 3000 feet are the DC series wells (DC-2, DC-3, DC-5, DC-6, DC-7, and DC-8) drilled in 1977-78; hydrologic information obtained from these wells during FY 1978 consist of pressure measurements by LBL in DC-2, DC-6, and DC-8, permeability measurements by Science Applications Incorporated in DC-2 (Deju, 1978), and permeability measurements by W.K. Summers Associates and by LBL in DC-6.

Recent reviewers of the available hydrologic information include Newcomb et al. (1972), Piper (1975), Atlantic Richfield Hanford Company (1976), Deju et al. (1977), and the National Academy of Sciences Committee on Radioactive Waste Management (1978). It is apparent from these reviews that the great bulk of the data presently available is from the single hole ARH-DC-1 and that more data is necessary to determine the hydrologic feasibility of the deep basalts for defense or commercial waste disposal.

3. Available Data on the Geometry of the Deep Groundwater System

a. Structure

The Pasco Basin is in the central part of the Columbia River flood basalts and contains the thickest known section of the Columbia River Basalt Group (from drill hole RSH-1). The basalt is folded into broad synclines and tight, occasionally slightly overturned anticlines (NAS, p. 141). The exact nature of fault displacement along the crests of some anticlines is now being studied by Rockwell Hanford Operations (Rockwell); surface exposures of these

faults are poor (Shannon and Wilson 1977; Rockwell Hanford Operations, 1977). Whether large displacements exist or not, throughgoing fractures in the axial zones may well exist and may influence groundwater flow. La Sala et al. (1973, p. 20) observed such fractures cutting across several flows at Wallula Gap.

Folding and faulting may affect groundwater flow in various ways. Newcomb generalized from his experience in the area that 1) recharge may be facilitated where water-bearing rocks are brought near the surface and fractured; 2) tilting may control groundwater gradient; 3) lateral permeability may be reduced by gouge-filled fault zones, causing zones of confined water; 4) faulting and folding controls the shape of groundwater basins and 5) deformation increases vertical circulation between zones. (Newcomb, 1965, p. 32; Newcomb et al., 1972). La Sala et al. (1973) found that sharp folds and faults may be barriers to lateral flow. Ledgerwood and Deju (1976, p. 26) found that the layers comprising the "uppermost confined aquifer" (from the lower Ringold formation down to the Mabton Formation) appear to be connected along the Gable Mountain anticline axis. Some hydrologically significant folding is buried beneath sediments in the northern part of the Reservation (Ledgerwood and Deju, 1976).

It is clear that deformation may result in vertical faults or fractures; whether such tectonically caused fractures act mainly to increase vertical permeability or to decrease horizontal permeability might depend on whether particular faults and tectonic joints are filled with gouge. Rockwell (1977) found mylonitic material at the surface in a shear zone at Wallula Gap. Macnish and Barker (1976) attributed low transmissivities in the Horse Heaven Hills area to the effects of deformation, and generalized that fractures due to tight folding are likely to reduce groundwater flow, due to offsetting of permeable zones and plugging by pulverized rock.

b. Nature of Layering

The basalt flows and interbeds are fairly continuous geologic units; individual flows in the Upper Yakima basalt have been traced for tens of kilometers (NAS, 1978, p. 138). However, the upper flows are complicated by lenticular and discontinuous relationships (Energy Research and Development Administration, 1975, p. II-3-B-9) and tend to pinch out at the margins of the basin and to the northwest (Ledgerwood and Deju, 1976). The latter

authors state that "the structural and stratigraphic relationship of the uppermost basalt flows beneath the Hanford Reservation is extremely complex." Correlation of the Grande Ronde basalt flows by core analysis is still tentative and based on few holes (ARHCO, 1976).

Due to the highly complex distribution of fractures, hydrologic continuity may exist across layers of different ages in certain areas. From a hydrologic point of view, such hydraulic continuity may have far greater importance than the geologic correlation of a single layer over long distances. Porous or fractured zones of various sorts -- flow-top breccias, vertical and horizontal cooling joints, vesicular zones, and tectonically caused joints -- control groundwater movement in the basalt and are likely to have considerable lateral variation (La Sala et al., 1973, p. 22; NAS, 1978, p. 138-140).

The interbeds themselves may act more as barriers to groundwater movement than as conduits (Newcomb et al., 1972; NAS, 1978, p. 140). La Sala et al. (1973, p. 22-23) found the most permeable zones in the basalt sequence to be not interbeds, but fractured upper contacts of certain flows. Knowledge of exactly which types of rock contribute to deep flow could be improved in some cases by better correlation of hydrologic and lithologic data in deep holes (Piper, 1975, p. 35-37).

4. Existing data on the hydrologic properties of the deep basalts

a. Permeability

Prior to FY 1978 the best current source of information on the permeability of the deep rock units was the 1971 report by La Sala and Doty on DC-1 (pages 42-48; page 62). From field tests conducted on intervals spanning various lithologies, La Sala and Doty computed values on the order of 10^{-7} cm/sec for the hydraulic conductivity of "dense basalt". Laboratory tests on core samples of basalt without open fractures gave hydraulic conductivities on the order of 10^{-9} cm/sec; this was taken to represent the intergranular permeability. It was concluded that the observed field permeability in "dense basalt" was due mainly to cooling joints and other fractures.

Drill-stem tests for permeability have recently been run by Rockwell in RSH-1. Preliminary results indicate permeabilities on the order of 10^{-8}

cm/sec overall (RHO, 1977, p. 26) and 5 x 10^{-7} cm/sec for the interflow zone lying directly beneath the Umtanum (Laughon and Deju, 1978). This latter figure is in contrast with La Sala and Doty's determination of 2.4 x 10^{-3} cm/sec [50.8 gpd/ft^2] for a fractured 10-foot-thick zone in DC-1 at a depth of about 3230 feet (page 45). In 1967 drill-stem tests of seven fracture and interflow zones in RSH-1 were run by Cook Testing Company for Battelle Northwest Laboratories; their results ranged from 2.9 x 10^{-8} to 1.8 x 10^{-5} cm/sec (0.03 to 19 millidarcies) (Raymond and Tillson, 1968).

Data on the aperture and continuity of fractures at depth are lacking. Good core recovery for deep basalts in holes DH-4 and DH-5 (98.4%) provides some evidence that fractures at depth may largely be closed or healed (NAS, 1978, p. 138). Deju et al., (1977, p. 30) state that fractures in the Pasco basin tend to be sealed with clays to an unusually high degree. This clay is said to come from "numerous thin beds of clay-rich sediment and saprolite deposited during the outpourings of the Columbia River Basalt". NAS (1978, page 140) noted that sedimentary interbeds are notably lacking in the lower part of the basalt sequence. Lithologic descriptions of a few specimens of core from DC-1 and DDH-1 do not mention clayey sediment below the Vantage (La Sala and Doty, 1971). In support of a difference in fracture permeability between the Pasco Basin and other basins, Deju et al. (1977) note that the Pasco basin contains significantly less groundwater of economic value than other basins in the region; however, it is not clear from that reference whether this is due to hydrologic or land-use factors.

It is important to determine what the nature of anisotropy in permeability might be. There is speculation but little data. Piper (1975) generalized from water-well yields in other areas of the flood basalts that large vertical piezometric gradients are not common and that among major water-producing wells yield increases with depth. From these conclusions he suggested that the basalt sequence might approach isotropy on a very coarse scale. On the other hand, La Sala et al. reason (1973, p. 25) that since tabular bodies such as flow-tops and interbeds transmit water, "the average permeability of the rock section as a whole is therefore much greater in the direction concordant with the dip than in the discordant or cross-bed direction. In an area uncomplicated by structural features, water will tend to move more readily in a horizontal rather than a vertical direction."

Based upon the results of La Sala et al. (1973), Ledgerwood and Deju state that the vertical permeability of the interbeds is an order of magnitude lower than that in the horizontal direction. Intera (1977, p. 15) concurs that such anisotropy is generally the case for aquifers containing interbedded shale or clay.

Field data distinguishing vertical from horizontal permeability in the basalt are lacking: conventional tests cannot provide such data (see Section IIA-1 of this report). Tanaka et al. (1974, page 24) attempted to derive a vertical permeability for use in a hydrologic model of the Columbia Basin Irrigation Project area to the north and east of the Hanford Reservation:

> In the absence of reliable field data on the vertical hydraulic conductivity of basalt in the project area, several hydraulic conductivity values were estimated indirectly by analysis of the head response in basalt to application of known amounts of irrigation water, and these values were tested as model parameters. After repeated trials on the model, comparing different values of hydraulic conductivities to head response in the upper and lower aquifers, an average value of 0.00002 foot per day (within a range of 0.000001 foot/day to 0.000037 foot/day) [7×10^{-10} cm/sec; 3.5×10^{-10} cm/sec to 1.3×10^{-8} cm/sec] gave computed heads that were similar in response to measured heads in both aquifers.

Deju et al., state (1977, p. 28) that hydraulic conductivities in the central volume of a dense, thick basalt flow are usually two to three orders of magnitude less than 10^{-10} cm/sec.

b. Storativity

La Sala and Doty (1971, p. 35) give values for the storage coefficient for 4 segments of basalt in DC-1; the lowest value (1.4×10^{-6}), obtained for the basalt section freest from interbeds and breccia, was close to the compressibility of water. A storage coefficient of 2.5×10^{-3} for a basalt aquifer in the Odessa area was calculated by Luzier and Burt (1973) by comparing groundwater withdrawals with changes in piezometric contours over an interval of one year (as described in Tanaka et al., 1976, p. 10).

c. Effective Porosity

La Sala and Doty (1971) give values for effective porosity of different basalt types and interbeds (p. 62) which were estimated by Fenix and Scisson from geophysical logs: 1 percent for "dense" basalt; 5 percent for vesicular basalt; and 10 percent for basalt with closely spaced fractures. La Sala and

Doty (1971) expressed some doubt about the applicability of these geophysical techniques to dense, massive rocks, and were uncertain about whether a correction for hole diameter had been applied. For a discussion on the interpretation of porosity and caliper logs, see Section IIB2 of this report.

Effective porosity is important because velocity and arrival-time calculations are dependent on it. A low estimate of porosity yields a high estimate for contaminant travel time from a repository to a given point (Piper, 1975; NAS, 1978). Based on their very preliminary calculations of average permeabilities and porosities for interbeds and different types of basalt, La Sala and Doty (1971) thought it likely that the highest velocities might be obtained in thin fracture zones in basalt, as opposed to vesicular basalt, dense basalt, or interbeds.

5. Initial conditions; distribution of fluid potentials and fluxes

For the uppermost confined aquifers, sufficient data exists from piezometers in the five DB holes and a few others to draw a tentative piezometric surface (USERDA, 1975; Ledgerwood and Deju, 1976). Piezometers were installed below the Mabton in DH-4, DH-5, DDH-3, and ARH-DC-1 in 1971-72 (La Sala, 1976). However, regarding the deeper basalts, NAS (1978, p. 162) finds that "in all the Hanford Reservation, only bore hole ARH-DC-1 is fitted with multiple piezometers which tap successive levels deep in the confined-water zone, and in which heads have been measured periodically, at sufficiently short intervals of time, and over a sufficiently long term to obtain fully reliable values" (p. 162). The heads in the three piezometers monitoring the deepest levels (piezometer no. 1, 4849-4760 feet; piezometer no. 2, 4051-3931 feet; and piezometer no. 3, 3242-3177 feet) have remained within about 1.5 feet of each other since they were first measured in 1972. Head in the next higher piezometer (no. 4, 2987 - 2913 feet) has fallen by about 25 feet since 1972 (ARHCO, 1976); it appears to be reaching a steady-state value (NAS, 1978) about 10 feet lower than that in the three deepest piezometers. The shallowest piezometer (no. 5, 2105-1219 feet) shows a head about 7 feet lower than the three deepest piezometers. A discussion of the reaction of these piezometers to swabbing for geochemical sampling in neighboring well DC-2 is presented in Section IIB1 of this report.

NAS points out that these heads are higher than the unconfined groundwater level in that area and higher than low-water stage of the Columbia

River (by about 10 feet and 55 feet respectively, in piezometers 1, 2, and 3). Hence that report concludes that the potential gradient in the deep basalts in the vicinity of DC-1 would be generally upwards and towards the river, the zone of lowest apparent potential, at piezometer 4, possibly being in most direct contact with the river. The heads in all the "uppermost confined aquifers" (down to and including the Mabton) appear to increase with depth (Ledgerwood and Deju, 1976).

Heads measured in the deep holes RSH-1 and ARH-DC-1 showed a decrease in pressure with depth (Raymond and Tillson, 1968; La Sala and Doty, 1971). In RSH-1, six zones between 1929 feet and 5997 feet showed progressively decreasing heads. However, the well was only shut in for two to three hours before pressure measurements were taken (Raymond and Tillson, 1968); hence it is likely that these measurements were perturbed by the effects of drilling (NAS, 1978). In DC-1, heads measured in the piezometers have been higher than those measured during drilling (NAS, 1978; La Sala and Doty, 1971). La Sala and Doty measured heads averaging about 165-170 feet below land surface from 362 feet to 2700 feet; averaging roughly 5 feet higher than that from 2800 to 3450 feet; and averaging about 30 feet lower than that from 3800 to 4280 feet. These measurements from DC-1 are compared with measurements from DC-2 and the piezometer data in section IIB1 of this report.

Some information is available on horizontal variation of potential at depth in the basalt. Higher heads exist in two artesian wells, drilled to 777 and 1108 feet below land surface, in Cold Creek Valley about 7 miles west-northwest of DC-1. Heads measured in these wells in 1951 are about 544 feet and 570 feet higher than the highest piezometer heads in DC-1 (NAS, 1978; La Sala et al., 1973). In DH-5, about 20 miles northwest of DC-1, the head in a piezometer at 5002-4851 feet below land surface (La Sala, 1976) is about 130 feet higher than that of the highest piezometer heads in DC-1 (NAS, 1978).

The occurrence of perennial springs in the Rattlesnake Hills and Cold Creek Valley, and of generally high confined-water heads on the western margin of the reservation, are as yet unexplained anomalies (NAS, 1978). NAS and Piper (1975) speculate that there might be perched water in the Rattlesnake Hills. In the Cold Creek Valley, tight folding or faulting may account for the high pressures oberved there (Newcomb (1961), as discussed in Brown (1970); Ledgerwood and Deju, 1976).

Evidence on actual fluxes and velocities in the deep basalts is scanty. Age dates of deep groundwater may be used as a constraint on estimates of velocity. La Sala, Doty, and Pearson obtained six carbon-14 ages for basalt groundwaters on and near the Reservation southwest of the Columbia which they considered representative. A spring in Dry Creek Valley was taken to represent present-day recharge in the Dry Creek and Cold Creek Valleys; ages were adjusted to give this spring an age of zero years. Water from 540-640 feet in DC-1 was dated as at least 12,000 years old (La Sala et al., 1973, p. 38). Hydrogen and oxygen isotope data from this well indicated recharge under cooler conditions than the present climate (La Sala and Doty, 1971, p. 53). The two artesian wells in Cold Creek Valley mentioned above yielded ages of 19,000 years for the deeper and 13,000 years for the shallower well. Water from a 1000-foot deep well on the south slope of Rattlesnake Ridge gave an age of 30,000 years, and a 1,200-foot deep well in Dry Creek Valley gave an age of 16,000 years.

6. Boundary Conditions

Since LBL was primarily asked to consider the deep groundwater system below the Mabton, the boundary conditions that need to be considered relate to the communication between the deep system and the shallow unconfined system within the Pasco Basin, between the deep system and the Columbia and Yakima Rivers, and between the deep system and the groundwater basins outside the Pasco Basin. It was also necessary to investigate communication across the lower boundary of the deep system itself.

Regarding the first of these questions, quantifying vertical exchange of groundwater across confining basalt units will be necessary for an accurate description of the upper boundary of the deep system. Modelers of basalt hydrology in the Odessa-Lind area to the north of the Pasco Basin (Luzier and Skrivan, 1975), the Walla Walla River basin to the east (MacNish and Barker, 1976), and a large area bordering the Reservation on the north and east (Tanaka et al., 1974) all found vertical water movements difficult to estimate. In all cases, the assumed vertical hydraulic conductivity of the confining layer involved was varied empirically to "fine tune" the model's behavior. Luzier and Skrivan (1975, p. 23) stated, "The model is quite sensitive to recharge variations. During the study, vertical leakage was the parameter that was most often varied and which posed the biggest problem."

It was found necessary to vary the vertical conductivity significantly at different points in the areas modeled.

These modelers found it necessary to assume that some vertical movement of groundwater occurred through confining basalt layers at depths of several hundred feet in these surrounding areas. Estimates of yearly quantities involved were made for the Columbia Basin Irrigation Project area to the north and east of the Pasco Basin for vertical flow into a "lower aquifer" (a simplified representation of all the water-bearing levels in the Yakima Basalt, including a productive zone below the Vantage). Estimated net vertical flow totalled 6700 acre-feet per year in a 3600-square-mile-area. This was from 31% to 100% of net lateral flow into the "lower aquifer" in the three subregions modeled (Tanaka et al, 1974).

It is reasonable to assume that there is some quantifiable vertical movement of water through deep basalt units in the Pasco Basin. Piper (1975, p. 39) states that "the difference in hydraulic potential between the highly permeable unconsolidated deposits above and the less permeable flood-basalt sequence below, also between zones within the basalt, is generally no more than a few feet of head. In the writer's judgement, the relatively small head differences signify restricted interchange of water rather than hydraulic discontinuity."

The areas of the Pasco Basin where deep groundwater systems may communicate with overlying systems is not known. Ledgerwood and Deju (1976) found it likely that the shallower confined aquifers are interconnected in the hinge zones of anticlines.

The relations existing between the deep basalts and the Columbia and Yakima Rivers can only be guessed at based on the limited evidence available. Based on the differences in hydraulic potential described in the last section, it has been speculated that the Columbia River is a discharge area for the deep basalts, and that in particular the zone tapped by piezometer number 4 in ARH-DC-1 (2987-2913 feet) may represent a potential pathway to the lower potential at the Columbia River, bypassing the overlying region of slightly higher head (NAS, 1978, p. 165-67).

Recharge and discharge areas for the shallow system can be discerned. Lysimeter experiments in the vicinity of the 200 areas indicate that no appreciable natural recharge to the unconfined zone is occurring in the lowland areas under the present climatic regime (Brownell et al., 1975).

Recharge to the shallow groundwater zones may be occurring in such areas as the Rattlesnake Hills and Horse Heaven Hills, where precipitation is higher (NAS, 1978, p. 157). Ledgerwood and Deju (1976) found that for the confined aquifers above 1000 feet, deep recharge was probably occurring on the margins of the basin (p. 23). Piezometric contours for the uppermost confined aquifer show a marked trough along the course of the Columbia River (USERDA, 1975), indicating that the river may be a major discharge area.

For deep groundwater, La Sala et al. (1973, p. 4) speculated that uplands on and near the Reservation, including Cold Creek and Dry Creek Valleys and the Saddle Mountains, are recharge areas, that the Horse Heaven Hills are a groundwater divide, and that discharge is to the Columbia River. However, whether these recharge and discharge boundaries are the same for aquifers above 1000 feet as for the deep system remains to be seen. The authors state (p. 49) that they "cannot yet sufficiently describe the characteristics of the flow in the region as to direction and velocity, particularly at depths below 1000 feet." Recharge of deep groundwater may come from as far away as the Cascade Mountains (ARHCO, p. 68).

C. THE MATHEMATICAL MODEL

1. Required Attributes

It is evident from the preceding description of the field problem that the natural system spans an area of several hundred square miles and extends in depth to 5,000 feet or more below ground level. The system boundaries are apparently complex and irregular and the flow system is occupied by numerous layers of widely variable continuity, which are, in addition, considerably folded and faulted. Although primary porosity may be of importance locally, by and large the layers are characterized by fractures of widely variable pattern (horizontal, columnar, entablature) and spacing. The system is probably characterized by time dependent boundary conditions and with a variable, three dimensional distribution of fluid potentials. Above all, whatever effort is expended on collecting detailed data, such data will always be accompanied by uncertainty and hence the simulation results are also bound to be accompanied by significant uncertainties.

To simulate such a complex natural system one would require a general three dimensional mathematical model, capable of simulating transient groundwater flow in region with complex geometry, arbitrary variation of material conditions, and arbitrary initial conditions. Depending on the scale of interest within the flow region the simulator must have the capability to model fractured or fractured-porous media.

A very desirable attribute, which may be difficult to incorporate in a model, is the quantitative consideration of uncertainty. In the ideal case, the model would have the ability to accept uncertainty parameters as input data and associate corresponding confidence limits to the output results. If this ideal cannot be attained, then the available models will have to be used to study the system's sensitivity to various parameters of interest. Such sensitivity analysis will, hopefully, lead to a proper appreciation of uncertainty.

The equations governing transient groundwater flow will now briefly be discussed with special reference to the Pasco Basin hydrology task. Also the different models available at LBL for simulating groundwater systems will be be presented.

2. Theory of Transient Groundwater Flow

Consider a volume element of arbitary shape and size in a dynamic groundwater system. Let the element be small enough so that the fluid potential does not vary rapidly over the element, and so that one could associate an average value of fluid potential with the volume element. The average potential of the element is continuously changing with time due to the movement of water into and out of the element and the consequent changes in the quantity of fluid, M_w, stored in the element.

For this element, one could write the mass conservation equation in an integral form as,

$$\rho_w G_v - \int_\Gamma \rho_w \vec{q} \cdot \vec{n} d\Gamma = \frac{DM_w}{Dt} \tag{1}$$

where ρ_w is water density $[M/L^3]$

G_v is the volumetric generation rate (source or sink) from the volume element $[L^3/T]$

$\vec{q}$ is Darcy velocity $[L/T]$

$\vec{n}$ is unit outer normal to the surface segment, Γ, and D/Dt is the total or material derivative, chosen with the assumption that the volume element has a constant volume of solid material.

If we now introduce Darcy's law in the form

$$\vec{q} = - \frac{k\rho_w g}{\mu} \nabla (z + \psi) \tag{2}$$

where k is the absolute permeability $[L^2]$

g is the gravitational constant $[L/T^2]$

μ is the dynamic coefficient of viscosity $[M/LT]$

z is the elevation above datum [L] and

ψ is the pressure head [L],

then (1) becomes

$$\rho_w G_v + \int_\Gamma \rho_w \frac{k\rho_w g}{\mu} \nabla (z + \psi) \cdot \vec{n} \, d\Gamma = \frac{DM_w}{Dt} \tag{3}$$

Since, on the right hand side of (1) and (3) it is of primary interest to have fluid pressure head, ψ, as the dependent variable rather than M_w, we introduce the quantity, M_c, by the relation,

$$\frac{DM_w}{Dt} = \frac{dM_w}{d\psi} \frac{D\psi}{Dt} = M_c \frac{D\psi}{Dt} \tag{4}$$

The quantity M_c, which has the dimension of [M/L] has been termed the fluid mass capacity of the volume element (Narasimhan and Witherspoon, 1977) and represents the mass of fluid released from or taken into storage by the element for a unit change in the average pressure head.

For a volume element which may or may not be fully saturated, M_c can be written as (Narasimhan and Witherspoon, 1977)

$$M_c = V_s \rho_w \left[e S \rho_w \beta \, g + S \gamma_w a_v + e \frac{dS}{d\psi} \right] \tag{5}$$

where V_s is the volume of solids in the element $[L^3]$

e is the void ratio

S is the saturation

β is the compressibility of water $[LT^2/M]$

γ_w is the unit weight of water $[M/L^2T^2]$

a_v is the coefficient of compressibility of the porous medium $[LT^2/M]$

$a_v = -\frac{de}{d\sigma'}$, in which σ' is the effective skeletal stress.

In writing (5) a simplifying assumption has been made that the porous medium deformation is basically one dimensional. Also, it is assumed change in pressure head is fully converted to change in effective skeletal stresses (see Narasimhan and Witherspoon, 1977 for details).

If we confine our attention to saturated flow, which is most likely to be characteristic of the deep basaltic system in the Pasco Basin, then M_c in (5) can be simplified to

$$M_c = V_s \rho_w \underbrace{[e \rho_w \beta g}_{\substack{\text{Expansion} \\ \text{of water}}} + \underbrace{\gamma_w a_v]}_{\substack{\text{Deformation of} \\ \text{porous medium}}} \tag{6}$$

In the light of (4), (3) becomes

$$\rho_w G_v + \int_\Gamma \rho_w \frac{k \rho_w g}{\mu} \nabla (z + \psi) \cdot \bar{n} \, d\Gamma = M_c \frac{D\psi}{Dt} \tag{7}$$

The symbol Γ in (1), (3), and (7) represents the closed surface bounding the volume element. If portions of Γ coincide with the external surface of the flow region, then the integrand in respect of these portions will consitute the known boundary condition of the problem.

3. Fractured or Fractured-Porous Media

Equation (7) may either pertain to a volume element that may consist of porous material or a fracture or a fictitious porous material representing a

a fractured porous medium according to certain assumptions. In the case of a volume element representing a fracture, the absolute permeability k may be computed by the following empirical relation between permeability and fracture aperture,

$$k = \frac{b^2}{12} \tag{8}$$

where b is the aperture of the fracture. As for the deformation term occurring in M_c [equation 6], a_v will represent, in some fashion, the stiffness of the fracture.

Thus, equation (7) is fairly general and can be practically applied to fractured or fractured porous media in respect of transient fluid flow. Nonetheless, it must be mentioned here that if the main feature of interest is the nature of the deformation of of the fracture itself, rather than fluid flow, one may have to consider a detailed stress analysis of the fracture, which is beyond the scope of (7).

4. The Differential Equation

As will be seen later, from a numerical modeling point of view, (7) is ideally suited as a general governing equation. Indeed, one can proceed directly from (7) to construct a variety of mathematical models (Narasimhan, 1978) to solve problems involving complex geometry. Yet, the general practice in the literature is to state physical processes as differential equations. Hence, it is appropriate here to establish the relationship of (7) to the differential equation.

Note that if the deformable volume element is defined to have a constant volume of solids, its bulk volume is constantly changing. Assume that the average bulk volume of the element during a small interval of time is represented by $\overline{V}$. Then, multiplying and dividing both sides of (7) by $\overline{V}$, we get,

$$\frac{\rho_w G_v}{\overline{V}} + \frac{1}{\overline{V}} \int_\Gamma \rho_w \frac{k\rho_w g}{\mu} \nabla (z + \psi) \cdot \overline{n} \, d\Gamma = \frac{M_c}{\overline{V}} \frac{D\psi}{Dt} \tag{9}$$

If we now consider that $\overline{V} \to 0$ in the limit and define new quantities, $g_v = G_v/\overline{V}$, $M_c/\overline{V} = m_c$,

then

$$\rho_w g_v + \text{div}\left[\rho_w \frac{k\rho_w g}{\mu} \nabla (z + \psi)\right] = m_c \frac{D\psi}{Dt} \tag{10}$$

in which, by definition,

$$\text{div}\,\vec{A} = \lim_{\bar{V}\to 0} \frac{1}{\bar{V}} \int_{\Gamma} \vec{A} \cdot \vec{n}\, d\Gamma \tag{11}$$

The term m_c may be termed "specific fluid mass capacity." In groundwater literature, density variations of water are usually neglected and the conservation equation is written in terms of volume, rather than mass. In this connection, the term S_s, specific storage, is often used instead of m_c.

In view of (6) it is easy to see that

$$S_s = \frac{M_c}{\bar{V}\rho_w} = \frac{V_s}{\bar{V}} \left[e\rho_w \beta g + \gamma_w a_v\right]$$

$$= \frac{\rho_w g}{1 + e} \left[e\beta + a_v\right] \tag{12}$$

However, since $n = \frac{e}{1 + e}$ and $\frac{1}{1 + e} = (1 - n)$

we can finally write,

$$S_s = \rho_w g \left[n\beta + (1 - n)a_v\right] \tag{13}$$

If we now divide (10) through by ρ_w, and recognize that $Dz/Dt = 0$, then (10) simplifies to the well known partial differential equation of transient groundwater flow,

$$g_v + \text{div}\,[K\nabla\phi] = S_s \frac{D\phi}{Dt} \tag{14}$$

where $K = k\rho_w g/\mu$ and $\phi = (z + \psi)$.

5. Numerical Implementation

The task of numerical simulation basically consists in dividing the flow region of interest into appropriate volume elements and to apply to each of these volume elements, the general integral equation (7), duly taking into account the boundary conditions and the initial conditions of the system. Depending on how the volume elements are defined and how the gradient within

the integrand in (7) is computed, numerical methods can be divided into three broad groups.

The oldest and the most widely known of these is that of finite differences. In the context of equation (7), the finite difference scheme is equivalent to dividing the flow region into volume elements bounded by surfaces normal to the axes of the global coordinate system and evaluating the gradient at the interface as the ratio of difference in head between the nodes on either side of the interface and the distance between them.

In the finite element approach, which has come into considerable prominence over the past decade, the volume elements are defined implicitly by a scheme of weighted volume integration (Narasimhan and Witherspoon, 1976; Narasimhan, 1978), while potential gradients are evaluated by first writing an expression for the variation of potential in the general multidimensional space and then evaluating the derivatiives of this expression at any given point and direction in the flow region.

Inasmuch as the finite difference approach seeks to directly evaluate the differential equation by approximations, it is constrained by the need for regularly shaped volume elements. This constraint is often inconvenient when one has to handle arbitrarily heterogeneous systems with complex geometry. It can easily be overcome, however, by directly considering an integral governing equation such as (7) or its equivalent instead of the differential equation. An advantage of the finite element approach, which employs a volume integral equivalent of (7), is that it can handle volume elements of arbitrary shape. Moreover, the multidimensional technique of measuring potential gradients in the finite element method also enables one to handle those cases in which k may be an arbitrarily oriented tensor.

There is yet another integral method called the Integrated Finite Difference Method (IFDM) (Narasimhan and Witherspoon, 1976), in which the volume elements are explicitly defined and to which (7) is directly applied. For gradient computations, this method uses the simple finite difference approach. This simple but powerful method can handle complex geometry with great facility and can handle multidimensional nonlinear problems with ease. In conceptual comparison, finite element method has better ability to handle arbitrary tensors than the IFDM. However, extension of the finite element method to three dimensions may be somewhat cumbersome. On the other hand, the IFDM is very convenient for three-dimensional problems in which the

coefficients may vary with time.

Actually the classical finite difference approach is a special case of the IFDM. When regularly shaped volume elements are chosen in the IFDM, the resulting numerical equations are identical with the finite difference equations.

A question that is often asked is how one might choose from the three different approaches that are available. Since the finite difference approach can always be applied as a special case of the IFDM, there are only two general approaches to choose from, the finite element, and the integrated finite difference approaches. However, the question of choice is in actuality inappropriate. Since each of the methods has special advantages, the perferred course is to have both methods available on hand and to use the one that is most convenient for the specific class of problems to be solved.

6. Hydrological Models at LBL

A suite of mutually related mathematical models are currently available at the Lawrence Berkely Laboratory to simulate heat and mass transfer in groundwater systems. Of these, those that are of relevance to Pasco Basin hydrology relate to flow of water in saturated-unsaturated deformable groundwater systems. As was pointed out in the last section, integral techniques offer greater flexibility and power in modeling complex systems than the differential techniques. For this reason, all the LBL models are based on the integral approach. In particular, all except one of the models are based on the Integrated Finite Difference Method (IFDM), while the remaining employs the Finite Element Method (FEM). We will now briefly discuss some of the esssential features of these approaches and how they are incorporated into the computational algorithms.

7. The IFDM and the FEM Concepts

The theme of the integral numerical approach is to divide the flow region into appropriately small subdomains and apply the mass conservation equation (7) to each such element, assuring compatibility between adjoining elements. Thus, modeling involves two basic tasks: a) describing the size and shape of each volume element and its relationship to its neighbors and b) quantitatively evaluate the gradient in fluid potential at the interface between neighboring elements.

In the IFDM, each volume element is directly described by stating its volume and the area of the surfaces bounding it and by identifying each pair of communicating neighbors. For maximum accuracy in evaluating the integrand in (7), the volume elements are so defined and their representative nodal points so chosen that the line joining the nodal points is perpendicular to the surface element in between the nodes. As for measuring gradient of fluid potential, the simple concept of finite differences is used.

In the FEM on the other hand, the nodal points are first conveniently distributed over the flow region and the volume element associated with each nodal point is then indirectly defined as a fraction of a larger subregion formed by lines joining neighboring nodal points, through a process of weighted integration (Narasimhan and Witherspoon, 1976; Narasimhan, 1978). In In order to measure gradients of potential, the FEM takes a generalized approach which is far more powerful than the finite difference concept. In this generalized approach, the variation of potential is first defined over a "finite" element which may be one-, two-, or three-dimensional. The gradient of potential at any point and in any desired direction within the finite element is then evaluated by differentiating the defined variation of potential over the finite element.

At this juncture, it is pertinent to briefly describe the FEM. For the sake of comparison with the IFDM and for the sake of clarity, we will derive the FEM equations from the IFDM governing equation (7).

First, apply the divergence theorem to the surface integral in (7) and express that equation in an equivalent volume-integral form

$$G_V + \int_V \nabla \cdot \kappa \nabla \phi \, dv = VS_s \frac{D\phi}{Dt} \tag{15}$$

Now, distribute a conveniently large number of nodal points over the flow region of interest and partition the region into subregions by joining adjacent nodal points through lines. For purposes of illustration, let us consider a flow region which is divided into a number of triangular subregions as shown in Figure IV-1. Let there be N nodal points in the flow region. Consider, for purposes of illustration, a nodal point designated by ℓ. In Figure IV-1 this nodal point lies at the apex of seven triangular elements.

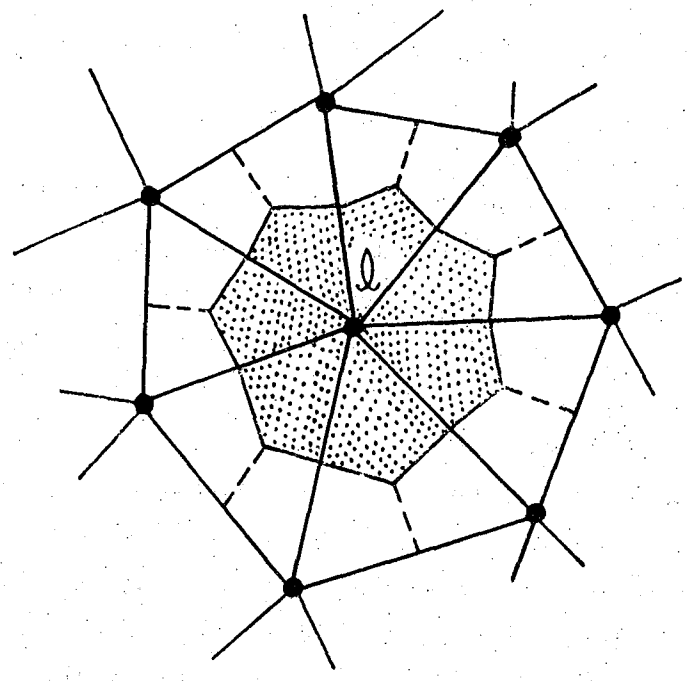

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Figure IV-1. A representative nodal point ℓ and its neighbors in a flow region divided into a number of triangular finite elements. Stippled area is the subregion associated with nodal point ℓ.

Within each of these triangles the potential varies at any given instant in time according to the relation

$$\phi^e(x,y) = \xi_\ell(x,y)\,\phi_\ell(t) + \xi_2(x,y)\,\phi_2(t) + \xi_3(x,y)\,\phi_3(t)$$
$$= \xi_i(x,y)\,\phi_i(t),\ i = \ell,\ 2,\ 3 \tag{16}$$

in which $\phi^e(x,y)$ denotes the potential at any point within the element e, $\xi_i(x,y)$ is a weighting function for point i, and $\phi_i(t)$ is the potential at point i at the instant t. The function ξ_i is such that at any point within e, $\xi_\ell + \xi_2 + \xi_3 = 1$. In (16) the repetition of i implies summation over $i = \ell$, 2, and 3. Also, the subscripts 2 and 3 denote the other two nodal points besides ℓ of element e.

Now, if we wish to apply the mass conservation equation in (15) to the volume element associated with ℓ in figure IV-1, the region of integration V should represent the stippled region in the figure. However, it is easy to see that the stippled region actually forms a fractional part of the larger region made up of the seven triangles and shown by the heavy line surrounding nodal point ℓ. If we wish to apply (15) to the subregion associated with ℓ, we could evaluate the volume integral by a process of weighted integration within each element ℓ and summing up the results for all the seven elements associated with ℓ. Thus, in the light of (16), equation 15 as applied to Figure IV-1 can be written as,

$$G_{v,\ell} + \sum_{e=1}^{7} \int_{V^e} w_\ell\ \nabla\cdot k\nabla\xi_i\phi_i\ dV = \left(\sum_{e=1}^{7} \frac{1}{3} V^e\ S_s^e\right)\frac{D\phi_\ell}{Dt} \tag{17}$$

where $w_1(x,y)$ is the weighting function for node 1 and $V_1 = \sum_{e=1}^{7} \frac{1}{3} V^e$, where V^e is the volume of element e.

We now have to choose an appropriate weighting function. Since w_1 associates a portion of the divergence (or the rate of accumulation of fluid within an elemental volume element dV) with nodal point ℓ, it can be seen that $w_1 = 1$ at the location of nodal point ℓ. $w_\ell = 0$ at points located on the side opposite point ℓ in each of the seven elements. Also, it is reasonable to assume that w varies uniformly (linearly) from ℓ at 1 to zero along the sides zero along the sides meeting at ℓ. As it happens, the weighting function ξ_ℓ in

(16) exactly satisfies this requirement for w_ℓ. Hence we can conveniently let $w_\ell = \xi_\ell$ in (17) and write

$$G_{v,\ell} + \sum_{e=1}^{7} \int_{V^e} \xi_\ell \; \nabla \cdot k \nabla \xi_i \phi_i \; dV = \left(\sum_{e=1}^{7} \frac{1}{3} V^e \; S_s^e \right) \frac{D\phi_\ell}{Dt} \tag{18}$$

Equation (18) is indistinguishable from the Galerkin finite element equations (Neuman, 1975) that are conventionally derived from the differential equation.

In order to actually implement (18), Green's first identity of the form

$$\int_V a \nabla^2 b dV = \int_\Gamma a \nabla b . n d\Gamma - \int_V \nabla a . \nabla b dV \tag{19}$$

is first applied to the volume integral in (18) to obtain

$$G_{v,\ell} - \sum_{e=1}^{7} \int_{V^e} \nabla \xi_\ell . k \nabla \xi_i \phi_i \; dV + \sum_{e=1}^{7} \int_{\Gamma^e} \xi_\ell k \nabla \xi \phi . n d\Gamma = \left(\sum_{e=1}^{7} \frac{1}{3} \; V^e S_s^e \right) \frac{D\phi_\ell}{Dt} \tag{20}$$

In (20) the surface integral embodies all the boundary conditions that are known by definition. A major portion of the effort in FEM therefore centers around evaluating the volume integral in (20). Compare this with the surface integral to be evaluated in (7) for the IFDM.

From a practical viewpoint the IFDM is intrinsically multidimensional and the problem is defined locally around each nodal point. A global coordinate system is not a prerequisite for setting up the problem. To this extent the IFDM emphasizes the invariant physics of the problem. However, the IFDM does demand an explicit definition of the size, shape and bounding surfaces of each volume element, which may require additional effort. Nevertheless, the additional effort can be very profitable since the computation of volumes and surface areas can be calculated as accurately as needed, outside the mainstream of the flow calculation, and can be provided as input data to the latter.

8. Discretized Equations

Apart from the previously described conceptual peculiarities, there are other aspects of numerical modeling which are common to the IFDM as well as

the FEM. The first of these is the act of advancing in time, and the second is the manner of solving a set of simultaneous equations.

Both the IFDM and the FEM (Narasimhan et al., 1978; Neuman and Narasimhan, 1976) lead to a set of discretized equations of the form,

$$G_{v,\ell} + \sum_{\substack{e \\ \ell \neq m}}^{7} U_{\ell,m} \left(\phi_m - \phi_\ell\right) + \sum_{b} U_{\ell,b} \left(\phi_b - \phi_\ell\right) = V_\ell S_{s_\ell} \frac{\Delta\phi_\ell}{\Delta t} \tag{21}$$

ℓ, $m = 1, 2, 3, \ldots N$, where N is the total number of volume elements in the flow region. In (21) $U_{\ell,m}$ denotes the fluid conductance between the volume element ℓ and internal elements m; $U_{\ell,b}$ denotes the fluid conductance between volume element ℓ and the boundary element b. The "conductance" between two volume elements is defined as the quantity of fluid per unit time crossing the interface between the element when the difference in fluid potential between the elements is unity.

If we define $U_{\ell,m} = 0$ and $U_{\ell,b} = 0$ for all elements m and b not connected to ℓ, then (21) can be conveniently written as a matrix of equations,

$$\sum_{\ell \neq m} U_{\ell,m} \phi_m - \left(\sum_{\ell \neq m} U_{\ell,m} + \sum_{b} U_{\ell,b}\right) \phi_\ell = -G_{v,\ell} + V_\ell S_{s_\ell} \frac{\Delta\phi_\ell}{\Delta t} \tag{22}$$

Or, if we define

$$U_{\ell\ell} = -\left(\sum_{\ell \neq m} U_{\ell,m} + \sum_{b} U_{\ell,b}\right) \tag{23}$$

and

$$D_{\ell m} = \left(\frac{-G_{v,\ell} + V_\ell S_{s\ell}}{\Delta t}\right) \delta_{\ell m} \tag{24}$$

where

$$\delta_{\ell m} = \begin{cases} 1, & \ell = m \\ 0, & \ell \neq m, \end{cases}$$

then, (22) can be summarized as

$$[U]\ \{\phi\} = [D]\ \{\Delta\phi\} \tag{25}$$

9. Advancing in the Time Domain; Explicit and Implicit Equations.

Consider (21), which is fundamental to both the IFDM and the FEM. The quantity of interest that needs to be computed using this equation is $\Delta\phi_\ell$. Of

the other quantities in the equation, $G_{v,\ell}$ is the a priori known source term; $U_{\ell,m}$, V_ℓ and S_{s_ℓ} are known from material properties and $U_{\ell,b}$ is known from the boundary conditions. The quantities ϕ_m and ϕ_l are only partly known in that only their inital values ϕ_m^o and ϕ_l^o are known a priori. In order that $\Delta\phi$ may be evaluated using (21), we have to use $\overline{\phi}_m$ and $\overline{\phi}_\ell$ which are appropriate mean values of ϕ_m and ϕ_ℓ over the time interval Δt. Thus, we define

$$\overline{\phi}_m = \phi_m^o + \lambda\Delta\phi_m \tag{26a}$$

$$\overline{\phi}_\ell = \phi_\ell^o + \lambda\Delta t,\ 0 \leq \lambda \leq 1 \tag{26b}$$

Substituting (26a), (26b) into (21) and rearranging

$$\frac{\Delta_t}{V_\ell S_{s_\ell}}\left[G_{v,\ell} + \sum_{\substack{m \\ \ell \neq m}} U_{\ell_m}\left(\phi_m^o - \phi_m^o\right) + \sum_b U_{\ell,b}\left(\phi_b - \phi_\ell^o\right)\right]$$

$$+ \frac{\lambda\Delta_t}{V_\ell S_{s_\ell}}\left[\sum_{\substack{m \\ \ell \neq m}} U_{\ell_m}\left(\phi_m^o - \Delta\phi_\ell\right) - \sum_b U_{\ell_b}(\Delta\phi_\ell)\right] = \Delta\phi_\ell \tag{27}$$

If λ is set to zero, then (27) reduces to

$$\frac{\Delta_t}{V_\ell S_{s_\ell}}\left[G_{v,\ell} + \sum_{\substack{m \\ \ell \neq m}} U_{\ell_m}\left(\phi_m^o - \phi_\ell^o\right) + \sum_b U_{\ell,b}\left(\phi_b - \phi_\ell^o\right)\right] = \Delta\phi_{\ell,\ \text{explicit}} \tag{28}$$

Note in (28) that all the quantities on the left hand side are a priori known and hence $\Delta\phi_\ell$ is explicitly computed in a simple fashion. Hence (28) is an explicit (also called forward differencing) equation.

As pointed out by Narasimhan and Witherspoon (1976), (28) will become unstable and yield physically unrealistic estimates of $\Delta\phi_\ell$ if Δt exceeds a critical value with reference to the volume element. This critical value Δt_ℓ is called the stable time step or time constant of volume element ℓ. It can be shown that

$$\Delta t_\ell = \frac{V_\ell S_{s_\ell}}{\left(\sum_{\substack{m \\ \ell \neq m}} U_{\ell,m} + \sum_b U_{\ell,b}\right)} \tag{29}$$

If one desires to use an arbitrarily large Δt and still obtain realistic solutions, then, $\lambda \geq 0.5$. Customarily, $\lambda = 0.5$ is called the "central differencing" scheme while $\lambda = 1$ is called the backward differencing scheme.

Note from (27) that when $\lambda > 0$, $\Delta\phi_\ell$ occurs on both sides of the equation and hence (2b) is an implicit equation. The set of implicit equations constitute a set of simultaneous equations which has to be appropriately solved for the $\Delta\phi_\ell$'s.

10. Mixed Explicit-Implicit Scheme

Since, from (29), Δt_ℓ is a local criterion involving ℓ and its immediate neighbors it follows (Edwards, 1968) that one could compute $\Delta\phi_\ell$ explicitly for all those volume elements for which $\Delta t_\ell > \Delta t$ and implicitly for all those volume elements for which $\Delta t_\ell \leq \Delta t$. This is the mixed explicit-implicit approach which is followed in the IFDM as well as the FEM computer programs at LBL used for hydrological modeling.

Moreover, it can be shown (Narasimhan et al., 1978) that for maximum accuracy λ should be close to 0.5 when the time derivative of ϕ_1 is varying more or less uniformly with time and λ should be close to 1 when the system is approaching steady state and large Δt's are being used. Hence, in the LBL models λ is computed internally within the program for each time step such that $0.57 \leq \lambda \leq 1.0$. The value of 0.57 is used as the lower limit to damp out stable oscillations that may sometimes arise when $\lambda = 0.5$.

11. Iterative Solution Scheme

A system of simultaneous equations such as (27) or (25) can be solved either by direct methods or indirect methods. Among the direct methods one could mention: methods involving the use of determinants; methods involving matrix inversion; and methods involving successive elimination of unknowns. In the field of groundwater hydrology the most widely used direct technique is perhaps the method involving the successive elimination of variables, of which many variants exist. While the direct approaches provide a number of advantages, their chief disadvantage is that when there are a large number of mesh points over the flow region, the computer storage requirements become large. This is particularly inconvenient in large two-or-three-dimensional problems.

While improved matrix-solving programs are being developed by different workers to overcome this difficulty, an alternate way to avoid the major

disadvantage of the direct approach is to solve the equations by indirect techniques.

The LBL models, both IFDM and the FEM, employ an indirect, accelerated iterative scheme sugggested by Evans et al. (1954). Briefly, the accelerated iterative scheme consists of making the following substitutions in (27):

$$\Delta\phi_\ell, \text{ left hand side} \rightarrow (1 + s)\ \Delta\phi_\ell^{k+1} - s\Delta\phi_\ell^{k} \tag{30a}$$

$$\Delta\phi_\ell, \text{ left hand side} \rightarrow \Delta\phi_m^{k} \tag{30b}$$

$$\Delta\phi_\ell, \text{ right hand side} \rightarrow \Delta\phi_\ell^{k+1} \tag{30c}$$

where k, k + 1 denote iteration number and s is the acceleration factor, empirically found to be optimal when s = 0.2.

In the light of (28) and (30), equation 27 can be written as

$$\Delta\phi_{\ell,\text{ explicit}} + \frac{\lambda\Delta t}{V_\ell S_{s_\ell}}\left[\sum_{\substack{m,\\ \ell\neq m}} U_{\ell,m}\left(\Delta\phi_m^{k} - \left[(1+s)\Delta\phi_\ell^{k+1} - s\Delta\phi_\ell^{k}\right]\right) - \sum_b U_{\ell,b}\left(\left[1+s\right]\Delta\phi_\ell^{k+1} - s\Delta\phi_\ell^{k}\right)\right] = \Delta\phi_\ell^{k+1} \tag{31}$$

Collecting similar terms and rearranging we can finally write an expression of $\Delta\phi_\ell$ at the (k+1) iteration in terms of the values of $\Delta\phi_\ell$ and $\Delta\phi_m$ at the the kth iteration as

$$\Delta\phi_\ell^{k+1} = \Delta\phi_{\ell,\text{ explicit}} + \frac{\lambda\Delta t}{V_\ell S_{s_\ell}}\left\{\sum_{\substack{m\\ \ell\neq m}} U_{\ell,m}\,\Delta\phi_m^{k} + s\Delta\phi_\ell^{k}\left(\sum_{\substack{m\\ \ell\neq m}} U_{\ell,m} + \sum_b U_{\ell,b}\right)\right\} - \Delta\phi_\ell^{k+1}\left[(1+s)\left(\sum_{\substack{m\\ \ell\neq m}} U_{\ell,m} + \sum_b U_{\ell,b}\right)\right] \tag{32}$$

To start the iteration process, that is, $\kappa = 0$, one has to use judiciously estimated values for $\Delta\phi_m^{o}$ and $\Delta\phi_\ell^{o}$ and continue the iteration process using (32) until the maximum change in $\Delta\phi_\ell$ between two successive iterations

$$\left|\Delta\phi_\ell^{k+1} - \Delta\phi_{\ell\ \max}^{k}\right|$$

is less than any desired error tolerance. For fuller details of the iteration scheme see Narasimhan et al. (1978).

12. Description of LBL Computer Programs

For simulating isothermal groundwater systems, there are currently three computer programs available at LBL. Two of these, TRUST and TERZAGI are based on the IFDM concept while the third, FLUMP, is based on the FEM approach.

All three programs can handle flow regions of complex geometry, arbitrary heterogeneity, arbitrary initial conditions and time- or potential-dependent boundary conditions and sources. The TRUST and TERZAGI codes can both handle one-, two- or three-dimensional problems while the FLUMP code handles one- or two-dimensional or axi-symmetric flow regions. Whereas TRUST and TERZAGI can only handle anisotropy in a limited fashion by orienting the volume elements in conformity with the principal axes of anisotropy, FLUMP can handle arbitrarily oriented anisotropy.

TRUST is a very general program and can simulate saturated-unsaturated flow in deformable porous media. In dealing with the storage term, TRUST separately computes the parameters due to expansion of water, deformation of the soil skeleton and desaturation of pores. TERZAGI is a simplified subset of TRUST which handles only unsaturated flow. FLUMP handles saturated unsaturated flow but does not handle soil deformation in detail. All the three programs handle porous media flow and can also handle flow in fractured porous media or fractured media. The validation of the TRUST and TERZAGI models are presented in Narasimhan and Witherspoon (1976; 1978). All three programs can easily handle effects of wellbore storage, damage to the formation permeability around a well or cavity, effect of fractures with aperture-dependent permeability and so on. Although the fracture flow results have not yet been published, the validity of the three methods in respect of handling wells intercepting finite and infinite conductivity fractures has already been tested by comparison with known analytical and semi-analytical solutions. The aforesaid programs are all written in FORTRAN IV language and are fully operational on the CDC 6400, 6600, and 7600 systems. A summary of the three computer programs is presented in Table IV-1.

13. Improvement Needs for LBL Models

The numerical modeling capabilities currently available at LBL are quite significant and it is fair to say that the computing ability exceeds

TABLE IV-1

SUMMARY OF LBL HYDROLOGY MODELS

Program Name	Dimensionality	Concept	Summary of Capabilities
TRUST	one-, two-, or three-dimensional	IFDM	Saturated-unsaturated flow in deformable systems; porous or fractured-porous media; complex geometry; arbitrary heterogeneity; limited anisotropy; time-dependent boundary conditions or sources; one-dimensional deformation.
TERZAGI	one-, two-, or three-dimensional	IFDM	Same as TRUST, but limited to purely saturated flow.
FLUMP	one- or two- dimensional; axi-symmetric	FEM	Same as TRUST, but no deformation. Arbitrary anisotropy.

our ability to collect field data to adequately quantify the field phenomena. If suitable data were forthcoming from the field, the available models can indeed predict the system response under various scenarios of boundary conditions, sources, and initial conditions.

A limitation of the current LBL models is that they all are intrinsically deterministic. As has already been pointed out at the beginning of this chapter, the flow system parameters can not be known with certainty. Confidence limits on the potential range of system response must be provided for the decision-making process.

Therefore, an important capability which would improve the LBL models would be the accomodation of statistically expressed input parameters such as the mean values and variance of permeability distributions and the statistical expression of output parameters indicating mean system behavior and its variance. With this view in mind, a literature search has been made to understand the current state of knowledge in regard to incorporating uncertainty into numerical models.

The importance of uncertainty in hydrological models has been considered by Freeze (1975); Tang and Pinder (1977); Cooley (1977); Gelhar (1974); McMillan (1966), Neuman et al. (1976); and Warren (1961). These workers consider the parameters such as permeability and storativity occurring in the governing equations as stochastic or random variables with some mean value and with certain variance and distribution about the mean. How these statistical quantities can influence the final result can be quantitatively investigated either by generating a large number of solutions using Monte Carlo type simulations (Freeze, 1975) or could be studied by solving a "stochastic" differential equation (Tang and Pinder, 1977). Examination of available literature indicates that the subject of quantification of uncertainty in numerical models is still in its infancy and needs further intense study. From the point of view of the Hanford project, it should be very profitable to devote effort towards incorporating stochastic parameters into the LBL models.

D. NUMERICAL ANALYSIS OF WELLBORE STORAGE EFFECTS

Numerical modeling techniques were used to aid in planning and analyzing well tests on the Hanford Reservation. Two-well tests were studied because

three sets of paired wells (DC-1/DC-2, DC-4/DC-5, and DC-7/DC-8) were available. These paired wells offered the opportunity to measure response to pumping in an observation well. Problems with wellbore storage were expected in running and analyzing these tests due to the low permeability of some of the basalt units. When wellbore storage effects are significant the early part of the drawdown data only reflects removal of water from the well. Until this effect is overcome the log-log drawdown vs. time curve as measured in the pumping well has a unit slope and a measurement of permeability cannot be made. The lower the permeability, the longer it will take to overcome wellbore storage effects.

Currently available techniques for the analysis of response in an observation well do not include the effects of wellbore storage in the pumping well. Numerical analysis was used to address these two problems: (1) how long would it take to get a response in an observation well, and (2) what is the effect of wellbore storage on the drawdown data in an observation well?

Two types of well tests were considered. The first was a simple pumping test and the second was a leaky aquifer test. The leaky aquifer test offers the opportunity to measure the vertical permeability of a lower permeability layer overlying or underlying the higher permeability layer being sampled by measuring drawdown in both layers simultaneously.

The LBL groundwater flow program TERZAGHI was used for both problems. The mesh used is shown in Figure IV-2. The aquifer nodes are numbered 1000 and 1 through 40. The aquitard nodes have 3 digit numbers. The well is node 1000. For the first problem, that of observation well response in a simple pumping test, all aquitard nodes were eliminated.

The results of the numerical analysis are as follows:

(1) Observation well response in an aquifer pumping test with wellbore storage. Parameters used in the model are given in Table IV-2. Permeability values were chosen as representative of Lower Yakama Basalt Flows (ARH-SF-137, p. 89, Table V).

The drawdown curves obtained are shown in Figures IV-3 to IV-7. The curves approach the Theis solution as radius from the well decreases and dimensionless storage parameter α, increases. The real time necessary to obtain a response in the observation well increases with an increase in wellbore storage effect. That is, the required testing time increases with

Table IV-2

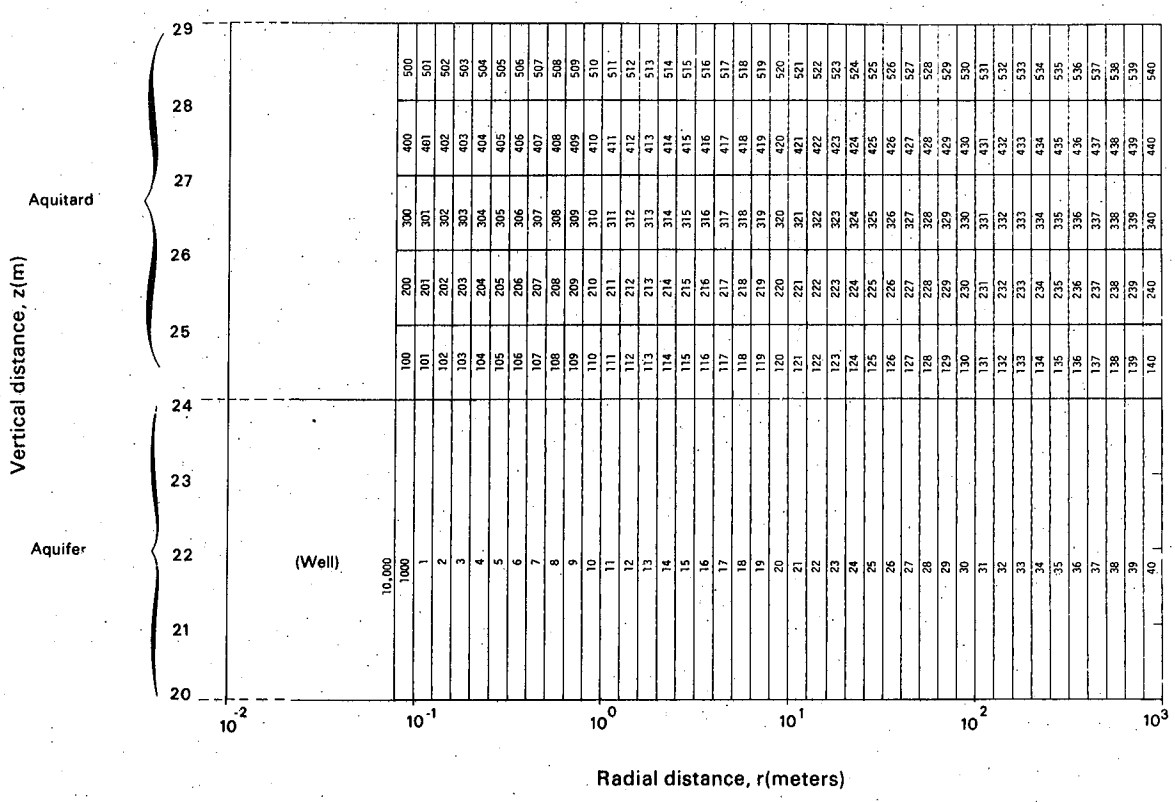
PARAMETERS USED TO ANALYZE OBSERVATION WELL RESPONSE WITH WELLBORE STORAGE

Run	Pumping Rate, Q (m^3/day)	Permeability of the Aquifer, K (m/day)	Pumping Well Radius r_w(m)	Specific Storage $S_s(m^{-1})$	Wellbore Storage Coefficient $\alpha = S_s h$ (dimensionless)	Aquifer Thickness h(m)
1	1.0	8.427×10^{-4}	.09	$.25 \times 10^{-1}$	10^{-1}	4.0
2	1.0	8.427×10^{-4}	.09	$.25 \times 10^{-2}$	10^{-2}	4.0
3	1.0	8.427×10^{-4}	.09	$.25 \times 10^{-3}$	10^{-3}	4.0
4	1.0	8.427×10^{-4}	.09	$.25 \times 10^{-4}$	10^{-4}	4.0
5	1.0	8.427×10^{-4}	.09	$.25 \times 10^{-5}$	10^{-5}	4.0

Table IV-3

PARAMETERS USED TO ANALYZE LEAKY AQUIFER/WELLBORE STORAGE

Run	Permeability of the Aquifer, K (m/day)	Permeability of the Aquitard, K′ (m/day)	Pumping Well Radius r_w(m)	Specific Storage $S_s(m^{-1})$	Wellbore Storage Coefficient, $\alpha = S_s h$ (dimensionless)	Pumping Rate, Q (m^3/day)
1	0.2025×10^{-3}	0.2025×10^{-6}	.05	$.25 \times 10^{-1}$	10^{-1}	1.0
2	0.2025×10^{-3}	0.2025×10^{-6}	.05	$.25 \times 10^{-2}$	10^{-2}	1.0
3	0.2025×10^{-3}	0.2025×10^{-6}	.05	$.25 \times 10^{-3}$	10^{-3}	1.0
4	0.2025×10^{-3}	0.2025×10^{-6}	.05	$.25 \times 10^{-4}$	10^{-4}	1.0
5	0.2025×10^{-3}	0.2025×10^{-6}	.05	$.25 \times 10^{-5}$	10^{-5}	1.0
6	0.2025×10^{-3}	0.2025×10^{-6}	.09	$.25 \times 10^{-1}$	10^{-1}	1.0
7	0.2025×10^{-3}	0.2025×10^{-6}	.09	$.25 \times 10^{-2}$	10^{-2}	1.0
8	0.2025×10^{-3}	0.2025×10^{-6}	.09	$.25 \times 10^{-3}$	10^{-3}	1.0
9	0.2025×10^{-3}	0.2025×10^{-6}	.09	$.25 \times 10^{-4}$	10^{-4}	1.0
10	0.2025×10^{-3}	0.2025×10^{-6}	.09	$.25 \times 10^{-5}$	10^{-5}	1.0
11	0.2025×10^{-3}	0.2025×10^{-6}	.1125	$.25 \times 10^{-1}$	10^{-1}	1.0
12	0.2025×10^{-3}	0.2025×10^{-6}	.1125	$.25 \times 10^{-2}$	10^{-2}	1.0
13	0.2025×10^{-3}	0.2025×10^{-6}	.1125	$.25 \times 10^{-3}$	10^{-3}	1.0
14	0.2025×10^{-3}	0.2025×10^{-6}	.1125	$.25 \times 10^{-4}$	10^{-4}	1.0
15	0.2025×10^{-3}	0.2025×10^{-6}	.1125	$.25 \times 10^{-5}$	10^{-5}	1.0



XBL 7812-13470A

Figure IV-2. Mesh used for numerical solution of wellbore storage effect.

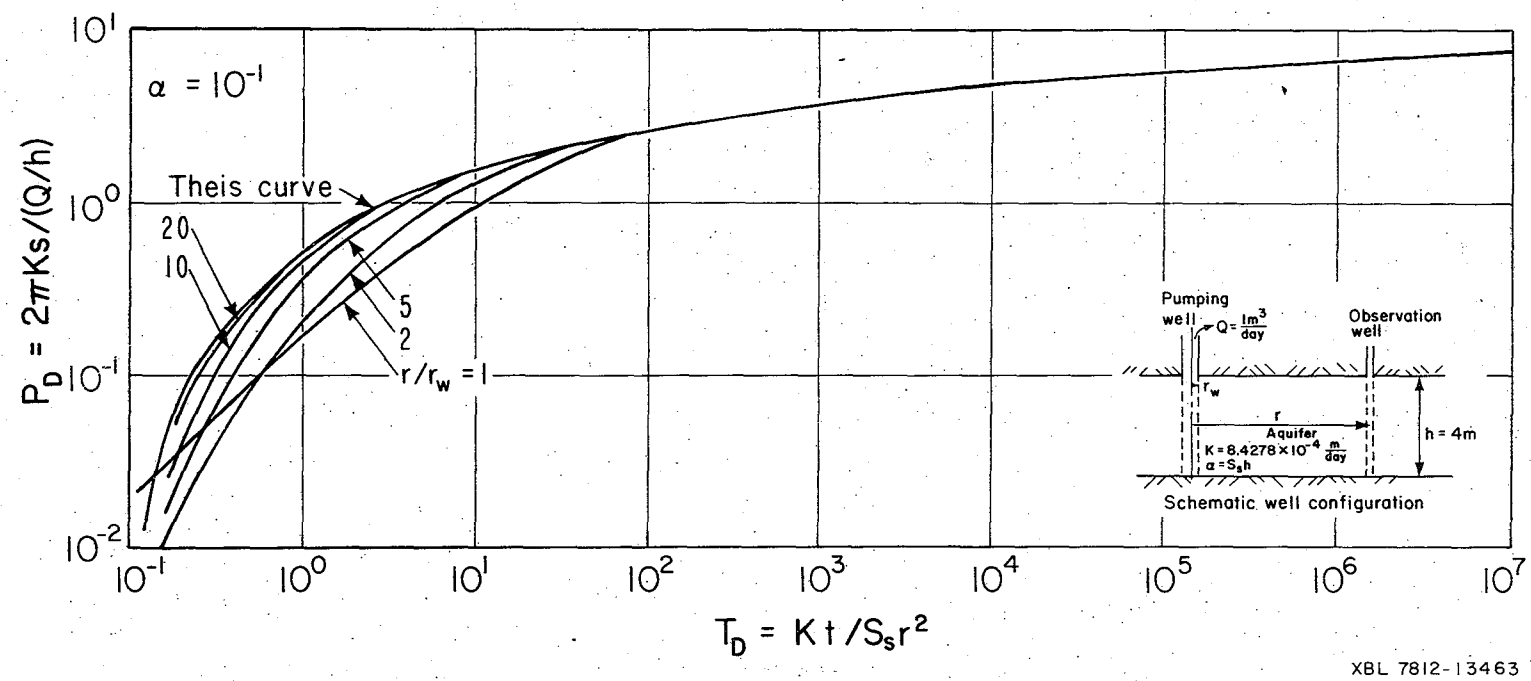


Figure IV-3. Curves for drawdown in observation wells with wellbore storage in pumping well, $\alpha = 10^{-1}$.

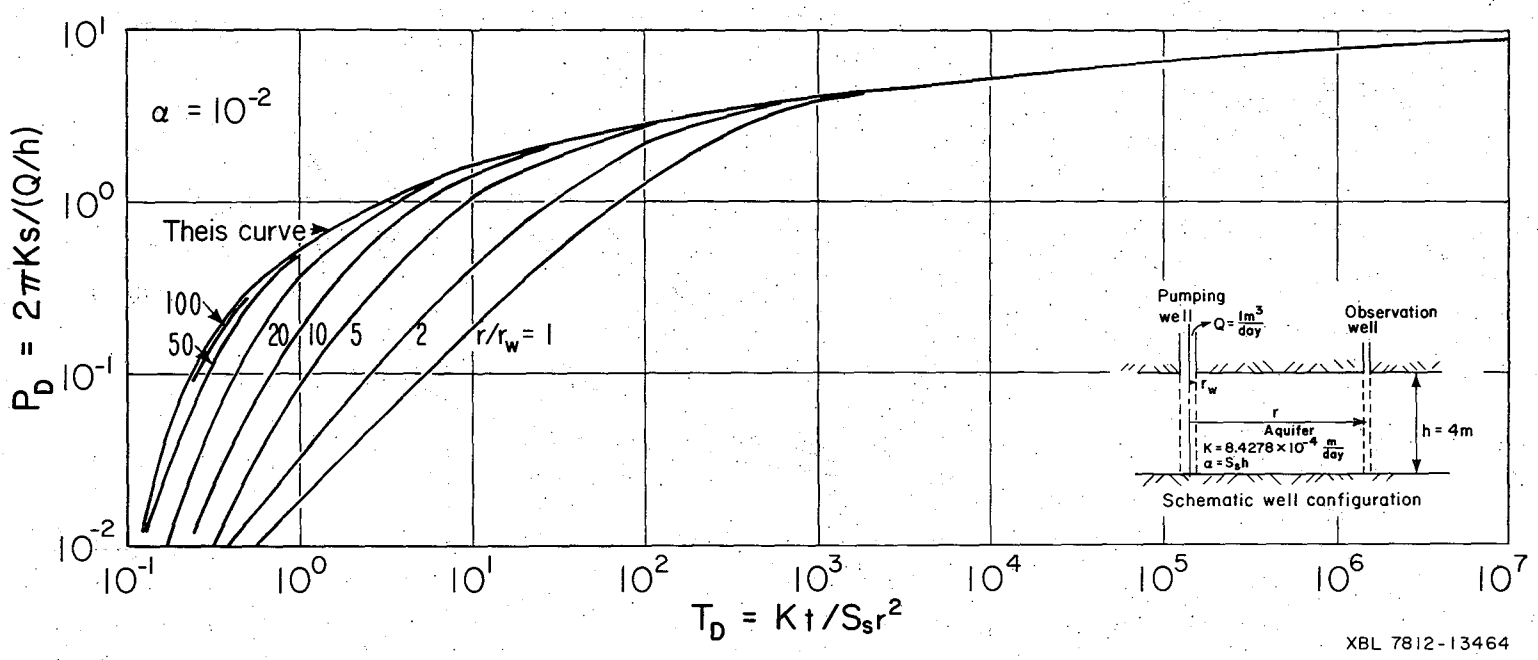


Figure IV-4. Curves for drawdown in observation wells with wellbore storage in the pumping well, $\alpha = 10^{-2}$.

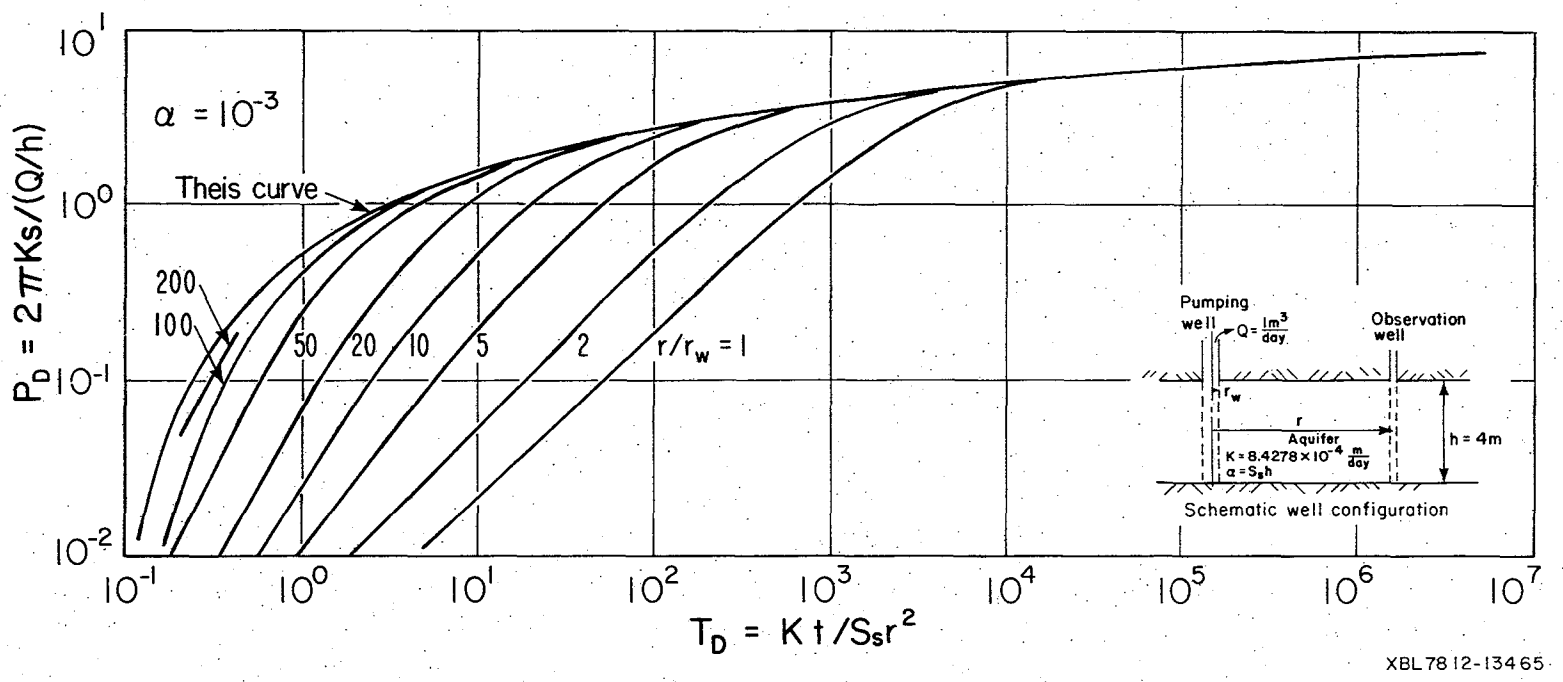


Figure IV-5. Curves for drawdown in observation wells with wellbore storage in the pumping well, $\alpha = 10^{-3}$.

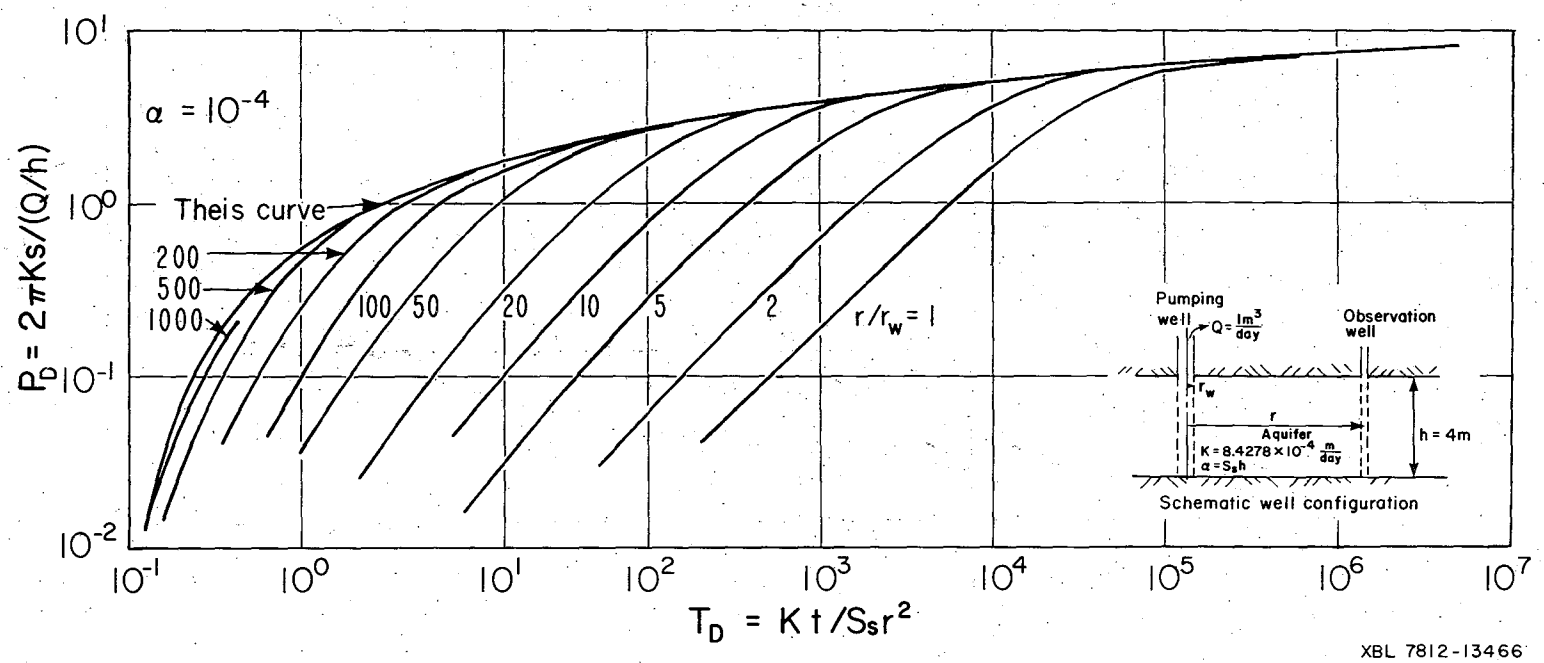
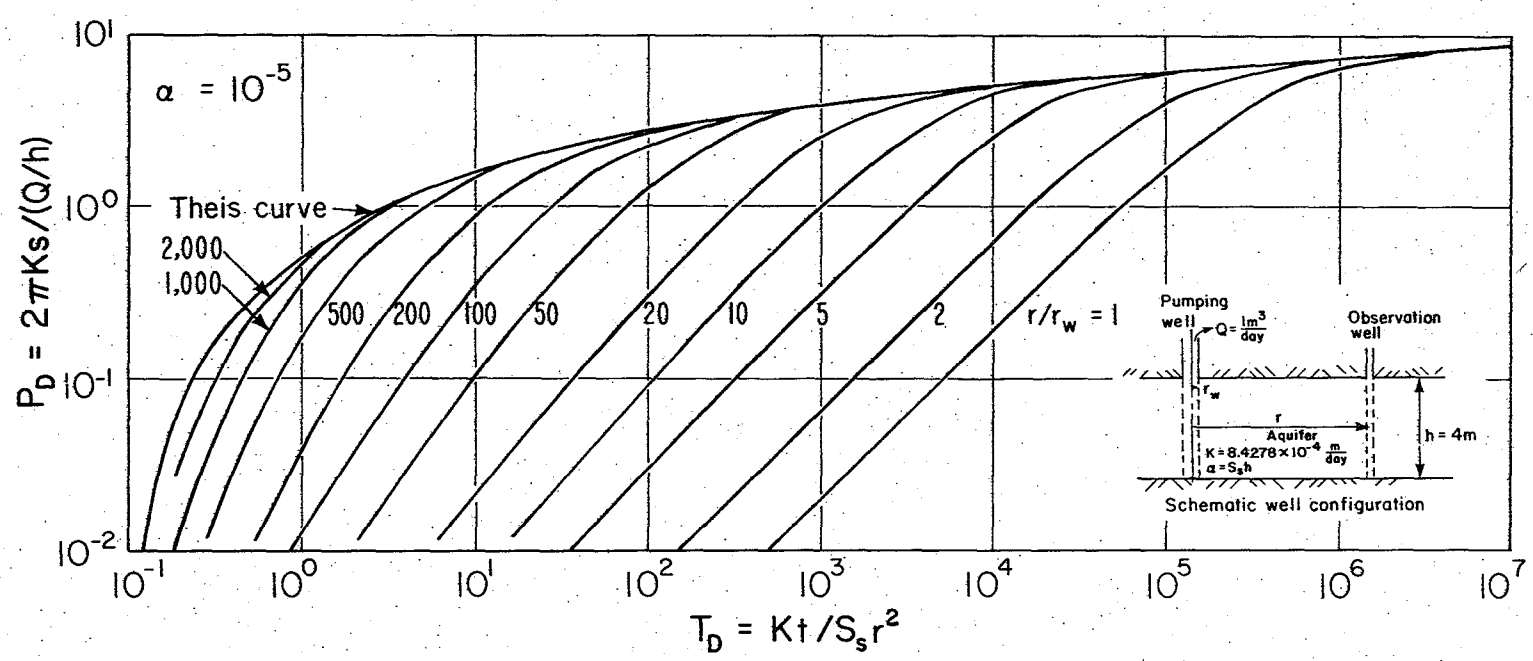


Figure IV-6. Curves for drawdown on observation wells with wellbore storage in the pumping well, $\alpha = 10^{-4}$.



XBL 7812-13462

Figure IV-7. Curves for drawdown in observation wells with wellbore storage in the pumping well, $\alpha = 10^{-5}$.

increases in well radius and distance of the observation well from the pumping well, and with decreases in storage coefficient S_s and permeability.

The curves shown in Figures IV-3 through IV-7 can be used to show that a drawdown response of 10 cm in an observation well 9 m away will be observed in less than a day for $\alpha = 10^{-5}$ and in about 2400 days for $\alpha = 10^{-1}$ for the pumping rate, permeability and geometry shown. However, for $\alpha = 10^{-5}$ the drawdown data in the observation well will not be on the Theis curve until $t \cong 120$ days. For $\alpha = 10^{-1}$ all the drawdown data for this observation well will essentially lie on the Theis curve. For lower permeabilities longer testing times than these could be needed.

(2) Leaky aquifer/wellbore storage solution.

Fifteen different cases were analyzed for times up to 100 days. Three different well radii were used each with five different values of α. Parameters used in the model are given in Table IV-3.

Figure IV-8 shows drawdown in the aquitard as r = 0.9 meters, z = 0.5 meters and t = 100 days as a function of pumping well radius and α. Response in the aquitard decreased with higher values of well radius and increase in α. The solution of $\alpha = 10^{-3}$ was chosen for comparison to the analytic solution developed by Neuman and Witherspoon (1972) (Figure IV-9). The solutions for $\alpha = 10^{-4}$ and $\alpha = 10^{-5}$ were not comparable because the top of the aquitard experienced a pressure decline within the time framework of the problem. Neuman's solution assumes an infinite aquitard and is therefore a different case. The solutions for $\alpha = 10^{-1}$ and $\alpha = 10^{-2}$ were not as good as the solution for $\alpha = 10^{-3}$ because drawdowns were very small in the aquitard and finer mesh resolutions would be required for accurate comparison with Neuman's solution.

The ratio of drawdown in the aquitard (s′) to drawdown in the aquifer (s) is plotted against wellbore radius, r_w, in Figure IV-10. Drawdown, s′, is computed for a point in an aquitard 9 meters from the pumping well and 0.5 meters from the aquifer. The parameters and geometry used are typical of what might be found in the Pasco Basin. At least 15 days of pumping will be required to get any measurable response in the aquitard for these conditions.

These models could be used for well test analysis by developing a set of type curves for the particular well radius and distance to the observation well that is actually tested.

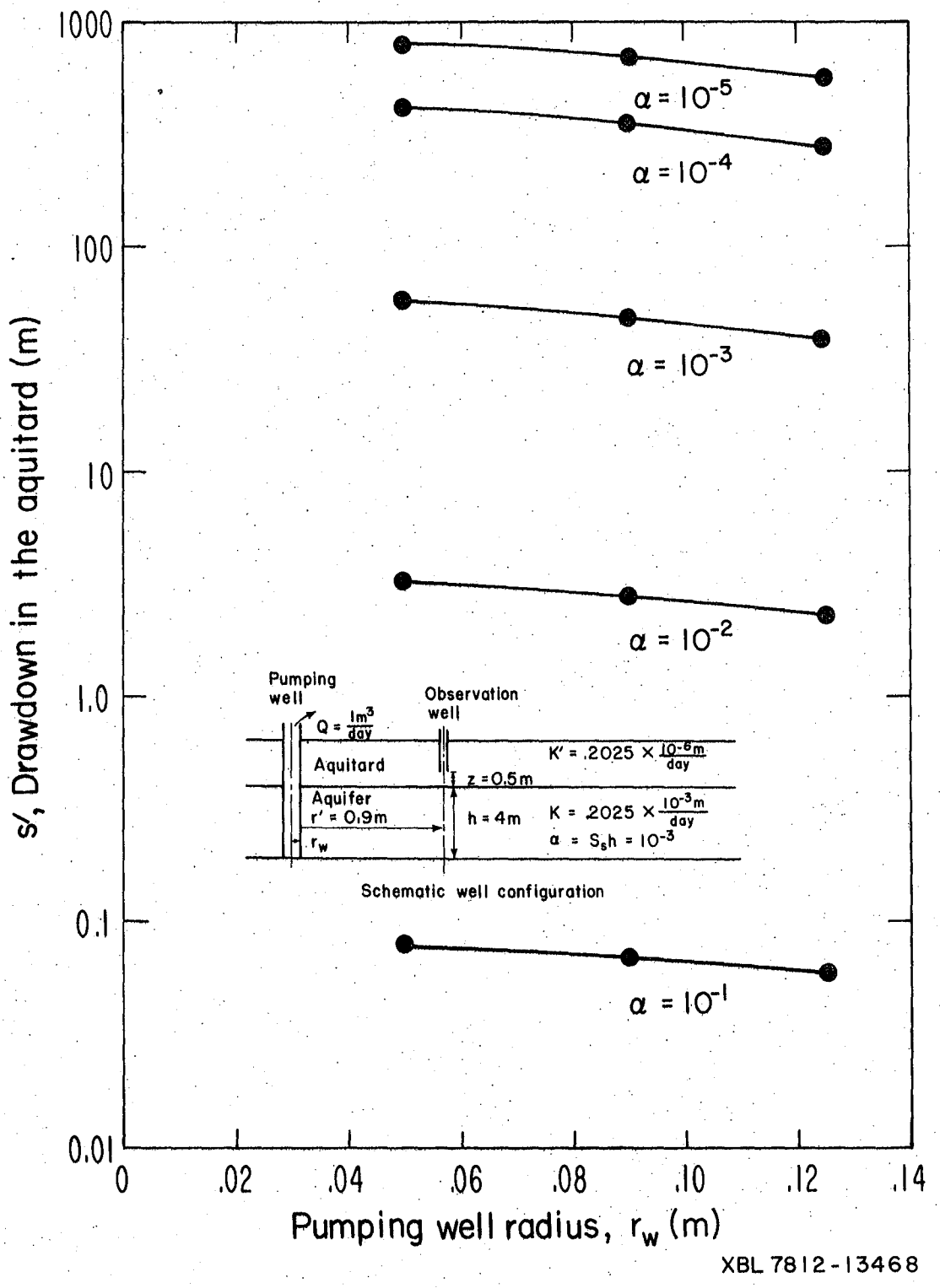


Figure IV-8.

Drawdown in the aquitard as a function of pumping well radius for various values of α at t = 100 days, r = 0.9 m.

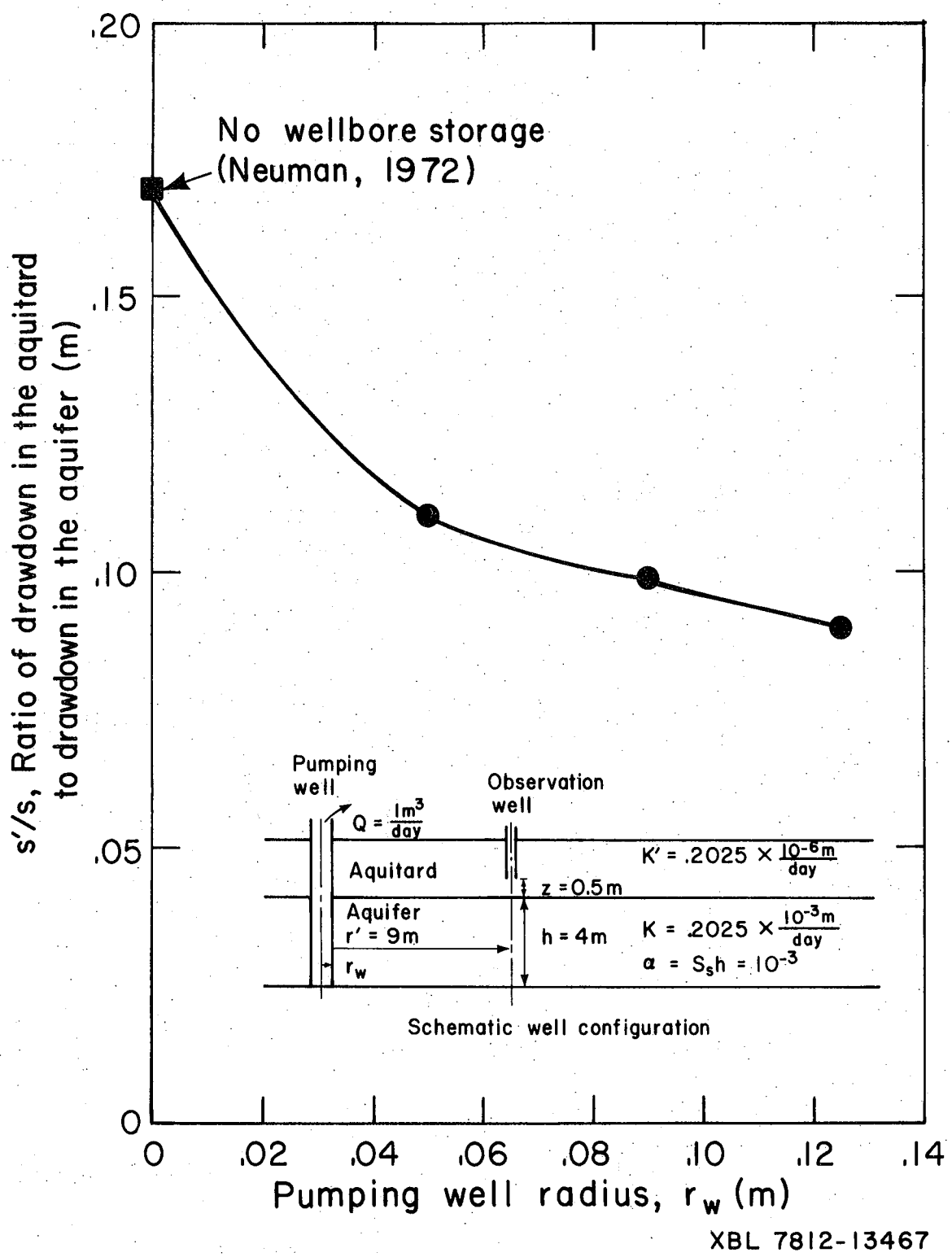


Figure IV-9.

Ratio of drawdown in the aquitard to drawdown in the aquifer, s'/s at r = 9 m, as a function of pumping well radius at t = 100 days, $\alpha = 10^{-3}$.

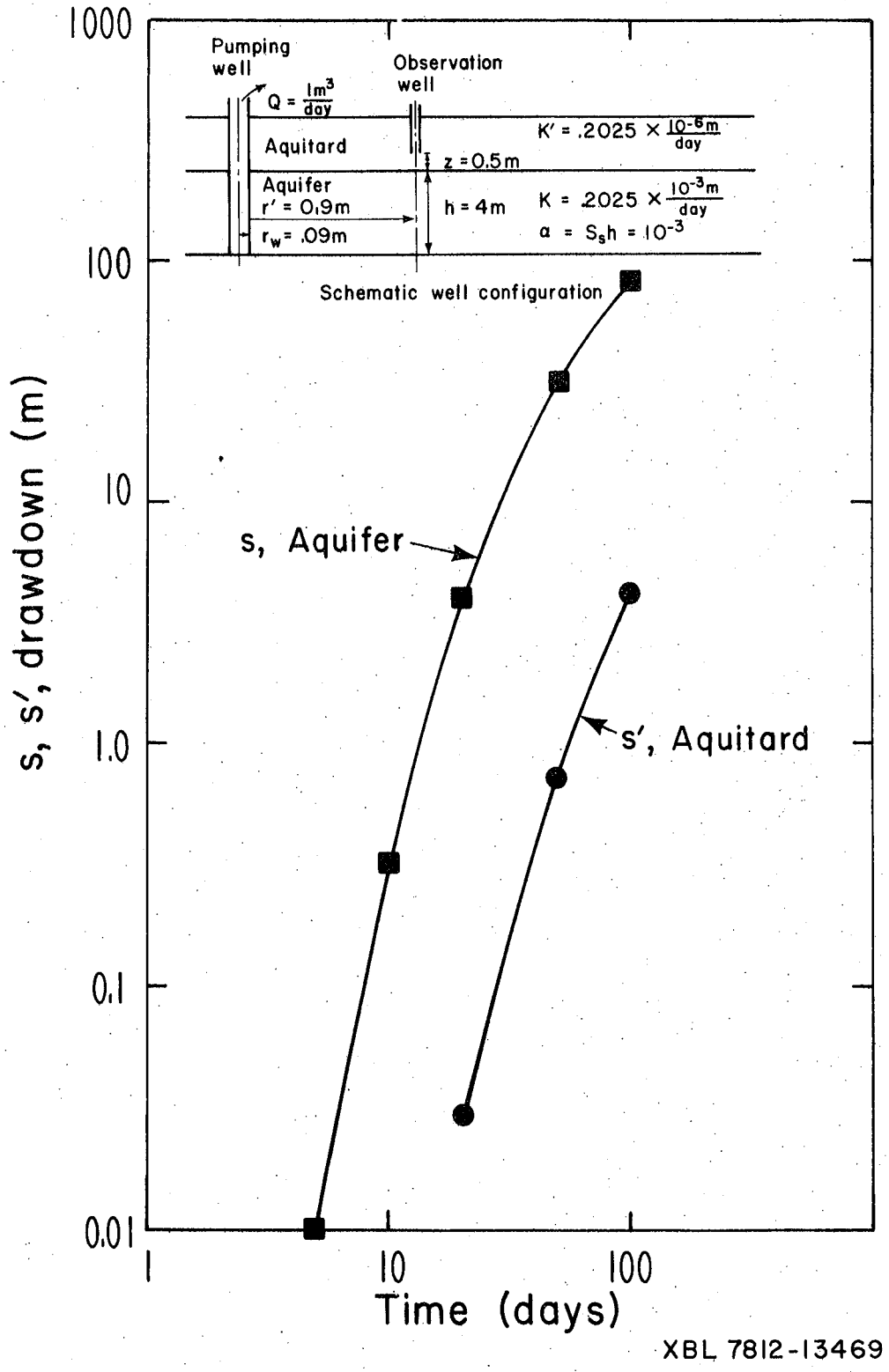


Figure IV-10. Drawdown in aquifer and aquitard at r = 9 m as a function of time. $\alpha = 10^{-3}$, $r_w = .09$ m.

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APPENDIX A

RECOMMENDED HYDROLOGIC FIELD TESTS

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Note: This appendix is an excerpt from Lawrence Berkeley Laboratory Publication No. 5011, "Recommended Well Drilling and Testing Program", July 1978.

APPENDIX A

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Introduction

An understanding of the groundwater flow system in the Pasco Basin is an essential part of the site evaluation procedure for locating a nuclear waste repository. It has been widely recognized that transport by groundwater is the only significant mechanism for release of radionuclide contaminants from a repository to the biosphere. With this in mind, a hydrology program must first be aimed at determining flow paths and velocities on a regional basis. The data required to evaluate regional hydrology comes mainly from well tests and geologic investigation.

This discussion of hydrology field tests is presented in four sections. Data requirements for geohydrologic characterization of the study are discussed from the standpoint of mathematical modeling in Section 1. Procedures for selecting field tests to satisfy data needs are indicated in Section 2, and detailed discussion of the various types of field tests are presented in Section 3. Finally, a discussion of the need for long-term well monitoring is presented in Section 4. The monitoring program and each type of test is discussed in terms of equipment availability and constraints, test procedures, time requirements, and accuracy.

1. Data Requirements for Hydrologic Modeling

a. The Geohydrologic Environment

The Pasco Basin is a structural basin in the southwestern part of the Columbia Plateau. The basin is defined predominantly by flexures: anticlines on the north, south and west and a broad monocline on the east. The bedrock of the region is the Columbia River Basalt Group. This group consists of series of individual basalt flows separated in some cases by interbedded sedimentary units. These basalt flows and sedimentary units are not necessarily continuous throughout the basin. Within each flow the cooling environment and subsequent history have given rise to distinct subunits, such as flowtop breccias, rubble zones, vesicular zones, entablatures, colonnades, and pillow palagonite zones. These infraflow structures are not necessarily continuous throughout a flow and all types of subunits may not be present in a given flow at a given location. Folding and faulting of these units is extensive although not all folds and faults have surface expression. Clearly the Pasco Basin has highly complex, heterogeneous geology.

As a consequence of the complexity of the geological framework, the groundwater regime of this basin should also be quite complicated. Detailed work on the shallow groundwater system in the Pasco Basin area has revealed the existence of vertically separated flow systems. Deeper drilling has shown that circulating groundwaters exist at depths of 3000 feet or more. An understanding of the disposition of the complex deep circulating systems is of paramount importance in evaluating the hydrogeological barrier to waste transport from a proposed repository. Success in this regard is dependent on our ability to obtain a broad data base. Well spacing within the basin must be sufficiently dense to assure that the data necessary for a reliable analysis can be collected.

b. Methods of Analysis

It is evident from available knowledge that groundwater in the bedrock of the Pasco Basin will flow through both fractures present in a more or less impermeable basalt and interbeds which behave as porous media. Depending on the scale of interest, such a hydrologic regime can be modeled either with discrete fractures or as an equivalent porous medium. For example, for a

detailed simulation of flow in the vicinity of the repository one could model flow in discrete fractures, while from the point of view of regional groundwater flow one could use the equivalent porous medium model to great advantage.

In addition, the model must have the ability to handle complex flow region geometry in two or three dimensions, anisotropy and heterogeneity of material properties, and the time-dependent variation of boundary conditions and material properties.

Groundwater flow in both porous and fractured media occurs in a network of void spaces which penetrate the system. Flow in the system is generated by a hydraulic gradient (I), which can be defined as the change in head per unit of horizontal distance in a given direction. The conductance of such flow is called the relative permeability (K) of the medium, and is related to the discharge (Q) by the familiar Darcy equation:

$$Q = K\ I\ A \tag{1}$$

where

Q = volumetric flow rate (L^3/T)

K = relative permeability (L/T)

I = hydraulic gradient (L/L)

A = cross section area (L^2)

Dividing both sides of the foregoing equation by the area A, an expression for apparent flow velocity V is obtained:

$$\frac{Q}{A} = V = K\ I \tag{2}$$

where V = apparent flow velocity (L/T). Each of the above terms has directional properties. Both velocity and gradient are vectors and the relative permeability is a tensor which varies in direction in response to changes in the physical properties of the void spaces. Equation (2) can thus be expressed in terms of a three-dimensional non-diagonalized tensor:

$$\begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix} = \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{bmatrix} \begin{bmatrix} I_x \\ I_y \\ I_z \end{bmatrix} \tag{3}$$

where the subscripts x, y and z indicate the orthogonal field coordinates. The x-component of velocity is written

$$V_x = K_{xx} I_x + K_{xy} I_y + K_{xz} I_z \tag{4}$$

where K_{xy} is the permeability to flow in the x-direction due to the component of gradient in the y-direction. If the orientation of the field coordinates coincides with the directions of principal permeabilities, the cross terms in the permeability tensor are reduced to zero and Equation (3) becomes:

$$\begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix} = \begin{bmatrix} K_x & 0 & 0 \\ 0 & K_y & 0 \\ 0 & 0 & K_z \end{bmatrix} \begin{bmatrix} I_x \\ I_y \\ I_z \end{bmatrix} \tag{5}$$

A complete discussion of the permeability tensor and derivation of the permeability ellipsoid for fractured media is described by Wilson and Witherspoon (1970).

c. Parametric Requirements--A Guide to Field Testing

The input data required for the mathematical model fall into four broad categories:

o Geometry	Limits of the system; nature of layering structure
o Initial conditions	Regional groundwater flow pattern; fluid potential distributions; flow velocities
o Material Properties	Permeability; storativity; porosity
o Boundary Conditions	Relationship to adjacent basins or the shallow groundwater system; role of Columbia River

The geometry of the Pasco Basin will be defined through a process of synthesizing all available geophysical, geological, and other knowledge, from both surface and subsurface data. Wells will be needed to investigate structural effects in the Pasco Basin. The edges of the Basin, especially at Sentinel Gap and to the east and northeast, are areas where basalt flows found deep under the center of the basin come close to the surface. The same is true for the tops of the ridges, particularly the Rattlesnake Hills. Plunging synclines such as Cold Creek and Dry Creek Valleys could be conduits for water into the Basin. Water may be impounded behind faults such as the Saddle Mountains thrust fault or Priest Rapids fault or such faults may serve as conduits. Examination of deformed areas by means of deep vertical or

inclined boreholes may provide evidence of increased vertical circulation which will be of vital interest to repository siting.

The initial fluid potential distribution would have to be obtained primarily through profiling of fluid pressures in newly drilled as well as existing wells and through monitoring carefully installed piezometer clusters. Clearly the accuracy with which the pressure distribution is determined depends on the density of wells over the entire area.

Three basic material properties are needed as input into the model to analyze saturated flow: permeability, rock mass compressibility, and porosity. Well tests will be designed to measure both horizontal and vertical permeability. Compressibility and porosity are combined in the storage coefficient which can be measured as a rough average in a pumping test. It may be possible to obtain porosity from tracer tests. The model requires the assignment of material properties throughout the flow region. Again, accuracy will depend on well density.

In the analysis of a regional groundwater system in fractured rock such as in the Pasco Basin, the difficulty of identifying all significant discrete fractures forces us to make assumptions about the nature of the material properties of the rock units. The primary assumption is that fractured rock masses, when examined on the megascopic scale of basin flow, behave largely as equivalent porous media. With the exception of large throughgoing discontinuities, which may be modeled as discrete fractures, a numerical model of the Pasco Basin hydrologic system must be essentially a porous-media model. Field tests are directed at providing these equivalent-porous-media permeabilities for the modeling effort.

There are two basic approaches for obtaining equivalent permeabilities. The first method is to do large scale tests which automatically average the effects of individual fractures. To produce representative data these tests must be performed on a volume of rock at least as large as the representative elementary volume. Bear (1972) has defined the size of a representative elementary volume (REV) (Figure A-1). If the test is performed on a volume smaller than the REV, the effect of adding a small volume to the test volume will have a significant effect on the value of the parameter measured. This is the domain of microscopic or single fracture effects. The volume is representative when small increases in the test volume have no significant effect on the value of the parameter. This is the domain of porous media or equivalent porous media effects.

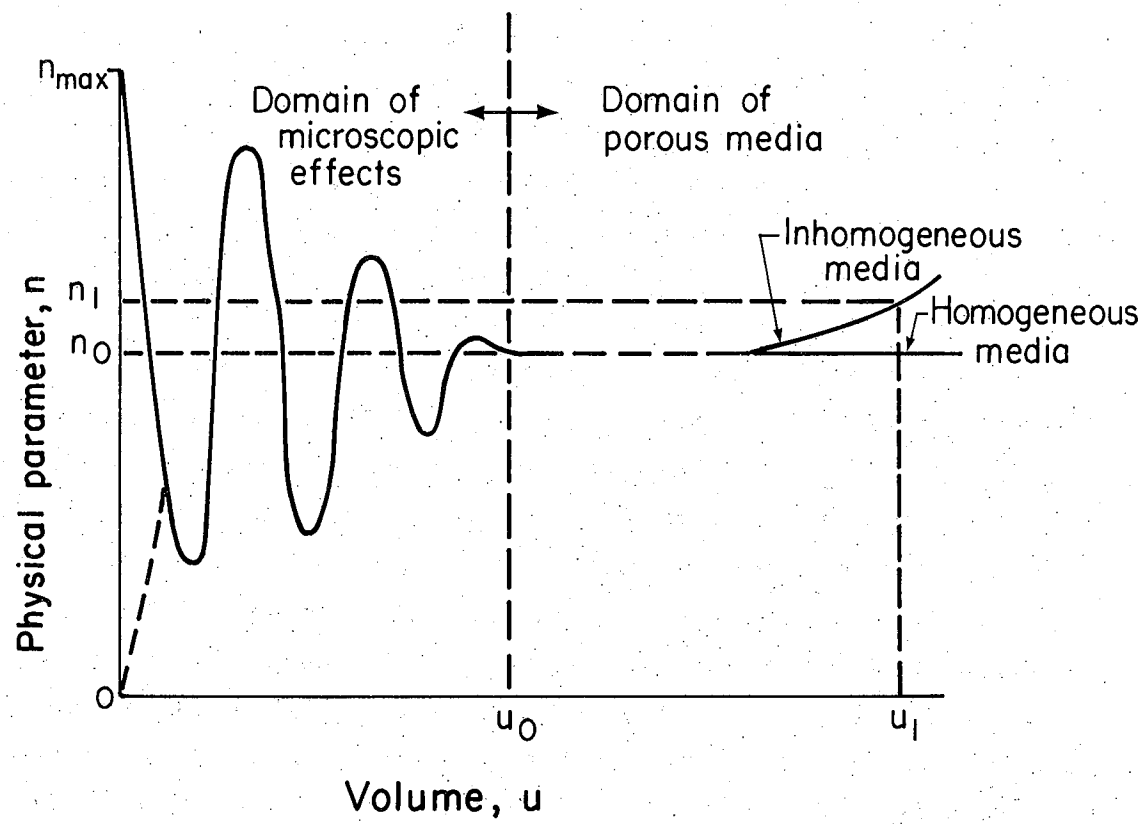

Figure A-1. Definition of a representative elementary volume (after Bear, 1972).

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In theory the size of the test can always be increased; for example, by increasing the packer interval. However there are practical limits to this process. In rock such as the Columbia River basalts, the dimensions of a REV may easily exceed the thickness of the unit being tested. Also, in order to perturb a large volume of rock, the test may take a long period of time. Furthermore, methods for obtaining vertical permeability with large-scale tests are limited to two-hole tests and inclined-borehole tests. The availability of twin holes and inclined boreholes will be limited and it may take very long periods of time to do two-hole tests. Finally, the interpretation of both tests will be in doubt if there are a large number of thoroughgoing fractures neither perpendicular nor parallel to the hole.

Because of the above difficulties, it will be necessary to also use a second approach. In this method, small-scale tests on individual or small groups of fractures are run in order to measure apertures and orientations. The distribution of aperture and orientation is then used to build a statistical picture of the permeability tensor.

Storativity can also be measured in large or small scale tests. The large scale measurements are accomplished by performing a pumping or injection test with an observation well. Without an observation well it may only be possible to estimate storativity. Small scale tests measure stress-conductivity relationships in individual fractures. These individual measurements plus a measurement or estimate of the total distribution and volume of the fractures can be used to estimate storativity.

Effective porosity is measured in order to calculate particle velocity. As mentioned above, the velocity calculated by equation (2) is an apparent velocity and not the true intergranular velocity. The latter is equal to the volumetric flow rate divided by the effective cross-sectional area of the pores (rather than the gross area of pores and grains). In a random and relatively uniform porous medium, the average true velocity is essentially equal to the apparent velocity divided by effective porosity, defined as the ratio of interconnected pore volume to gross volume. Effective porosity values can be obtained from tracer tests.

This simplified relationship breaks down, however, in a fractured medium where void spaces occur in the form of open fractures and are often highly irregular in size. In comparing a volume of rock containing ten fractures of 10 μ aperture and one fracture of 100 μ aperture, the true

velocity in the single large fracture will be 100 times the velocity in the small fracture because velocity is a function of fracture aperture squared. Therefore, dividing the total flux per unit area by the total porosity would give a meaningless value for velocity. It thus becomes very important when identifying true flow rates in a fractured medium to consider fracture apertures rather than gross porosity data.

The flux or head must be determined along all boundaries of the flow region as a function of time. To determine these conditions, data are needed from wells both across and along the boundaries. A boundary may be either aribitrary or natural, but it is essential that precise conditions along the boundary be determined. The placement of wells necessary for this purpose is discussed in Section II C1 of the main report. Long term monitoring of pressure and chemistry in some some of these wells will be necessary for understanding the time dependence of the boundary conditions.

d. Independent Verification of Theoretical Models

Three methods can be used to verify or calibrate the theoretical models which will be developed. The first is to monitor pressures with time to see it they correspond with predicted values. The second is to use tracer tests to get independent values of local velocity and direction and again see if they correspond to values calculated by the model. The third is to use dating and geochemical analyses to obtain historical values of regional velocity and direction and again check against the values predicted in the model. Adjustments can then be made in the model(s) to minimize the difference between predicted and measured values.

2. SELECTION OF FIELD TESTS

a. Data Requirements - Test Matrix

Data required for geohydrologic characterization of the Pasco Basin are related to a suite of geohydrological, geochemical and geophysical field tests in Table A-1. An effort has been made to limit matrix entries to direct relationships between required data and tests which produce such data. However, some of the more important indirect relationships regarding combinations of tests from which required data may be inferred are also indicated and are footnoted. The purpose of this matrix is to serve as a

reference guide to data requirements and tests and is not intended to be exhaustive of all possible data-test relationships. Discussions of each of the seven types of tests shown in Table A-1 are presented in Section 3 and long-term monitoring is discussed in Section 4 of this Appendix. A discussion of general considerations in test selection which apply to most types of geohydrological, geochemical, and geophysical tests follows.

b. General Considerations in Test Selection.

A number of physical and economic constraints must be considered in the selection of field tests to provide the basic data required for geohydrologic evaluation of the Pasco Basin. Most of these constraints are general in nature and apply to all types of field tests. The process of test selection involves achieving a balance which best satisfies the requirements of accurate data acquisition while at the same time satisfying the physical constraints of the environment in which testing occurs and the economic constraints of reasonable testing times and costs. A procedure which is highly suitable for permeability testing in large boreholes within near surface aquifers, for example, may not be at all acceptable from both physical and economic standpoints in deep 3-inch NX boreholes. Specific constraints which must be considered in test selection are discussed below.

i. Borehole Environment

The required test equipment must be capable of operating in the environmental conditions of the borehole. These conditions include borehole diameter, depth, sidewall roughness, water chemistry and water temperature. Certain types of tests may be precluded because the hole may be too small or too deep, the temperatures may be too high, or the chemical environment too caustic. Pumping drawdown tests, for example, may be precluded for highly permeable zones in small, deep boreholes because of a lack of high capacity pumping equipment. In such environments, formation permeability would be obtained by other types of data.

ii. Drilling Techniques and Testing During Drilling

Drilling techniques affect the roughness of the borehole wall, the degree of physical disturbance of the rock mass around the borehole, and the degree of infiltration of drilling fluids and cuttings into the rock mass.

TABLE A-1
DATA REQUIREMENTS - TEST MATRIX

Required Data	Borehole Tests							
	Geophysical Logging	Pressure	Permeability	Tracer	Geochemical	Fracture Studies[1]	Hydraulic Fracturing	Monitoring[4]
Hydraulic Gradient		x						x
Permeability & Storativity[2]	x		x	x[12]	x[12]	x[5]	x[6]	
Porosity & Density	x[13]			x		x[13]		
State of Stress & Elasticity	x[10]					x[10]	x[11]	
Geochemical Evolution					x	x		
Flow Direction and Velocity	x	x[3]	x[8]	x	x[7]			x
Age of Groundwater					x			x
System Geometry	x	x[9]	x[9]	x	x	x		x
Water Chemistry & Temperature	x				x			x
Fracture Descriptions	x					x		

[1] Includes analysis of core.

[2] Directional permeability of porous media and individual fractures obtained by selected permeability tests using results of borehole logging geophysics and hydraulic fracturing.

[3] Pressure data provide flow direction only.

[4] Includes long term pressure testing, geochemical sampling, and tracer testing.

[5] Provides data on fracture apertures, orientation and frequency used in establishing permeability tensor.

[6] Provides data for application of independently determined stress-aperture relationship for fractures.

[7] May provide information on source of groundwater based on age or characteristic constituents.

[8] Provides flow direction velocity data when gradients are known.

[9] Anomolous data provide indirect indications of system geometry.

[10] Test provide elastic properties only.

[11] Test provides state of stress only.

[12] Permeability data may be inferred from geochemical sampling operations and tracer tests under certain conditions.

[13] Test provides total porosity only.

Rotary drilling, for example, generally results in a rougher hole walls. The degree of physical disturbance of the borehole wall also affects the success of downhole devices for fracture orientation and aperture identification.

Drilling affects hydrologic testing and sampling in the following ways:

1. Reduction of permeability through invasion of cuttings into fractures.
2. Contamination of native groundwater through drillwater invasion.
3. Invasion of drilling mud into borehole wall causing a positive skin effect.
4. Change in formation pressures due to influence of fluid pressure in the well.

After drilling is complete factors (2) and (5) may continue due to crossflow between strata of different hydraulic potential.

To some extent these problems can be alleviated through choice of drilling technique or fluid. Use of air or aerated water for drilling maintains a lower head in the hole than in the formation thus reducing water invasion to the formation. Such drilling, however, does not generally allow retrieval of core and may result in a positive skin due to well wall damage.

If water is used for the drilling fluid as in core drilling, lost circulation material can and should be added as required to limit contamination and mud invasion to the formation. Such material may, however, be difficult to remove.

Hydrologic testing and groundwater sampling in previously contaminated boreholes generally require time-consuming expensive cleanout procedures. Estimates of the time necessary to remove contaminants from a formation have been made assuming contamination inflow at a constant head difference of 75 meters into the formation and removal by swabbing at a constant head difference of 1000 meters into the well. Figure A-2 shows the number of invasion volumes, i.e., the volume of drilling fluid that invaded the formation during drilling, that are removed by swabbing as a function of time. It may not be unusual for 20 invasion volumes to be removed before the water is clean enough for geochemical sampling. Assuming that the sampling zone was exposed to drilling fluid contamination for one month during drilling, it would take about 45 days of constant swabbing to remove 20 invasion volumes and produce an acceptable sample under the above assumptions.

Most measures designed to limit contamination may have an adverse effect

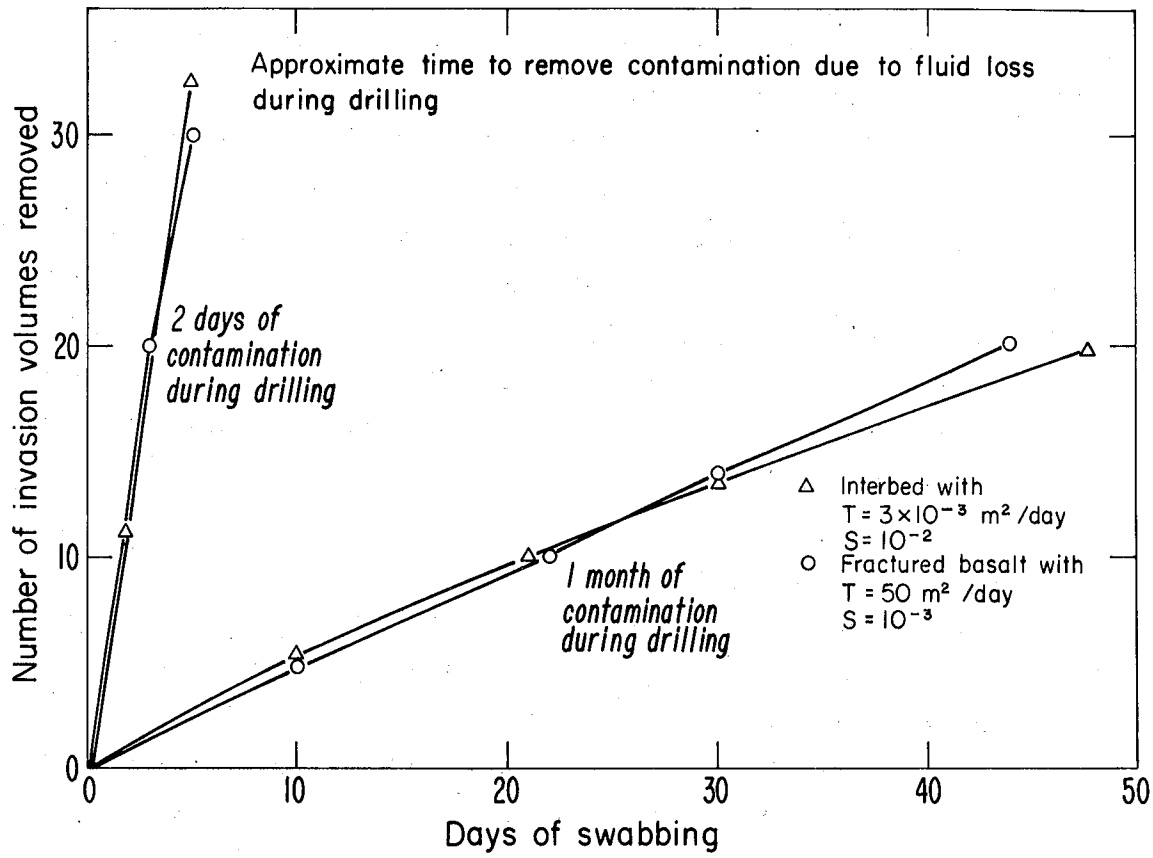

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Figure A-2. Approximate time to remove contamination due to fluid losses during drilling.

on permeability and pressure measurement. One alternative is to have separate holes dedicated to core, geochemical sampling, and permeability work using drilling techniques best suited to the purpose of the hole. However, the number of holes is limited and individual holes will need to serve multiple purposes. The most practical alternative is the sampling of test zones and measurement of pressures and permeabilities as the hole is drilled. Since deterioration of water sample and pressure measurement quality increase with time, allocation of time during the drilling schedule is imperative.

The sequence in which field tests are performed must be considered from the standpoint of the effect of each test on subsequent tests. It would be undesirable, for example, to contaminate the formation with injection test fluids prior to geochemical sampling. Similarly, it would be undesirable to perturb the formation by sampling prior to making static preessure tests. Therefore the order of testing should be pressure testing, then water sampling, then injection testing.

iii. Hole Preparation for Testing

For previously drilled holes where the opportunity to test during drilling has been lost, cleanout procedures will be required prior to testing. If during drilling a large positive head was maintained in the borehole, drilling fluids, cuttings and lost circulation material will be forced out into the rock from the hole. Before testing begins certain steps must be taken to remove the introduced drilling materials and make the hole stable for packer operations.

Before hole cleaning begins a caliper and temperature log should be made. The caliper log is necessary to pick packer setting points. The temperature log, when compared to subsequent logs run during the cleaning process, will be used to determine flow zones where the cleaning has been most effective.

For cleaning, a relatively low head must be established in the borehole, to draw the drilling materials out of the rock into the hole. Heavy particles will settle to the bottom of the hole and fluids will be lifted out of the hole. This can be accomplished with either swabbing or air lifting while a single packer is set in the hole. For a hole that extends more than 1000 feet below casing, it is recommended that a single packer be set about 500 feet above the bottom of the hole and at subsequent 500 foot

intervals up the hole. This will ensure that the low head affects all parts of the hole. As each interval is cleaned a temperature log should be run to determine what part of the hole has been producing water. Depending on the length of the open part of the hole this preparation should take from two days to two weeks.

iv. Equipment Availability and Sensitivity

Test selection must be compatible with the availability of necessary equipment and desired accuracy of the resulting data. The problem of inappropriate or unavailable equipment to meet specific testing demands within the deep borehole environment has already been noted and specialized testing equipment has been designed and fabricated by LBL for the Pasco Basin field program. Also of importance is the availability of commercial equipment on a timely basis. The selection of field tests must take into account the lead time required to obtain necessary equipment and to assemble a working test unit in the field.

Test selection must also be compatible with the availability of equipment which is sufficiently sensitive to meet required levels of accuracy. In testing the permeability of fractures with very small apertures, for example, it may be necessary to shift from a procedure which relies on measurement of flow rate to one which relies on measurement of pressure decay. The flexibility to vary the field test procedure as required is an important prerequisite for a successful field program.

When all hole cleaning is completed a caliper log should be run to see if the hole has been enlarged or blocked by the flow into the wellbore. If the hole is open or blocked by the flow into the wellbore. If the hole is open a complete suite of geophysical tests should be run. These data, combined with the temperature logs run during cleaning, can then be used in picking sampling intervals.

v. Value of Observation Wells and Inclined Holes

Observation wells or inclined boreholes are needed for determination of certain hydrologic parameters. One or more observation wells are required for accurate determination of the storage coefficient. Vertical permeability may be inferred from tests in inclined boreholes or, under certain circumstances, from ratio tests in pairs of holes. The availability of

observation wells and inclined holes at a test site will influence the types of test which can be performed and to some extent the type of data which can be obtained at that site.

vi. Economic Constraints

Economic constraints affecting the selection of field tests are an important and well-recognized part of any program. Economic considerations limit the number and duration of field tests, and affect to some degree all aspects of the testing program from the size and depth of boreholes to the selection and availability of testing equipment. The field tests have been selected and the testing program formulated to assure that the maximum amount of reliable data will be acquired within the economic constraints imposed. For example, tests are planned to minimize the requirements for duplicate equipment, the size of the field staff, and the number of trips which must be made into and out of the hole.

vii. Time Constraints and Maintenance of Schedules

Time considerations and maintaining program schedules are especially important to the Pasco Basin hydrology project because of the national goals which have been established for solution of the nuclear waste storage problem. These time constraints require that field tests be selected on the basis of the reliability of the test procedure and equipment to yield the required data on schedule. Time constraints can best be met through the formulation of a realistic program. Successful formulation of such a program requires extensive experience with the testing equipment, test procedures, site conditions, the stores, support services, and geologic environment within the Pasco Basin.

3. DESCRIPTION OF FIELD TESTS

a. Borehole Geophysical Measurements

i. Introduction

Wireline borehole measurements have two functions in a project such as the hydrological investigations at Hanford. Firstly, geophysical logs furnish background data upon which the physical features of the geology can be inspected and evaluated and detailed plans for test work can be made. This has been the dominant (but not exclusive) use of the borehole

methods at Hanford and is referred to in the petroleum industry as "openhole logging." Openhole logging is done before the hole is cased or altered for engineering purposes.

Secondly, and just as important, a wireline facility is the only way that subsidiary information required during the course of the drilling and testing program can be obtained. We shall refer to this mode as "operational logging." Typical requirements are the examination of the flow profile, inspection of casing or tubing for damage, certifying the effectiveness of acidization or hydrofracturing, etc. Typical tools include the flowmeter, thermometer, gradiomanometer and caliper. However, the actual requirements are rather unique and more important in the case of an investigatory hydrological program. Also, since this aspect of wireline measurements has been neglected in the past at the Hanford site and in most similar field investigations, it is worthwhile to discuss a few examples to illustrate the utility of such a measurement system.

In hydrological investigations the drilling history and the consequent modifications to the borehole wall can be quite important and in fact constitute part of the hydrological data base. For example, a major flow zone encountered during drilling must often be sealed off before the drilling can proceed. Hence wireline measurements are important to determine the exact horizon of the fluid exodus, usually accomplished with a flow sensor or a temperature profile. After cementing the hole to stop the circulation loss, another temperature profile can determine where the cement was actually emplaced by observing the heat produced exothermally during the curing process. As another example, if deep hydrofracturing becomes an important method of determining the in situ stress at Hanford, then a method of inspecting the wall of the borehole both before and after the fracturing operation is necessary. Such an inspection can be accomplished with either optical or sonic techniques. And as a third example, a sensitive caliper inspection of the borehole wall can show where packer setting may be hazardous.

ii. <u>Comparison of Open-Hole and Operational Logging</u>

The distinction between open-hole and operational logging will, of course, not be clear in some applications, but in general the distinction is

clear enough that there are some obvious practical implications. One of these is that the open-hole requirements can more or less be planned and scheduled well in advance of the actual required logging operation. Hence it can be budgeted on a footage basis, depending upon the logging program selected. On the other hand, the operational logging is necessarily an "ad hoc" requirement which can and will change from day to day and even from hour to hour. It cannot be budgeted on a footage basis, but must be accounted for on an equipment and manpower basis, and is in practice much better done by the personnel doing the hydrological test work.

iii. Previous Logging Programs at Hanford

A large number of borehole logs have already been obtained at Hanford over the past 8 or 9 years. In fact, almost 100 logs have been run on DC-1 alone. However these existing logs have been obtained and used on an "as needed" basis. A review of these logs has been conducted by LBL, and is reported in detail in Section IIB2 of the main report. The following general statements can be made concerning success of various techniques:

- The dominant features of all the open-hole logs reflect the startling contrasts between the massive basalt flows to the vesicular and interbed zones. In this respect all the logs reflect the marked changes in pore volume and any one of the suite of logs can be used to pick the basalt flow (porosity) boundaries. Porosity contrasts become even more apparent when the logs are compared to the photographs of the core. Hence the ability to pick lithologic changes from the logs is well in hand and the logs have been used for this purpose for some time.
- On the other hand, the correlation of individual flows between boreholes is unsatisfactory, being based on geochemical analysis of the rock. For this reason, other types of logs have been run recently which may be sensitive to subtle changes in mineralogy, but these results have not yet been completely analyzed.
- Other logs such as the dipmeter and televiewer have received only limited use at Hanford, but the results are highly encouraging and need to be assessed more carefully before specific recommendations can be made in regard to their use.
- Several flow-sensitive logs have been run with radioactive tracer and temperature tools. These logs are very useful and data quality

is quite good. The results would be even more useful if more detailed descriptions of the test circumstances were available.

- The users of logs at Hanford are diverse; the types of logs run and the range of commerical suppliers are equally diverse. Hence the analyst must work with data supplied by different physical measurement methods from tools from different manufacturers, even in the same borehole. This problem is not especially severe as long as the logs are used in a qualitative fashion, but if quantitative data are to be extracted from the logs, some standardization would be desirable.

b. Borehole Fracture Logging

i. Introduction

Fracture logging gathers detailed data on fractures intersecting boreholes. Such logs are used to construct a picture of the fracture system at depth primarily for hydrologic and engineering purposes. Fracture logging techniques include core logging, TV camera logging, borehole camera logging, televiewer logs and oriented impression packers. Detailed caliper logs can also sometimes be used to interpret fractures.

ii. Core Logging

Core logging is a widely accepted means of studying fracture systems. Core logging procedures currently used at Hanford are reasonably thorough and complete. A useful addition to the log, however, would be a photograph of each box taken at the time the core is logged. Numbers now being given to fractures should be shown on the photographs. A sketch can be used instead of a photo (Goodman, 1978).

For hydrologic purposes, core provides useful insights, but it can be misleading. As discussed in the section on permeability, aperture cannot be determined in core except for fractures that are clearly healed. Coring tends to create fractures but such fractures can generally be recognized by a trained observer if they are in intact rock. Healed fractures that have been opened may, however, be difficult to recognize. Coring also tends to disturb fracture filling and coatings; this can be minimized through triple tube drilling.

iii. TV Camera Logs, Borehole Camera, Televiewer

TV camera logs have come a long way towards providing a very useful product. TV logs have high resolution (<0.1 mm) and, unlike core, provide a record of fracture aperture to guide hydrologic testing. The drawbacks are the expense and a depth limitation stemming from problems in transmission cable length and deterioration of image quality in clouded water. They also have a large number of conductors which tend to be bulky, thus requiring large reels and very heavy power winches.

LBL has used two different cameras; one manufactured by Undervattens Foto in Sweden and the other by Sperry Services of Huntsville, Alabama. Both provide continuous video records with depth recorded on the image. Currently, the Swedish camera claims a depth capability of about 5000 feet versus Sperry's 1600 feet. The Sperry camera provides higher resolution and may be adaptable to deeper applications.

Borehole camera surveys do not have the depth limitations of TV logs, but they are discontinuous, do not provide immediate readout, and are somewhat more cumbersome for data analysis.

Televiewer logs record irregularities of the borehole wall acoustically (Zemanek, et al, (1969). The televiewer log has two major advantages over television: it can be run with standard four conductor logging cable, and it does not require clear water in the hole. They provide continuous records like TV logs, but do not have the same degree of resolution, hence they are not as useful as TV logs for aperture distribution studies.

iv. Impression Packer

Impression packers are packers with soft rubber or wax coatings which record the impression of the borehole wall when the packer is inflated. They can be equipped to work with standard orienting tools, such as Sperry Sun magnetic and gyroscopic compasses. Because impression packers generally require separate trips into the hole for each impression, they are impractical as a means of making fracture records over long intervals of holes. They are most suitably applied to recording the orientation and appearance of major fractures or discontinuities that appear in the core (Harper and Hinds, 1977).

Where core is oriented totally or partially by core reconstruction, as is now being done by Hanford geologists, impressions of major

features can be used to orient the core and provide a check on the remnant magnetic methods currently in use.

v. Summary

Fracture logging from core is the basic fracture mapping tool but is not entirely adequate due to core damage in drilling and an inability to determine fracture apertures. TV logs serve as a useful complement in providing the in situ aperture data. For hydrologic studies, TV logs are used to select fractures for small scale injection tests and to facilitate meaningful interpretation of large scale injection tests. This is especially true when one or two fractures are dominating flow into or out of a particular zone. If apertures determined by a TV log show strong correlation with hydraulically determined apertures, much of the small scale injection work discussed in the permeability section may not be necessary, thus saving much cost and time. Impression packers should be limited to major features due to the long time involved in testing one zone. The televiewer and borehole camera will be necessary only if TV logs prove impractical due to cost, unavailability, or water clarity constraints.

vi. Time Requirements

The time required for fracture logging of core will not be covered here because this aspect is within the scope of other RHO contractors. TV logging should be done on all holes and can be done at about 500 feet per day, thus requiring 8 days for a 4000 foot hole. In addition, one month per hole should be allowed for interpretation. The logging equipment should include hoists and tower, making a service rig unnecessary.

Impression packer work will require 0.5 days per run and will require a service rig.

Orientation should be done by a service company such as Sperry-Sun or Eastman, either of which has a minimum fee whenever an engineer is sent. Therefore as many impressions should be run during a given block of time as possible.

c. Permeability Tests

i. Introduction

Analysis of the permeability of the deep strata of the Pasco Basin is a

complicated mix of porous-media and fractured-media problems. Interflows and flow-tops act as porous media and may lend themselves to classic tests such as the pump test. Massive basalts with their complicated fracture systems will require several approaches.

The basic questions are:

- How to determine the permeabilities to be used in realistic regional groundwater flow models.
- How to characterize specific flow paths for determination of fluid velocities.

The following discussion of permeability begins with a general discussion of fracture flow concepts (an understanding of porous media flow on the part of the reader is assumed) and follows with descriptions of specific tests and their applicability to the basalt problem. Tracer tests are discussed in section 3d.

ii. Basic Concepts of Fracture Flow

Aperture

The permeability of a single fracture, k_f, based on the parallel plate flow analogy can be given by

$$k_f = \frac{g\ (2b)^2}{12\nu}$$

where g is the gravitational constant, ν is the kinematic fluid viscosity, and 2b is the effective opening or aperture of the fracture. In terms of a flow rate in a single fracture per unit width, q, this relationship is

$$q = \frac{g\ (2b)^3\ i}{12\nu}$$

where i is the pressure gradient. This cube relationship of flow rate and fracture aperture has been confirmed for natural joints in experimental studies by Iwai (1976).

The flow equation for the porous medium equivalent of a fractured medium has the form

$$\{V\} = [k_p]\ \{i\}$$

where $\{v\}$ is the velocity vector, $\{i\}$ is the potential gradient vector and $[K_p]$ is a second order tensor that can be formed from the permeability terms of each fracture or fracture set. Whereas most permeability tests

measure flow rate, q, and gradient i, we can define the area permeability, K_p by the following relationship

$$q_A = k_p i$$

Where q_A is the flow rate per unit area. For a set of fractures with aperture 2b and frequency λ, the single fracture permeability K and area permeability K_p are related by:

$$[k_p] = 2b\nu[k]$$

Assuming a uniform set of fractures oriented in the X-Y plane with aperture 2b,

$$[Kp] = 2b\lambda \begin{bmatrix} \frac{g\ (2b)^2}{12\nu} & o & o \\ o & \frac{g\ (2b)^2}{12\nu} & o \\ o & o & o \end{bmatrix} = \begin{bmatrix} \frac{\lambda g\ (2b)^3}{12\nu} & o & o \\ o & \frac{\lambda g\ (2b)^3}{12\nu} & o \\ o & o & o \end{bmatrix}$$

The principal permeabilities and their orientations are the eigenvalues and eigenvectors of the permeability tensor formed from the combination of the tensors of the individual fractures.

Natural fractures differ from parallel plates due to surface roughness and other aperture variations. A natural fracture and a parallel-plate fracture having the same distance between the walls will have different hydraulic characteristics. The aperture (2b) used in computing permeability of a real fracture is an effective aperture, equal to that of a parallel-plate fracture having the same hydraulic behavior as the natural fracture. For natural fractures, true aperture and effective aperture may differ by an order of magnitude, the true aperture generally being greater (Gale, 1975).

The significance of the squared and cubed relationships between fracture aperture, velocity and flow rate can be seen by analyzing a simple fracture system as it might be encountered in a well (Figure A-3). Suppose a well penetrates a joint system oriented normal to the borehole with a spacing of 1m and aperture of 10 μ. Suppose one fracture in this array has an aperture of 100 μ. Under the same gradient the larger aperture fracture will maintain a flow velocity which will be 100 times that of the smaller fracture. Volume flow rate will be 1000 times that of the single smaller fracture.

Extending this example further, two test zones, one with a single 10μ fracture, the other with 1000 1μ fractures, will have the same permeability.

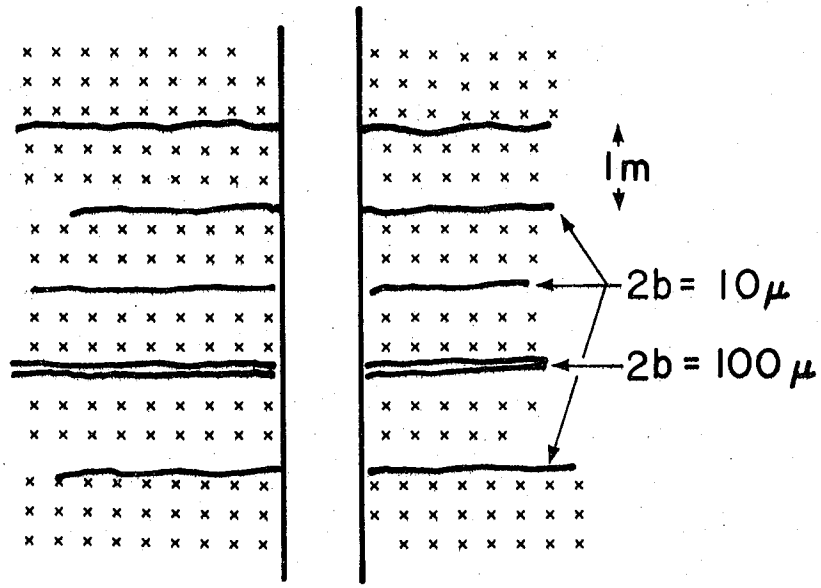

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Figure A-3. Joint system with varying fracture apertures; larger aperture fracture will have 100 times the velocity and 1000 times the flow rate of each small fracture.

Under identical hydraulic gradients each system will have the same volume flow rate, but the particle velocity of the flow will be 100 times greater in the system containing the single 10μ fracture. Fracture aperture, therefore, has the same control on flow velocity as porosity does in porous media.

This points out an important difference between fractured media and porous media, namely, that in porous media porosity and permeability can be independent, whereas in fractured media porosity and permeability are strongly coupled with fracture aperture. Further discussion of the aperture-velocity problem can be found in Maini and Hocking (1978).

Core analysis and fracture logging are not sufficient to detect variations in the aperture of small fractures. Nor do most geophysical tools have the resolution to distinguish such features. Hence in borehole test zones that appear lithologically and geophysically identical, permeability test results can vary by several orders of magnitude.

Orientation

Given the strong dependence of flow properties on aperture, it becomes crucial to know the orientation of fractures being tested and if there is variation in aperture with fracture orientation. The orientation of the large aperture fractures with respect to the potential gradient makes a major difference in groundwater flow velocity and direction. For basalts, several aperture-orientation relationships may exist. For example, in the colonnade, vertical fractures are likely to have larger apertures than horizontal fractures. If the regional stress field at Hanford is highly anisotropic, it may be that fractures in some orientations are closed while others are not.

The problem of aperture-orientation relationships make the drilling of boreholes in a variety of orientations essential. Whereas the number of fractures intersected by a borehole varies with the sine of the fracture dip relative to the borehole axis (Terzaghi, 1965,) well tests in fractured rock tend to be dominated by fractures normal to the wells and will be unlikely to yield much information on the permeability of fractures parallel to the well. The ratio test, however, is an exception to this statement (see section 3ciii).

Orientation considerations affect as well the choice of large scale versus small scale permeability tests. "Small scale" refers to tests on

short zones containing one or two fractures; "large scale" refers to tests with larger packer spacings (>10 feet). Snow (1968) devised a method for determining the average spacing of hydraulically significant fractures from large scale tests of those fractures. It is difficult, when using a large test zone, to determine which fractures are responsible for the flow and how the fractures are oriented. Figure A-4 shows an example of how such data can be difficult to interpret. Imagine a rock mass containing a steeply dipping joint system and a horizontal fracture system. In (a) the horizontal system has on the average, one tenth the aperture of the other system. In (b) this relationship is reversed. In a large scale test as shown, the two zones, labeled 1 will have the same measured permeability as will the two zones labeled 2. However the orientation of the permeability tensor will remain ambiguous. The orientation of the permeability tensor of the rocks in (a) will be quite different than in (b), but large scale tests cannot detect this. The problem can be alleviated by use of a downhole TV camera or possibly seisviewer logs if resolution is sufficient. Small scale tests would resolve this question.

The determination of anisotropic permeability depends on the interrelationship of fracture aperture, orientation, and spacing, as well as knowledge of single fracture properties. This distribution can be used to calculate directly the permeability tensor, as was done by Bianchi and Snow (1969) or Louis and Pernot (1972). Another alternative is to determine the statistical distributions of aperture and orientation as input to a stochastic model.

Continuity

The results of fracture mapping in many geologic environments have shown that fractures cannot be assumed to be continuous within their own plane. This continuity may be decreased depending on the extent of fracture coatings and fillings. Continuity is the most difficult fracture parameter to measure in situ. Many well tests affect only a zone close to the wellbore, hence a change in aperture at a distance from the hole cannot be detected. Tests that affect large volumes of rock mass are the best way to evaluate continuity. Deviations from type curves for pump tests, slug tests, and pulse tests can be qualitatively interpreted in terms of continuity (Wang, et al, 1977). Additional tests for continuity can be made using single fracture cross-hole tests (Figure A-5).

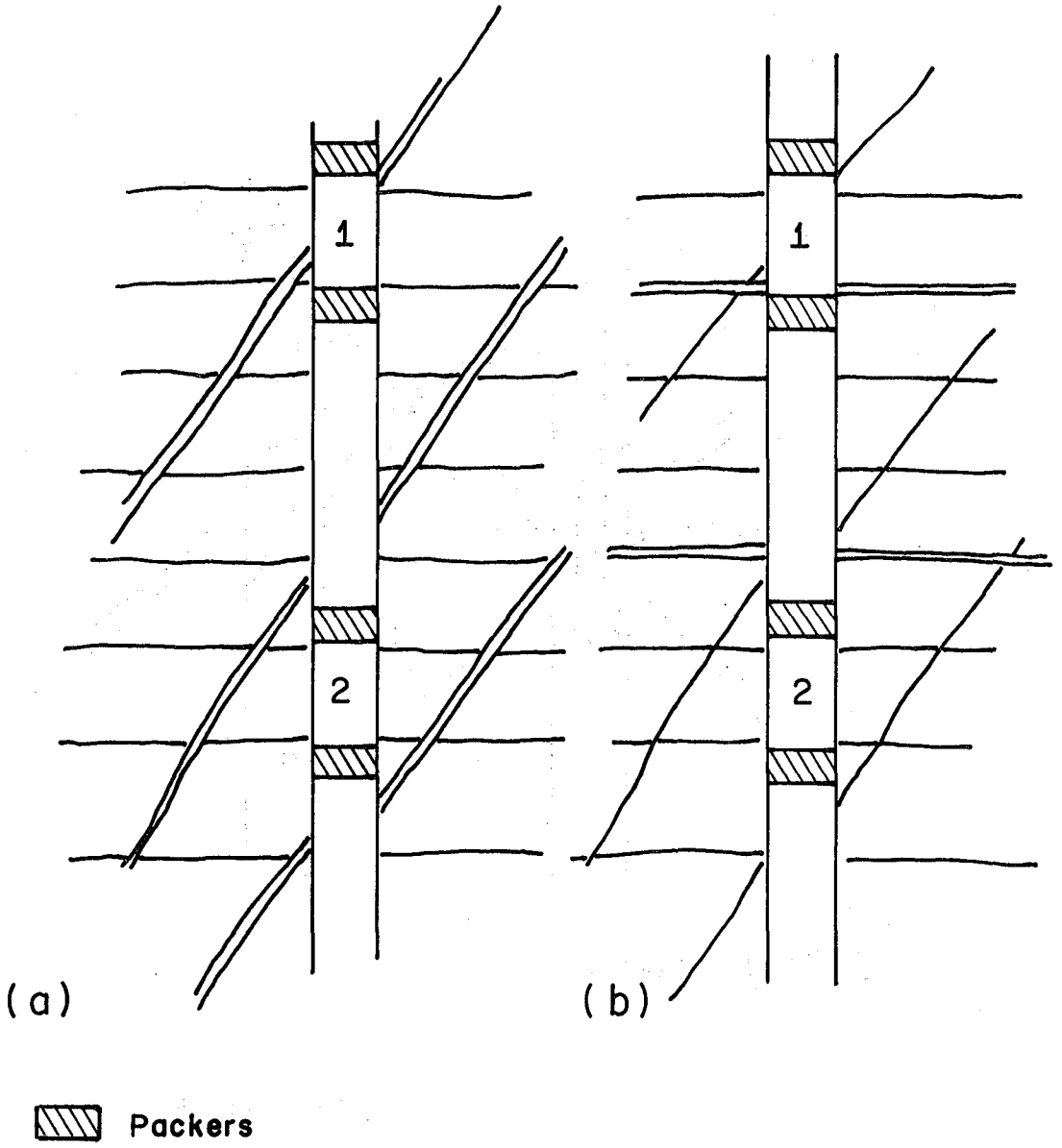

Figure A-4. Ambiguity of large-scale permeability tests
a. permeability of zones 1 and 2 differ due to intersection with steeply dipping fracture system
b. permeability of zones 1 and 2 differ due to aperture variation in horizontal fracture zone

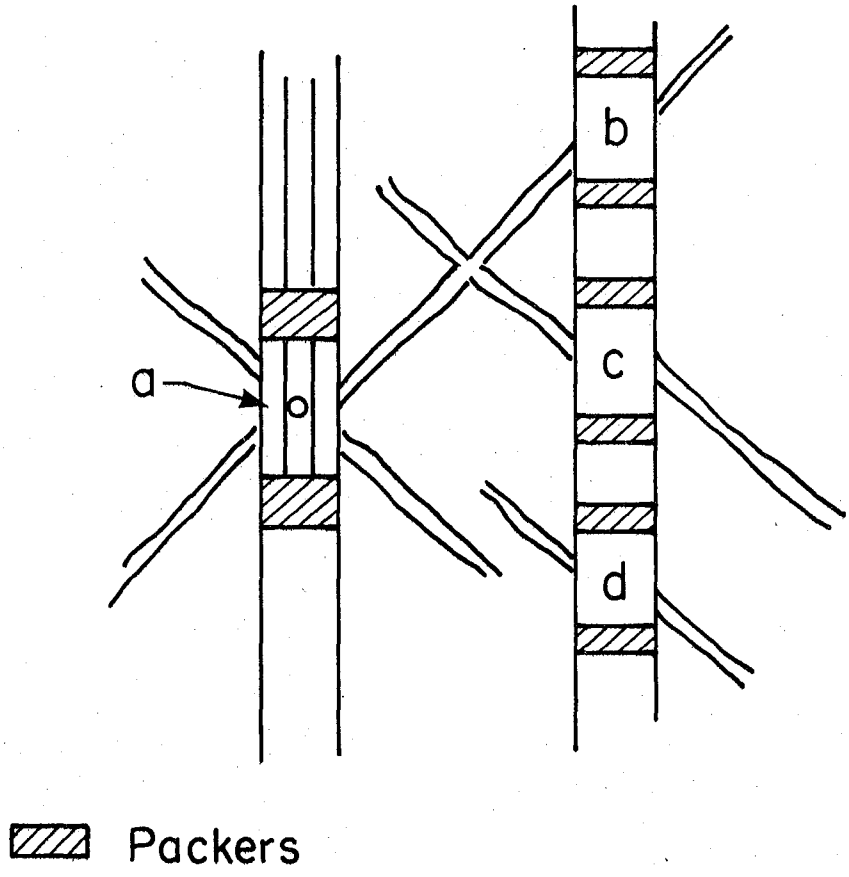

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Figure A-5. Schematic diagram cross hole fracture continuity test
a. injection interval
b, c, d pressure monitoring intervals

Large Scale vs. Small Scale Permeability Tests

Small scale tests have the function of determining orientation-aperture relationships, statistical aperture distributions, and single fracture continuity. A statistical description of fracture aperture, continuity, spacing, and orientation will provide a means of assigning a probability to the occurrence of a specific large aperture fracture flowpath extending from within a massive basalt to more permeable overlying and underlying interbeds. Identification of specific fracture systems will also permit direct computation of transit times for contaminant transport and the assignment of a probability of occurrence to these transit times.

The disadvantage of small scale tests is that they are time consuming if statistically significant numbers of fractures are to be tested. Furthermore, single fracture tests are dominated by conditions near the well bore.

Larger scale tests (packer spacing greater than 10m) smear the effects of the individual fractures and are intended to give a permeability of a volume of rock more representative of the rock mass. Bear's (1972) concept of a representative elementary volume (REV) is useful in determining what size of test should be done. Tests of volumes smaller than the REV show large variations in value; tests of volumes larger than the REV are more constant. The results of sequential tests along a borehole are additive and may be cumulated to determine the REV. Larger scale tests should have the following functions:

- When done over the entire length of each borehole at ∿10m spacing, they can be used to determine the size of the REV and, crudely, the spacings of major fractures (Snow, 1968).
- They can be used to verify permeability conclusions based on small scale tests.
- Only large scale, cross-hole tests can be used to evaluate continuity within large rock volumes.

The major types of permeability tests are discussed in detail below. The types of data which can be derived from the various tests are summarized in matrix form on Table A-2.

iii. Pump Tests, Ratio Tests

Pump tests are the most widely used type of permeability test. Standard pump test analysis follows the classic solutions of Theis (1935) for

TABLE A-2

PERMEABILITY DATA - TEST MATRIX

Test[1]	PERMEABILITY			STORATIVITY
	Horizontal	Vertical	Complete Tensor	
Pumping Withdrawal Tests				
Constant Discharge (Standard)	X (5)			X (2)
Constant Discharge (Ratio)	X (5)	X (7)	X (5)	X (2)
Constant Drawdown (Standard)	X (5)			X (2)
Constant Drawdown (Ratio)	X (5)	X (7)	X (5)	X (2)
Steady State Injection Tests				
Large Scale	X (5)			X (2)
Small Scale	X	X	X (3)	X (2)
Slug Tests	X			X (6)
Pulse Tests	X	X	X (3)	X (4)

(1) All tests are single hole tests unless otherwise noted.

(2) Determination of storativity (storage coefficient) requires response at an observation well.

(3) Determination of complete permeability tensor through small-scale injection requires a large number of tests on single fractures of known orientation.

(4) Storativity may be approximated from the elastic response of the system to pressures of varying magnitude.

(5) The horizontal two-dimensional permeability tensor may be determined if drawdown data from a number of observation wells were available. Otherwise an effective radial permeability is obtained. When combined with results of ratio tests, a three-dimensional permeability tensor may be determined for confining layers.

(6) Slug or bailer tests are generally insensitisve to storativity but may be used to approximate this parameter in a well of constant diameter.

(7) Vertical permeability may be estimated for relatively impermeable layers above or below an aquifer.

confined aquifers and Hantush (1956) for leaky confined aquifers.

The procedure involves withdrawing water from a well, maintaining either a constant discharge rate or a constant drawdown. Levels are monitored in the pumped well and in observation well(s). Tests involving either stepped or continuously varying discharge can also be analyzed, but generally with some loss in accuracy. After pumping is ended, water level recovery can also be monitored and yields the same type of permeability data as the drawdown portion of the test.

Standard pumping tests yield data on horizontal permeability, and, if an observation well is available, storativity may also be measured. If the permeability of a particular stratigraphic zone is required, the part of the well within that zone must be isolated with packers, and water pumped only from that zone. The same zone must also be isolated in the observation well if a meaningful measure of storativity is to be made. These procedures are most successful if the stratigraphic zone being tested is relatively more permeable than the zones immediately above and below.

Standard pump test assumptions include complete aquifer penetration, radial flow, and homogeneity and isotropy on the part of the aquifer. Where penetration is incomplete, results are generally considered valid provided the horizontal permeability is significantly greater than the vertical, thus assuming radial flow.

Pump tests are limited to higher transmissivity formations, and have historically had a limited application to fractured rock. Although methods for interpretation of pump tests are now being developing (Gringarten and Witherspoon, 1972), the problems of application to massive basalt are twofold. First, vertical flow is likely to be significant, especially in the colonnade, hence radial flow solutions are not applicable. Second, low transmissivity formations have significant wellbore storage, which renders the early part of the drawdown data unusable. A test using the configuration shown in Figure A-6 may have a significant pumping period before wellbore storage is overcome, depending on transmissivity. For a typical transmissivity of $10^{-3} cm^2/s$, 33 days will be required. Because of these two problems, pump tests appear inapplicable for direct use on the massive basalts.

The more permeable flow tops and interbeds, on the other hand, are ideal for pump testing provided their transmissivities are greater than about 10^{-2} cm^2/s. Such stratigraphic units lend themselves to porous

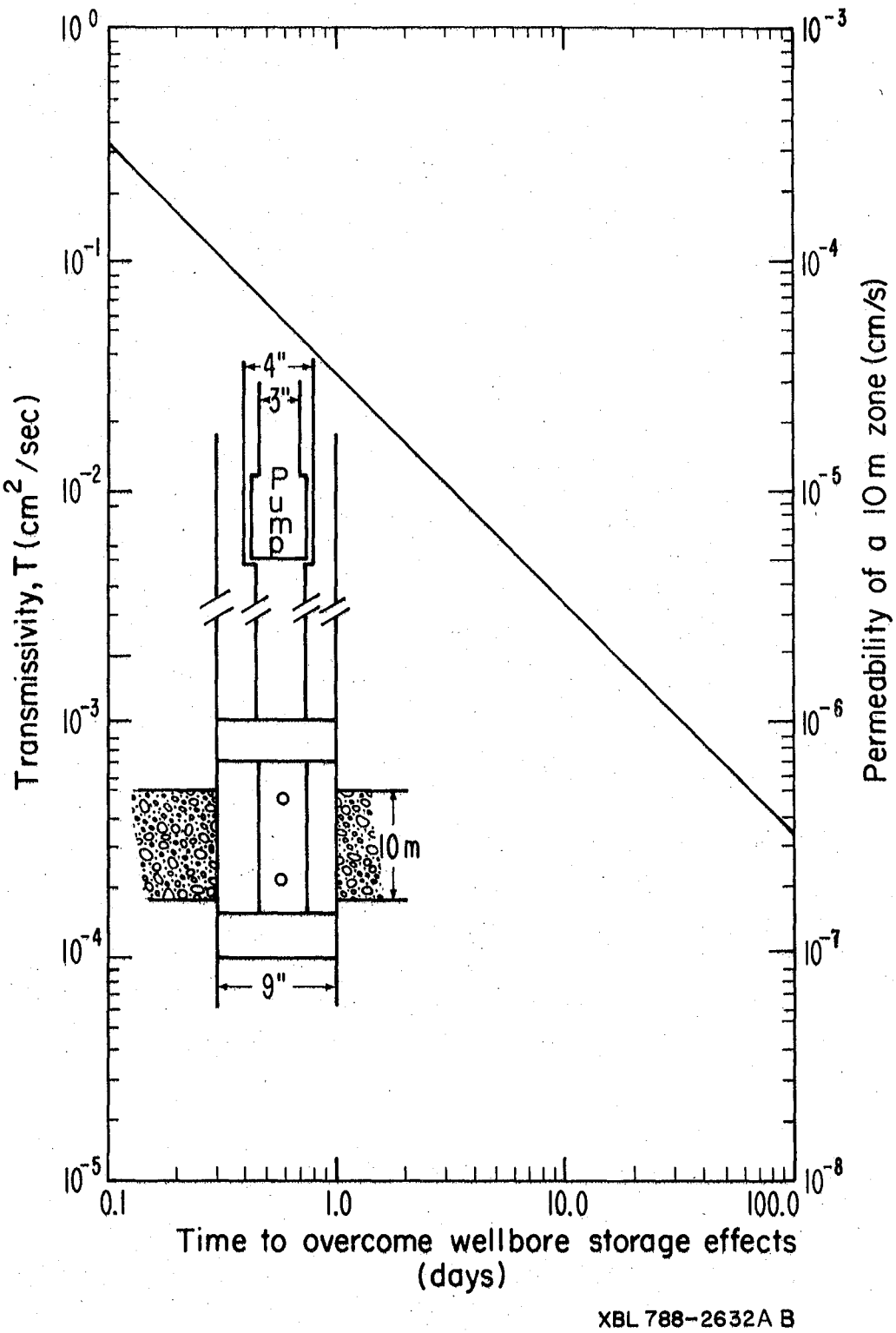

Figure A-6. Persistence of wellbore storage effect.

media type analyses.

A useful variation of the standard pumping withdrawal test is called the ratio test (Neuman and Witherspoon, 1972). This variation permits a measure of vertical permeability in the less permeable zones above and below the pumped aquifer when the permeability contrast between the zones and the aquifer is so large that flow in the less permeable zones becomes essentially vertical. Vertical permeability is obtained by measuring the change in water pressure in these zones while the aquifer is being pumped. This water pressure change must be measured in isolated zones in either the pumped well or in an observation well. A schematic drawing of the ratio test downhole equipment is shown on Figure A-7.

Pump tests can provide a measure of vertical fracture continuity not only through the ratio test analysis but also through analysis of observation well response by leaky aquifer methods. Another way of obtaining vertical permeability in vertical wells is to do injection testing in the non-horizontal fractures intersecting those wells.

Time required for ratio testing is currently being studied numerically at LBL. It is doubtful that a ratio test would last less than two weeks based on preliminary analysis. Due to the time involved in each test, applicability of pump-ratio tests might be limited to highest priority zones, specifically flow tops bounding or near the Umtanum.

The system LBL has proposed consists of a submersible pump with a pressure transducer level indicator in the pumping well, and a multiple packer system instrumented with transducers to monitor pressure in the aquifer and zones above and below the aquifer (Figure A-7). The zone to be pumped will be isolated with packers on 2 7/8" tubing. The upper 1000 feet of the string will need to be 4" I. D. tubing to allow installation of a Reda Submersible pump capable of 100 feet of lift. This pump will be lowered into the 4" tubing on 2 7/8" tubing. A constant flow regulator will be installed at the surface and will recycle part of the pumped water back into the 4" tubing to maintain the flow rate. Details of this flow regulator are in Gale (1975).

The observation well will contain a four packer string with three pressure transducers to monitor zones in, above, and below the aquifer. The system will contain solenoid valves to bleed off any pressure built up due to packer inflation. Discharge will be monitored using an electronic flow transducer. All data will be recorded on a data logger capable of sampling

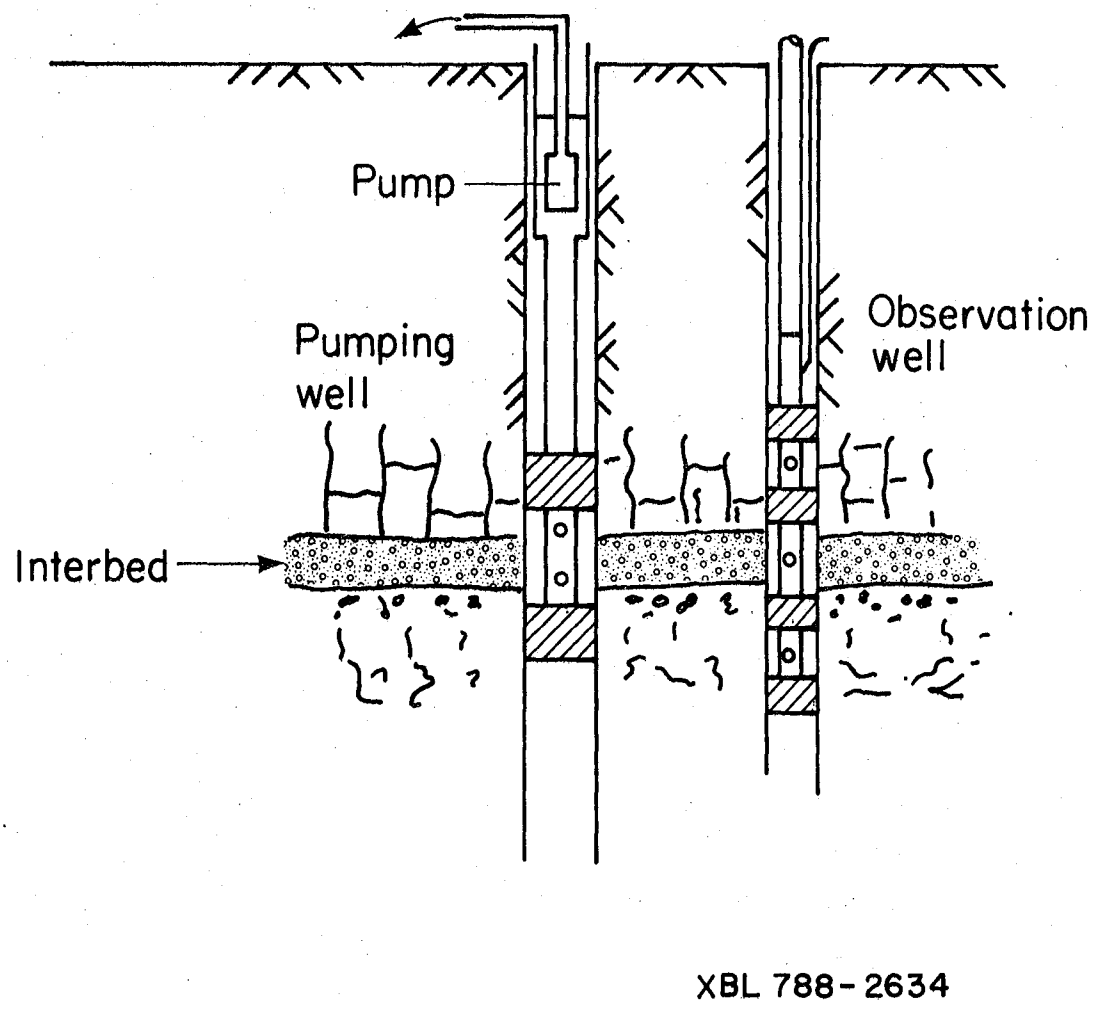

Figure A-7. Schematic equipment configuration for ratio test.

all data channels at programmable intervals and transferring the data to computer compatible format.

iv. Steady State Injection Tests

Steady state injection tests are the most commonly used tests in evaluating crystalline rock permeability for engineering investigations. They are extensively discussed in Zeigler (1976), Snow (1966, 1968), Louis and Maini (1970) and Banks (1972). Alternate names for the test include Lugeon test and pressure test.

Procedures consist of injecting water between packers at constant pressure. When the flow rate becomes constant, it is assumed steady state has been reached and the pressure is increased to obtain another steady state flow. Three to six such points are obtained. Ideally the pressure-flow rate curve should be linear; non-linearity may be caused by fracture deformation, turbulent flow, or packer leakage (Louis and Maini, 1970). Permeability can be calculated based on any one data point on the linear portion of the curve.

Steady state injection tests can be used with any packer spacing--large spacing for gross measurements, small spacings for single fractures or other features. Solutions exist for rock mass permeability in large tests or fracture aperture in small tests. Steady state tests have been used for permeability stress-depth determinations (Davis and Turk, 1964), anisotropic permeability from multiple oriented holes (Louis and Pernot, 1972; Snow, 1966), and to determine spacing of major fractures (Snow, 1968).

Drawbacks include such factors as uncertainty over whether steady state is indeed reached and the dominance of near-field fracture characteristics due to the rapid pressure drop away from the borehole. These tests can be run quickly and the amount of time required for testing does not depend on permeability. The lower limit of permeability depends on the ability to measure flow rate. Equipment already obtained by LBL can test permeabilities as low as 5×10^{-9} cm/s based on a 10m packer spacing. The steady state injection test is best when used as a reconnaissance test, with large packer spacings (10 to 15 meters), for testing the entire length of each borehole. This approach assures no major flowpath has been overlooked and provides a measure of the distribution of hydraulically significant fractures. To be most effective, holes of at least three different orientations are essential (Snow, 1966).

Based on a testing rate of three to four tests per day, complete testing of the open part of boreholes DC-4, DC-6, and DC-8 would require one month each.

Small scale tests can be used on single fractures to determine anisotropic permeability. The current lower limit of effective fracture aperture detection is about 10μ and single fracture tests should be limited to zones of greatest interest. Based on a testing rate of three to four per day, sixty to eighty tests can be run in a month. Fractures to be tested are chosen on the basis of core analysis and preliminary aperture surveys with TV log or televiewer.

The current system designed by LBL (Figure A-8) consists of a double packer assembly with packer spacing mounted below an electronics package containing a pressure transducer for injection pressure and packer pressure, a solenoid valve for packer deflation, and a temperature sensor.

Once the solenoid valve is field proven, two more packers will be added to isolate zones above and below the test zone. Each of these packers will be monitored to check for leakage. When the packers are inflated, the zones, if of very low permeability, are pulsed at 200 to 300 psi. Because this pressure must decay before a reading can be taken, solenoid valves will be installed to each zone to bleed off this pressure.

A possible variation of this instrument which may be fabricated is the four packer system of Louis (Sharp, 1970). Water is injected into all three zones but flow is measured only in the central section (Figure A-9). The purpose of the apparatus is to assure that only radial flow is monitored. Louis' system is bulky due to the need for separate injection lines for each of the zones. This can be avoided by installing an electronic flow meter downhole and dividing the injection fluid at the tool.

v. Slug Tests

Slug tests consist of the instantaneous addition or withdrawal of water from a well or the packed-off zone of a well and monitoring the transient head response (Cooper et al., 1966). Type curves vary only slightly with storativity; hence permeability is the only value that can practically be computed.

Because slug tests are generally of short duration, the results, as with steady state injection tests, tend to be representative of the materials close to the well. It is therefore important that the well be fully

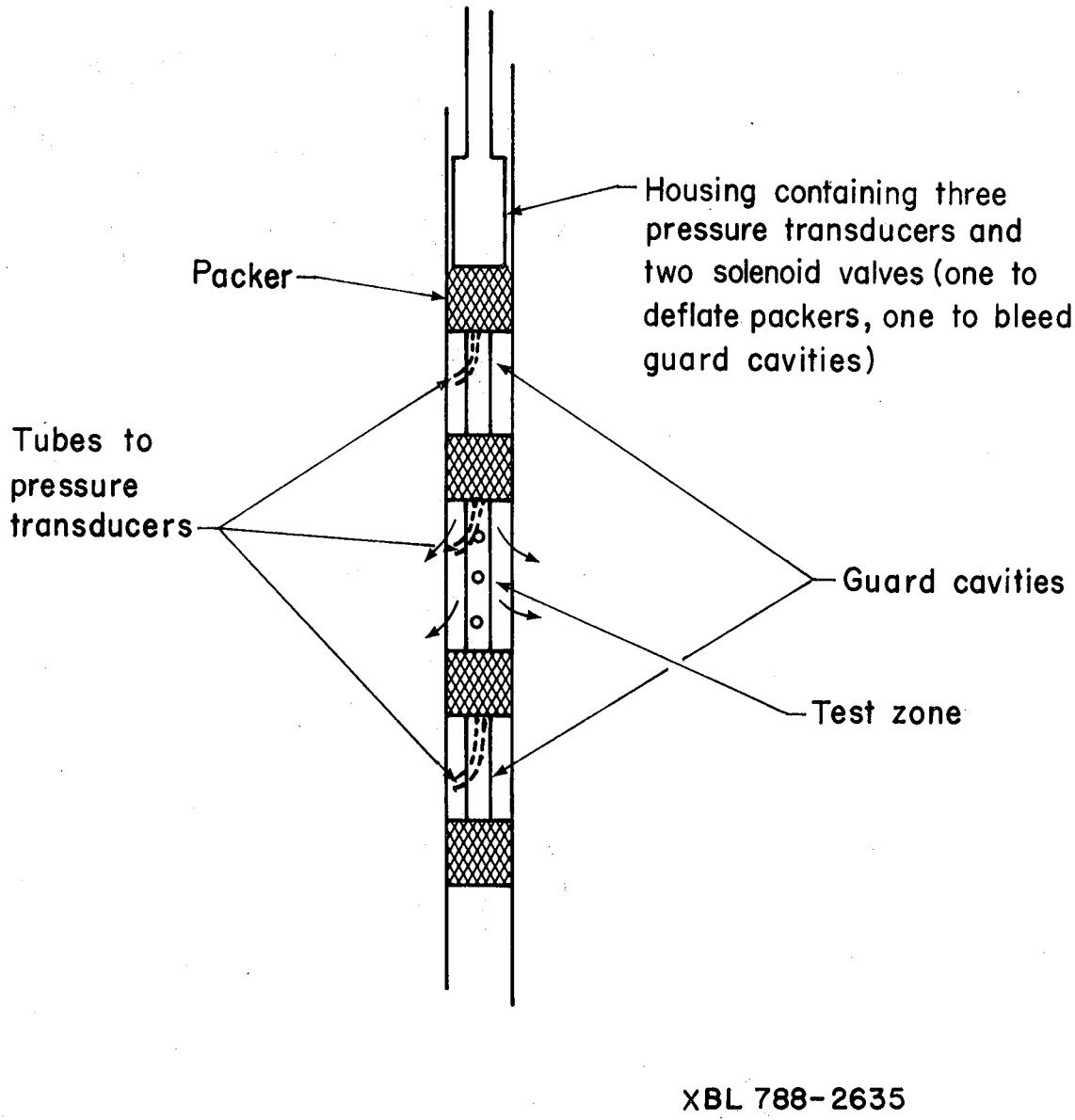

Figure A-8. Four-packer system to detect packer leakage.

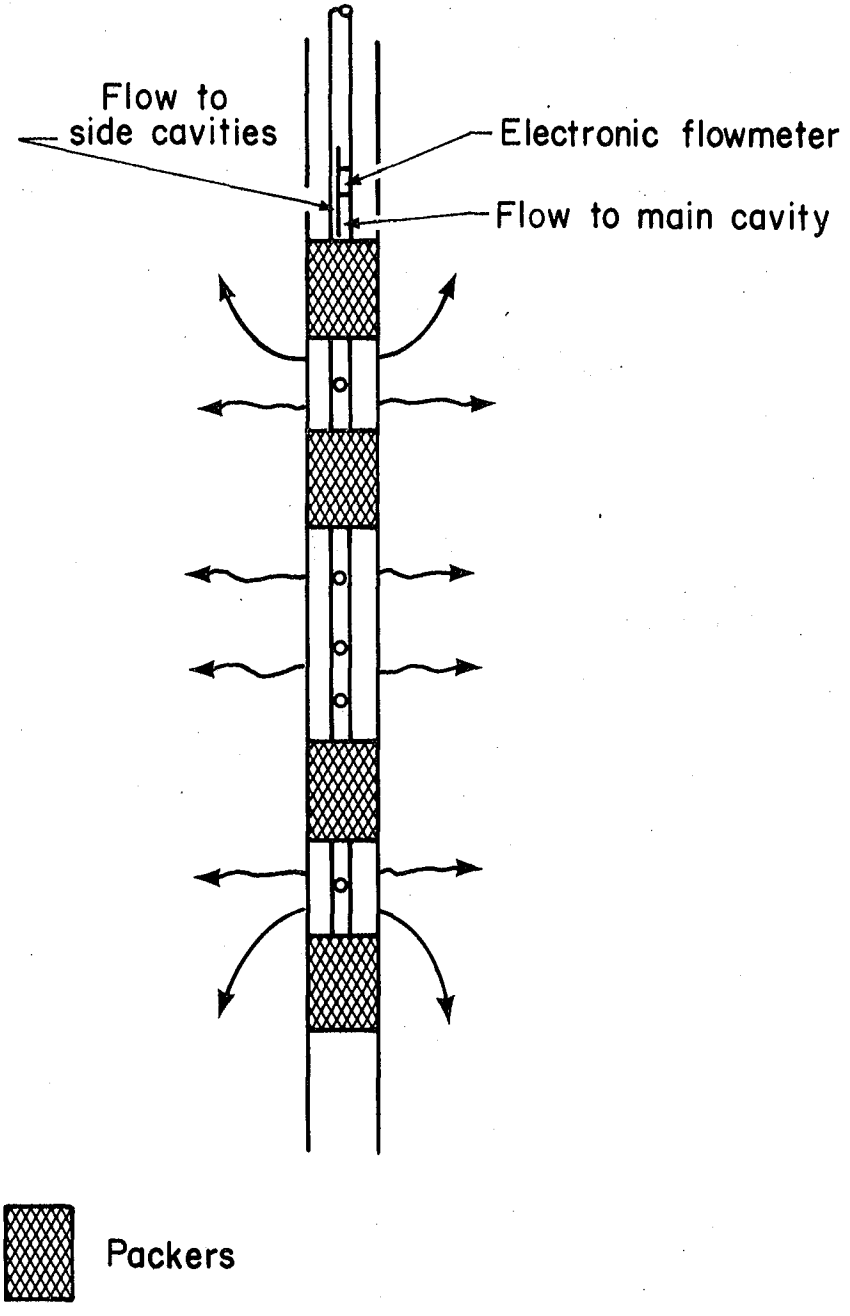

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Figure A-9. Three-cavity injection test to assure radial flow.

developed. Slug tests in formations of very high permeability tend to decay so rapidly that meaningful data cannot be obtained, while those performed in formations of low permeability may require an exceptionally long time to decay. Decay time versus permeability for a 10m test interval is shown in Figure A-10. A rock of transmissivity of 10^{-4} cm^2/s would require about 6 days to test.

The standard analysis of slug test data is, like pump test data, based on complete penetration of a confined aquifer. Papadapoulos et al. (1973) urge caution in other applications, especially where the horizontal permeability is not significantly greater than the vertical. This factor must be recognized when running slug tests on fractured basalt. The downhole test equipment is identical to that of the steady state injection test. As with other injection tests, four packer systems will provide assurance against undetected packer leakage.

vi. Pulse Tests

This test was specifically designed (Wang et al., 1977) for rapidly measuring hydraulic conductivity within single fractures of very low conductivity. The test involves monitoring the decay of an instantaneous increase in pressure within a small isolated interval of the wellbore containing a single fracture. This test differs from the standard slug test in that the pressure decay being measured is that of a small volume of water within the isolated interval of the wellbore rather than the slowly declining head of a large column of water feeding into the interval. The pressure decay in the pulse test is due solely to the compressibility of water stored within the isolated interval of the wellbore. The time required for 10% pressure decay in pulse tests vs. permeability is shown in Figure A-11. A permeability as low as 10^{-10}cm/s can be tested in less than one hour.

Early data from the pressure pulse test may be used to measure hydraulic conductivity, while later data give an indication of fracture geometry beyond the wellbore. The results of a number of tests performed on single fractures of different orientations can provide an estimate of the three-dimensional fracture permeability tensor in the same manner as for the small injection tests. The two tests are, in fact, complementary because the upper limit of accuracy for the pressure pulse test coincides with the lower limit of accuracy for the small injection test.

The LBL pressure probe may be useable as a pulse tester. The probe

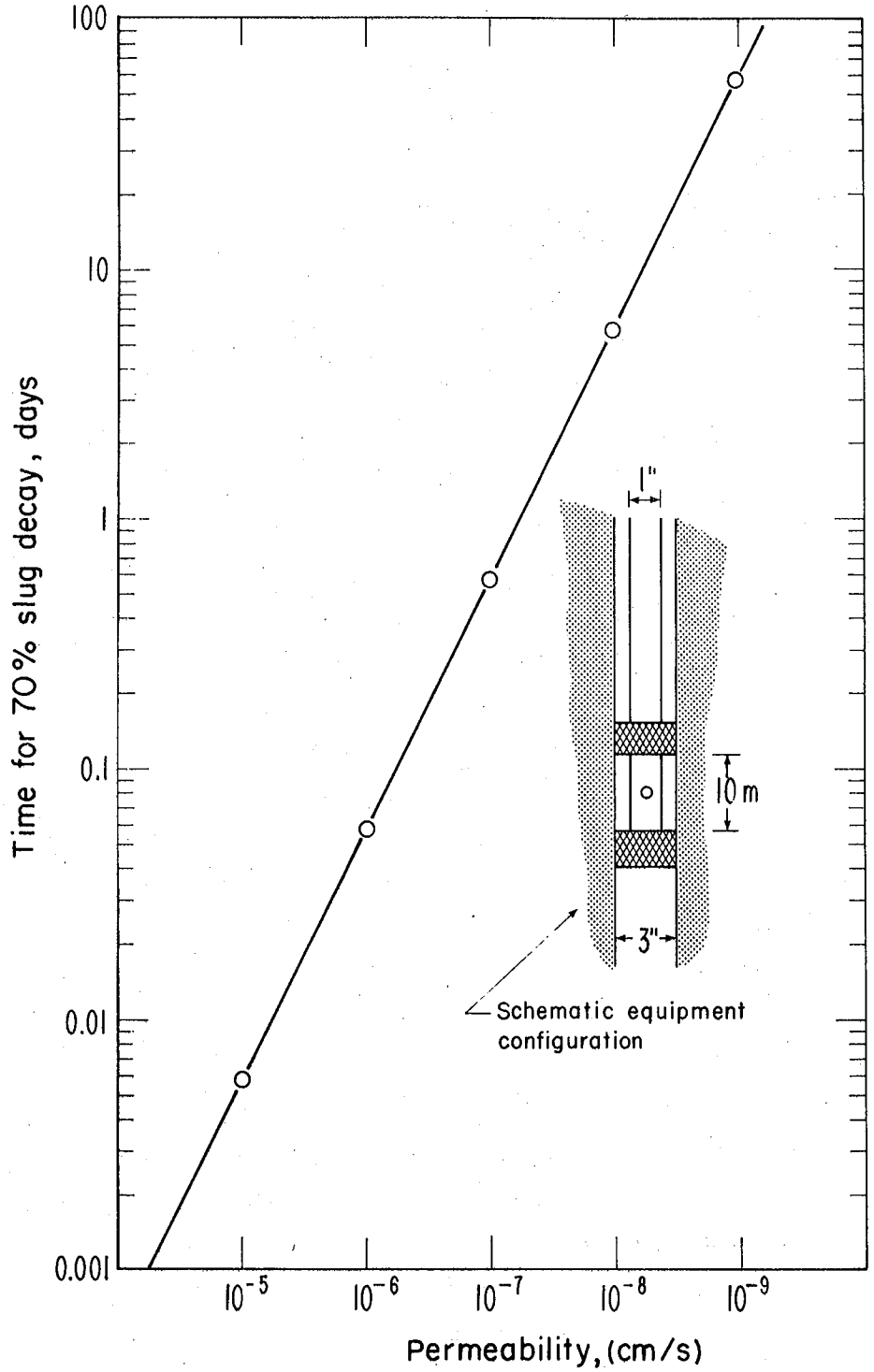

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Figure A-10. Time required for pressure decay in slug tests.

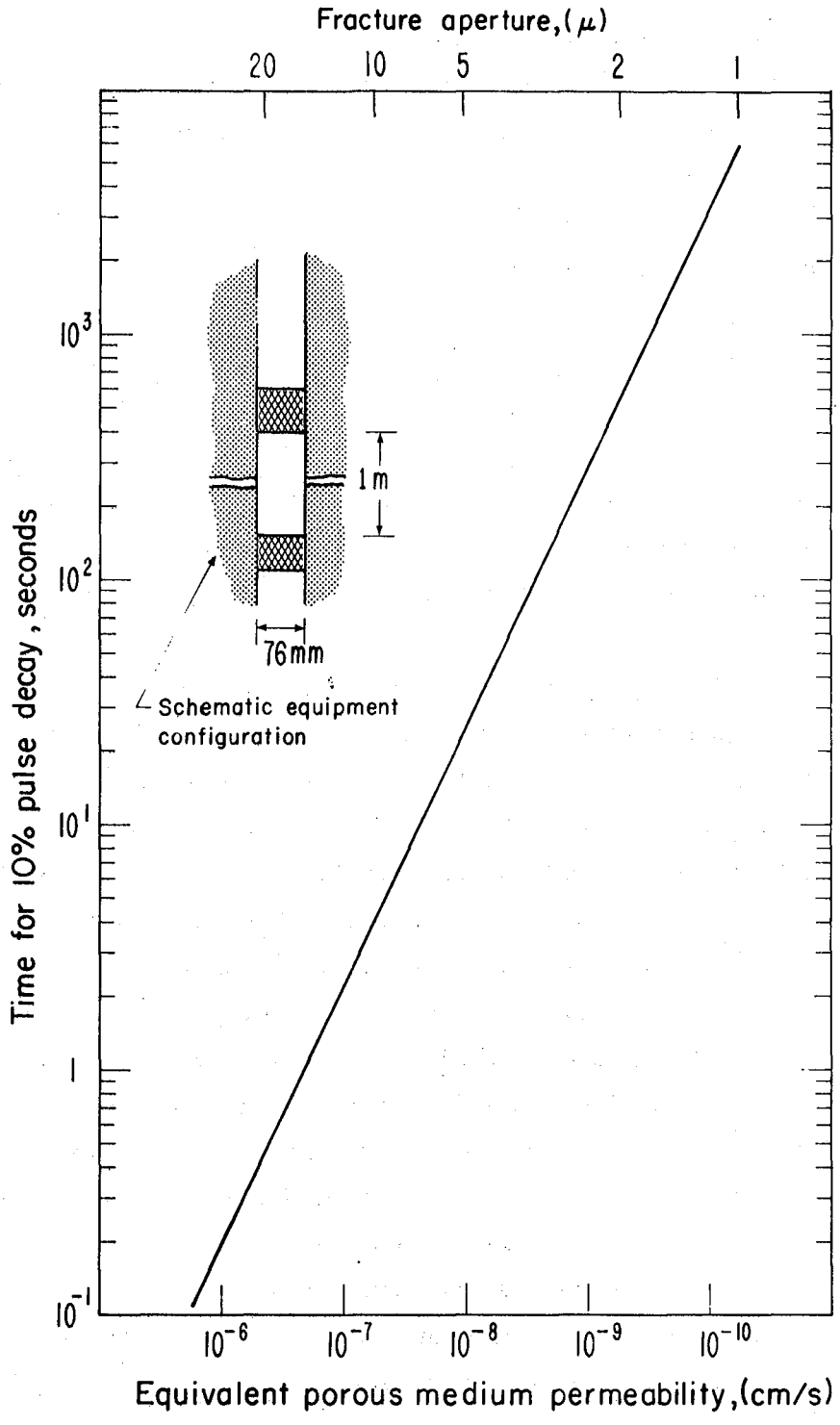

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Figure A-11. Time required for pressure decay in pulse test in fractured rock for test geometry in insert.

contains a solenoid valve between the test zone and the drill pipe. By pressurizing the pipe with the valve closed and then quickly opening and closing the valve, a pulse will be generated which may be interpretable by Wang's curves. Laboratory testing of the tool using the simulated borehole developed by Dr. John Gale at the University of Waterloo may be required to prove the concept.

d. Pressure Measurements

i. Introduction

As Darcy's law states, fluid flow is dependent on pressure gradient. Measurement of pressure, or hydraulic potential, provides basic information for determining in three dimensions the direction of groundwater transport. Such measurements provide, as well, qualitative insight into the hydrologic role of geologic features such as faults, folds, and fracture systems.

ii. Procedures and Equipment

Quantitative hydraulic potential data have been traditionally gathered through the measurement of water levels in standpipe piezometers. These piezometers consist of either a single open well cased to the zone of interest or a well with individual standpipes open to isolated zones of a single well. Standpipe piezometers have the following drawbacks:

- High cost for each sampling point.
- Difficulty of obtaining large numbers of sampling points.
- Long time periods to achieve stable values.

Qualitative hydraulic potential can be obtained through spinner logs or radioactive tracer logs, which provide information on the vertical movement of water in the well. The direction of movement indicates the direction of the vertical component of potential gradient. This information is qualitative and does not allow comparison of absolute potential values between wells. It cannot therefore be used to determine the magnitude or direction of horizontal pressure gradient.

Packer systems with downhole pressure transducer are an alternative to standpipe piezometers. In these systems packers are used to isolate a zone of a borehole; a pressure transducer in the closed interval is used to determine hydraulic potential. In standpipe the attainment of a stable value requires movement of a volume of water equal to ΔHA_w where ΔH is

the head difference between the standpipe and the formation and A_w is the standpipe cross section area. In packer systems, the volume of water in the packed off section does not change. Only a small mass from exchange will equilibrate pressure since the compressibility of water is very low. Equilibration of pressure is rapid.

The system used by LBL for pressure measurement consists of double inflatable packers with a housing containing a pressure transducer (Figure A-12). A separate small diameter inflation line for the packers allows resetting of the tool at different zones without removing it from the hole. An electrical line provides continuous pressure readout at the surface. Equilibration time can be lengthened by the pulse of pressure caused by packer inflation. The magnitude of this pulse increases with decreasing permeability of the zone being tested. A typical record of such a test including the inflation pulse is shown in Figure A-13. The LBL pressure measurement system solves this problem by including a solenoid valve to bleed the pressure from the test zone after packer inflation.

The basic advantages of packer systems are:

- Less time required to reach a stable value.
- Ability to do a large number of zones in a single well.

Major uncertainty in pressure measurements centers on criteria established for deciding when a stable value equal to the undisturbed hydraulic potential has been reached. As soon as well drillers penetrate a zone the hydraulic potential at the wellbore is disturbed. Initially the disturbance is due to the injection of drilling fluids under higher pressure. After the well is completed, perturbations are due to communication between intervals of different initial potentials within the wellbore. The radius of influence of these perturbations, extends radially with time. Therefore the longer the well has been open, the longer the period of time required to achieve a reading of the undisturbed pressure in any given interval. In such wells, it is possible to quickly determine the relative pressures in each interval; however the time required to reach the undisturbed value is difficult to predict.

The solution to this problem lies in taking pressure measurements over two time intervals. In the first, pressure measurements for a given zone are made as soon as possible after the zone has been penetrated by drilling. This requires building into the drilling program frequent pauses for testing. In the second, measurements will be made during long term monitoring

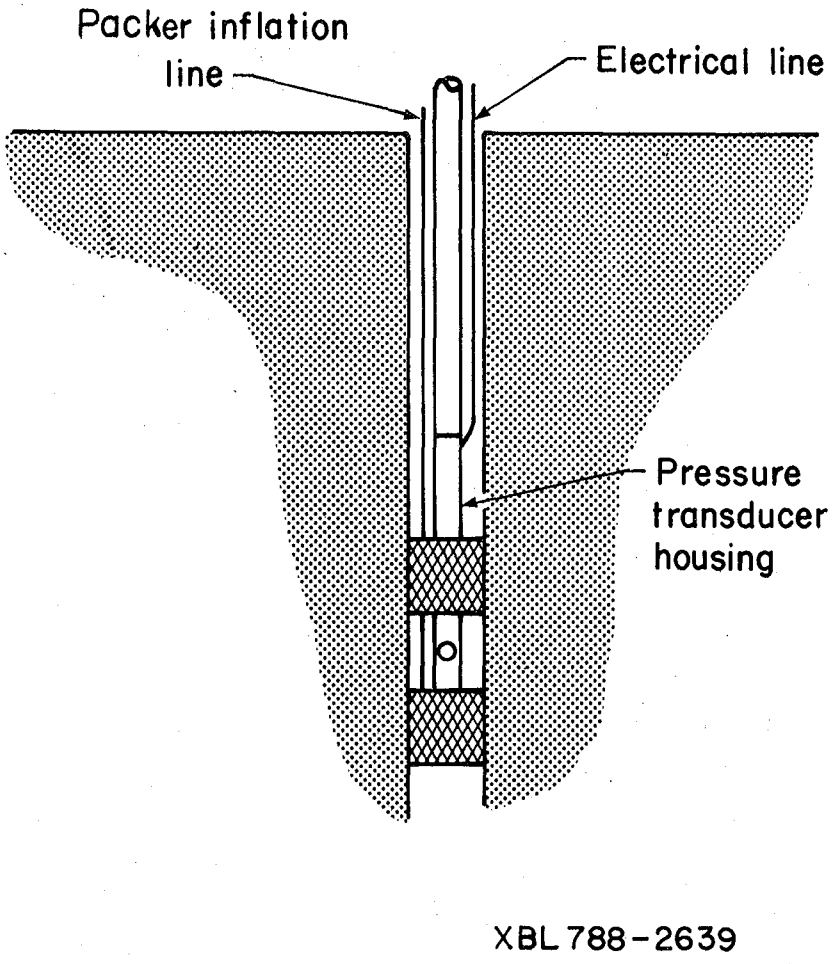

Figure A-12. Schematic pressure measurement instrumentation.

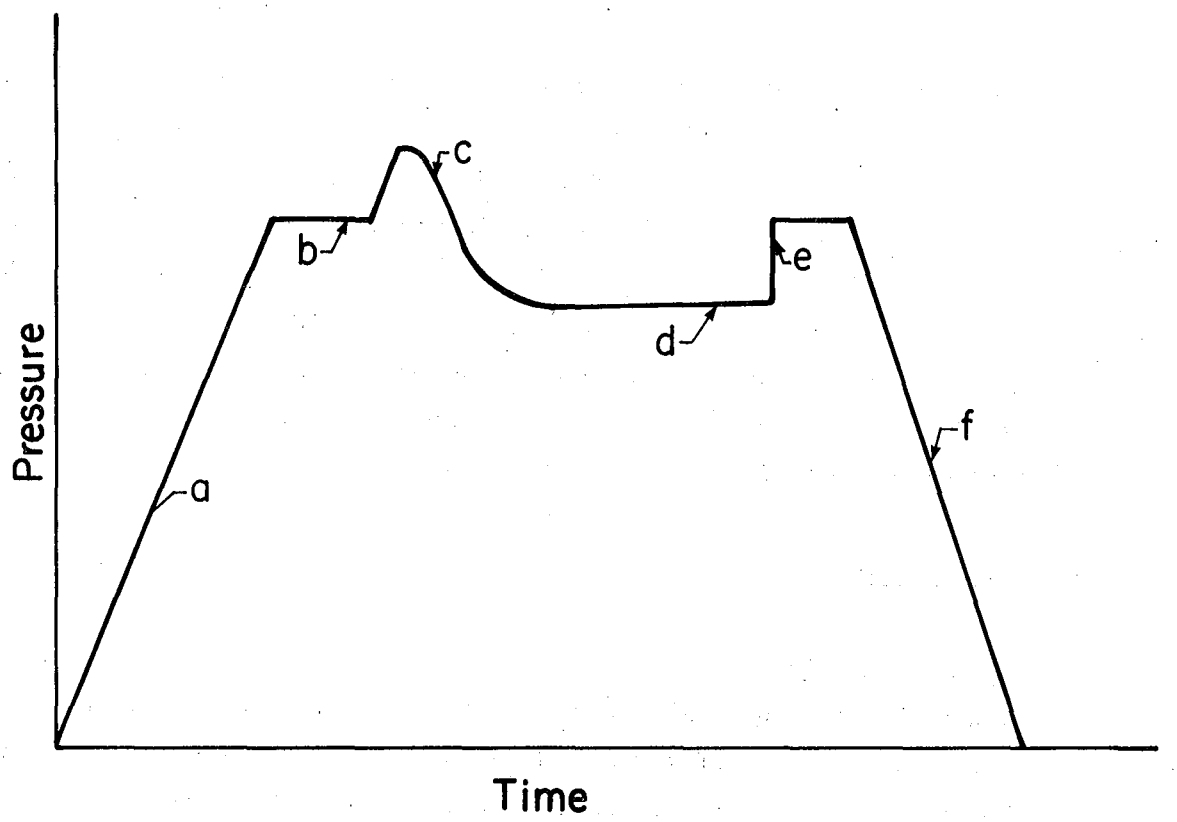

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Figure A-13. Typical pressure test record
a. running into hole
b. reach test zone
c. inflate packers
d. reach stable pressure
e. deflate packers
f. running out of hole

of the well after all other testing is complete. Equipment specifications and procedures for this testing are included in the section on monitoring.

iii. Time Required

The actual duration of a pressure measurement once the packers are set can be anything from a few minutes to a few days depending on the permeability of the rock, the period of time the well has been open, and factors of equipment design (e.g., packer inflation pulses). In addition, three to six hours should be allowed for running the tools in and out of the hole. As an alternative to taking pressure measurements after the hole is completed, pressure measurements could be obtained at specific intervals by interrupting the drilling process. Depending on the permeability, such tests would require one to two days each.

e. Tracer Tests

i. Introduction

Depending on the configuration of wells available, tracer tests can be used to obtain values of permeability, effective porosity, local water flux and dispersivity. By using radionuclides along with conservative tracers it may be possible to obtain in situ values of the partition coefficient. Tracer arrivals can also indicate the degree of continuity between fractures.

Permeability can be obtained from a hydraulic test, thus the need to know permeability alone does not justify doing a tracer test. Effective porosity, however, is difficult to measure in situ in any other way. Effective porosity is needed for calculation of particle velocities where the water fluxes are known, thus it is a necessary parameter in calculating the arrival time of contaminants. Local values of water flux can be measured directly with tracers. The measurement of dispersivity will probably not be important to regional hydrology but could be useful in site specific studies at a later date.

There are, however, major problems with tracer tests. In fractured media the results may be difficult to interpret because the actual flow paths cannot be readily defined. It may be possible to overcome this problem by doing the test on a large scale so that the effects of individual fractures are averaged and an equivalent porous medium can be assumed. However, large scale tests may take years to complete and in low perme-

ability rocks tracer tests may be completely impractical. Alternatively, it may be possible to do tracer tests on individual fractures or a small number of fractures that have been packed off. Interpretation of the test would then be easier but a large number of tests would be needed to obtain representative values.

Tracer tests should be approached cautiously and on a site specific basis. As much as posssible should be learned about the local hydrology before a tracer test is chosen and performed. Permeability should be measured and the geometry of the system described as fully as possible. When this has been done, two major configurations of tracer tests can be considered: one well tests and two well tests.

ii. One Well Tests

The one well tests are the point dilution test and the pulse test. In the point dilution test a tracer is introduced into a packed-off section of a quiet well, and the decline in tracer concentration is monitored. Dilution of the tracer is be due to flow of water through the well under the natural gradient. The magnitude of the natural Darcy velocity and water flux can be calculated. If either porosity or fracture aperture is known the particle velocity may be calculated. If a tracer such as strontium is used and an absorptive well screen is placed between the packers, the well screen can be pulled up after the test and analyzed for the location of greatest strontium concentration. In this case both the magnitude and direction of flow can be measured.

In the pulse test water containing a tracer is pumped into a well for a certain amount of time. The well is pumped out at the same rate and the concentration of tracer in the effluent is monitored. If a conservative tracer is used the shape of the concentration vs. time graph will yield a value for dispersivity. If both a radionuclide and a conservative tracer are used it may also be possible to determine the partition coefficient for the radionuclide.

There is a distinct advantage associated with single well pulse tests in fractured media as opposed to two well tests. The flow path into the well is just the reverse of the flow path out. In a two well test there will in general be uncertainty about the flow path between the two wells.

iii. Two Well Tests

There are three possible two well tests: divergent flow, convergent flow and doublet flow. In the divergent flow test water containing a tracer is pumped into one well and concentration is monitored in the other. In the convergent flow test tracer is supplied at a low rate in a hole some distance from a pumping well. In the doublet test one well is pumped and one is injected at the same rate with tracer being added to the injected fluid and monitored in the pumped fluid. For all three tests the induced flow rate must be much larger than the natural background rate. For simplicity of analysis and conservation of the tracer the convergent flow test is preferable to the other two. However, the doublet test is faster given the same pumping rate. All three tests will provide values of permeability and porosity.

A major problem with two well tracer tests may be the difficulty in analyzing results in a fractured media. In this case it may only be possible to obtain qualitative results as to the degree of hydraulic connnectivity between fractures.

iv. Time Requirements

The time required to do tracer tests in high permeability formations may be quite reasonable, but in low permeability formations years may be required to get a result. However, by not getting results over a certain time period it may be possible to assign upper bounds to the permeability or velocity.

v. Choice of Tracer

The choice of tracer determines the type of sampling and analytical system necessary and the cost of monitoring. Tritium must be analyzed off-site at approximately $200 a sample. Dyes or fluorocarbons could be analyzed on site at much less cost. There are many factors to be assessed in the correct choice of a tracer. The most reliable, sensitive tracers on site that can presently be analyzed are fluorocarbons which can be detected with gas chromatography. This technique would be adaptable to a wide range of synthetic fluorocarbons. Several fluorocarbons could be used simultaneously which would allow monitoring of several effects at once. Tritium may be practical for long term tests requiring infrequent sampling.

vi. Equipment needs:

The following equipment would be necessary for performing tracer tests:

- o Tracer injector system and flow detection screen in a packed off zone:
- o Downhole sampler and winch or pump for bringing samples to the surface;
- o Field laboratory for sampling and analysis;
- o Gas chromatograph and extraction system coefficient for the radionuclide.

f. Geochemical Sampling and Analysis

i. Introduction

Subsurface waters on the Pasco Basin should be sampled and analyzed in order to determine their origin and history. This can be accomplished through coordination with other projects involving hydrological and modeling studies to establish the flow paths of subsurface waters in the Pasco Basin, and also through detailed mineralogical studies of the chemical alteration of Hanford basalts and associated rocks.

The subsurface waters should be obtained from specified horizons from existing and new deep wells drilled through the basalt horizons on the Hanford Reservation and vicinity. Selected horizons within these wells should be sampled, primarily from (but not necessarily restricted to) the Saddle Mountains, Wanapum, and Grande Ronde basalt formations. In addition, samples should be obtained from springs and artesian wells, and other water sources that may require analysis for interpretive purposes.

If lost-circulation materials or other techniques are not employed during drilling, extensive invasion of the aquifer by drilling fluids can occur. Calculations given in Section 2b indicate that as much as 10 days of swabbing may be required in order to obtain a sample of sufficient size relatively free of contamination. Although insufficient work has been done to date to verify that this amount of swabbing may be required, it is clearly possible that such may eventually prove to be the case. Sampling techniques for subsurface waters should be modified to take into account the problems resulting from prior drilling and the use of swabbing. This should be accomplished through:

- Quantification during sampling of the degree of contamination due to sampling procedures.
- Additional time for sampling a given horizon to insure freedom from contamination.

iii. Alternative Sampling Techniques

Improved downhole sampling techniques, such as the use of samplers designed specifically for recovery of fluids from the formation as opposed to the wellbore, and specially engineered samplers to collect large samples (several liters) from packed-off intervals within the wellbore, should be investigated. Downhole pumps, either at the level of the formation to be sampled or at other levels below the hydraulic head of the formation, may also alleviate the sampling problem. Special downhole samplers will be required for gas analyses, even if swabbing continues to be the only practical process for water sampling, because of the danger of contamination from the atmosphere.

iv. The Use of Non-adsorbing Tracers During Drilling

To measure the concentration of contaminants in the groundwater sample, a chemical tracer that can be detected by simple procedures in the field must be added to the drilling fluid. The tracer should possess the following characteristics:

- It should be readily detectable at very low concentrations by simple procedures in the field.
- It should be chemically stable, i.e., it should persist without significant decomposition for at least the interval between drilling and subsequent sampling.
- It should be chemically inert, i.e, it should not be adsorbed on the rock, or react chemically with rock or with other groundwater components.
- It should not occur naturally.
- It should remain with the drilling fluid, and not partition or separate by diffusion or by phase separation.
- It should be cheap, readily obtainable, non-toxic, and easy to add to drilling fluids in the field.

Fluorocarbon compounds miscible with water appear to possess the required properties, and may prove to be ideal tracers. A technique is under develop-

ment by Glen Thompson of the University of Arizona, Tucson, Arizona, to use gas chromatographs for detecting fluorocarbon tracers at the PPT level after stripping by helium from the water. This method possesses the disadvantages of not allowing continuous monitoring, although samples may be processed at 10 minute intervals. A continuous monitoring technique for fluorocarbon tracers, using diode laser and/or Raman Spectroscopy has been proposed, and may be developed as part of an independent LBL project.

v. Quantification of Contamination Due to the Sampling Procedure

Analytical techniques have increased both in precision and sensitivity to such an extent during the last decade that the weak link in the data gathering process is now the sampling procedure. In order to evalute the effect of sampling on sample contamination, various potential contaminants should be investigated in the laboratory and their effect on subsurface water sample integrity quantified. Potential sources of contamination include:

- o drilling muds and detergents;
- o grease, pipe dope and lubrication fluids;
- o rubber packers, swabs, metal tubing, and housings filters;
- o sample bottles and handling procedures.

Contamination can be studied through a series of leaching studies using either Hanford groundwater or synthetic fluids corresponding closely in composition to Hanford groundwaters. Experiments should be conducted at 120°F to simulate sampling temperatures. During the leaching process, periodic solution samples should be taken for analysis for such trace elements, as Zn, Pb, Cu, Fe, Mg, Si, Ca, and Al. Partial to complete chemical analyses should be made of potential contaminants in order to identify those elements that are more likely to affect the groundwater composition.

vi. The Uses of Chemical and Isotopic Analyses

The chemical and isotopic composition of a groundwater provides much information that can elucidate the origin, age and subsequent history of the water. To get this information successfully requires a number of samples taken from various parts of the aquifer system. In addition, the groundwater hydrology, including the direction of flow, expected flow rate, and magnitude of flow must be known.

Chemical analyses of groundwater in the aquifers can be used to:

- o Estimate the temperature of the water at its point of origin.

- Identify trace elements characterizing specific horizons.
- Infer mixing between aquifers.
- Determine if the water has been subjected to higher temperatures.
- Establish the degree of equilibrium with the country rock matrix, and to correlate with coexisting alteration products.
- Determine the nature of chemical reactions likely to proceed between the groundwater and the country rock, thereby providing support for interpreting isotopic data for age determinations.

Isotopic analyses of groundwaters can be used to:

- Estimate the apparent age of the water.
- Determine the source of the water.
- Estimate the origin of the water in terms of temperature, contact or reaction with organic materials, geographic location, and climate.
- Interpret the extent that chemical reactions and/or mixing have occurred during transit through the aquifers.
- Establish relative ages.
- Identify boiling or vapor phase separation.

g. Hydraulic Fracturing

i. Introduction

Hydraulic fracturing is the only generally accepted method of obtaining in situ stress values at great depth in boreholes. The basic method as discussed by Haimson and Fairhurst (1970), and Kehle (1964), consists of isolating an unjointed section of a borehole and pressurizing it with water until a fracture is generated. The pressure required to first maintain the opening of the crack, is theoretically equal to the minimum horizontal principal stress. The maximum horizontal principal stress can be calculated from the breakdown pressure and intact rock tensile strength based on elastic theory. It is assumed that one of the principal stresses is vertical and equal to the vertical lithostatic load. Because the crack will propagate normal to the minimum horizontal stress, the orientation of the stress field can be determined through use of oriented impressions of the crack.

In situ stresses affect the hydrology both in a regional sense and in the immediate vicinity of the repository. High differential horizontal stresses will definitely influence the effect of excavation and thermal

loading on fracture aperture and thus on the rock-mass permeabilities. Discrete fracture models which include the response of fracture flow systems to stress perturbations require in-situ stress as an input. In a regional sense, stress data can be used to predict decrease with permeability with depth, and given knowledge of basalt stress-permeability relationships, a basis for predicting the orientation of relatively open fractures.

In situ stress data is also esssential for repository design; rock displacement and the response of fractures to excavation depend strongly on in situ stress state. If the stress state is known prior to excavation, tunnels can be favorably oriented to assure maximum stability (Haimson, 1975).

ii. Equipment constraints

The technology of hydrofracturing is well developed for 3-inch boreholes. Two commercial sources exist--Terra Tek of Salt Lake City and Prof. B. C. Haimson of the University of Wisconsin. The USGS has conducted numerous hydrofracturing experiments (Bredehoeft et al., 1975) as part of its tectonics research and maintains a mobile unit for hydrofracturing.

iii. Test Procedures

The steps in the hydrofracturing test consist of first setting two straddle packers over the zone of interest, then pressurizing the zone with water until the rock fractures. This fracturing can be detected either through the pressure drop read at the surface or with downhole acoustic monitoring instruments (Zobach and Pollard, 1978). After fracturing, the shut-in pressure is recorded; the rock is repressurized and additional shut-in pressures are obtained.

Later an impression packer is set over the fractured zone to obtain the orientation of the fracture. While the packer is set it is oriented with a gyroscopic borehole survey tool. A borehole television camera or a borehole seisviewer may be used in place of the impression packer. The orientation of these tools is more difficult and less reliable in the magnetic basalts.

iv. Time

If a packer system that can be reset downhole is used, it is possible to test as may as four zones per 12 hour day. The fracturing of 12 zones between the Vantage and the bottom of the deep holes at about 4500 feet

would require, conservatively, one week. Obtaining the orientation requires removal of the impression packers between zones; hence about two impressions can be done per day. Total testing time is about 1.5 weeks for a 4500-foot hole.

IV. LONG TERM WELL MONITORING

a. Site Selection of Monitoring Wells

Wells for monitoring long-term regional hydrologic trends should be situated at key locations throughout the study area. If properly selected, the number of monitoring wells need not be large. An ideal site for identification of regional trends would be one from which data could be accurately extrapolated through the use of models or other means to estimate regional trends in other parts of the basin. Data from such a site should therefore be generally representative of conditions in as large an area as possible and should not be located near some natural anomaly such as an unusually permeable fracture system or an isolated saline interbed.

A monitoring well should also not be located in an area where the formations have been or are likely to be disturbed by human activities, such as deep well drilling or mining. The drilling of a deep well nearby, for example, could perturb the local flow regime by inducing anomalous water pressures, and could contaminate the local groundwater by loss of drilling fluids into the bedrock. The effect of these disturbances could take years to subside, during which data from the monitoring well would be of little value in identifying regional trends.

b. Need for Long-Term Monitoring

i. Water Pressure

Fluid pressure should be monitored to observe the decay of man-made perturbations during drilling and testing. When man-made perturbations are negligible, monitoring should proceed to detect the changes in pressure due to the dynamic state of flow in the system. This monitoring should be commenced as soon as it is practical to do so.

The rate of change of pressure in the monitored wells will be used for interpretation of the original pressure measurements in all wells. These original measurements represent the base line data used in the analysis of the groundwater flow system. However these pressure measurements cannot

actually be taken all at one time. They will be taken over a period of several years. The significance of the error caused by this procedure can be evaluated using the pressure vs. time data from the monitored wells. Pressure vs.time data are also invaluable for calibrating the models used for analysis. If the model predicts changes in pressure that are significantly different from those measured, the model parameters, initial conditions, geometry and/or boundary conditions can be re-evaluated or refined until a more accurate match is obtained. This procedure should greatly improve our confidence in the predictive ability of the model.

ii. Geochemistry

Sampling and partial analysis of wells on a regular basis would satisfy the need to:

- o Monitor the decrease in levels of contamination due to drilling.
- o Observe any changes or trends in groundwater chemistry over time caused by natural variation or man-made perturbations.
- o Check on the reproducibility of sampling and analysis techniques.

Ideally, such a monitoring program should involve a minimum of time, costs and logistics. A simple solution may be provided by choosing a well under artesian conditions and using the hydrostatic head to raise water to the surface. It will be much easier to obtain clear, clean, uncontaminated samples from a freely flowing well than from a swabbed well, although this criterion should not be paramount in site selection.

The following partial chemical analyses could be made on samples regularly taken from a monitoring well:

- o Every two months: Neutron Activation Analysis, X-Ray Fluorescence, Atomic Absorption Analysis, Dissolved Gasses, including CO_2, H_2S and O_2, pH, Alkalinity, Temperature, Redox, Conductivity.
- o Every six months: Isotope Analysis for age dates and ratios.

c. Monitoring Systems

i. Equipment

The ideal system for well monitoring would have the following characteristics:

- o Allow accurate long-term measurement of water pressure in multiple zones.

- Allow extraction of water samples for geochemical analysis.
- Permit isolation of monitored zones from one another and from the surface.
- Be usable in pre-existing wells.

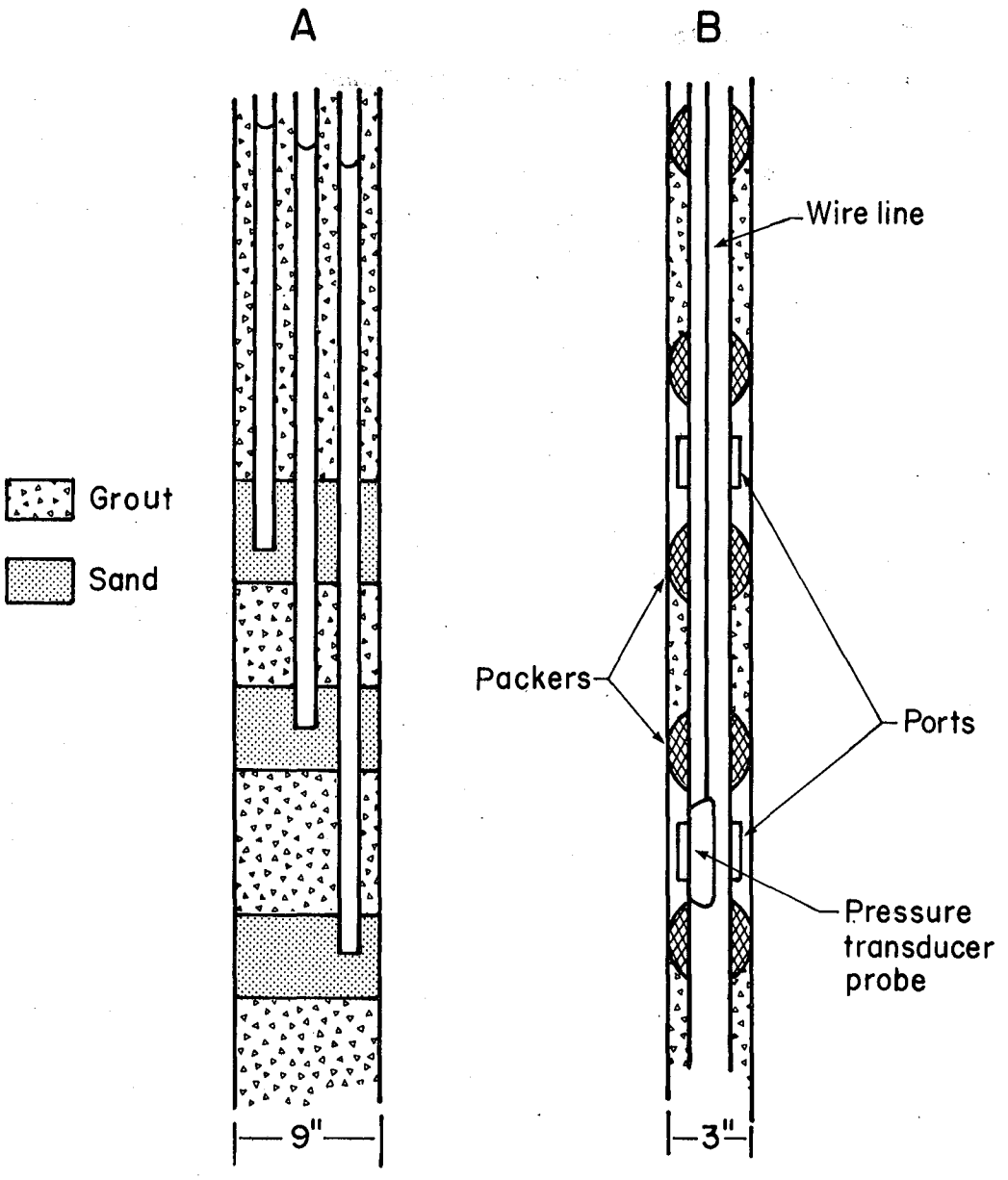
There are two systems that may prove useful: multiple standpipes in a large diameter hole such as currently exists in DC-1; and a multiple-ported single pipe such as that developed by Westbay Instruments of West Vancouver, British Columbia.

Multiple standpipes (Figure A-14A) could be installed in either DC-5 or DC-7 which are both large enough to accommodate such a system. Four to five standpipes could be installed in ten to twenty foot sand filled zones of the borehole. These zones would be separated by cement or other grouting material. Pressure data would be monitored from water levels in the standpipes and serve as a check on the other pressure measurement data. A disadvantage of using these wells for monitoring is that companion wells DC-4 and DC-8 would have to be plugged to minimize communication between zones. Groundwater samples can be obtained by swabbing the tubing if an adequate sand filter is installed.

The advantages of standpipe systems include: (a) proven technology; and (b) relative simplicity. The disadvantages are: (a) large diameter holes are required; and (b) the number of monitored zones is limited by the number of standpipes which fit into the well.

A second potential monitoring system is the multiple ported piezometer. The basic system as developed by Westbay Instruments (Figure A-14B) consists of a single tube with spring loaded ports for pressure and groundwater sampling. The zones to which these ports open are isolated from one another by packers permanently filled with grout. Except for the monitored zones, the areas between the packers are also grouted. Tools for pressure measurement and sampling pumps are lowered inside the piezometer tube to the zones of interest, and there, using a downhole electric motor, are clamped to the tubing wall making a seal over the port and opening it in one step. The major advantages of this system are:

- rapid time for pressure equilibration.
- potential for multiple port spacings as close as five feet or 20 per 100 feet in a small diameter (NX) well.



A– Multiple standpipes for groundwater pressure and chemical monitoring

B– Westbay multiple ported picrometer system (Ports are opened by pressure tool)

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Figure A-14. Monitoring equipment.

The disadvantages are:

- o the system has only been developed thus far for shallow (< 1000′) wells.
- o the long term reliability of the system has not been proven. A Westbay system has been installed at LBL for evaluation.

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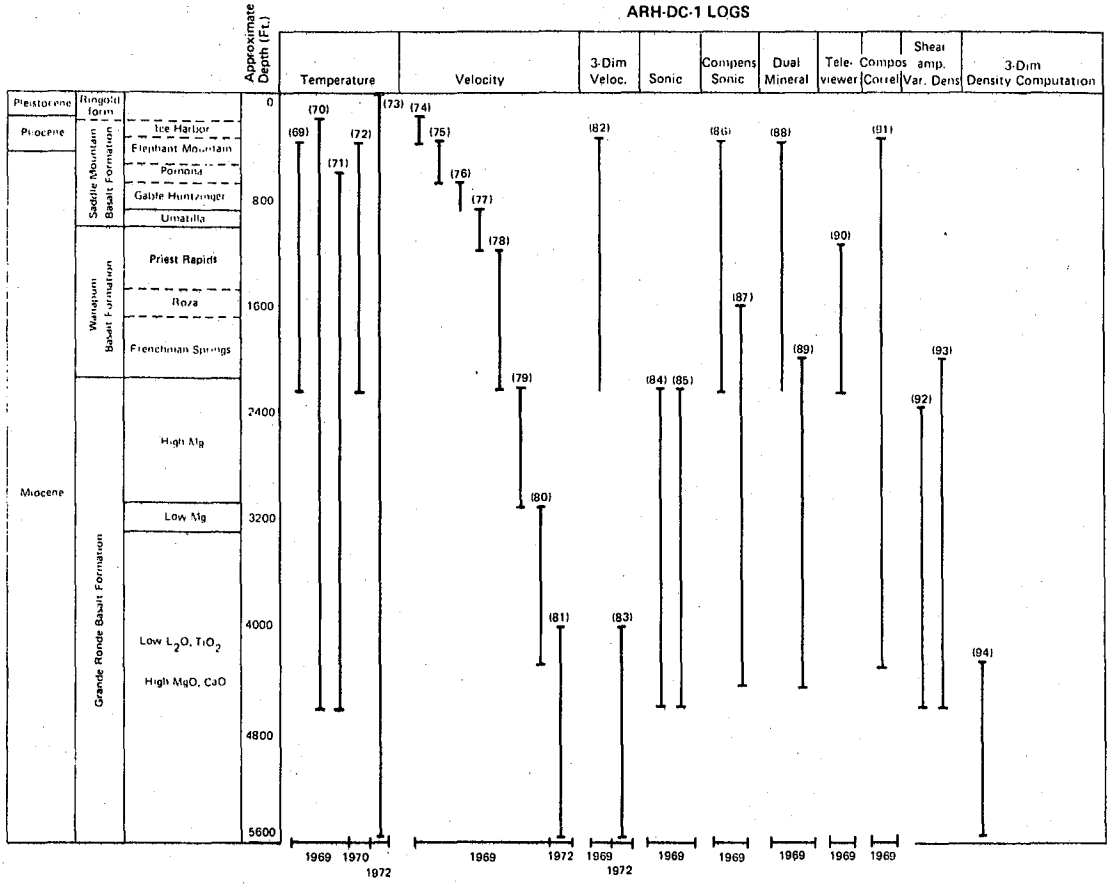
APPENDIX B

List of Geophysical Logs Run in Pasco Basin Wells



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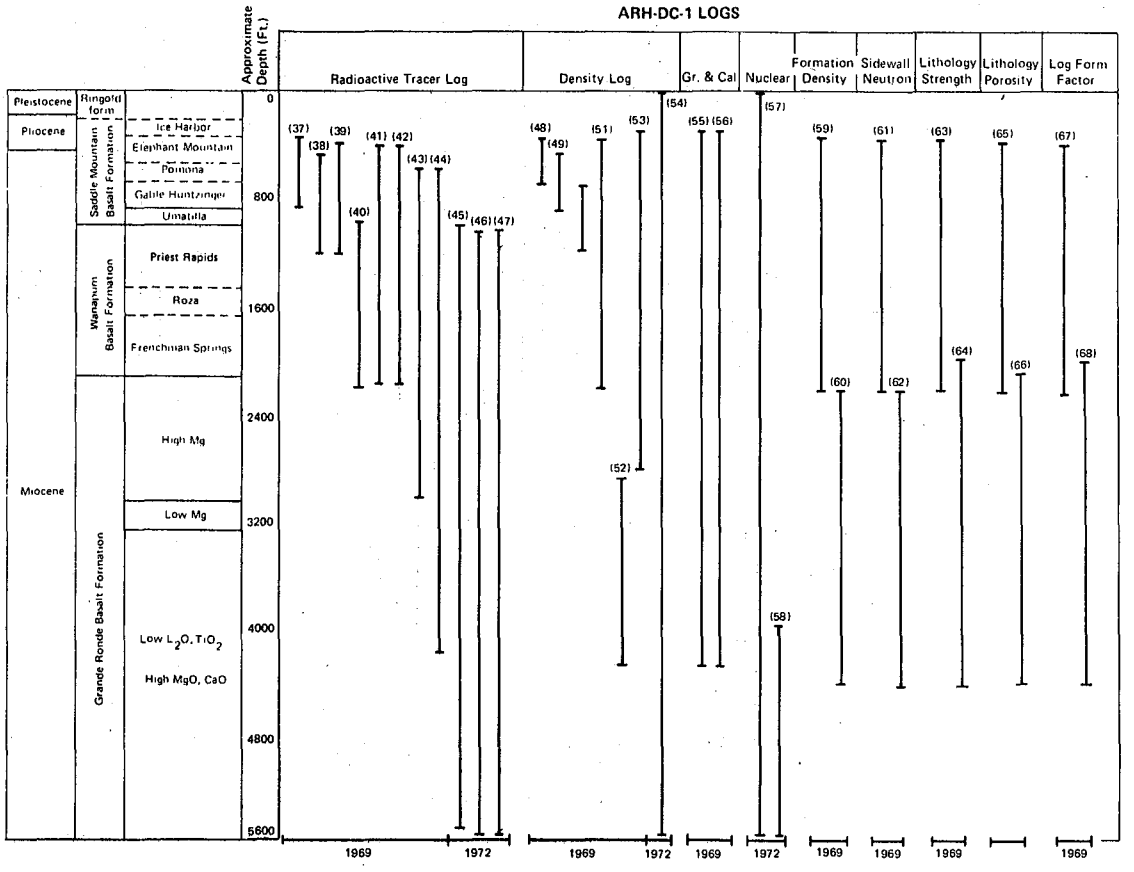

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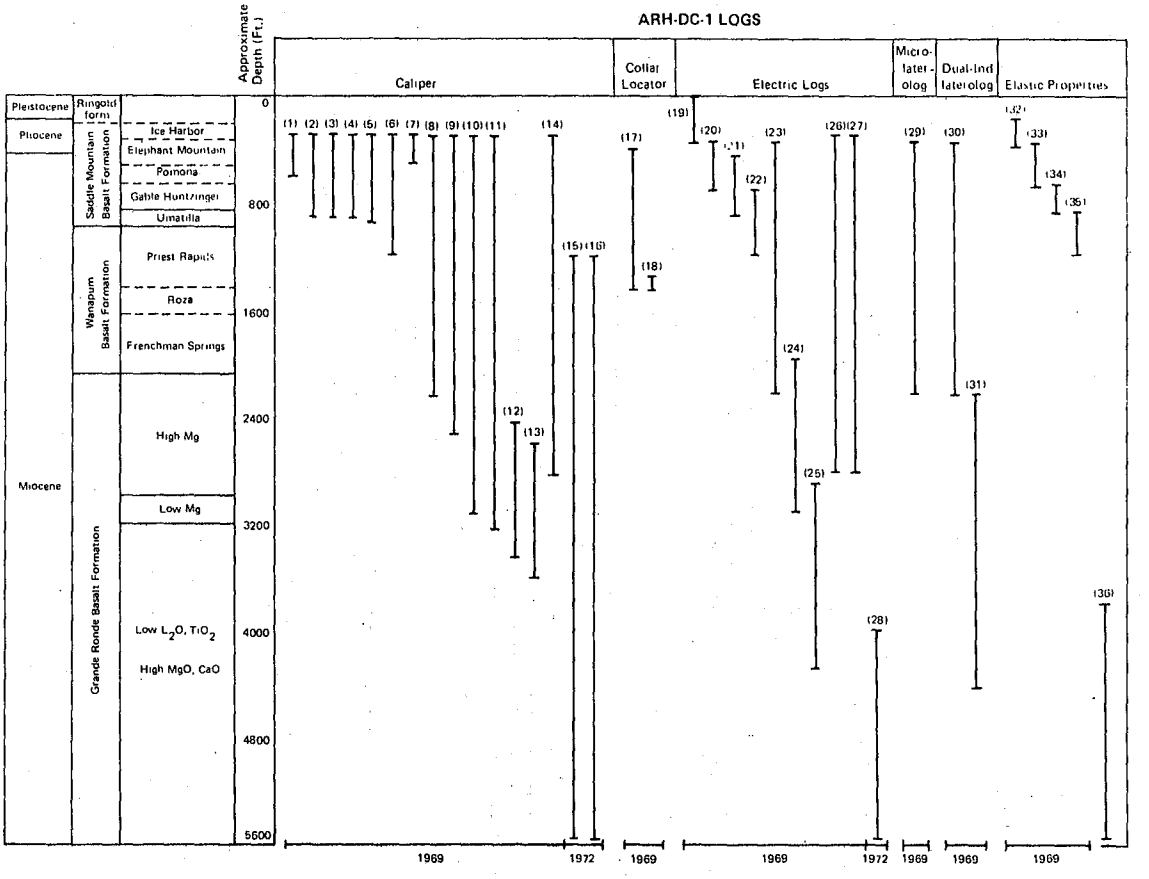

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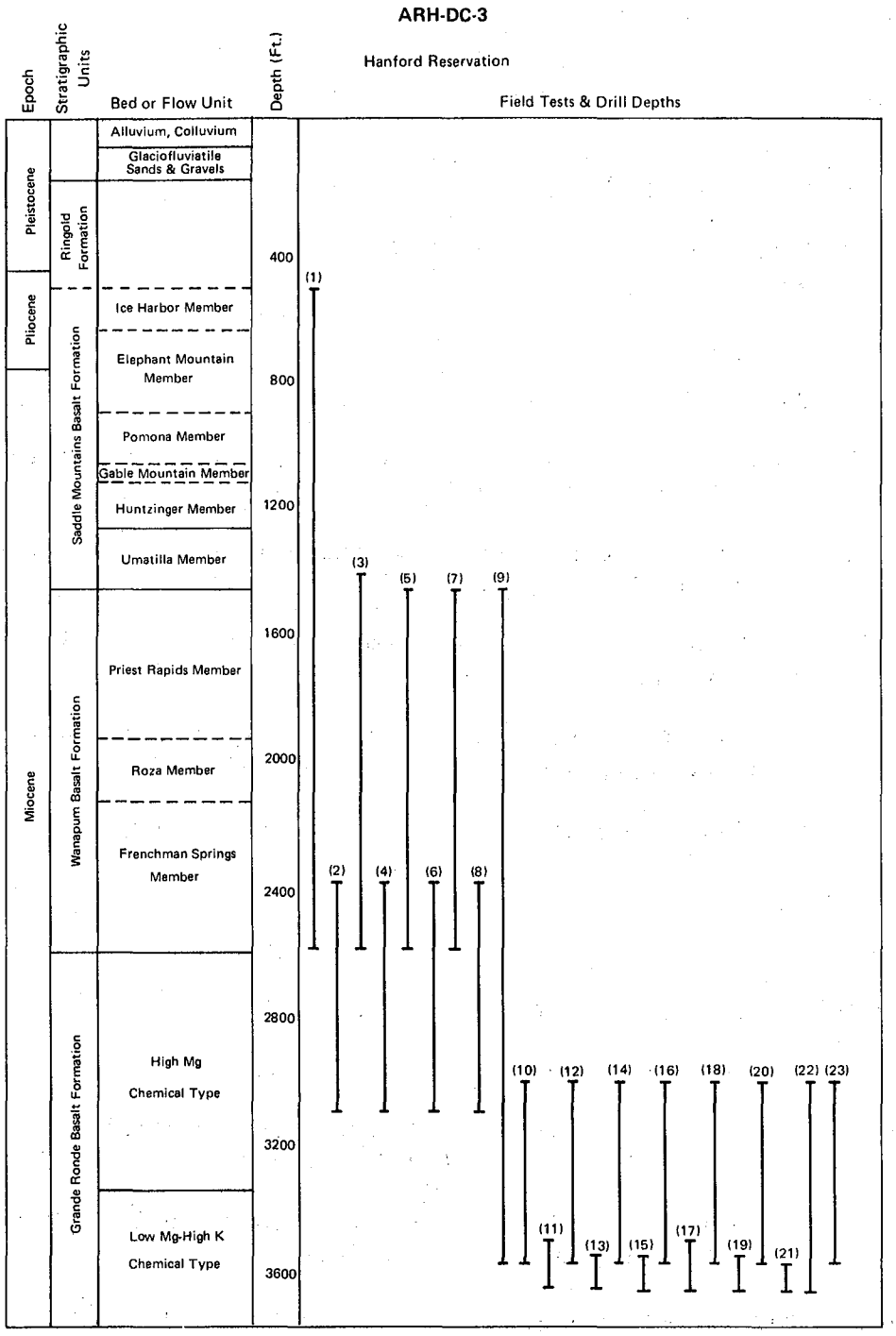
DC - 1 LOGS

Log		Date	Run	Depth	Remarks
Caliper Log	(1)	5-6-69	# 2	300'-596'	All Birdwell Logs
	(2)	5-17-69	# 3	300'-890'	
	(3)	5-18-69	# 4	300'-886'	
	(4)	5-24-69	# 5	300'-914'	
	(5)	5-25-69	# 6	300'-945'	
	(6)	5-26-69	# 7	300'-1180'	
	(7)	6-3-69	# 8	300'-502'	
	(8)	6-8-69	# 9	300'-2224'	
	(9)	6-15-69	#10	300'-2520'	
	(10)	6-19-69	#11	300'-3101'	
	(11)	6-27-69	#12	300'-3222'	
	(12)	7-1-69	#13	2447'-3447'	
	(13)	7-5-69	#14	2597'-3597'	
	(14)	8-18-69	#17	300'-2820'	
	(15)	4-6-72	#17	1200'-5550'	
	(16)	4-6-72	#20	1200'-2820'	(2 copies)
Casing Collar Locator	(17)	8-31-69	# 1	400'-1443'	Birdwell Logs
	(18)	9-2-69	# 2	1350'-1447'	
Electric Logs	(19)	4-30-69	# 1	0'-362'	Birdwell Logs
	(20)	5-6-69	# 2	350'-693'	
	(21)	5-18-69	# 3	450'-890'	
	(22)	5-26-69	# 4	700'-1179'	
	(23)	6-8-69	# 5	350'-2224'	
	(24)	6-19-69	# 6	1970'-3104'	
	(25)	7-12-69	# 7	2900'-4273'	
	(26)	8-19-69	# 8	300'-2814'	
	(27)	8-19-69	# 9	300'-2810'	
	(28)	4-6-72	#10	4000'-5550'	

Log		Date	Run	Depth	Remarks
Microlaterolog	(29)	6-7-69	# 1	364'-2230'	Schlumberger-Microcaliper, Resistivity (2 copies)
Dual Induction Laterolog	(30)	6-7-69	# 1	364'-2238'	Schlumberger-SP, Gamma Ray, Laterolog 8, Medium Induction Log, Deep Induction Log
	(31)	7-18-69	# 2		
Elastic Properties	(32)	4-30-69	# 1	190'-348'	Moduli-Shear, Bulk, Young's, Density, Poisson's Ratio (unknown authors)
	(33)	5-6-69	# 7	364'-670'	
	(34)	5-18-69	#11	669'-884'	
	(35)	5-26-69	#13	885'-1174'	
	(36)			3800'-5550' (Birdwell)	
Radioactive Tracer Log	(37)	5-20-69	# 4	361'-886' (Computations)	All Birdwell Logs
	(38)	5-26-69	# 5	450'-1171' (Computations)	
	(39)	5-26-69	# 6	390'-1171' (Computations)	
	(40)	6-9-69	# 7	970'-2214' (Data log)	
	(41)	6-10-69	# 8	420'-2184' (Data log)	
	(42)	6-10-69	# 8	420'-2184' (Computations)	
	(43)	6-20-69	# 9	570'-3018' (Data log)	
	(44)	7-13-69	#10	570'-4180' (Computations)	
	(45)	4-8-9-72	#11	1000'-5470' (Static)	
	(46)	4-8-9-72	#12	1060'-5550' (Dynamic)	
	(47)	4-8-9-72	#11-12	1060'-5550' (Computations)	
Density Log	(48)	5-6-69	# 2	350'-692'	All Birdwell Logs-Bulk Density, Proximity Index
	(49)	5-18-69	# 3	450'-890'	
	(50)	5-26-69	# 4	700'-1182'	
	(51)	6-8-69	# 5	350'-2224' (2 copies on #5)	
	(52)	7-12-69	# 7	2900'-4271'	
	(53)	8-18-69	# 8	300'-2824'	
	(54)	4-7-72	# 9	0'-5550'	
Gamma Ray & Caliper	(55)	7-12-69	# 1	300'-4274'	Birdwell-Gamma Ray-2 copies
	(56)	7-12-69	#15	300'-4274'	Birdwell-Gamma Ray-2 copies

Log		Date	Run	Depth	Remarks
Nuclear Log	(57)	4-6-72	# 1	0'-5550'	Birdwell-Gamma Ray-Neutron
	(58)	4-7-72	# 1	4000'-5550'	Birdwell-Epithermal Neutron
Compensated Formation Density Log	(59)	6-7-69	# 1	364'-2228'	Schlumberger-Caliper, Bulk Density
	(60)	7-18-69	# 2	2238'-4438'	
Sidewall Neutron Porosity Log	(61)	6-7-69	# 1	364'-2228'	Schlumberger-(2 copies) Caliper, Gamma Ray, Porosity (%)
	(62)	7-19-69	# 2	2228'-4438'	
Lithology-Strength Index	(63)	12-1-69	# 1	380'-2233'	(2 copies)-% Bulk Volume, Porosity, Deformation Modulus, Caliper, Matrix Set Index. (Schlumberger)
	(64)	7-15-69	# 2	2010'-4450'	
Lithology-Porosity Index	(65)	7-15-69	# 1	380'-2238'	Schlumberger-% Bulk Volume, Neutron Porosity
	(66)	10-1-69	# 2	2010'-4435'	Caliper Secondary Porosity Index
R_{we} - Log Formation Factor	(67)	7-15-69	# 1	380'-2238'	Schlumberger-Gamma Ray, Caliper, Log F_{cp}, R_{we}
	(68)			2000'-4437'	
Temperature Log	(69)	6-7-69		364'-2230'	Schlumberger (2 copies)
	(70)	7-21-69		200'-4602'	Schlumberger (2 copies)
	(71)	7-21-69		600'-4600'	Schlumberger - Differential Temperature
	(72)	1-22-70		364'-2230'	Schlumberger - Differential Temperature
	(73)	4-5-72		0'-5550'	Birdwell
Velocity Log	(74)	4-30-69	# 1	190'-348'	All Birdwell Logs
	(75)	5-6-69	# 2	364'-668'	
	(76)	5-18-69	# 3	669'-884'	Synthesized
	(77)	5-26-69	# 4	885'-1173'	
	(78)	6-8-69	# 5	1174'-2218'	
	(79)	6-19-69	# 6	2219'-3099'	
	(80)	7-12-69	# 7	3100'-4267'	
	(81)	4-26-72	# 8	4000'-4267'	

Log		Date	Run	Depth	Remarks
3-D Velocity Log	(82)	6-8-69	#17	350'-2215'	12' spacing - Birdwell Logs
	(83)	4-7-72	#27	4000'-5550'	6' spacing
Sonic Log	(84)	7-21-69	# 1	2229'-4593'	Schlumberger-SP, Caliper, Shear Amplitude, Compressional Amp.
	(85)	7-21-69	# 1	2229'-4593'	Schlumberger-SP, Caliper, Shear Amplitude, Variable Density
Borehole Compensated	(86)	6-7-69	# 1	364'-2229'	Schlumberger-SP, Caliper, Interval Transit Time
Sonic Log	(87)	7-19-69	# 2	1808'-4428'	Schlumberger (2 copies)
Dual Mineral	(88)	7-15-69	# 1	380'-2238'	Schlumberger-SP, Caliper, ϕ_{cp}, ϕ_s, ρ_{me}
	(89)	7-15-69	# 2	2000'-4440'	
Borehole Televiewer	(90)	6-7-69	# 1	1139'-2226'	Schlumberger
Composite for Correlation	(91)	8-8-69		350'-4271'	Birdwell-composity of 3-D, Density, Caliper, Electric, Gamma Ray
Shear Amplitude	(92)			2350'-4600'	ARHCO
Variable Density	(93)			2000'-4600'	ARHCO
3-D Denisty Computations	(94)			4260'-5550'	Computer printouts-V_p, V_s, Shear, Bulk, Young's, Poisson, RHO, Poem 1,-2,-3, Porg -1,-2,-3, Density



XBL7811-12526

DC - 3 LOGS

Schlumberger

(1) Compensated Neutron Formation Density: Caliper, Gamma Ray, Gamma-Gamma, Neutron. 9-6-77 (560-2582 feet)

(2) Compensated Neutron Formation Density: Caliper, Gamma Ray, Gamma-Gamma, Neutron. 9-10-77 (2380-3097 feet)

(3) Temperature. 9-6-77 (1420-2582 feet)

(4) Temperature. 9-10-77 (2380-3096 feet)

(5) Induction-Electric Log: Spontaneous Potential, Conductivity, Short Normal. 9-6-77 (1448-2582 feet)

(6) Induction-Electric Log: Spontaneous Potential, Conductivity, Short Normal. 9-10-77 (2377-3096 feet)

(7) Borehole Compensated Sonic Log: Caliper, Gamma Ray, ΔI, Variable Density, Amplitude. 9-6-77 (1448-2580 feet)

(8) Borehole Compensated Sonic Log: Caliper, Gamma Ray, ΔI, Variable Density, Amplitude. 9-10-77 (2380-3095 feet)

(9) Continuous Dipmeter. 9-28-77 (1450-3571 feet)

Birdwell

(10) 3-D Velocity. 9-77 (3000-3565 feet)

(11) 3-D Velocity. 10-4-77 (3500-3627 feet)

(12) Induction Electric Log: Spontaneous Potential, Conductivity, Short Normal. 9-28-77 (3000-3566 feet)

(13) Induction Electric Log: Spontaneous Potential, Conductivity, Short Normal. 10-4-77 (3575-3631 feet)

(14) Density Borehole Compensated: Caliper, Gamma Ray, Gamma-Gamma. 9-28-77 (3000-3570 feet)

(15) Density Borehole Compensated: Caliper, Gamma Ray, Gamma-Gamma, 10-4-77 (3550-3635 feet)

(16) Caliper and Temperature Log. 9-28-77 (3000-3568 feet)

(17) Caliper and Temperature Log. 10-4-77 (3500-3632 feet)

DC - LOGS

Birdwell (cont'd)

(18) Neutron Borehole Compensated: Gamma Ray. 9-28-77 (3000-3571 feet)

(19) Neutron Borehole Compensated: Gamma Ray. 10-4-77 (3550-3634) feet)

(20) Interval Transit Times and ΔI Shear/ΔI Pressure. 11-9-77

(21) Interval Transit Times and ΔI Shear/ΔI Pressure. (3575-3627 feet)

(22) Elastic Properties Log. 11-3-77 (3000-3627 feet)

(23) Com-Pro Log. 10-4-77 (3000-3568 feet)

DC - 5

-Compensated Neutron Log
1-25-78
(610-2604)
Schlumberger

-Compensated Density Log (Neutron)
8-10-78
(2636-3962)
WELEX

-Compensated Acoustic Velocity Log
8-9-78
-includes Caliper
WELEX

-Dual Induction Guard Log
8-9-78
(2636-3962)
-includes SP, Resistivity, Conductivity

-Temperature
8-14-78
(0-3100)
WELEX

-Temperature
8-14-78
(0-3960)
WELEX

DC - 6

Washington State University
(0-4300)

-RESIS/SP

-Caliper

-Fluid Resistivity

-Fluid Temperature

-Neutron-Neutron

-Nuetron-Gamma

-Gamma-Gamma

-Natural Gamma

(Casing extends to 2260 Feet)

DC - 7

-Compensated Density Log (Neutron)
8-1-78
(2780-4097)
-includes Gamma Ray, Compensated Gamma Density, Neutron Porosity

-Compensated Acoustic Velocity Log
8-9-78
(2780-4089)
-includes Caliper
WELEX

-Dual Induction Guard Log
8-9-78
(2780-4097)
-includes SP, Resistivity and Conductivity
WELEX

-Temperature
8-13-78
(0-4099)
WELEX

-Borehole Gravity Meter Survey
6-16-78
(3240-3870)
EDCON

DC - 8

-Sonic
6-13-78
(1612-2734)
EDCON

-Magnetic Susceptibility
6-13-78
(1612-2734)
EDCON

-Resistivity/IP
6-13-78
(1612-2734)
EDCON

DC - 2

-Temperature
6-12-78
(0-3300)
EDCON

APPENDIX C

Field Operating Procedures

Physical Testing - Pressure Test With Pneumatic Packers

Water Pressure Measurements with Pneumatic Packers:

Water pressure measurements with pneumatic packers shall be carried out in accordance with these procedures, with particular regard to considerations of quality assurance outlined in the introduction.

Any deviation from these procedures must be referred to an approved in advance by the LBL engineer responsible for field testing. These changes must be documented in the field log book. Any permanent changes or revisions in these procedures, that may develop from experience or necessity in the field, must be approved according to quality assurance conditions established by Lawrence Berkeley Laboratory. These addenda shall be written up on an approved change sheet, and distributed to all parties holding controlled copies of these Field Operating Procedures.

Prepared by_____ _____Engineer, LBL

Thomas Doe/Date

Independent Review by _University of Waterloo

John Gale/Date

Reviewed by_____ :incipal Investigator

Paul A. Witherspoon/Date

QA Review by_____ _____QA Engineer, LBL

Vincent McMahon

1.0 Scope

This procedure applies to all pressure measurements where air is used for packer inflation.

2.0 Introduction

The object of pressure measurements is to obtain data of the spatial variations in hydraulic potential. These data define the basis for determining directions of ground water movement. Pressure measurement testing consists of 1) lowering a packer or set of packers to the desired test zone, 2) inflating the packers to isolate the zone, 3) continuously recording the water pressure in the cavity until a stable value is reached, and 4) deflating the packers and moving to the next zone. These procedures are intended to minimize the possibility of error due to such factors as drift of electrical instrumentation or packer failure and to standardize recording of the data.

3.0 Description of Equipment

The test system consists of a water tight pressure transducer housing mounted on packers. A single packer is used for measurements at the end of a borehole (Fig. 1a). Double packers are employed for straddling zones within a borehole (Fig. 1b). Signal transmission and packer inflation are provided by a multiconductor electrical cable and a high strength nylon tube respectively. The downhole system is supported by drill rod or high strength tubing. The uphole data system consists of a time-based strip chart recorder, constant-current transducer power supply, and a digital voltmeter. A complete equipment list is given in Table 1.

4.0 Procedures

4.1 General Considerations

4.1.1 All data shall be recorded on LBL data sheets and maintained in a field notebook. At regular intervals of no less than one week copies of data sheets are to be forwarded to the program manager at LBL in Berkeley for permanent storage.

4.1.2 All testing procedures are to be carried out with regard to LBL Document 2077, "Health and Safety Regulations" and any regulations which may be enforced at the drilling site by other contracting companies.

4.1.3 A daily log of all field activities is to be maintained by the LBL field engineer and kept in the field notebook.

4.1.4 Pressure measurement involves a transient decay or buildup of pressure to a stable value. The decision as to when this value is reached or when a test should be terminated shall be the responsibility of the LBL field engineer.

4.1.5 All test records shall be reviewed for content and accuracy by the LBL field testing supervisor. The reviewer shall sign and date the form in the spaces provided. Records shall be reviewed at intervals of no less than one week.

4.2 Transducer Calibration

4.2.1 The pressure transducer is to be calibrated before and after it is run into the hole.

4.2.2 The transducer is to be calibrated against a Bourdon gage accurate to within 0.5 psi which has been calibrated to an instrument traceable to the National Bureau of Standards.

4.2.3. Calibrations shall be done from 0 psi to the pressure rating of the transducer and back to 0 at intervals of 5% of the transducer pressure rating (e.g. at 50 psi intervals for a 1000 psi transducer).

4.2.4 All calibrations shall be done at the same input current and within the same electrical cable used in testing.

4.2.5 Transducer input shall be set to the current specified on the power supply-monitor for that transducer.

4.2.6 Output shall be recorded using a digital voltmeter accurate to 0.1 mv.

4.2.7 Transducer shall be checked for drift by operating it at 0 pressure 15 minutes before calibration. Transducer shall not be calibrated until drift ceases. All calibrations shall be done at the same input current and with the same electrical cable used in testing. Calibration data is to be recorded on a transducer calibration sheet (Attachment 1).

4.3 Pressure Transducer Operation

4.3.1 Transducer output shall be read with a digital voltmeter

accurate to 0.1 mv and recorded on the pressure data sheet (Attachment 2) at the following times in the test procedure:

a) before lowering into the hole
b) before each packer inflation
c) when a stable reading is reached
d) after the packers are deflated
e) after the instrument is removed from the hole

4.3.2 During each test the output of the transducer shall be continuously monitored with a strip chart recorder. Output readings detailed in 4.3.1 should be recorded on the strip chart paper. The strip chart record shall be stored in an envelope stapled to the pressure data sheet. The hole number, depth interval, date, and recorder are to be recorded on the strip chart paper.

4.4 Packer Operation

4.4.1 Prior to running the packer into the hole, all "O" ring seals shall be inspected where possible, and each packer shall be inflated to 300 psi in a steel pipe immersed in water to check for air leakage. After the transducer housing has been mounted on the packer, the system is to be immersed in water and the packer mandrel pressured with air to 300 psi to check for leakage.

4.4.2 During testing packer pressure shall be maintained at 500 or a pressure appropriate to the packer specifications psi above the ambient water pressure except as specified in 4.4.4.

4.4.3 Inflation shall be done with a nitrogen bottle and a 0-1000 psi pressure regulator. The packer inflation line shall consist of nylon tubing with a minimum working pressure of 2000 psi; only high pressure stainless steel tube fittings shall be used in the inflation line.

4.4.4 After a stable water pressure has been reached, the packer(s) shall be inflated with an additional 100 psi. The stable pressure reached after this second inflation will serve as a check on the packer seal.

4.4.5 The LBL field engineer shall be responsible for proper inflation of the packers.

4.4.6 The packer line is to be secured during deflation to prevent whiplashing.

4.5 Handling of Equipment in the Hole

4.5.1 To assure that the intended depth zone is reached the LBL field engineer shall record the following on the pressure data sheet:

a) lengths of all instrument components
b) number of lengths and subs required for the test
c) total amount of tubing on site

4.5.2 The LBL engineer shall specify the number of tubing lengths to be used in each test and the amount left sticking out of the hole. This data shall be recorded on the pressure data sheet and kept in the field notebook.

4.5.3 A polaroid photograph shall be made of each instrument run into the hole. Lengths shall be recorded on this photograph as well as pipe diameters and threads for reference in fishing operations. The photographs shall be kept on site in the field notebook.

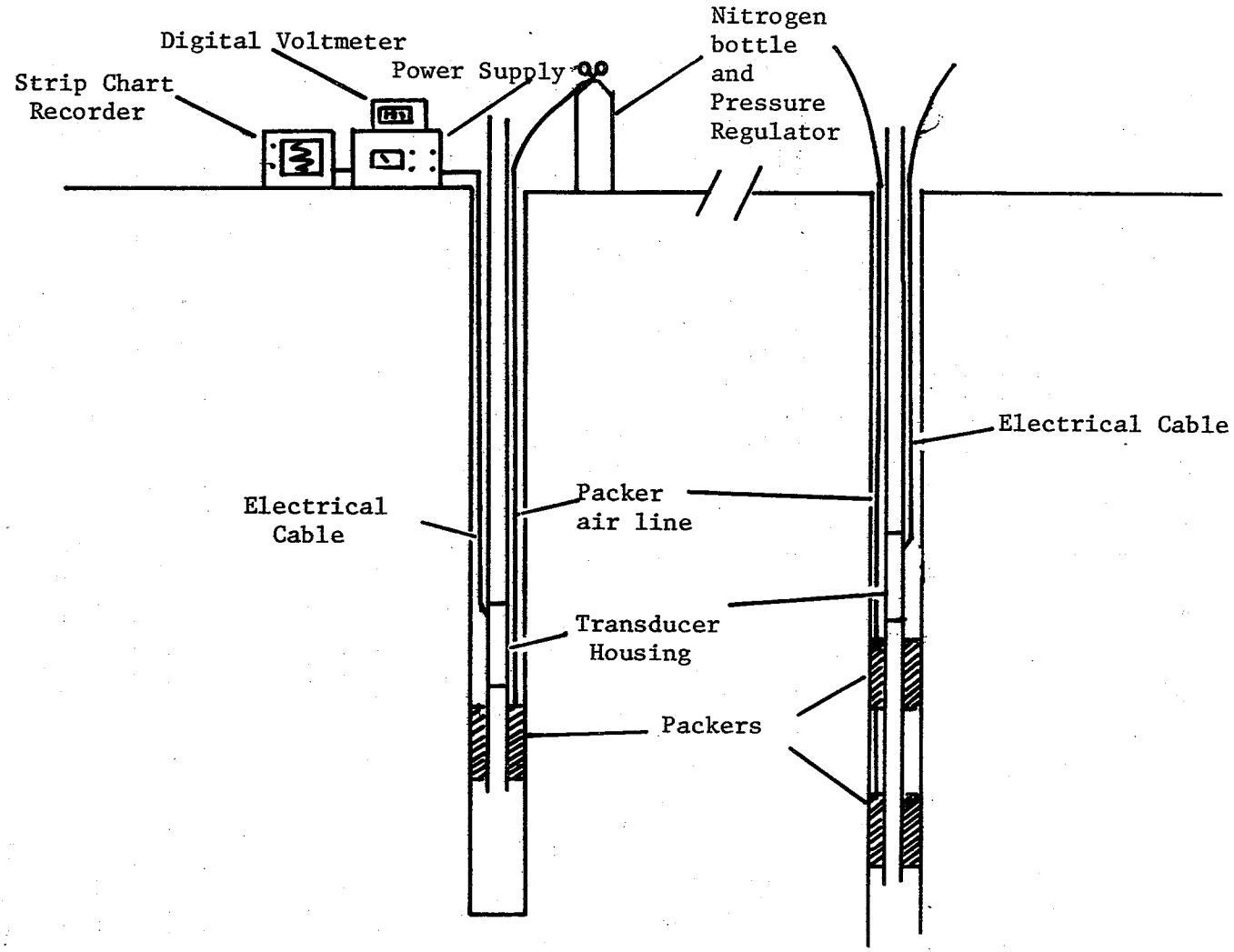


Figure 1 (a) Single packer arrangement for bottom hole pressure measurement

(b) Double packer arrangement for pressure measurement in discrete zones

Attachment 1

TRANSDUCER CALIBRATION SHEET

Date_____ LBL Field Engineer_____

Transducer No. _____ Input current _____mA

Transducer Manufacturer _____ Input Voltage _____V

_____ Initial reading _____mV

Transducer Range _____psi Calibration_____psi/V

Cable No. _____

Cable Length_____feet

Pressure Gage (psi)	Transducer Output (v)	Pressure Gage (psi)	Transducer Output (v)

Reviewed by_____ Date_____

Attachment 2

Pressure Data Sheet

Hole _____ Date _____

LBL Field Engineer _____

Depth Data

Elevation of Drill Collar _____ feet above MSL
Length of Transducer Housing _____
Length of Packers _____ feet
Length of Straddle Pipe _____ feet
Number of Tubing lengths on site _____
Number of Tubing lengths downhole _____
Length of tubing unit _____ feet
Length out of hole _____ feet
Top of straddled zone _____ feet of depth
Bottom of straddled zone _____ feet of depth
Zone lithology _____

Packer data

Inflation fluid air _____ water _____
Inflation pressure _____psi
2d inflation pressure _____psi

Transducer data

Transducer No. _____ range _____
Electrical Cable No. _____
Calibration _____psi/mV Calibration Date _____
Output with transducer at surface _____mV
Output before packer inflation _____V
Stable output after inflation _____V
Stable output after 2d inflation _____V
Output after deflation _____V
Output with transducer returned to surface _____V

Reviewed by _____ Date _____

Table 1

EQUIPMENT LIST

PRESSURE TEST WITH PNEUMATIC PACKERS

-	Drill rod
-	10-conductor electrical cable
-	high pressure packer inflation line
1	LBL Piezometric Profiler
1	LBL fracture hydrology pressure monitor
1	1-channel strip chart recorder
2	NX pneumatic packers
1	bottled Nitrogen pressure source for packer inflation

APPENDIX D

Field Operating Procedures
Groundwater Sampling

Groundwater sampling from wells and springs for geochemical analysis shall be carried out in accordance with these procedures, with particular regard to considerations of Quality Assurance outlined in the introduction.

Any deviation from these procedures must be referred to and approved by the LBL engineer responsible for field sampling. These changes must be documented in the field log book. Any permanent changes or revisions in these procedures, that may develop from experience or necessity in the field must be approved according to Quality Assurance conditions laid down by Lawrence Berkeley Laboratory.

These addenda shall be written up on an approved change sheet, and distributed to those parties holding controlled copies of these Field Operating Procedures.

Prepared by_____ _____Engineer, LBL
Allen Kearns

Reviewed by_ _____Geologist, LBL
Harold Wollenberg

Independent Review by_ _____Geochemist, LBL
John A. Apps

QA Review by_ _____QA Engineer, LBL
Vincent McManon

1.0 GENERAL CONSIDERATIONS

1.1 Aquifers shall be sampled in a manner that eliminates or minimizes contamination from surface water, drilling fluid, other aquifers, or the atmosphere.

1.2 On-site analyses and sample treatment shall be carried out to determine, or stabilize, those parameters which may be expected to change with time or during shipment to analytical laboratories.

1.3 Methods to continuously monitor the level of contamination shall be developed and carried out to ensure the accuracy and reliability of samples, and their conformity with the formation water being sampled.

1.4 Each sample shall be labeled with an approved code number on the body of the sample vessel. The label on the body shall indicate sample number, date and time, source, required analysis, treatment, relevant comments concerning the integrity of the sample (e.g., possible contamination) and the name of the sampler.

1.5 Each sample point shall be documented with details on swabbing and sampling times, results of field analyses and evaluations of contamination levels. This information shall be maintained in a bound notebook. A log shall also be maintained on the time and amount of any drilling lubricant additions. An accurate record of such additions is essential for determining the potential interference of contamination on analysis and interpretation of data.

1.6 Duplicates where possible, shall be routinely sampled, treated and stored.[1] These duplicates may be analyzed in the event of loss or damage of the primary sample, or as randomly selected "blind" samples for analytical verification. Analytical blanks shall be performed on sample bottles for atomic absorption, neutron activation, and X-ray fluorescence analysis.

1.7 Well water used as the basis for drilling fluid shall be sampled and analyzed as an unknown, so that its potential for contamination may be assessed.

1.8 For spring samples, a record of the location of the spring, air and water temperature, exact time and position within the spring and depth of sample at each spring site shall be recorded in the field log book. A photograph of the spring site shall be taken.

---

[1] U.S. Environmental Protection Agency Manual of Methods for Chemical Analysis of Water. EPA-625-76-74-003a.

1.9 All sample vessels shall be labeled, sealed with plastic tape, packaged in suitable containers to avoid damage and shipped by an approved carrier. All containers shall be clearly addressed to ensure safe and speedy delivery to the analytical laboratories.

1.10 All sampling procedures shall be carried out with regard to LBL/2077: Health and Safety Regulations and other regulations which may be enforced at the drilling site, by the contracting companies.

1.11 All field analysis data shall be recorded at the time of analysis on an approved data sheet, and maintained in the field log book. A copy of this data shall be forwarded to the Program Manager's office for record.

2.0 PROCEDURES

2.1 SAMPLE ACQUISITION

2.1.1 Minimization of Contamination

2.1.1.1 All procedures shall be carried out to minimize or avoid any mixing of produced water with the atmosphere, surface waters, drilling waters or introduced fluids. Considerations unique to a specific analysis shall be mentioned in that section.

2.1.1.2 A closed gas system shall be maintained during the swabbing process to avoid atmospheric contamination. This shall be nitrogen gas in the well system above the swab as it travels upwards. This closed gas system shall be maintained at a positive pressure to be determined and documented by the LBL engineer on site.

2.1.1.3 An argon closed gas system shall be maintained within the sampling apparatus in the field laboratory. The LBL engineer on site shall be responsible for the maintenance of the closed gas system.

2.1.1.4 Atmospheric contamination shall be assessed[2] by the determination of dissolved oxygen in the formation sample, and results recorded in the field log book.

[2] Horizon Ecology: Dissolved Oxygen Meter Manual.

2.1.1.5 Drilling fluid and groundwater contamination may be evaluated by tritium levels or inferred from neutron activation analysis and X-ray fluorescence data.

2.1.1.6 For on-site determination pH, temperature, Eh, and conductivity shall be monitored during swabbing. This is not sufficient for determining formation water and is only a rough guide. Total organic carbon may be useful in wells where detergents or polymeric drilling muds have been used.

2.1.1.7 For reliable assessment, a tracer shall be added in the parts per billion range to the drilling fluid at the time of drilling. This shall be preferably a fluorocarbon to be detected by gas chromotography or a fluorescent dye to be detected by a fluorometer.

2.1.1.8 Temperature and pH may also be monitored to observe the stabilization of these properties with time during swabbing. Stability may indicate the presence of formation water, which shall be monitored by the fluorometer.

2.1.1.9 All conventional polyethylene vessels with which a sample shall come in contact shall, unless specifically stated, be acid-leached and washed and distilled-water rinsed before usage.

2.1.2 <u>Swabbing from Wells</u>

2.1.2.1 Well samples shall be obtained by swabbing except when production is too low to provide a sample. In this case, at the discretion of the LBL engineer on site, a downhole sampler shall be used to obtain a reduced volume sample. This shall be documented in the field log book.

2.1.2.2 The swabbing system shall be closed to atmospheric contamination by a positive pressure of nitrogen. A siphon tube leading from the wellhead into argon-flushed polyethylene carboys shall be used for the collection of groundwater, when it has been determined that contamination is at an acceptable minimum. These carboys shall be used for temporary storage of groundwater prior to sub-sampling.

2.1.3 Sampling from Springs

2.1.3.1 Springs shall be sampled at a recorded depth with a portable Masterflex pump using silicone tubing and avoiding unnecessary aeration, turbulence and the air-water interface. Any sediment or turbidity present in the spring should be avoided, where possible. Samples, except those for gas analysis, shall be filtered at the time of sampling.

2.1.3.2 Samples shall be collected in polyethylene carboys for temporary storage prior to sub-sampling. Field analysis for unstable parameters shall be carried out at the spring where possible, or at the earliest opportunity following sampling.

2.1.3.3 In all cases of delays in sub-sampling or field analysis of unstable parameters, a record shall be kept in the field log book of times and conditions between sample procurement and analysis.

2.2 FIELD ANALYSIS OF SAMPLES

Analysis shall be carried out at the time of sampling to determine those parameters which may change with time or transit. All analytical data shall be recorded on the approved data sheet. Any treatment used to stabilize samples shall be approved and documented.

2.2.1 pH and Temperature

2.2.1.1 These measurements may be made in a flow-through cell at the same time as redox potential is being determined.

2.2.1.2 The Orion specific ion meter and combination pH electrode shall be standardized before operation, according to the instrument instruction manual.[3]

Two different pH buffers shall be used for standardization, the first with a pH of 7 and the second to bracket the anticipated sample pH.

2.2.1.3 Temperature shall be determined by a conventional thermometer immersed in the spring or sample at the same time as the pH determination.

[3] Orion Research (1977): Form IM407A/F/L/7721

2.2.2 Redox Potential

Redox potential shall be determined as described by Jenne[4], using an Orion combination redox electrode standardized according to Orion Research specifications. Measurements shall be made at the same time as pH and temperature are determined.

2.2.3 Sulfide

2.2.3.1 Total sulfide and dissolved sulfide shall be determined as follows.

2.2.3.2 Total sulfide - add 0.15 ml 2 N zinc acetate to a 100 ml glass bottle if analysis is to be delayed for more than one hour. Add sample and mix gently by rotating about a transverse axis. Then proceed with 2.2.3.4.

2.2.3.3 Dissolved sulfide - filter 100 ml sample through a 0.2μ nuclepore filter. Add zinc acetate as above if delays are necessary then proceed with 2.2.3.4.

2.2.3.4 Sulfide levels shall be determined by an iodometric titration as soon as possible after sampling[5].

2.2.3.5 Sulfide shall be determined at a later stage in the analytical laboratory and cross-checked with field analysis data. A 100 ml sample shall be collected as in 2.2.3.2 and 2.2.3.3.

2.2.4 Carbon Dioxide

2.2.4.1 Carbon dioxide shall be determined as soon after sampling as possible, by a titrimetric method[6].

2.2.4.2 Carbon dioxide shall also be determined at a later stage in the analytical laboratory and cross-checked with field analysis data.

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[4] E. A. Jenne, USGS (Methods in Trace Element Hydrobiogeochemistry: No. F-2).

[5] Standard Methods: For the Examination of Water and Wastewater: 428d. 14th Edition, 1975. APHA-AWA-WPCF.

2.2.5 Alkalinity

2.2.5.1 Alkalinity shall be determined by titration to pH 8.3 and pH 4.5 end points with a back titration to correct for interfering anions.

3.0 ISOTOPIC ANALYSES OF SAMPLED WATER

3.1 Tritium

3.1.1 A 1 litre sample shall be siphoned into a new amber glass bottle filled previously with argon. Samples shall be collected outside the field laboratory leaving a 1" headspace and tightly capping with Polyseal polyethylene caps. Any information concerning contamination by drilling fluids or surface waters shall be sent with the sample.

3.1.2 A 1 litre sample shall be taken in a new glass bottle that has no previous use or cleaning treatment. Bottles shall be flushed with argon and the sample siphoned into the bottle outside the field laboratory. A 1" headspace shall be left in the bottle which shall be tightly capped with Polyseal conical polyethylene plugs.

3.1.3 Under no circumstances shall a luminous faced wrist watch be worn by a sampler during sampling for tritium levels, nor should such watches be worn inside the field laboratory.

3.1.4 When samples are tightly capped there are no special time or temperature restraints during transit.

3.2 $^{34}S/^{32}S$

3.2.1 These samples may be taken at the wellhead from the polyethylene carboys used for sub-sampling. A 5 litre sample is required but a 10 litre sample is preferable if sulfate levels are low or water is plentiful.

3.2.2 Ratio in SO_4 - a 2-1/2 gallon Cubitainer prewashed with 1 N HCl shall be added to limit biological growth and remove carbonates. The acidified sample shall be bubbled with argon for 30 minutes to remove H_2S. If H_2S is present, then the acidified sample shall be bubbled with argon for 30 minutes to remove it.

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[6] Brown, E. et al. 1970. USGS, TWRI; Bk 5, Pt 1A, p. 41-44. (Methods in Trace Element Hydrobiogeochemistry, No. F-4.)

3.2.3 Ratio in SH/H_2S - a 5 or 10 litre sample shall be taken and a 1 ml litre 10% cadmium acetate solution added to precipitate cadmium sulfide and ensure there shall be no biological oxidation to SO_4.

3.2.4 Containers must be clearly labeled with treatments.

3.3 $^{12}C/^{13}C$

3.3.1 Analysis shall be made on gas evolved from the ^{14}C sample.

3.3.2 A separate sample may be evolved by bubbling argon into the Cubitainer sample in 3.2.2 for 4 hours and trapping evolved CO_2 in 1 litre of carbonate-free 50% NaOH, held in two consecutive traps.

3.4 $^{18}O/^{16}O$ and Hydrogen/Deuterium

3.4.1 Both analyses shall be carried out in the same laboratory on an unfiltered sample collected in a 15 ml glass bottle rinsed twice with formation water.

3.5 ^{14}C

3.5.1 The sampling and extraction system for ^{14}C shall be enclosed to avoid atmospheric contamination, with a positive pressure of nitrogen used to remove CO_2 into NaOH traps.

3.5.2 Two 13-gallon polyethylene carboys prewashed with 1 N HCl and rinsed with distilled water shall be used to collect swabbed water. A 100-litre sample shall be collected in these carboys which shall be flushed through for 5-10 minutes with CO_2-free nitrogen.

3.5.3 The extraction system shall include two 13-gallon polyethylene carboys with three tall form gas washing bottles connected in series with tygon tubing. The gas shall be delivered to the bottom of each carboy by silicone tubing. The gas delivery tube in the first gas washing bottle shall be open-ended and the second and third tubes shall be extra porous sintered glass blocks. A nitrogen flow rate of 1-2 litres/minute shall be maintained.

3.5.4 Extraction shall be carried out as follows:

3.5.4.1 Allow 50 ml concentrated reagent grade sulfuric acid to enter each carboy from the separating funnel under a flow of nitrogen.

3.5.4.2 With minimum aeration and under nitrogen flow, add 1.0 - 1.5 litres total volume carbonate-free 8 N NaOH solution into the three gas washing towers.

3.5.4.3 Seal off the extraction system and adjust flow rate to 1.5 litres/minute, and extract for 16 hours or overnight.

3.5.4.4 Pool the three gas washing vessels into two 1-litre Nalgene polyethylene containers previously given a 1 N HCl acidic wash and distilled water rinse.

3.5.4.5 Seal with plastic tape leaving a small space for expansion during transit.

3.6 ^{222}Rn

3.6.1 The sample shall be taken from the middle of the swab pull and collected in two 500 ml polyethylene containers. The containers require no washing or treatment procedures beforehand. The sample shall be sealed with plastic tape.

3.6.2 Owing to the short half life of radon the time of sampling must be accurately recorded. Transit time shall be as short as possible with the analytical laboratory being advised of the arrival of the sample at the carrier depot.

3.7 $^{234}U/^{238}U$

3.7.1 Samples shall be taken from the sub-sampling carboys and filtered through a 0.2μ Nuclepore filter directly into cleaned, numbered and preweighed 50 ml polyethylene bottles.

3.7.2 Exactly 10 ml 6 M HCl shall be added to each bottle at the time of sampling. Sample volume is not critical but exact acid addition is essential for subsequent determination of volume in the analytical laboratory.

3.7.3 Bottles shall be tightly closed to avoid evaporation or leakage but no labels or tape shall be used which may alter the weight of the bottle.

3.7.4 There are no special restraints during shipment apart from sample bottles remaining upright.

4.0 CHEMICAL ANALYSES OF SAMPLED WATER

4.1 The following determinations shall be made on evaporated solids derived from the same filtered water sample.

4.1.1 Neutron activation analysis:

Values for elements in basic waters: Na, K, Rb, Cs, Ca, Ba, Sr, Zn, As, Mo, Se, Sb, W, Mn, U, Br.
Limits for elements which may or may not be detected in basic waters: Sc, Ti, V, Cr, Fe, Co, Ni, Cu, Ga, Ag, In, La, Ce, Nd, Sm, Eu, Tb, Dy, Yb, Lu, Hf, Ta, Ir, Au, Cd, Th.

4.1.2 Soft X-ray fluorescence:

Na, Ca, K, Si, Mg, Al, Fe, Ti, total S, total P, Cl.

4.1.3 Hard X-ray fluorescence:

Pb, Sr, Rb, As, Zn, Cu, Ni, Fe, Mn.

4.1.4 The sample shall be filtered (0.2μ Nuclepore) from the subsampling carboys or directly from the spring into three 1-litre LPE containers. These containers shall be previously washed with distilled water and AR Acetone and rinsed twice with the formation water at the time of sampling.

4.2 Zeeman Atomic Absorption:

Pb, As, Cu, Cd, Ag, Cr.

4.2.1 Determinations shall be made on evaporated solids derived from the water sample described in 4.1.4.

4.3 Carbon Rod Atomic Absorption:

Ag, Cd, Cu, Fe, Ni, Pb, Zn.

4.3.1 The sample shall be filtered (0.2μ Nuclepore) into a 1-litre CPE container previously ethanol washed and leached for 3 days with 1:1 HCl; rinsed with distilled water and leached for 3 days with 1:1 HNO_3; rinsed with distilled deionized water and leached for 3 days with 0.5% HNO_3; rinsed and stored with distilled deionized water until used and supplied with 5 ml of NBS 15.8 M HNO_3 for preservation of sample until analysis.

4.4 Mass Spectrometry of Gases:

H_2, N_2, O_2, Ar, CO, CH_4, CO_2, SO_2. H_2S, He.

4.4.1 Samples shall be collected in 1-litre stainless steel vacuum bottles (Whitey 304-HDF4-1000) previously evacuated at LBL. Helium-3 and krypton shall be added in carbon tetrafluoride carrier gas at the time of evacuation. This shall serve as an internal standard for the recovery of other noncondensible gases in the sampled water.

4.4.2 The sample bottle shall be connected to a stainless steel cross which has arms to a carbon tetrafluoride supply for purging the sample line, a vacúum pump for evacuating the cross and a teflon sample line connected to the sampling system or into a spring. This line shall carry swabbed water which has no atmospheric contamination into the sample bottle when the valve is opened to release the vacuum.

4.4.3 The actual purging and filling process shall be carried out in accordance with directions laid down by the analyst in charge of mass spectrometry of gases.

FIELD ANALYSIS LOG SHEET - GEOCHEMISTRY	Log Number:
Location: Well:	Sample Number:
Interval depth: Spring:	
Dates:	

Average Discharge: Total Discharge:

Sampling Remarks:

Contamination Monitoring

Time / Method													

Sample Analyses

pH	Redox (mV)	Temperature (°C)	Carbonate (mg/l)	Sulfide (mg/l)	Alkalinity (mg/l)	Dissolved O_2 (mg/l)	Conductance (μS/cm)

Sample Collection

CHEMISTRY								ISOTOPES			
NAA/XRF	AA	Gases	^{14}C	^{3}H	^{222}Rn	$^{234}U/^{258}U$	$^{12}C/^{13}C$	$^{18}O/^{16}O$	H/D	$^{34}SO_4/^{32}SO_4$	$^{34}SH/^{32}SH$

Analysis Remarks:

LBL Engineer:
Date:

U.S.GPO:1979-689-058(F)40

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